

**QUANTIFICATION OF ROCKS WETTABILITY USING
DIELECTRIC MEASUREMENTS**

BY

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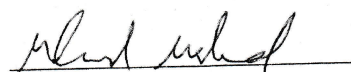


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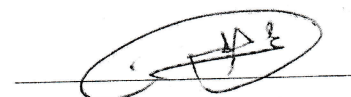


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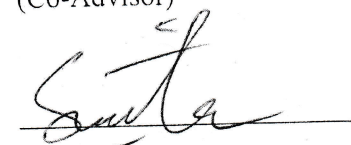
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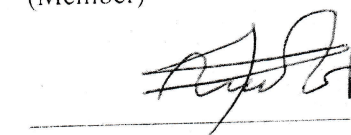
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This work is in the memorial of my brother, Yahya, who passed away on 06-Jul-2015 (May Allah shower him with mercy and grant him the paradise)

I Dedicate this work to:

My Mother,

My Father,

My Wife,

My Children,

My Brothers,

My Sisters,

and my dear friends,

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Above all, I am deeply grateful to Allah Ta'ala for keeping me well and strong during my incredible journey studying at one of the most prestigious universities worldwide, King Fahd University of Petroleum and Minerals. All glory belongs to the Almighty Allah for sending among us his prophet, Muhammed peace upon him, who taught us to Seek knowledge from the cradle to the grave, and bestowed upon me wisdom, expertise, and experience which enabled me to accomplish my master thesis dissertation.

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ABSTRACT

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Wettability is a crucial parameter which governs several petrophysical attributes of oil and gas bearing rocks. However, the traditional methods to measure the wettability are restricted to lab techniques which makes that measurement expensive and time-consuming. Therefore, the trend now is to utilize the down-hole logging tools to acquire this measurement while drilling without the need to extract any core samples. The NMR and dielectric logging are frequency-based measurements which are sensitive to wettability conditions. The distinctively high value of water's dielectric constant compared to oil and rocks helps in the direct petrophysical characterization of rocks. The scope of this research is to investigate closely the response of the dielectric measurements to the wettability changes in sandstone and carbonate rocks and to develop an empirical correlation to evaluate the wettability index using dielectric. A pair of standard sandstone and limestone samples (master and sister) were used in the study. A delicate procedure was followed to alter the wettability of the sister sample without compromising the pore structure. The USBM and NMR wettability indexes will be used for benchmarking the developed dielectric wettability index. The dielectric response showed a good correlation with the wettability condition of the samples. Uniquely in our study, the dielectric measurements were compared for the same samples before and after wettability alteration at $S_w = 1$. The imaginary permittivity and conductivity results at 10 MHz showed an linear relationship with the difference in the USBM wettability index with a coefficient of determination (R^2) of 0.9619. Furthermore, the dielectric measurements for the master samples were compared against the measurements for the treated sample at different water saturation endpoints, $S_w = 1$, S_{wirr1} , S_{or} , and S_{wirr2} . A linear relationship was observed between the wettability index of each sample and the drop in its imaginary permittivity and conductivity at 10 MHz as its saturation moved from $S_w = 1$ to S_{wirr1} with an (R^2) of 0.87 for the imaginary and 0.92 for the conductivity. Based on the later linear relationship

between the imaginary permittivity and by incorporating other parameters that are sensitive to dielectric measurements and wettability conditions, the dielectric wettability index correlation was developed. The developed correlation was able to predict the USBM wettability index of 6 samples with R^2 of 0.97 and RMSE of 0.076. Overall, the study provides a thorough investigation of the dielectric response to the wettability conditions at different saturations which was then utilized to develop an empirical correlation to calculate wettability index using dielectric. This research paves the road for extending the dielectric measurements to other petrophysical applications and utilizing them to build other empirical models that describe the fluid-rock and fluid-fluid interactions.

ملخص الرسالة

الاسم الكامل: علي عبد الوهاب عشيّش

عنوان الرسالة: القياس الكمي لقابلية بلل الصخور باستخدام القياسات العازلة الكهربائية

التخصص: هندسة البترول

تاريخ الدرجة العلمية: ديسمبر 2023

قابلية البلل هي خاصية مهمة تتحكم في العديد من السمات البتروفيزيائية للصخور المحتوية على النفط والغاز. ومع ذلك، فإن الطرق التقليدية المستخدمة في صناعة النفط والغاز لقياس قابلية البلل معقدة ومكلفة وتستغرق وقتاً طويلاً. لذلك، فإن الاتجاه الآن هو استخدام أدوات السجل الجيولوجي للحصول على هذا القياس أثناء الحفر دون الحاجة إلى استخراج أي عينات إلى السطح. إن الرنين المغناطيسي وقياس العزل الكهربائي هما قياسات تعتمد على التردد مما يجعلها حساسة لظروف قابلية البلل. يساعد التباين في الثوابت العازلة للصخور والنفط والماء في التوصيف المباشر للخصائص البتروفيزيائية للصخور. على الرغم من أن هناك العديد من الدراسات التي حاولت التحقيق في تأثير التغيرات في قابلية البلل على القياسات العازلة الكهربائية، لا توجد معادلة مباشرة مخصصة لتقييم مؤشر قابلية البلل باستخدام القياسات العازلة الكهربائية. نطاق هذا البحث هو التحقيق عن كثب في استجابة القياسات العازلة للتغيرات في قابلية البلل في الصخور الرملية والجيرية وتطوير معادلة تجريبية لتقييم مؤشر قابلية البلل باستخدام القياسات العازلة الكهربائية. تم استخدام زوج من عينات الحجر الرملي والحجر الجيري (رئيسية وشقيقة) في الدراسة. تم اتباع إجراء دقيق لتغيير قابلية البلل للعينة الشقيقة دون المساس بهيكل المسام. تم استخدام مؤشرات قابلية البلل (مؤشر مكتب التعدين بالولايات المتحدة الأمريكية ومؤشر قابلية البلل بالرنين المغناطيسي) لمطابقة المعادلة التي تم تطويرها. بشكل منفرد في دراستنا، تمت مقارنة قياسات العازل لنفس العينات قبل وبعد تغيير قابلية البلل عند درجات تشبع كامل بالماء. أظهرت نتائج الجزء التخلي للعدد المركب الخاص بثابت العازل الكهربائي والتوصيل الكهربائي عند 10 ميغاهيرتز علاقة خطية متناسبة مع الفرق في مؤشر قابلية البلل المستنتج بطريقة مكتب التعدين بالولايات المتحدة الأمريكية بمعامل تحديد 0.96. علاوة على ذلك، تمت مقارنة قياسات العازل الكهربائي للعينات الرئيسية بالقياسات الخاصة بالعينة المعالجة في نقاط نهاية تشبع المياه المختلفة. لوحظت علاقة خطية بين مؤشر قابلية البلل لكل عينة والانخفاض في الجزء التخلي للعدد المركب الخاص بثابت العازل الكهربائي والتوصيل الكهربائي عند 10 ميغاهيرتز عندما ينتقل التشبع المائي من 100% إلى قيمة التشبع المائي غير القابل للاستخراج مع معامل تحديد قدره 0.87 للجزء التخلي الخاص بثابت العازل الكهربائي و0.92 لقيم التوصيل الكهربائي. بناءً على هذه العلاقة الخطية الأخيرة وباستخدام قيمة العزل الكهربائي للماء والزيت وباستخدام قيم تشبع المياه العظمى والصغرى تم بناء المعادلة التجريبية لقياس مؤشر قابلية البلل والتي استطاعت التنبؤ بمؤشر مكتب التعدين بالولايات المتحدة الأمريكية لست عينات بمعامل تحديد قدره 0.97 وخطأ معياري قدره 0.0760. بشكل عام، توفر الدراسة تحقيقاً شاملاً لاستجابة قياسات العازل الكهربائي لحالات قابلية البلل المختلفة عند قيم تشبع مائي مختلفة والتي تم استخدامها فيما بعد لتطوير علاقة تجريبية لحساب مؤشر قابلية البلل باستخدام العازل الكهربائي. يمهّد هذا البحث الطريق لتوسيع قياسات العازل إلى التطبيقات البتروفيزيائية الأخرى واستخدامها لبناء نماذج تجريبية أخرى تصف التفاعلات بين السوائل والصخور وبين السوائل المختلفة التي تملأ مسامات تلك الصخور.

CHAPTER 1

INTRODUCTION

1.1. General Overview about Rocks Wettability

Rocks wettability can be defined as the preference of a solid grains to attract one fluid, known as the wetting phase, rather than another (Cassie and Baxter, 1944; Tanaka, 2001; Kubiak et al., 2011; Ghalami et al., 2019). The wetting phase will tend to spread on the grains' surface in the porous medium and fill the tiny pores including the pore throats (Vizika and Lombard, 1996; Sharma and Filoco, 2000; Kumar and Prabhu, 2007; Huang and Gates, 2020). This wetting mechanism forces the non-wetting phase to accumulate in the middle of larger pores as inclusions (Al-Mahrooqi et al., 2003; Jiang et al., 2013; Abbasi et al., 2021). Wettability defines the fluid-rock interaction in the porous medium and shapes the fluids distribution profile in the reservoir (Morrow, 1990; Robin et al., 1995; Abdallah et al., 2007; Al-Garadi et al., 2022; Yang et al., 2021; Selem et al., 2021). It plays a significant role in optimizing oil recovery (Morrow, 1990; Agbalaka et al., 2008). For hydrocarbon bearing rocks, the wettability controls the capillary forces and the relative movement of each fluid comparing to the other in the porous medium. Therefore, the wetting preference of the formation to oil or water influences many reservoir performance parameters, particularly its response to water flooding and enhance oil recovery (EOR) techniques (Zhao et al., 2010; Wang et al., 2011; Manshad et al., 2017; Liu and Wang, 2020). Thus, not considering the wettability or wrongly interpreting it, while designing the EOR process, could lead to irreversible damage to the formation which may severely impact the recovery (Abdallah et al., 2007; Humphry et al., 2014; Deng et al., 2020; Bai et al., 2021). **Figure 1** shows how the oil gets trapped in the pores of both water wet and oil wet rock systems during water flooding processes.

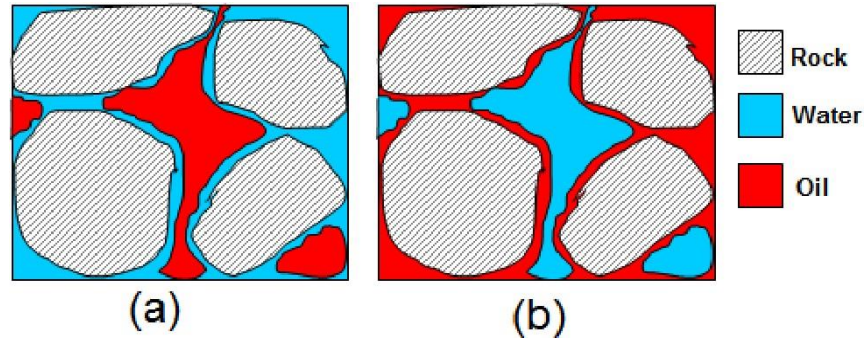


Figure 1 Oil entrapment in both; water wet (a) and oil wet (b) rock systems during water flooding operation. (after Salehi, 2009).

Usually, the entrapment of the oil in the porous medium, which is a common issue for maximizing recovery, happens through two different mechanisms; the adsorption to rock surface and snap-off mechanisms. In strongly water wet systems, the non-wetting oil tends to be trapped as isolated inclusions in the pores using the snap-off mechanism. As a thick layer of water is built on the walls of the pore throats while flowing, the oil droplets will snap and get trapped inside the pore bodies (Kazemi et al., 2022 and Singh et al., 2017). On the other hand, in oil-wet rock systems, the rock grain has larger affinity to oil molecules and hence oil gets adsorbed on the grains surfaces. **Figure 2** illustrates both trapping mechanisms for oil phases in water-wet and oil-wet rock systems. It can be comprehended from oil entrapment mechanisms that more residual oil and less recovery are associated with the two extreme wettability conditions, strongly water-wet and strongly oil-wet, whereas oil can be easily extracted at the mixed or intermediate wettability conditions. Therefore, reducing the intensity of oil and water witnesses towards mixed wettability conditions, which is the widely implemented practice in chemical enhanced oil recovery, helps significantly in releasing the trapped oil and maximizing the recovery, as reported by several oilfield records (Morrow, 1990 and Agbalaka et al., 2008).

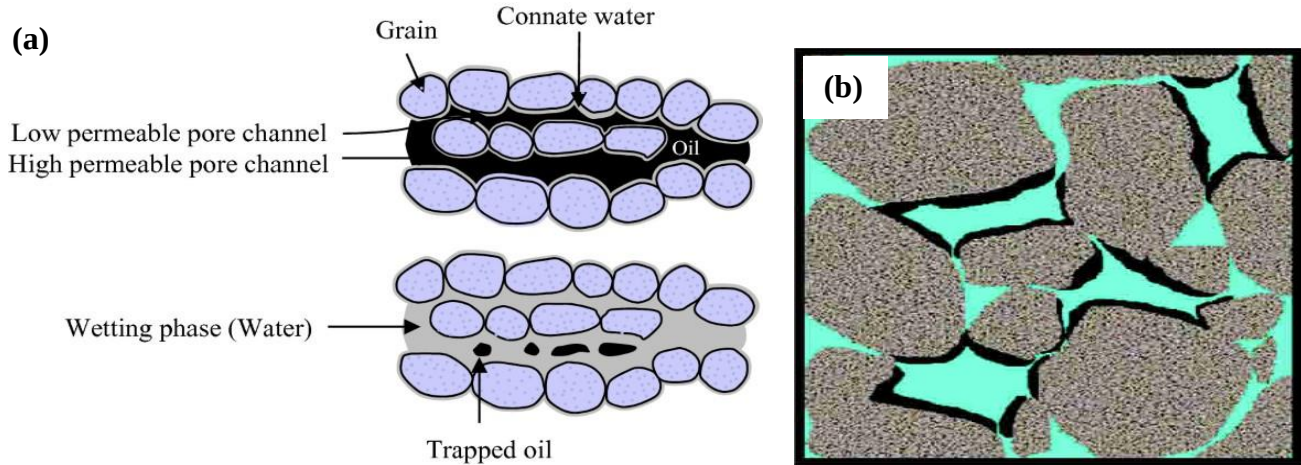


Figure 2 Oil entrapment using: (a) snap-off mechanism in water-wet systems (after Kazemi et al., 2022). (b) Adsorption on the rock grains in oil-wet rock systems (Black color represents the oil and green color represents the water). (Freedman et al., 2003).

1.2. The Impact of Wettability on the Petrophysical Characteristics of Porous Rocks

In this section, the fundamental concepts of electrical double layer and fluids distribution in the porous medium are to be discussed, which are the main concepts used to drive wettability index model using the dielectric measurements. Wettability is the responsible factor for controlling the relative flow of different fluids and shaping their distribution in the porous medium which impacts the recovery efficiency of reservoir rocks (Al-Garadi et al., 2022; Mirzaei-Paiaman, 2021; Mirzaei-Paiaman et al., 2022). The entire wettability spectrum of oil and gas reservoirs ranges from strongly water-wet to strongly oil-wet reservoirs. The rock structure consists mainly of pore spaces and solid grains. Pore sizes range from tiny pores (microscopic) to large ones (macroscopic). Anselmetti et al. (1998) set the boundary line between macro-porosity and micro-porosity as a 2-D surface area of $500 \mu m^2$, which is approximately projected to a pore length of approximately $20 \mu m$ (Baechle et al., 2004). Moreover, the pore structure consists of relatively larger pore bodies and tighter pore throats which connect pores together. On the other hand, fluid distribution in the pore spaces is not always homogeneous, especially when more than one fluid co-exists with different degrees of wettability. As illustrated in **Figure 1**, the wetting phase usually covers the surface of large grains and fills the tiny pores and pores' throats while the non-wetting phase fills the large bodies (Toumelin et al., 2008; Abdallah et al., 2007).

Wettability is the main factor that controls the fluid distribution in the pore spaces through its strong impact on the following parameters:

- (a) The fluid distribution in the micro and macro pore spaces.
- (b) The saturation amount of the irreducible water.
- (c) The performance of any immiscible displacement in the porous medium
- (d) The saturation of the residual oil.
- (e) Shapes the capillary pressure, relative permeability, and electrical properties curves of the porous medium.

1.2.1. Electrical Double Layer (EDL)

The electrochemical interactions between the grain and clay surfaces and ionic-active wetting phase form what is called the Stern and Gouy-Chapman layer, Electric Double Layers (EDL) (Garcia and Heidari, 2018). The Stern layer is the electrically static layer which contains the charges that are adsorbed by the surface of the grains while the other one has loose ions that are free to move. Consequently, a diffusive layer is formed in the area between the stern layer and the bulk fluid. **Figure 3** illustrates the structure of the EDL and describes the charge distribution around the negatively charged grain particles. However, the EDL is developed only when there is an ionic activity between grains and an electrolytic wetting phase. Therefore, EDL usually disappears in polar oil-wetting conditions (Garcia and Heidari, 2018). This characteristic greatly helps in distinguishing water-wet media from oil-wet ones. Furthermore, when EDL exists, the electrical activity in the diffusive layer can be measured by what is called zeta potential (Fatehah et al., 2014).

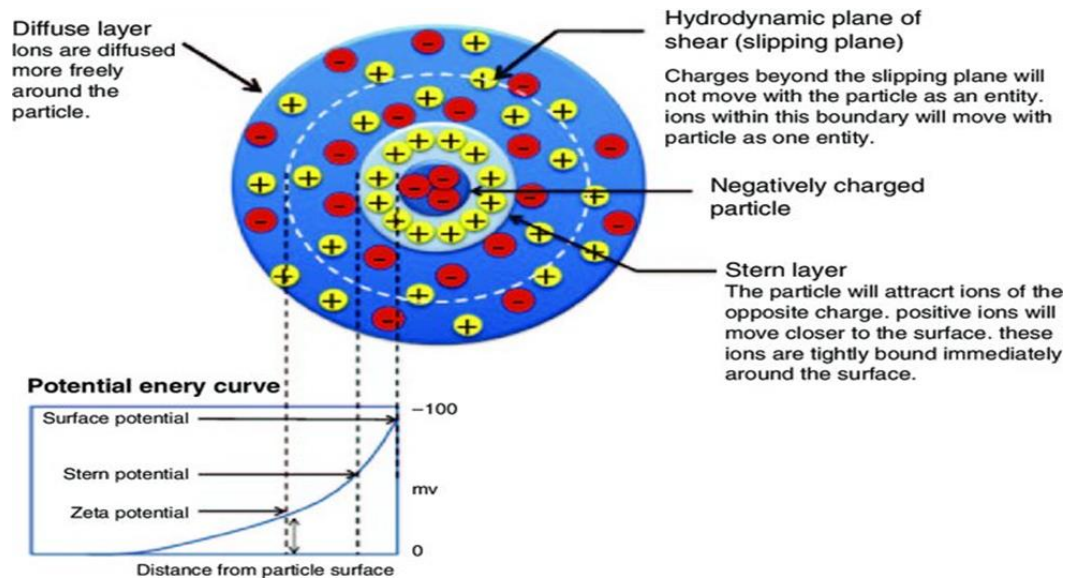


Figure 3 A schematic describes the profile of the electrolyte fluid-solid interface (After Fatehah et al., 2014).

Most reservoir rocks can be classified as partially or mixed-wet rocks due to the different drainage and imbibition cycles that the reservoir was exposed to. This nature of wettability can be assumed by either the presence of a combination of water and hydrocarbon-wet grains or the grain partially water wet and partially oil-wet (Abdallah et al., 2007). When the oil escapes from the source rock to water-wet-saturated pores during what is called the drainage process, it ends up residing in the larger pores while keeping the smallest pores saturated with water (Montaron, 2007). Furthermore, the dominant wettability of the matrix grains could be altered by the adsorption of organic polar materials on grain surfaces. This adsorption could yield to the presence of some oil-wet surfaces in a water-wet rock which makes it a fractionally water-oil wet rock. The fraction of the porous medium corresponding to water-wet can be defined as the fractional water wettability index, X_w (Montaron, 2007 and 2009; Garcia et al., 2018). A water-wet formation has a fractional water wettability index equal to one. An oil-wet formation, on the other hand, has a fractional wettability index, X_w , equal to zero. Therefore, an Amott index of -1 and +1 correspond to X_w of zero and one, respectively. However, the relationship between the Amott-Harvey index and X_w might not be linear and needs further investigation. X_w has been used in a couple of studies which will be discussed later.

1.2.2. Fluid-Fluid Interactions

Away from grain surfaces and pore throats, bulk fluid resides in the pore body. The non-wetting phase usually forms continuous or discontinuous inclusions within the wetting phase. The amount and size of inclusions depend on wetting and non-wetting phase saturations (Garcia and Heidari, 2018). If two or more immiscible fluids with different electrical properties exist in the pore spaces, an electrical double layer also develops at the fluid-fluid interface, creating a boundary between the two phases with a spatial distribution of electrical charges (Volkov et al., 1996). However, in the presence of only one phase, this layer disappears, and the inclusion will represent only one fluid. The fluid-fluid interactions have a significant impact on the dielectric measurements especially at the low to medium frequency ranges (Bona et al., 2002). These interactions masks the dielectric response under the lowest frequency range utilized in our study.

1.3. Wettability Measurement

Although obtaining an absolute wettability measurement is significantly challenging, there are several methods utilized to measure the wettability. Contact angle is one of these methods which requires a very fine surface for the sample to be measured. It can be defined as the angle that resulted from the balance of all surface tension forces between the fluid phases and the solid surface, as illustrated **Figure 4** (Singh et al., 2016; Siddiqui et al., 2018; Sadeghinezhad et al., 2020). The magnitude of the contact angle is controlled by multiple forces, called the interfacial tensions. These forces are illustrated in **Figure 4**. There are two opposite tension forces applied by the solid surface at the interface between liquid and its vapor. One of these forces attracts the liquid phase and is called solid-liquid surface tension, γ_{sl} , while the other force attracts the vapor and it is called solid-vapor surface tension, γ_{sv} . Because of both forces, a contact angle and a resultant interfacial tension between the fluid and its vapor are formed.

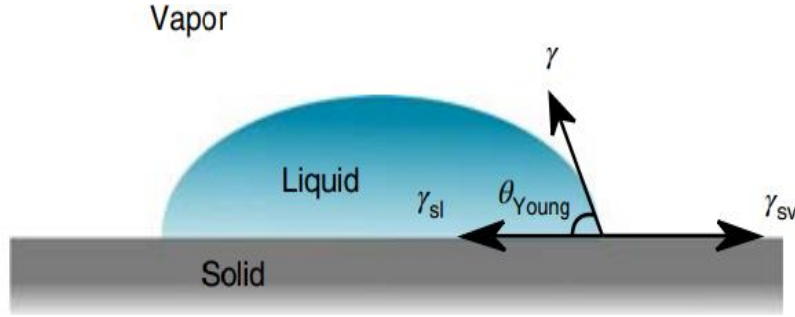


Figure 4 Contact angle and interfacial tension forces which control the wettability conditions. γ_{sl} is solid-liquid surface tension while γ_{sv} is solid-vapor surface tension. γ is the interfacial tension resulted from both surface tensions. The angle, θ between γ and solid surface is the contact angle. (After Huhtamäki et al., 2018).

Practically, measuring the contact angle for core samples is associated with large uncertainties due to surface roughness and contamination (Iglauer et al., 2014 and Al-Yaseri et al. 2022). Furthermore, contact angle cannot represent the wettability status concerning the oil and gas production because it focuses more on the surface interactions between grain surface and fluids and ignore the other factors impacting the flow such as the presence of multi-fluid with complex distribution, pores size distribution and the pores structure complexity (Teklu et al., 2015; Mohammed and Babadagli, 2015; Al-Yaseri et al., 2016; Siddiqui et al., 2018; Ferrari et al., 2021; Arif et al., 2021). In general, the competition between different fluids during the flow is governed by the capillary pressure, P_c , can be defined by:

$$P_c = P_{nw} - P_w = \frac{2\gamma \cos \theta}{r} \quad (1)$$

Where,

- P_{nw} and P_w are the pressure of the non-wetting phase and the wetting phase, respectively.
- γ is the interfacial tension between the wetting phase, non-wetting phase, and the grain surface.
- θ is the contact angle in radian.
- r is the pore or pore throat size.

As equation (1) shows, the capillary pressure does not depend solely on the contact angle. It's highly affected by pores and pore throat sizes. This is why more representative measurement methods have been developed to quantify the wettability through what is called “wettability indices” which can comprehend all the parameters involved in the capillary pressure equation (Huang et al., 1997; Mohammed and Babadagli, 2015; Rahbar et al., 2018). In the industry, there are two widely used methods to measure the

capillary-based wettability index in the laboratory such as Amott-Harvey (Amott, 1959; Alveskog et al., 1998; León-Pabón et al., 2014) and United States Bureau of Mines (USBM) (Donaldson, 1969; Esfandyari et al., 2021; Mirzaei-Paiaman, 2021). In addition, a combination of those methods can be utilized (Okasha et al., 2007; Donaldson and Alam, 2008; Al-Ofi et al., 2017). However, these methods are time-consuming, not feasible by downhole measurements, and are associated with some uncertainties caused by the unintentional fluid loss while handling the samples and wettability alteration due to the transportation of core samples from their origin to the laboratory (Mohammed and Babadagli, 2015; Al-Hilali et al., 2016; Tandon et al., 2017). Moreover, these techniques are inapplicable to gas-brine-rock systems and fail to construct a solid basis to obtain an absolute wettability measurement and describes the distribution of the pore fluids, but instead, they provide relative values based on some reference wettability status (Al-Garadi et al., 2022). Therefore, there has been a demand arisen to explore the response of different physics-related measurements to wettability (Ahmadi et al., 2019; Sharifigaliuk et al., 2021).

Several petrophysical measurements can be utilized to calculate the wettability index (Odusina et al., 2011; Tiab and Donaldson, 2015; Alhammadi et al., 2017; Javaheri et al., 2017). For example, NMR T2 relaxation has a strong sensitivity to wettability (Looyestijn and Hofman, 2006; Johannesen et al., 2007; Odusina et al., 2011; Al-Muthana et al., 2012; Baban et al., 2021; Al-Garadi et al., 2022). This technique has been utilized to find a wettability index by Al-Mahrooqi et al. (2006) and K. Al-Garadi et al. (2022). In our study, we have used the USBM and K. Al-Garadi et al. (2022) wettability indices to benchmark our dielectric wettability index correlation.

Like NMR measurements, the dielectric response is sensitive to the rock constituents, pore geometry, and the fluid distribution in the pore spaces (Bona et al., 1998 and 2002; Abdelaal et al., 2013; Al-Ofi et al., 2018; Garcia et al., 2021). The solid-fluid and fluid-fluid interactions characterized by the wettability, significantly affect the dielectric polarizations under a wide range of varying frequencies (Garrouch and Sharma, 1994; Nguyen et al., 1999; Garcia and Heidari, 2018). The different polarizations due to these interactions lead to varying permittivity and conductivity values concerning the applied frequency. One more fact that supports the potential of dielectric to measure the wettability index is the vast contrast in the electrical and properties between oil and water. Therefore, the purpose of this study is to formulate a relationship that can find the wettability index from dielectric measurement.

CHAPTER 2

DIELECTRIC THEORY

2.1. Conceptual Background

Chelidze and Gueguen, 1999 explained the theory behind the dielectric polarization in porous media concisely. Dielectric response is a special electrical characteristic which a material can exhibit when varying-frequency electrical field is applied. Applying multifrequency electrical field to an object can result in both reversible and irreversible displacement of electrical charges. The first response is usually measured by specific conductivity, σ , while the second response is measured by what is called permittivity, or dielectric constant, ϵ (Chelidze and Gueguen, 1999). A material is classified as “dielectric” if it has the ability to store energy when an external electric field is applied. In other words, the dielectric response of a material depends on its electrical capacitance. Whenever the system contains loose ions, it exhibits some type of charges polarization when it gets exposed to electrical field, $\mathbf{E}$. Negative and positive charges will move and accumulate separately based on the direction of the applied field.

The polarization can be described by vector, $\mathbf{P}$, which represents the induced electric dipole moment per unit volume. For DC voltages, the overall electrical displacement vector, $\mathbf{D}_e$, consists of the displacement generated by the electric field and the secondary displacement induced by the polarization, if any polarization occurs. Therefore, $\mathbf{D}_e$ can be expressed as:

$$\mathbf{D}_e = \epsilon \mathbf{E} \quad (2)$$

Where, ϵ is the dielectric permittivity of the material in Farad per meter (F/m) and the unit of $\mathbf{P}$ and $\mathbf{D}_e$ is (*Coloumb/m or C/m*). The units of σ and $\mathbf{E}$ are (*Siemens/m or S/m*) and (*Volt/m or V/m*) respectively. Similarly, the overall current generated, $\mathbf{I}_t$, in the system by an alternating voltage applied can be divided into conduction current, $\mathbf{I}_c$, and displacement current, $\mathbf{I}_d$. However, while measuring the dielectric, the voltage is sent in an alternating pattern generating alternating currents, AC. Therefore, the actual the value of the voltage at time, t , is expressed as $\mathbf{V} = \mathbf{E}(\omega, t) = \mathbf{V}_0 e^{(i\omega t)}$, where, ω is the angular frequency in radian/s and $\mathbf{V}_0$ is the peak voltage at time zero. Also, the conductivity and permittivity values under AC voltage will become complex number. To express the overall current:

$$\mathbf{I}_t = \mathbf{I}_c + \mathbf{I}_d \quad (3)$$

While,

$$\mathbf{I}_c = \sigma \mathbf{E} \text{ and } \mathbf{I}_d = \epsilon_d^* \frac{\partial \mathbf{E}}{\partial t} = \epsilon_d^* i\omega \mathbf{E} \quad (4)$$

Hence,

$$\mathbf{I}_t = (\sigma + \epsilon_d^* i\omega) \mathbf{E} = \sigma^* \mathbf{E} \quad (5)$$

Where,

ϵ_d^* is the complex dielectric permittivity resulted from the dielectric polarization with excluding the conductivity part and has 2 parts, real and imaginary. It can be written as $\epsilon_d^* = \epsilon' - i\epsilon''$, where, ϵ' is the real permittivity value and ϵ'' is the magnitude of the imaginary part and is defined as the energy dissipation (loss) due to polarization which occurs during situations such as the rotation of dipole molecules of an electrolyte. On the other hand, σ^* is the complex conductivity and can be written as $\sigma^* = \sigma + \epsilon_d^* i\omega$. Equation (5) can be written as either the following:

$$\mathbf{I}_t = i\omega \epsilon^* \mathbf{E} \text{ or } \mathbf{I}_t = \sigma^* \mathbf{E} \quad (6)$$

Where,

$$\epsilon^* = \epsilon_d^* + \frac{\sigma}{i\omega} = \epsilon' - i\left(\epsilon_d'' + \frac{\sigma}{\omega}\right) = \epsilon' - i\epsilon'' \quad (7)$$

$$\sigma^* = \sigma + \epsilon_d^* i\omega = i\omega \epsilon^* = \sigma' + i\sigma'' = i\omega (\epsilon' - i\epsilon'') \quad (8)$$

In equation 7, It worth to note that the magnitude of the imaginary part of the complex permittivity, which represents the loss of the dielectric signal in the material, consists of the loss due to dielectric polarization, ϵ_d'' , and the loss due to the ionic conduction or conductivity, $\frac{\sigma}{\omega}$. The loss term is primarily dominated by the presence of electrolytic solution within the material. We can express that by the following:

$$\epsilon'' = \epsilon_d'' + \frac{\sigma}{\omega} \quad (9)$$

Another important dielectric parameter is the ratio of the imaginary part of ϵ^* to the real part (or the real part of σ^* to the imaginary part) which is named by loss tangent,

$$\tan \delta = \frac{\epsilon''}{\epsilon'} = \frac{\sigma'}{\sigma''} \quad (10)$$

2.2. Dielectric Polarizations:

The dielectric measurement is normally displayed as a plot of ϵ'' , ϵ' or $\tan \delta$ versus the frequency, f , which can be obtained from the angular frequency by $f = \frac{\omega}{2\pi}$. The ionically lose material exhibits different

types of polarization which contribute to the overall permittivity. Several dielectric polarizations can be witnessed at the microscopic level such as ionic, dipolar, atomic, and electronic. **Figure 5** illustrates the dielectric behaviors corresponding to different polarization mechanisms and their appearance frequency. Each mechanism masks a certain bandwidth of frequency. For instance, dipolar orientation and ionic conduction are activated strongly at microwave frequencies. As an example, water molecules form permanent dipoles which rotate to follow an alternating electric field. On the other hand, atomic and electronic mechanisms produce low permittivity values and dominate the region of high frequency. Similar to NMR, each dielectric mechanism has its own cutoff frequency which is illustrated by peaks in the imaginary permittivity curve (see **figure 5**). These cutoffs are unique for each material. For example, water has a strong dipolar polarization which normally occurs at low frequencies, but its dipolar cutoff appears at frequency of around 22 GHz. On the other hand, Teflon has no dipolar mechanisms, and its permittivity is almost constant at low frequencies. As frequency increases, the contribution of slow mechanisms such as ionic and dipolar drop out leaving the stage for faster ones (atomic and electronic) to prevail in the real permittivity curve.

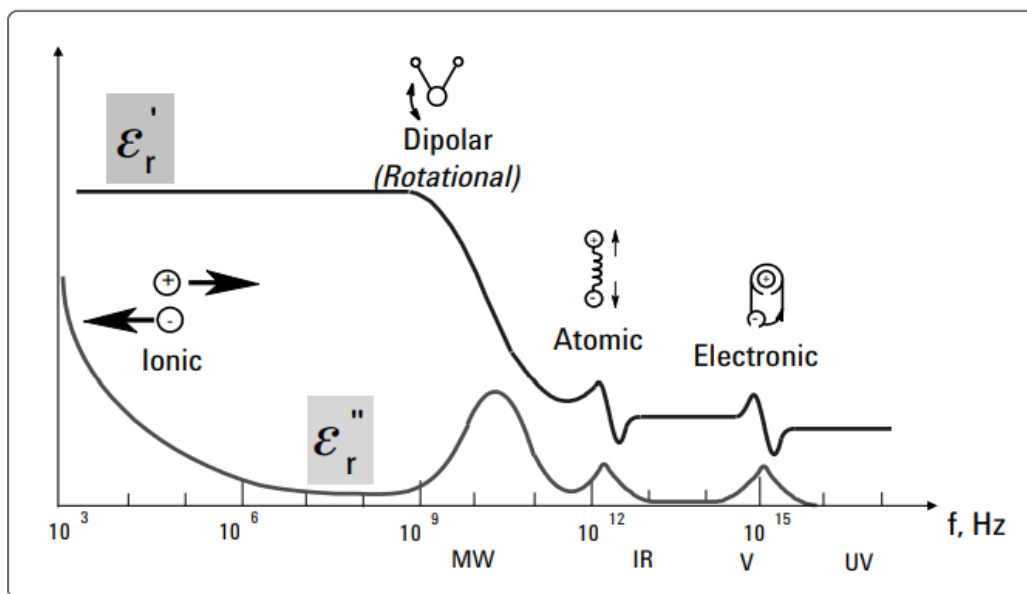


Figure 5 The general forms of dielectric polarizations (after Agilent Technologies).

2.2.1. Dipolar (Orientation) Polarization:

When atoms with different electronegativity combines to form a molecule, especially for molecules with covalent bonds, the atom with larger electronegative gains a greater fraction of the shared electrons and acquire partial negative charge while the other atom acquires partial positive charge. For example, HCl

forms a dipole with chloride has the partial negative sign and hydrogen gets the positive one (see **figure 6**).

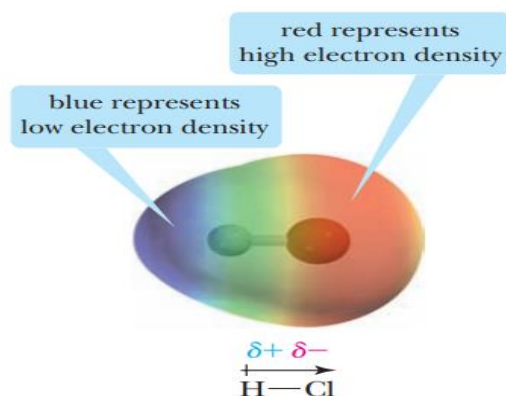


Figure 6 The electron density model of the HCl dipole (After Brown and Poon, 2014)

This rearrangement of electrons results in a charge distribution imbalance creating a permanent dipole moment which is randomly oriented in the absence of the electrical field (Agilent, 2006). Once the electrical field is applied, these dipoles will rotate and aligns in the direction of the electrical field. This is called dipolar or orientation polarization. Some dielectric losses due to friction are associated with the rotation which contribute to the imaginary part of the permittivity and loss tangent. The dipolar polarization causes variation (dispersion) in the ϵ'' and ϵ' curves at some the relaxation frequency which occur in the microwave frequency range. From the reciprocal of that frequency, an important dielectric property for loose materials is obtained which called Relaxation Time, τ . Fluids are the most common material which experience dipolar polarization.

2.2.2. Atomic and Electronic Polarization:

Atomic polarization is exhibited by different ions when the applied electrical field segregate the positive and negative ions a part. On the other hand, electronic polarization occurs when the electrical field stretch the negative electrons surrounding the atom apart from their positive nuclei. This type of polarization is dominant for dry solids at the microwave frequency level. However, some type of resonance starts at much higher frequency which mostly falls away from the frequency range of investigation. Under such frequency range, the atomic and electronic polarization produce relatively low values of ϵ' and they are mostly lossless (no contribution to ϵ'' and $\tan \delta$).

2.3. Relaxation Time, τ :

Relaxation time can be defined as time required for the dipoles to become aligned in the direction of the electrical field (or the time required for the aligned dipoles to return to back 1/e of its random equilibrium value). When the electrical field is turned on, the condensed solid and fluid starts to rotate and collide with each other to align in the direction of the electrical field within a period equals to the relaxation time. On the other hand, once the field is switched off, the molecules go back to their random distribution such that 1/e of their random equilibrium value is achieved within a similar period. This relaxation time corresponds to a critical frequency, f_c , which is obtained from dielectric plots. The relationship between the critical frequency and relaxation time can be expressed as the following:

$$\tau = \frac{1}{\omega_c} = \frac{1}{2\pi f_c} \quad (11)$$

At frequencies below the relaxation frequency, the alternating electrical field is not fast enough to orient all the dipoles and keep them in pace with the applied electrical field. On the other hand, larger frequencies are too fast such that the orientation cannot align in the direction of the electrical field. As the frequency increases below the relaxation frequency, the loss component, ϵ'' , is directly proportional to the frequency (see **figure 6**). However, as the frequency increases, the storage component, ϵ' , begins to decrease due to the phase lag between the electrical field and the dipole alignment.

2.4. Debye Relationship

The different types of dielectric polarization are mostly represented by an exponential decay relationship with governing parameters, τ , and maximum energy loss observed at f_c (Chelidze and Gueguen 1999; Debye 1929; Frolich 1990). This relationship is named Debye relaxation, and it is applicable for material which exhibit single constant frequency for relaxation. The complex permittivity can be expressed under this relationship as:

$$\epsilon^* = \epsilon' - i\epsilon'' = \epsilon_\infty + \frac{(\epsilon_s - \epsilon_\infty)}{(1 + i\omega\tau)} - i \frac{\sigma}{\omega} \quad (12)$$

Where,

ϵ_s is the static DC value of dielectric permittivity where the frequency equals to zero.

ϵ_∞ is the permittivity value at very high frequency.

For $\omega = 0$, $\epsilon(0) = \epsilon_s$ and For $\omega = \infty$, $\epsilon(\infty) = \epsilon_\infty$

Figure 7 illustrate the trend of ϵ' and ϵ'' following this relationship. As it can be seen, ϵ' shows constant value below and above f_c while ϵ'' shows very low values below and above f_c peaking at f_c . The curves were generated for water @ 30 °C with $\epsilon_s = 6.77 \times 10^{-12} \text{ F/m}$, $\epsilon_\infty = 4.34 \times 10^{-12} \text{ F/m}$ and $\tau = 7.2 \times 10^{-15} \text{ s}$.

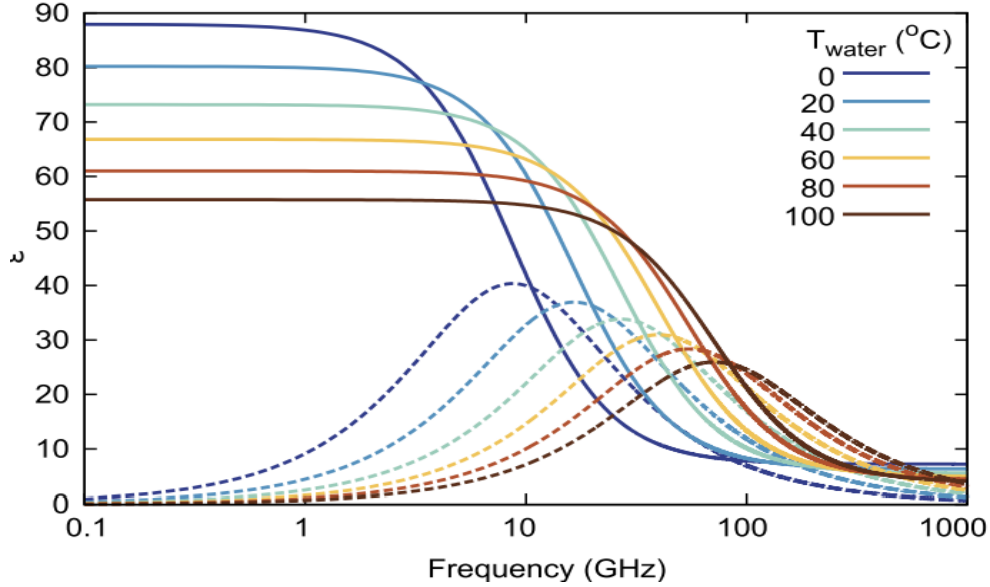


Figure 7 The Debye relationship describing the dielectric polarization of water at different temperature (Andryieuski et al., 2015). Continuous line represents ϵ' while the dotted line corresponds to ϵ'' .

2.5. Cole-Cole Empirical Expression:

The Cole & Cole (1941) empirical formula is more comprehensive than Debye relationship and has the advantage to describe the polarizations of materials exhibiting multiple relaxation times. This empirical expression describes the complex permittivity as the following:

$$\epsilon^* = \epsilon_{cc} - i \frac{\sigma}{\omega} \quad (13)$$

Where,

ϵ_{cc} is the Cole-Cole permittivity and can be written as:

$$\epsilon_{cc} = \epsilon_\infty + \frac{(\epsilon_s - \epsilon_\infty)}{1 + (i\omega\tau)^{1-\alpha}} \quad (14)$$

Where,

α is the Cole-Cole distribution function exponent.

The Cole-Cole diagram is constructed by plotting ϵ'' vs ϵ' . A material with single relaxation frequency will occur as a semicircle which has its center lying on the horizontal axis where $\epsilon'' = 0$ and the peak appearing at $1/\tau$. The peak corresponds to a value of $\frac{\epsilon_s - \epsilon_\infty}{2}$ which represents the radius of the semicircle.

Figure 8 displays the application of Cole-Cole diagram for the same material and with the same variables presented in **figure 7**.

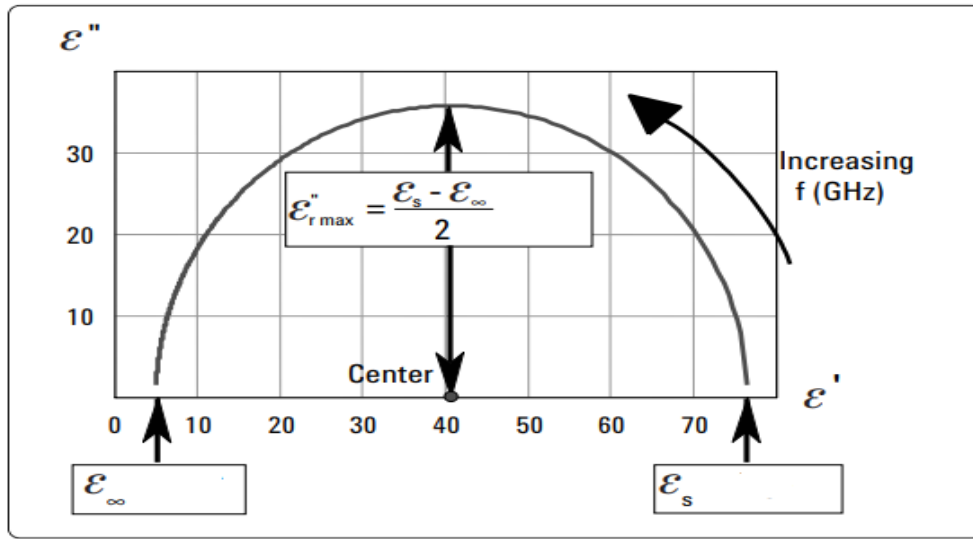


Figure 8 The Cole-Cole representation for the dielectric polarization (after Yurasov et al., 2020).

2.6. The Dielectric of Sedimentary Rocks:

The advantage of utilizing the dielectric measurement for the oil and gas reservoir rocks is the distinct variation between the permittivity and the conductivity values for the dry matrix and oil on one side and the dipolar water on the other side. **Table 1** illustrates the static permittivity and conductivity values for rock matrix and the potential saturating fluid.

Table 1 **Electrical properties of the materials (25°C) (Bona, 1998).**

Material	Static dielectric permittivity (Dimensionless)	100 Hz conductivity (S/m)
Dry matrix	3-7	$< 5 \times 10^{-5}$
Deionized water	78.8	1.57×10^{-3}
Brine with 75.8 g/l NaCl	67.0	9.5
Soltrol ¹	2.015	----

The dielectric permittivity of sedimentary rocks is a function of the composition, volume fraction, and spatial distribution of grains and fluids (Garcia et al., 2018). The dielectric approach can be implemented for fluid/rock or gas/fluid/rock systems; however, more consideration would be required for the case of gas/fluid/rock to ensure representative and repeatable measurements. In the oil and gas industry, the dielectric measurements of water and oil-saturated rocks are expressed by “generalized complex permittivity”, $\epsilon(\omega)$ (Bona et al., 1998):

$$\epsilon(\omega) = \epsilon_p(\omega) - i \frac{\sigma_{dc}}{\epsilon_0 \omega} \quad (15)$$

where, $i = \sqrt{-1}$ is the imaginary unit, $\epsilon_0 = 8.854 \times 10^{-12} \frac{\text{farad}}{\text{m}}$ is the vacuum permittivity, $\epsilon_p(\omega)$ is the permittivity contribution of all the occurring polarization effects, σ_{dc} is the DC water conductivity and $\epsilon(\omega)$ is the generalized complex permittivity that is measured in the laboratory. As it can be seen from 14, $\epsilon(\omega)$ is a sum of two terms:

- a. $\epsilon_p(\omega)$: Describes the interaction of matter with an external electric field. It is the permittivity that resulted from different types of polarization: electronic, atomic, dipole, and interfacial (or Maxwell-Wagner) polarizations. For water and oil-saturated rocks, the contributions of the first three mechanisms are always activated in the frequency range of investigation (100 Hz to 40 MHz) providing a constant contribution to $\epsilon_p(\omega)$. However, the Maxwell-Wagner (MW) polarization is the dominant contributor to the dispersion of the dielectric measurement in med to high frequencies and it is a frequency-dependent polarization (Bona et al., 1998). Therefore, the dispersion and variation of $\epsilon_p(\omega)$ with respect to frequency in the range of 100 Hz-40 MHz depends essentially

¹ Soltrol is an iso-paraffinic oil which has an ideal dielectric behavior, maintaining a static dielectric constant throughout the frequency range investigated and with negligible losses. (Bona et al., 1998).

on the MW polarization. $\epsilon_p(\omega)$ also consists of a real part and an imaginary part and can be written as:

$$\epsilon_p(\omega) = \epsilon'_p(\omega) - i\epsilon''_p(\omega) \quad (16)$$

- b. The real part of $\epsilon_p(\omega)$ is a measure of how much energy from the electric field is stored in the matter while the imaginary part is a measure of how dissipative or lossy the matter is in response to the electric field.
- c. $i \frac{\sigma_{dc}}{\epsilon_0 \omega}$: is the completely imaginary part that counts for the contribution of the free ions of the conductive pore-filling fluid, water. This effect is controlled by the DC conductivity, σ_{dc} . DC conductivity is a comprehensively used parameter in the oil and gas industry. It can be defined as the real part of the complex conductivity, $\sigma(\omega)$, at a very low frequency. For example, it has been utilized to express Archie's Law in terms of conductivity. (Bona et al., 1998 and 2002).

The type of polarization induced in the saturated porous medium by the multi-frequency electrical field varies widely, depending on the frequency applied. It can be divided into low and high-frequency polarizations. At low frequencies, dielectric dispersion results from the ionic polarization at the fluid-fluid and fluid-solid interface. In the medium to high-frequency range, dipolar, atomic, and electronic activities contribute to the dielectric measurements, see **Figure 9**. In this figure, yellow lines present components of the imaginary part of the dielectric constant; polarization loss and conductivity loss. The red line is the combined effect of both components on imaginary permittivity. The blue line represents the behavior of the real part of the complex permittivity because of different polarizations.

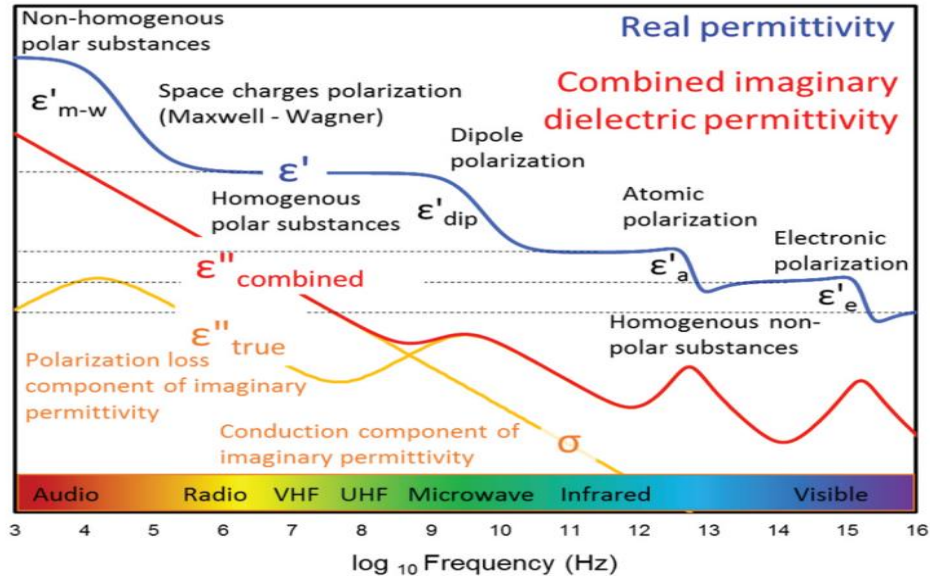


Figure 9 Multi-frequency dielectric measurements affected by different types of polarizations (after Josh (2014) who modified it from Guéguen and Palciauskas, 1994).

However, the available frequency bandwidth for our dielectric instrument ranges from 10 MHz to 3 GHz. In this range, expected polarization also can be classified into lower frequency and high-frequency polarizations. Low-frequency polarization is the one affected strongly by wettability and can also be classified into two categories, double layer α -Polarization and Maxwell-Wagner β -Polarization (See **Figure 10**).

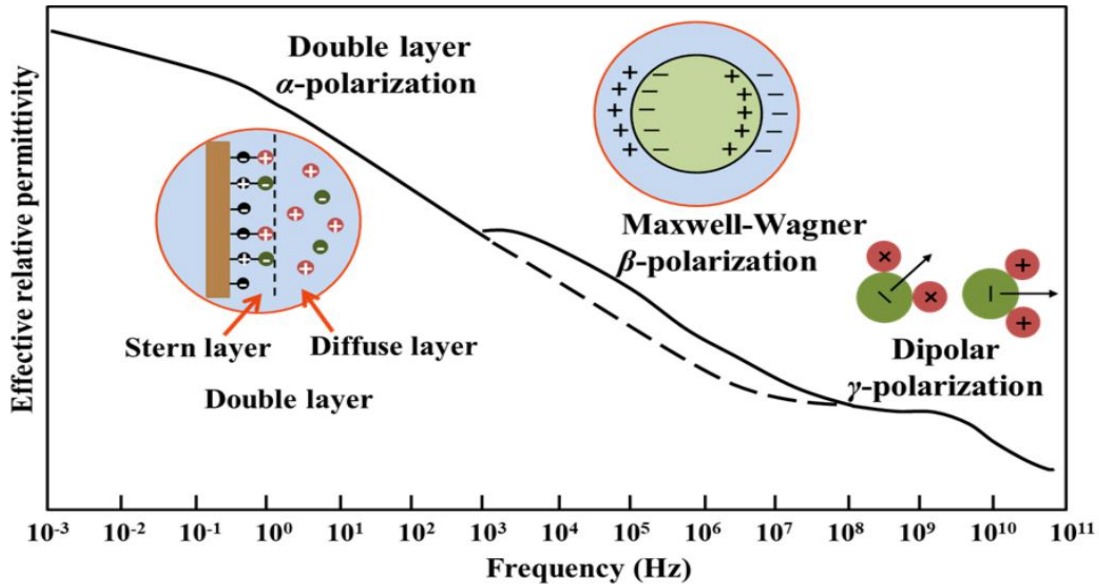


Figure 10 The polarization mechanisms responsible for dielectric dispersion in a porous medium (after Garcia and Heidari, 2018).

2.6.1. Low-Frequency Polarizations

The effects of wettability on dielectric properties of a rock can be classified into two categories: connectivity effects (at low frequencies, below 1 kHz) which occur close to the double layer area, and shape effects that occur due to the presence of fluid inclusions and fluid-fluid interactions (at intermediate to high frequencies, above 10 kHz) (Garcia and Heidari, 2018).

a. Double Layer α - Polarization

This type of polarization occurs at low frequencies, below 1 kHz. It's the polarization that occurs because of the mineral-electrolyte interface on the grain surface. This polarization is described the best by the ionic polarization. This happens when the grain surface is electrically charged and attracts some ions from the electrolyte fluid. The thermal motion of the ions in that area prevents the complete cancelation of electrical charges which consequently causes a high dielectric permittivity reading at such low frequencies (Garcia and Heidari, 2018). Due to these ions' thermal motion, this type of polarization is called charge transport or ionic polarization. However, in the absence of a conductive wetting phase on the grain surface, the response of the dielectric at this frequency will be relatively low.

b. Maxwell-Wagner β -Polarization

At frequencies higher than the α -polarization frequencies, the Maxwell-Wagner β -Polarization is initiated when two fluids having a contrast in their conductivities are present in the pore spaces. It is a result of the charge accumulation at two conductive fluids separated by nonconductive region. In other words, it appears in the interface between two fluids with different relaxation times for the charge carrier in each fluid. This polarization is effective to identify non-wetting phase inclusions within the wetting fluid.

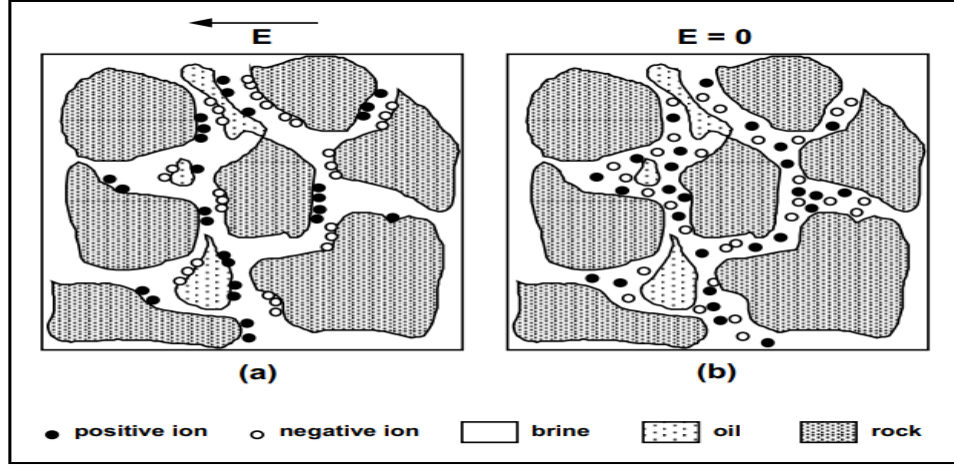


Figure 11 The Maxwell-Wagner (MW) polarization in a water-wet system which consists of brine, oil, and grains at irreducible water saturation (after Garcia and Heidari, 2018).

2.6.2. High-Frequency Polarizations (Dipole γ -polarization)

This type of polarization is called Dipole γ -polarization and occurs at frequencies greater than (10^8 Hz). It is activated when the frequency becomes high in a level that does not allow the previously mentioned relaxations to occur and only the relaxation resulting from the aligning of the polar water molecules, whether they are bound or free, will be dominant (Garcia and Heidari, 2018). Thus, at such a high frequency, the reflected dielectric signal will be sensitive to the presence of water molecules only despite their salinity or mobility. This frequency range is utilized in the dielectric logging tool which obtains direct water saturations. Also, the influence of the saturation effect on the dielectric wettability measurement can be analyzed.

The polarizations mentioned earlier have a different contribution to the calculated permittivity and conductivity. The Maxwell-Wagner polarization can be expressed in the simplest form by the following (Bona et al., 1998):

$$\epsilon_p(\omega) = \epsilon_\infty + \frac{\Delta\epsilon}{1+i\omega\tau} \quad (17)$$

Where, ϵ_∞ is an unrelaxed dielectric constant which can be taken as the asymptotic real permittivity value at very high frequency, $\Delta\epsilon$ is the relaxation amplitude ($\epsilon_s - \epsilon_\infty$) mentioned in eq. 12 and 14. Relaxation time, τ , amplitude $\Delta\epsilon$, and ϵ_∞ are dependent on the electrical properties of the grains and fluid and on the distribution of the fluid in the porous medium. $\frac{\Delta\epsilon}{1+i\omega\tau}$ can be called ϵ_{MW} . Sillars (1937) tried to develop expressions to find parameters mentioned in equations (18, 19, and 20). A 2-phase system was used to

calculate those parameters. The resistive phase is the rock and oil saturating the pores while the conductive part is assumed to be only the disperse of water. Assuming the water to take the shape of a spherical inclusion, the parameters were expressed in the following equations:

$$\tau = \epsilon_0 \frac{\epsilon_m(\beta-1)+\epsilon_w}{\sigma_{dc}} \quad (18)$$

$$\Delta\epsilon = \frac{\epsilon_m^2 \varphi S_w g \beta^2}{\epsilon_m(\beta-1)+\epsilon_w} \quad (19)$$

$$\epsilon_\infty = \epsilon_m \left[1 + \frac{(\epsilon_w - \epsilon_m) \varphi S_w g \beta}{\epsilon_m(\beta-1)+\epsilon_w} \right] \quad (20)$$

Where, ϵ_m is the permittivity of the insulating phase (matrix and oil), ϵ_w is the permittivity of the water, σ_{dc} is the DC conductivity of the water, β is the shape parameter for water inclusions (for spherical inclusion, $\beta = 3$, and for the elongated wetting phase spreading $\beta \gg 3$), g is orientation factor.

However, many measurements on sandstone samples did not agree with equation 17. They involved a new interaction that increased the dielectric response at mainly very low frequencies (less than 1 kHz). This happens when there is some type of charges transport activity at the interface between the grain's surface and the wetting conductive fluid which increase the response by the amount of $\epsilon_{PL}(\omega)$. This effect can be seen in the case of water-wet rocks or rocks with high clay content (Bona et al., 1998):

$$\epsilon_{PL}(\omega) = A \frac{(i\omega)^{N-1}}{\epsilon_0} \quad (21)$$

Where, A is the effective cross-sectional area of the sample and $0 \leq N \leq 1$.

Theoretically, the reading of the dielectric constant should equal the sum of the contribution of all types of polarizations that occurs at a certain frequency. Bona et al. (1998) showed that at frequencies ranges from 100 Hz to 10 GHz, the dielectric response can be described well by the mixed contributions of an unrelaxed dielectric constant ϵ_∞ , Maxwell-Wagner polarization contribution, $\epsilon_{MW}(\omega)$, and the EDL charge transport polarization, $\epsilon_{PL}(\omega)$:

$$\epsilon(\omega) = \epsilon_\infty + \epsilon_{PL}(\omega) + \epsilon_{MW}(\omega) \quad (22)$$

In conclusion, wettability plays a significant role in shaping dielectric dispersion, especially at low frequencies. At low water saturation, oil-wet samples show significantly low dielectric constant values at

low-MHz frequency bandwidth (Al-Ofi et al., 2017). Thus, dielectric technique is considered a highly promising wettability indicator, and this study will focus on finding a methodology to obtain an accurate wettability index.

2.7. Dielectric Acquisition

The dielectric properties of the core samples were surveyed using a network analyzer which measures the reflection from and/or transmission through a material. With the knowledge of the dimensions, the instrument will process the signal and generate different forms of dielectric measurements. The device can sweep high frequency stimulus-response survey from 3 kHz to 110 GHz. However, the measurement frequency range depends on the type of detector that will be used. The network analyzer consists of a signal source, receiver, and display (see **figure 12**). The source emits a signal at a single frequency to the sample under investigation. Simultaneously, the receiver is tuned to that frequency to detect the reflected signals from the material under test (MUT). The main outputs of the measurement are the magnitude of the reflected signal and the phase shift at that frequency. Then, the source will shift to the next frequency and follow the same process till the frequency bandwidth is totally covered. Finally, the reflection magnitude and phase shift will be plotted as a function of the frequency on the display. The device is usually calibrated on 3 points, two end points (short and open) and one point in between of known load. Different measuring instruments can be adapted for the measurement including coaxial probe, transmission line, free space, resonant cavity, and parallel plate. Each setup has its own characteristics, advantages, and measurement restrictions (see **figure 13**).

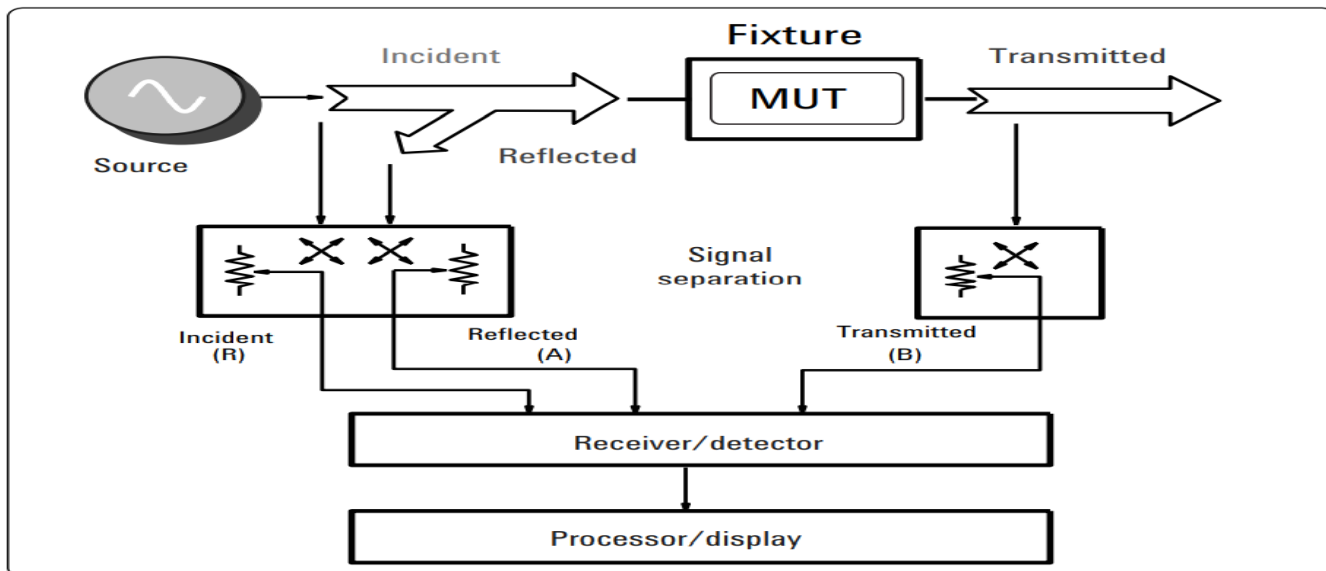


Figure 12 The process flow of the dielectric measurement obtained by the network analyzer (after Agilent Technologies)

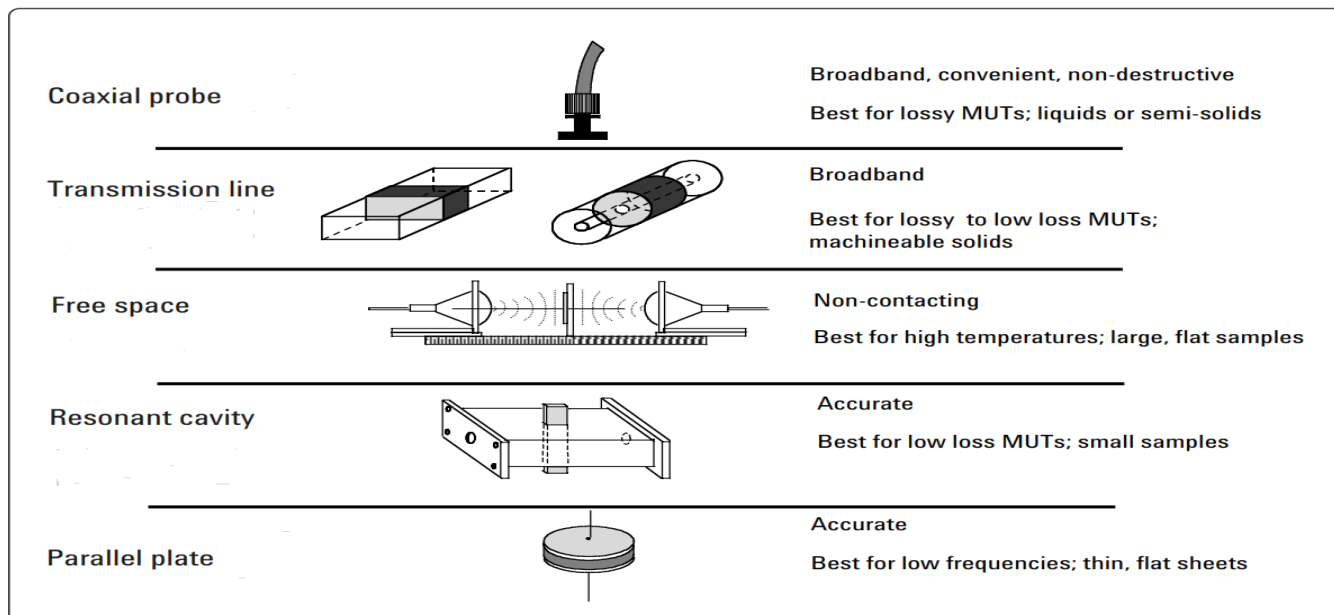


Figure 13 Comparison between the different dielectric detecting fixtures utilized by the network analyzer (after Agilent Technologies).

In our experiment, an open-ended coaxial probe was used as a detecting fixture. This technique covers a wide range of frequencies (1 MHz to 3 GHz) and applies the best to liquids and semi-solids. Also, it is a non-destructive, simple, and convenient measurement. However, it has its limitation in the permittivity

accuracy and **$\tan \delta$** resolution. The coaxial probe requires semi-finite thickness ($> 1 \text{ cm}$), non-magnetic MUT, isotropic and homogeneous object, flat incident surface and no air gap between the fixture and the MUT. This probe is a cut off section of transmission line and surveys the MUT by immersing it into the sample, if it is a liquid, or touching it to the flat face, if it's a powder or a solid material. The electrical fields at the probe-end “fringe” into the material and get disturbed as they meet the MUT (see **figure 14**).

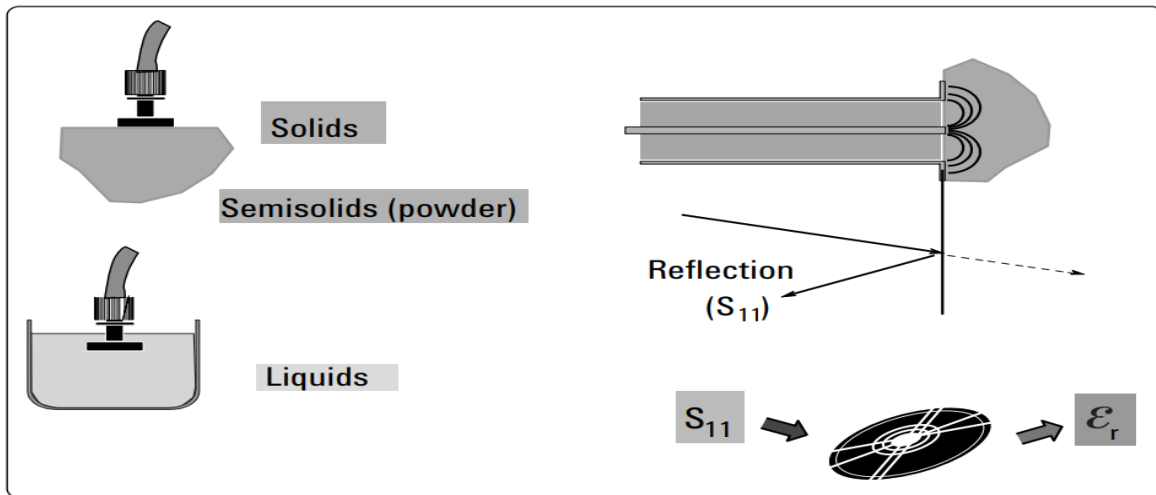


Figure 14 The dielectric measurement technique used by the coaxial probe (after Agilent Technologies).

CHAPTER 3

LITERATURE REVIEW

There have been several studies in literature which tried to relate the dielectric response to wettability (Oshaish et al., 2023^b). Different values of dielectric permittivity of water-wet and oil-wet sandstones have been observed by Poley et al. in 1978 (Nguyen et al, 1999). It was concluded that there is a consistent dielectric behavioral change as the wettability of the rock sample changes from water-wet to oil-wet. Garrouch and Sharma, 1994 conducted experimental measurements of dielectric properties on rock samples in a frequency range of 10Hz-10MHz which yield to the conclusion that wettability has an influence on the dielectric permittivity of fully brine-saturated rocks. Moreover, Knight and Abad (1995) concluded that hydrophobic sandstones possess a lower dielectric permittivity than the hydrophilic ones by measuring the dielectric constant with water saturations ranging from 0 to 100%.

In 1998 and 2001, Bona et al., investigated the impact of wettability on the dielectric measurements over a frequency ranging between 100 Hz and 50 MHz on standard Berea sandstone and sintered glass filters samples in 1998 and included reservoir rock samples in 2001. In 1998, the samples were either water-wet or oil-wet and the measurements were taken with 100% saturation of either brine or deionized water. They studied the effect of wettability and water conductivity on the real part and imaginary part of permittivity measurements. In addition, they analyzed the dispersivity by analyzing the loss tangent and obtaining some form of derivative within the frequency range. The outcome of the study was a qualitative interpretation of the relationship between the dielectric and wettability. As illustrated in **figure 12**, the first study revealed that water-wet samples exhibit higher real and imaginary permittivity especially at low frequency (lower than 10 MHz). However, real permittivity becomes less sensitive to wettability at frequencies greater than 10 MHz. Furthermore, the loss tangent indicates an excellent correlation with wettability. Two clear characteristics of loss tangent behavior in response to wettability and water conductivity which can be observed in **Figure 13**:

- i. The magnitude of $\tan \delta$ is significantly higher for water-wet samples compared to oil-wet ones saturated with the same type of the fluid.
- ii. As ω increases above zero, the $\tan \delta$ decreases before it rises again to form another peak in the range of MW polarization frequency. However, some samples showed only the low-frequency peak because the right-hand MW peak appears at higher frequency values than the plot range.

These samples are the ones saturated with conductive brine which causes faster relaxation that requires higher frequency to attain the MW polarization.

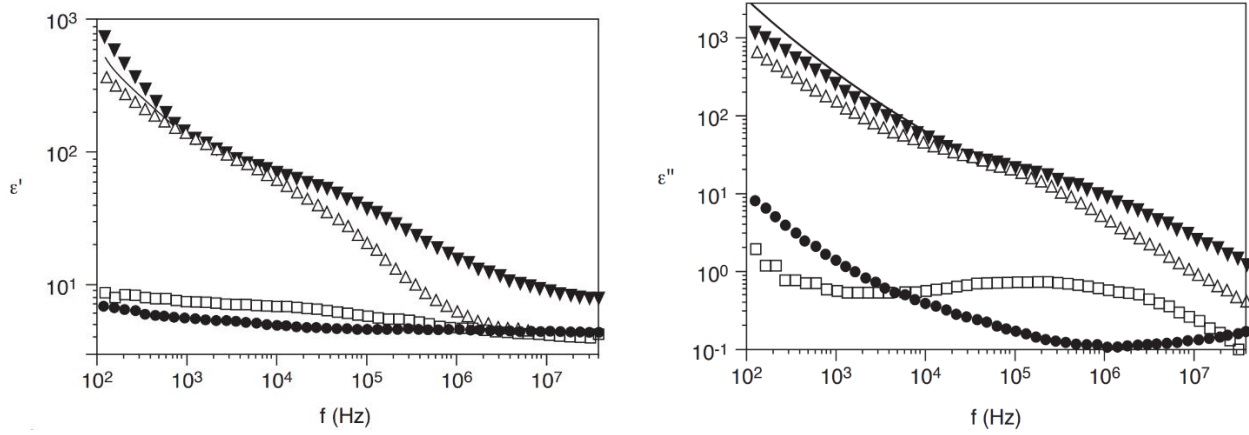


Figure 15 Real (ϵ') and imaginary (ϵ'') permittivity curves for water-wet and oil-wet glass filter samples saturated with brine and DI water.

LEGENDS: Open Up Triangles: (WW / Deionized Water). Solid Dots: (WW / Brine). Open squares: (OW / Deionized Water). Solid Down Triangles (OW / Brine).

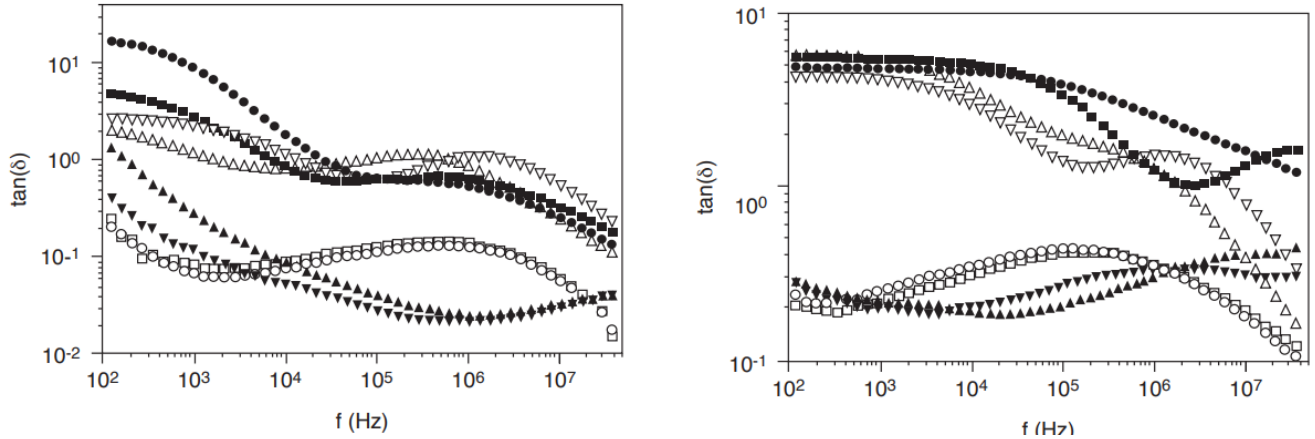


Figure 16 Dielectric loss tangent behavior for water-wet and oil-wet glass filter samples

LEGENDS: Open squares & circles: (OW / Deionized Water). Up & Down Open Triangles: (OW / Brine). Up & Down Solid Triangles (WW / Deionized Water). Solid squares & circles: (WW / Brine)

In 2002, the same scholars investigated more representative water-wet and oil-wet samples. Oil wet samples were extracted from the reservoir and salinized with a method published by Takach et al., 1989, which includes an adsorption process of dimethyl silane on the rock surface at 290 °C. Same qualitative analysis

and dispersion behaviors were investigated in this study, as illustrated in **figure 14**, but with an extra effort to quantify the major dielectric properties responsible to describe this behavior. Primarily, these properties were τ , $\Delta\epsilon$, σ_{dc} and $\tan \delta$ and were calculated using equations (18, 19, and 20). In addition, other auxiliary parameters were also calculated which includes loss tangent peak $A_{\tan(\delta)}$, and maximum frequency, f_{max} , where this peak occurs at. The summary of calculated parameters is presented in **Table 2**.

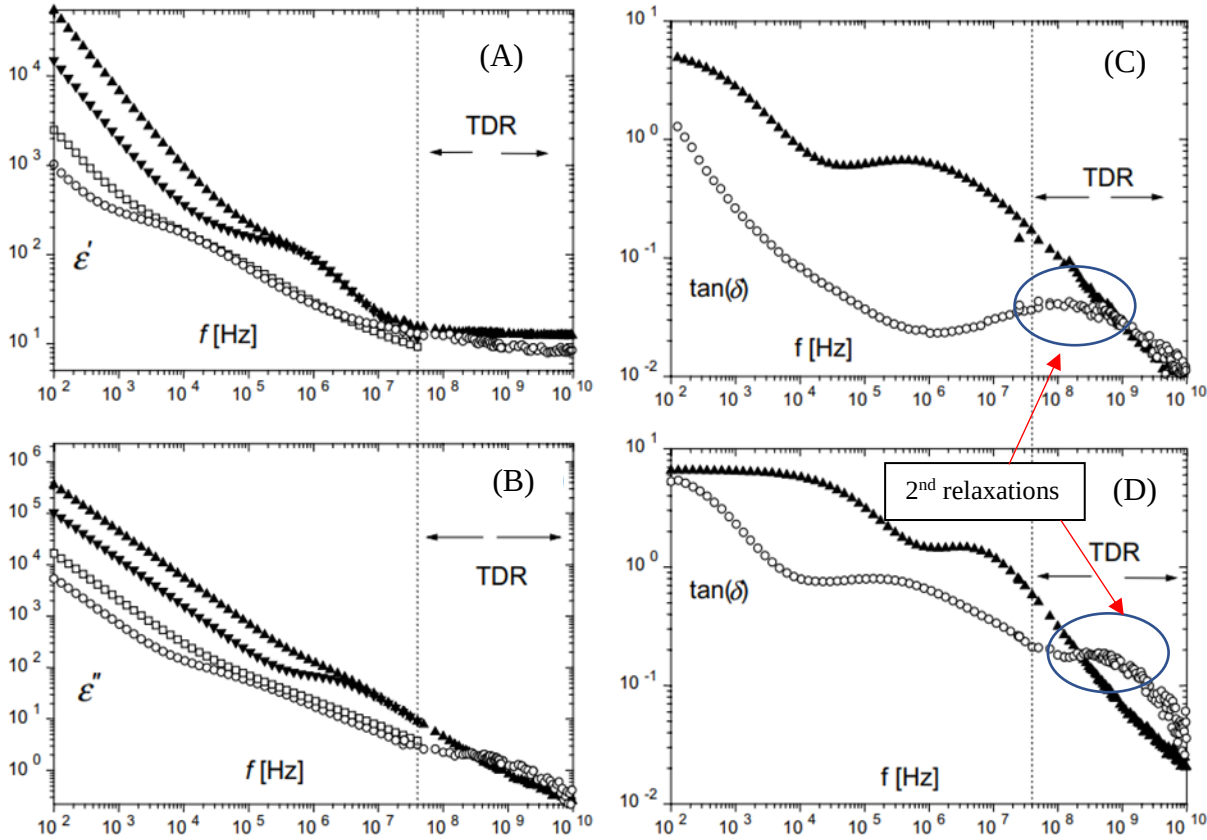


Figure 17 Dielectric permittivity and loss tangent behavior for water-wet and oil-wet samples at different saturations of water and oil (Bona et al., 2002). The second peak highlighted indicates the presence of wettability-altered pores (O-W) and the original WW ones. (A) and (B) represent the real and imaginary permittivity for 4 reservoir rock samples (Open circles: OW sample K-3. Open Square: OW sample K-98. Up solid Trtiangle: WW sample K13. Down Solid Triangle: WW sample K99). (C) and (D) represent the loss tangent for 2 glass filter and 2 reservoir sandstone samples (Open circles: OW samples glass4C (top) and K-3 (bottom). Solid Triangles: WW samples glass4H (top) and K13 (bottom)).

Table 2 Summary displays the rock properties and calculated wettability-sensitive parameters. Samples K3, B7, and R7 have two relaxation peaks. Each of them has two separate lines (After Bona et al., 2002).

ID	Wettability	Lithology	Porosity	S_w	I_w	I_o	$\Delta\varepsilon$	ε_∞	τ in μs	σ_{dc}	$A_{\tan(\delta)}$	f_{max}
1	OW	Carbonate	16.3	60.4	N/A	N/A	80	50.8	1.80E-03	7.30E-02	N/A	N/A
2	W-W	Carbonate	13.4	68.2	N/A	N/A	198	24.5	3.90E-03	3.30E-02	1.85	8.50
3	OW	Carbonate	18.3	20.6	N/A	N/A	173	12.5	2.75E+00	7.80E-05	0.80	0.53
4	W-W	Carbonate	17	36.1	N/A	N/A	315	14.2	1.23E-01	4.80E-03	1.26	8.20
5	OW	Carbonate	23.9	22.3	N/A	N/A	186	12.4	4.65E+00	1.90E-04	0.84	2.10
6	W-W	Carbonate	26.3	46.5	N/A	N/A	208	15.9	2.10E-02	1.80E-02	1.60	27.00
7	OW	Glass	37.9	2.6	0	0.85	0.5	3.2	8.10E-05	1.10E-07	0.04	1900.00
8	OW	Glass	36.5	3	N/A	N/A	0.5	3.5	1.00E-04	2.30E-07	0.04	1800.00
9	W-W	Glass	31	6.4	0.88	0	49.6	7.1	3.10E+00	8.10E-06	0.55	0.22
10	W-W	Glass	32.6	8.3	N/A	N/A	50.2	7.5	4.30E+00	7.90E-06	0.62	0.08
11	OW	Glass	30.3	7.5			0.6	3.7	1.35E-03	6.00E-08	0.04	150.00
12	OW	Glass	29.6	7.8	0	0.48	0.6	3.8	1.40E-03	1.70E-08	0.04	145.00
13	W-W	Glass	44.2	8.6			53.7	9.6	1.30E+00	5.10E-05	0.59	0.22
14	W-W	Glass	40.1	6	0.91	0	70.7	6.9	2.10E+00	1.70E-05	0.66	0.37
15	OW	Berea SS	19.1	44.6	0	0.39	17.7	2.1	7.20E-02	1.10E-07	0.40	10.70
16	OW	Berea SS	19.4	36.1	N/A	N/A	21.8	2.7	8.70E-01	1.00E-07	0.35	1.75
17	W-W	Berea SS	21.7	18.4	N/A	N/A	111	3	3.00E-01	3.80E-03	N/A	N/A
18	W-W	Berea SS	21.4	21.9	0.39	0	106	3.7	2.80E-02	2.50E-03	N/A	N/A
19	OW	Sandstone	12.2	18.6	N/A	N/A	248	9.4	4.78E+00	4.90E-05	0.85	0.34
20	W-W	Sandstone	12.8	13.7	N/A	N/A	110	10.5	1.31E-01	1.00E-03	1.21	4.50
21	OW	Sandstone	23.2	17.8	N/A	N/A	250	8.2	9.13	3.10E-05	0.8	0.14
22	OW	Sandstone					3.3				0.19	280
23	OW	Sandstone	22.2	16.9	N/A	N/A	223	5.6	6.89	9.50E-05	N/A	N/A
24	W-W	Sandstone	22.7	8.2	N/A	N/A	107	11.8	0.13	2.00E-03	1.46	3
25	W-W	Sandstone	21.8	9	N/A	N/A	130	8.16	0.109	5.90E-04	1.24	7.7
26	OW	Sandstone	13.5	12	N/A	N/A	177	12.9	0.34	1.70E-03	N/A	N/A
27	OW	Sandstone	22	8.4	N/A	N/A	88.4	7.1	0.24	2.20E-04	0.68	3.8
28	W-W	Sandstone	22.7	31	N/A	N/A	61	13.5	2.90E-02	5.70E-02	N/A	N/A
29	W-W	Sandstone	23.8	3.7	N/A	N/A	72	14.1	2.40E-02	1.60E-03	0.96	16
30	OW	Sandstone	13	33.2	N/A	N/A	64.6	6.4	4.83E-02	2.90E-05	0.67	17
31	OW	Sandstone					2.3		2.50E-04		N/A	N/A
32	W-W	Sandstone	13.8	63.2	N/A	N/A	222	4.6	1.47E-02	4.00E-03	1.3	120
33	W-W	Sandstone	13.3	47.4	N/A	N/A	137	15.5	2.47E-02	2.50E-02	N/A	N/A
34	OW	Sandstone	25	20	N/A	N/A	13	23	5.20E-03	5.80E-02	N/A	N/A
35	OW	Sandstone	25	20	N/A	N/A	70	6.4	9.30E-03	3.40E-02	N/A	N/A
36	W-W	Sandstone	25	20	N/A	N/A	159	17.1	1.50E+00	4.00E-01	N/A	N/A
37	W-W	Sandstone	25	20	N/A	N/A	110	22.2	8.05E-01	2.40E-01	N/A	N/A
38	OW	Sandstone	13.8	12.7	N/A	N/A	64	8.9	3.80E+00	1.30E-05	0.54	0.13
39	OW	Sandstone					24.4		7.30E-02		0.5	3.4
40	OW	Sandstone	13.8	11	N/A	N/A	57.6	4.4	1.87E-01	7.20E-06	0.72	6.6

41	W-W	Sandstone	13.8	30.1	N/A	N/A	66.4	9.8	1.40E-02	3.96E-04	0.98	36
42	W-W	Sandstone	13.8	7	N/A	N/A	32	9.2	8.40E-03	6.89E-05	N/A	N/A

The conclusion of this study can be summarized in the following points:

- a) The relaxation strength, $\Delta\epsilon$, for the water-wet sample, where the MW polarization appears, is higher than the values of the oil-wet ones. However, some salinized samples, such as K3, showed a higher value compared to the water-wet match, K13. This could be attributed to an ineffective salinization process that could not turn all the pores to oil-wet condition. This could be a result of the presence of remnant water-wet micro pores in the system which was confirmed by the presence of a second relaxation peak at a higher frequency. See **Figure 14**.
- b) Relaxation time for water-wet samples was significantly higher than the time for oil-wet samples. These values were sometimes double and sometimes one order of magnitude higher in water-wet samples comparing to the values for oil-wet ones. Anyhow, this discrepancy was not conclusive in all the samples. This is, again, can be referred to the remaining water-wet micropores mentioned in point a.
- c) The DC conductivity, σ_{dc} , of the samples were calculated by averaging the value of $\epsilon''(\omega)\epsilon_0\omega$ at 100 Hz. Generally, this value correlates very well with wettability. The DC conductivity of water-wet samples is at least ten times the value of the oil-wet matches. Sometimes, this difference increases and reaches to 2 orders of magnitude. For example, σ_{dc} for oil-wet K3 sample with water saturation of 17.8% is 3.10×10^{-5} (S/m) while it is 2.00×10^{-3} (S/m) for water-wet K13 sample which has only 8.2% water saturation. This means that, even though the oil-wet sample is saturated with double the amount of water in the water-wet sample, its σ_{dc} conductivity value is still 64 times less than the conductivity of the water-wet sample which confirms the strong relationship between this value and wettability. This could be attributed to the surface ratio effect. For conductivity, it appears that it does not matter how much water is present, it matters whether it forms a continuous phase or not.
- d) The last two dielectric parameters presented in the table are $A_{\tan(\delta)}$ and f_{max} . Both parameters are obtained from loss tangent curves. The loss tangent, $\tan(\delta)$, is a measure of the relative loss tendency in the dielectric signal in the rock, and it is being the ratio of the energy lost to the energy stored. The right-hand side plots in **Figure 14** represent the loss tangent behavior in the frequency range of (100 Hz to 10 GHz) for two glass samples and two K reservoir samples. In the low-

frequency range, charge transport (EDL polarization) will be the dominant polarization activated in the medium which decays after a certain frequency where the MW relaxation will start to take the lead of the polarization mechanism. This results in a clear peak in the loss tangent curve with a small amplitude value, $A_{\tan(\delta)}$, at MW frequency value, f_{max} . Water-wet samples showed peaks with higher amplitude at lower frequencies compared to oil-wet samples. This can be referred to as the strong dielectric properties of water which lead to a stronger polarization and slower relaxation comparing to non-polar oil. However, the salinized K3 sample showed a second peak at a later time indicating that there are still some tiny pores that remained water-wet after an inefficient salinization process.

Another study was conducted by Venkataramanan et al. (2014) on three Oolitic limestone core samples resulted in a similar outcome. However, the dielectric measurements after the wettability alteration were acquired only at irreducible water saturations (S_{wirr}). Two samples, B and C, were converted to oil-wet while sample A was maintained as water-wet. Different cycles of drainage and imbibition were performed to explore the dielectric response while altering the wettability. Wettability alteration was confirmed by NMR T-2 measurements. The oil-wet sample experienced a significant reduction in dielectric permittivity and conductivity values compared to the water-wet sample which both measured at S_{wirr} . **Figures 15 and 16** illustrate the response during drainage and imbibition cycles.

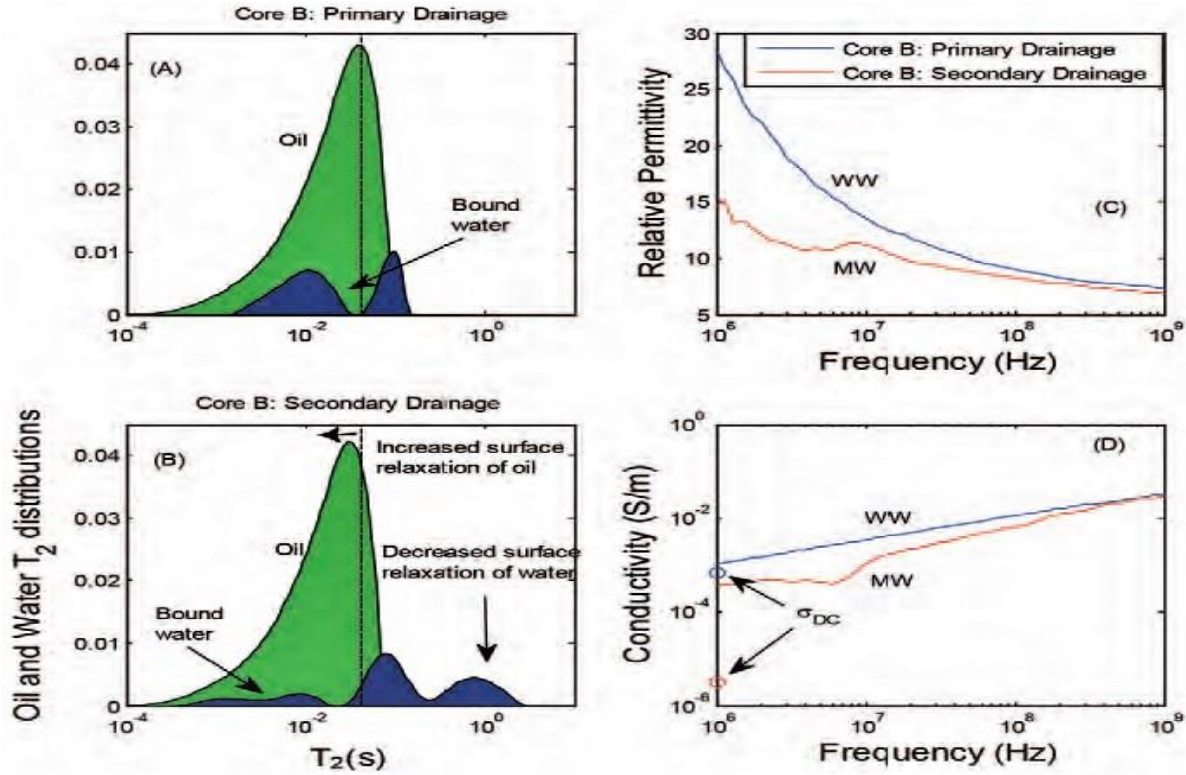


Figure 18 Dielectric and NMR T₂ distribution for sample B after primary drainage (no aging) and forced drainage (after altering the wettability by aging) at S_{wirr} . in the low-frequency range, the dielectric permittivity and conductivity experience a reduction due to wettability alteration (after Venkataramanan et al., 2014).

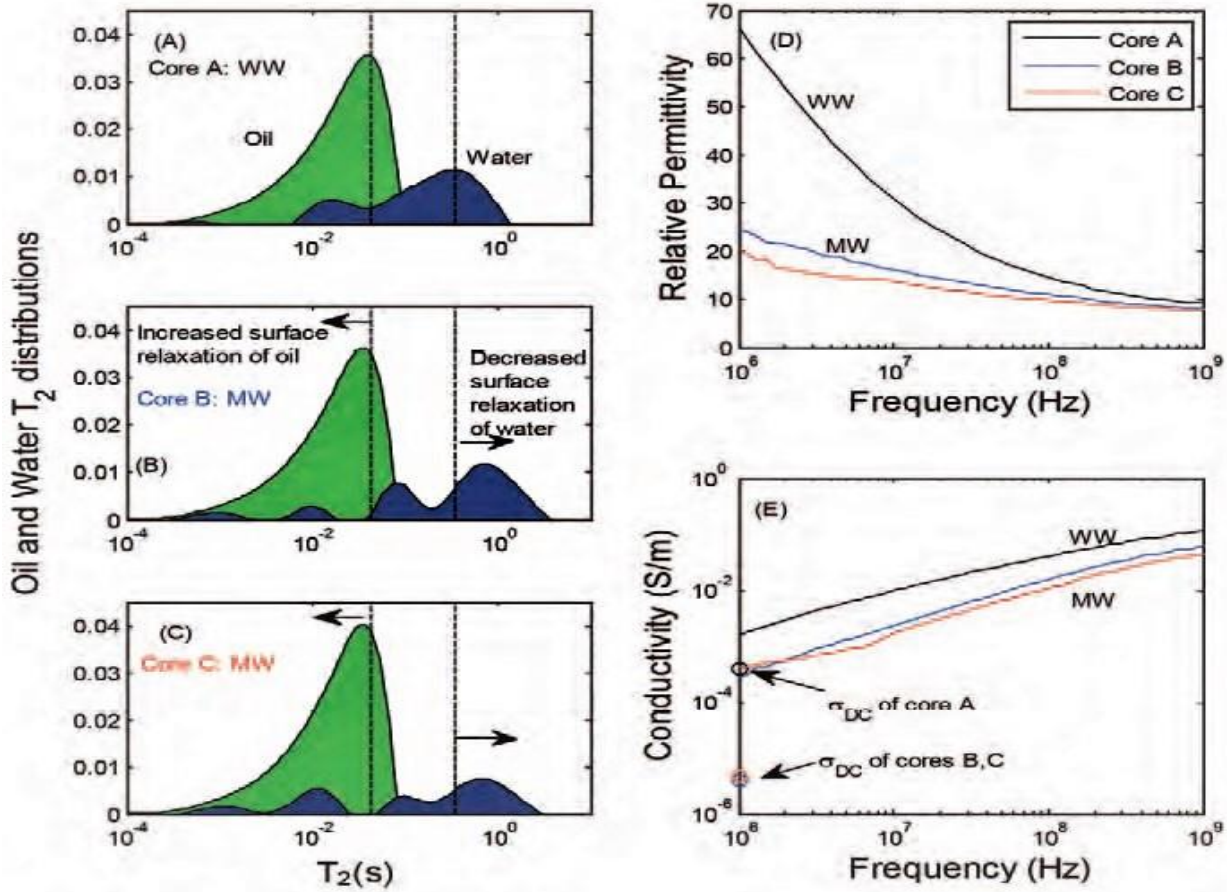


Figure 19 A comparison between the dielectric response and NMR T₂ during the spontaneous drainage for sample a which was maintained as water-wet (W-W) and samples b and c which were converted to mixed-wet (M-W). in the low-frequency range, the dielectric permittivity and conductivity experience a reduction due to wettability alteration (after Venkataramanan et al., 2014).

Furthermore, Newgord et al. (2018) worked on the correlation between the electrical properties of rock samples and their wettability. They developed a wettability triangle diagram in which the wettability can be qualitatively determined by plotting the saturation of isolated water versus the water saturation of the core sample. The developed diagram consists of 3 main regions: water-wet, mixed-wet and hydrocarbon-wet regions. The saturation values were obtained by applying Archie (1942) principle to the measured resistivity index. The resistivity values were measured using a multi-frequency impedance analyzer. The frequency at which the resistivity value was taken for the saturation calculations was chosen such that the phase shift is at its minimum value. In addition, a plot called “Conceptual qualitative diagram of the resistivity index vs. water saturation for different wettability conditions” was built with 3 separate curves

which represents the wettability conditions mentioned earlier. By measuring the resistivity index at different saturation and plotting them on the diagram, they will fit to the corresponding curve based on the wettability condition. The developed diagrams worked well in classifying the core samples with respect to their wettability condition but without quantifying the wettability index. Moreover, the separation between the curves, especially at high water saturation values, is very small which makes the judgement on the wettability condition difficult.

In 2017, Al-Ofi et al. have studied the dielectric response sensitivity to wettability alteration using the same technique utilized in USBM and Amott-Harvey methods. In that study, a dielectric dispersion was measured for 1.5 in long samples at different frequencies ranging from 10 MHz to 1 GHz. Core flooding apparatus was utilized to perform the drainage and imbibition cycles. A wettability-inert oil was used during the primary drainage to preserve the initial water wettability condition of the core samples. Afterward, surface-active stearic acid, Soletrol, was added to the oil during later stages of oil flooding (water drainage) in order to shift the rock wettability into the oil-wetting direction. For checking the model validity, NMR-T2 and contact angle measurements were taken with dielectric simultaneously. In this study, a model was developed to link the dielectric permittivity reading to the contribution of the fluid and matrix permittivity and their volumetric characteristics governed by porosity and saturation. Therefore, this study can be considered as a combination of both methodologies, experimental and model based. The model utilized by the study relies on a textural model (known as the SDR-06 model) (Seleznev et al. 2006) which uses a Maxwell-Garnett approximation to calculate the electrical properties of the compound media (Al-Ofi et al., 2017). This model applies the Complex Refractive Index Method (CRIM) on elliptical grains. However, the proposed model expresses the effective dielectric permittivity of the medium as the summation of the ϵ_R and input from dispersed particles of oil, brine, and rock with the weight coefficients, which depend on the volumes of the respective components (Al-Ofi et al., 2017).

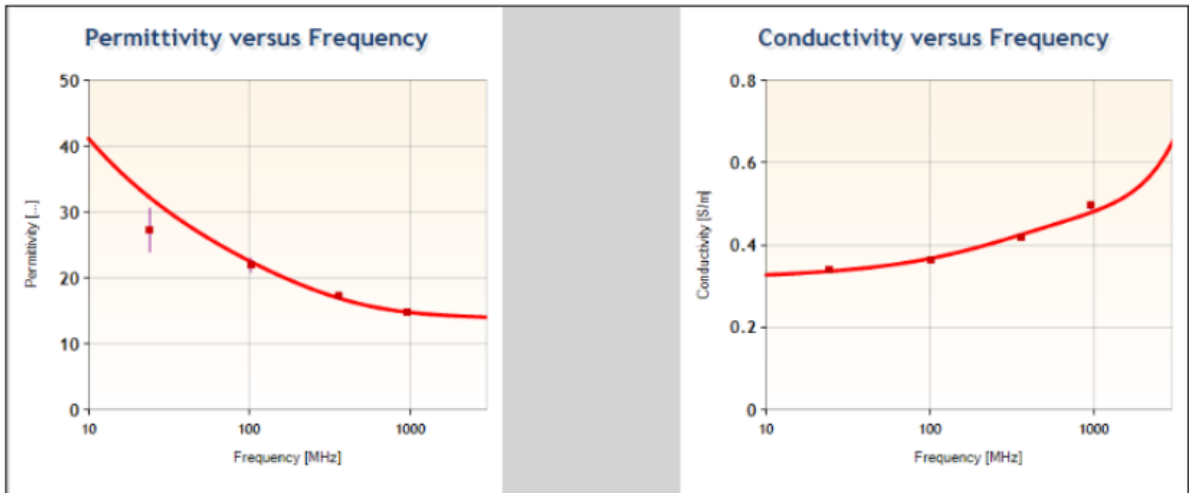
$$\epsilon^* = \epsilon_R + \frac{\frac{1}{3} \sum_{j=1}^n f_i (\epsilon_j - \epsilon_R) \sum_{i=1}^3 \frac{\epsilon_R}{\epsilon_R + N_j^i (\epsilon_j - \epsilon_R)}}{1 - \frac{1}{3} \sum_{j=1}^n f_i (\epsilon_j - \epsilon_R) \sum_{i=1}^3 \frac{N_j^i}{\epsilon_R + N_j^i (\epsilon_j - \epsilon_R)}} \quad (23)$$

where ϵ_j is the complex permittivity of the $j - th$ ellipsoidal inclusion phase with the depolarization factors N_j^i ($i = 1, 2, 3$) and volumetric fraction f_j . Inclusion fractions are assigned as follows: $f_m = (1 - \phi)$, $f_w = \phi S_w$, $f_{oil} = \phi (1 - S_w)$.

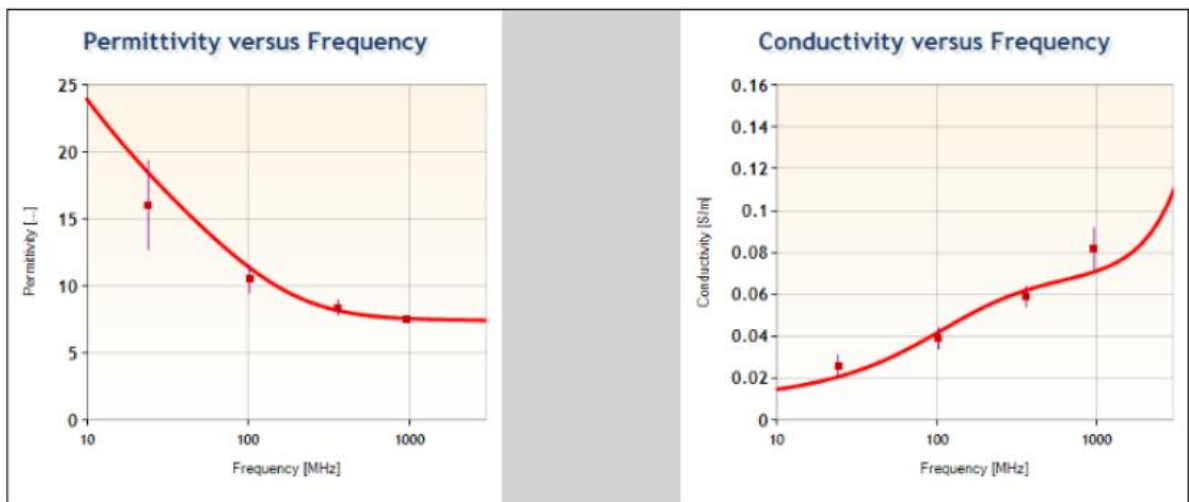
Besides the standard interpretation answers, the developed model was able to relate the dielectric dispersion to the geometrical parameters such as tortuosity and fluid distribution which ultimately led to relate it to wettability. The model used the dielectric measurements to obtain the geometrical characteristics and then invert them to wettability indicators. The study deduced a similar result to what was discussed previously. As more acid is injected into the system which makes it more oil-wet, the dielectric depolarization factor decreases due to the increase of MN-Parameter. MN-Parameter is the apparent cementation factor or water phase tortuosity while the dielectric depolarization factor is an indicator of the distribution of the fluid in the porous medium. In water-wet porous systems, the water forms a continuous phase that covers the grain surface. However, this continuous phase gets disturbed by introducing more acid which turns the medium into oil-wet and forces the water to form inclusions. Consequently, water tortuosity MN-Parameter increases, and dielectric depolarization factor declines. At the highest acid concentration, the water dielectric depolarization factor, DFWA, drops down from 1.40, which was obtained at the initial drainage stage, to 0.36 which is very close to the dielectric depolarization factor of spherical inclusions. Therefore, depolarization factors for water, DFWA, and oil, DFOM, are promising indicators of wettability states.

A significant change in the behavior of dielectric permittivity and conductivity values was observed while converting the sample to an oil-wet one (See **Figure 17**). As the figure illustrates, the conductivity value decreased as the wettability is converted to oil-wetting by injecting more acidic oil. The same trend applies to permittivity, especially under low frequencies. In addition, the variation in the permittivity due to the change in frequency, which is called dispersion, decreases as the sample becomes more oil wet. These observations can be explained by the formation of a new oil layer covering the grains due to wettability alteration. In 2018, Al-Ofi et al. extended their work to relate the dielectric response to wettability. They demonstrated linear relationships between the water tortuosity M-N parameter, platy grain concentration, depolarization factor and dielectric-obtained saturation exponent on one side and USBM wettability index on the other side. Those dielectric parameters were obtained for single dolomite core sample using 6 water saturation values: irreducible water saturation, 0.2, 0.4, 0.6, 0.8 and $(1 - \text{Residual oil saturation})$. The plots were generated for 3 wettability conditions and showed an excellent coefficient of correlation values.

S_w 100%



Soltrol
Drainage



After 0.1%
Acid 1-week
Soaking and
0.01%, 0.1%
and 1% Acid
Drainages.

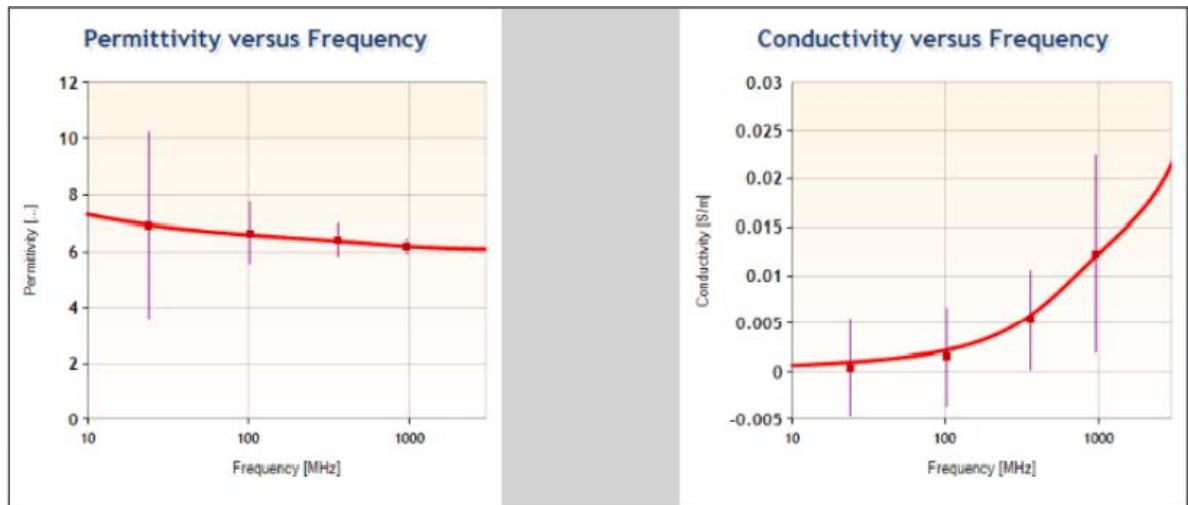


Figure 20 The permittivity and conductivity response during wettability alteration method using tex-tural model (after Al-Ofi et al., 2017).

Garcia and Heidari (2018) have characterized the multi-frequency dielectric dispersion in mixed wet rocks. They successfully built an analytical model to simulate the results obtained for 6 sandstone samples which were used Bona et al., 2002 study. Below 100 kHz, a significant drop in the dielectric constant as hydrocarbon wettability increases. On the other hand, the model was able to obtain the MW polarization which occurs at frequencies around 1 MHz due to the presence of a capacitive layer at the water-oil interface. Both responses were obtained successfully by the model and agreed with the lab measurements.

Overall, the proposed model went through the following calculations and assumptions:

- The mixed wet system consists of water wet regions and oil-wet regions. The EDL polarization is negligible when the grain surface is oil wet. Then, Maxwell Garnet and Hanai-Bruggeman's models were utilized to calculate the effective permittivity by considering the fraction of the grains in the water wet region and oil-wet region.
- The observed MW polarization at frequencies ranging from kHz to MHz is associated with the presence of an interfacial layer between the immiscible oil and water in the pore spaces. The fluid interface is described by a spherical shell of the wetting phase which covers the non-wetting dispersion. The transition area between the oil and water phases can be classified into 3 areas, pure water, pure hydrocarbon, and a capacitive spherical transition layer (see **Figure 16**). Then, Maxwell Garnet and Hanai-Bruggeman's models were utilized to calculate the effective permittivity by considering the oil and water saturations.

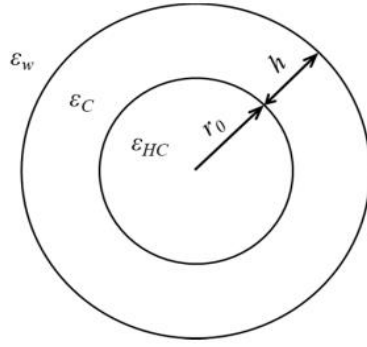


Figure 21 The model used to describe the hydrocarbon spherical drop which is coated by capacitive layer due to the presence of EDL layer at the water-oil interface (Garcia and Heidari, 2018).

c. Finally, effective permittivity was calculated based on the combination of both and b.

For wettability and grain surface effect (EDL Polarization), Maxwell Garnet and Hanai-Bruggeman formulas can be expressed as the following:

Maxwell Garnet Formula:

$$\epsilon_{solid} = \epsilon_{SC} + (1 - X_w) \epsilon_{SC} \frac{\epsilon_g - \epsilon_{SC}}{\epsilon_{SC} + X_w N_g (\epsilon_g - \epsilon_{SC})} \quad (24)$$

Hanai-Bruggeman Formula:

$$\frac{\epsilon_g - \epsilon_{solid}}{\epsilon_g - \epsilon_{SC}} = X_w \left[\frac{\epsilon_{solid}}{\epsilon_{SC}} \right]^{N_g} \quad (25)$$

Where,

ϵ_{solid} is the solid grains permittivity.

ϵ_{SC} the relative dielectric permittivity of the grains coated with the electric double layer. It can be calculated by $\epsilon_{SC} = \frac{\sigma_s}{i \omega \epsilon_0} + \epsilon_g$, where σ_s is the grain surface conductivity and ϵ_g is the permittivity of the mineral constituent of the grains.

X_w is the fraction of the grains which is water wet. It ranges from 0 to 1.

N_g is the depolarization factor (i.e., equal to 1/3 for spherical grains).

For saturation and fluid effect (MW Polarization), Maxwell Garnet and Hanai-Bruggeman formulas can be expressed as the following:

Maxwell Garnet Formula:

$$\epsilon_{fluid} = \epsilon_w + (1 - S_w) \epsilon_w \frac{\epsilon_{HC,C} - \epsilon_w}{\epsilon_w + S_w N_{HC,C} (\epsilon_{HC,C} - \epsilon_w)} \quad (26)$$

Hanai-Bruggeman Formula:

$$\frac{\epsilon_{HC,C} - \epsilon_{fluid}}{\epsilon_{HC,C} - \epsilon_w} = S_w \left[\frac{\epsilon_{fluid}}{\epsilon_w} \right]^{N_{HC,C}} \quad (27)$$

Where,

ϵ_{fluid} is the fluid phase permittivity and ϵ_w is water permittivity.

$\epsilon_{HC,C}$ is the effective dielectric permittivity of the hydrocarbon phase. It can be calculated from the following:

$\epsilon_{HC,C} = \epsilon_C \frac{2(1-\nu)\epsilon_C + (1+2\nu)\epsilon_{HC}}{(2+\nu)\epsilon_C + (1-\nu)\epsilon_{HC}}$, where, ϵ_C is the dielectric permittivity of the inner layer, ϵ_{HC} is the dielectric permittivity of the bulk hydrocarbon phase and ν the volume fraction of the inner layer compared to the total inclusion volume. It can be expressed as $\nu = \left(1 - \frac{h}{r_0}\right)^3$ (See **Figure 18**). S_w is the water saturation and $N_{HC,C}$ is the hydrocarbon depolarization factor.

By combining both effects, wettability, and saturation, both formulas can be used to find the permittivity of the porous medium as the following:

Maxwell Garnet Formula:

$$\epsilon_R = \epsilon_{fluid} + (1 - \phi) \epsilon_{fluid} \frac{\epsilon_{Solid} - \epsilon_{fluid}}{\epsilon_{fluid} + \phi N_f (\epsilon_{Solid} - \epsilon_{fluid})} \quad (28)$$

Hanai-Bruggeman Formula:

$$\frac{\epsilon_{Solid} - \epsilon_R}{\epsilon_{solid} - \epsilon_{fluid}} = \varphi \left[\frac{\epsilon_R}{\epsilon_{fluid}} \right]^{N_f} \quad (29)$$

Where,

ϵ_R is the permittivity of the porous medium and N_f is the depolarization factor of the whole fluid.

The process flow of the model went as follows:

- 1- Calculate the effective permittivity of the hydrocarbon inclusions, $\epsilon_{HC,C}$, the effective permittivity of the water wet grains, ϵ_{SC} , and the effective permittivity of the water ϵ_w based on water salinity and temperature.
- 2- Calculate the effective permittivity of the grains, ϵ_{solid} , based on the obtained ϵ_{SC} and the given X_w values.
- 3- Calculate the effective permittivity of the fluid, ϵ_{fluid} , based on the given S_w and the obtained $\epsilon_{HC,C}$ and ϵ_w values.
- 4- Calculate effective permittivity of the rock, ϵ_R , based on the given porosity and the obtained ϵ_{solid} and ϵ_{fluid} values.

Table 3 lists the basic properties and types of samples analyzed in the study using the procedure explained before.

Table 3 Basic properties and types of samples analyzed (After Garcia and Heidari, 2018).

Sample #	Lithology	Wettability	φ (%)	S_w (%)
1	Sandstone	Oil-wet	23.2	17.8
2	Sandstone	Water-wet	22.7	91.8
3	Sandstone	Oil-wet	22.2	16.9
4	Sandstone	Water-wet	21.8	81.0
5	Sandstone	Oil-wet	19.1	44.6
6	Sandstone	Water-wet	21.4	21.9

The model outcomes showed an excellent correlation with lab measurement. The permittivity values obtained by the model were compared against the laboratory measurements conducted by the previously mentioned Bona et al. (1998) and Bona et al. (2001) studies. **Figure 19** illustrates the comparison between

model results and Bona lab measurements. From the figure, we can see an excellent correlation between the model-obtained results with the measured data for both oil and water-wet samples, especially for K-Reservoir samples.

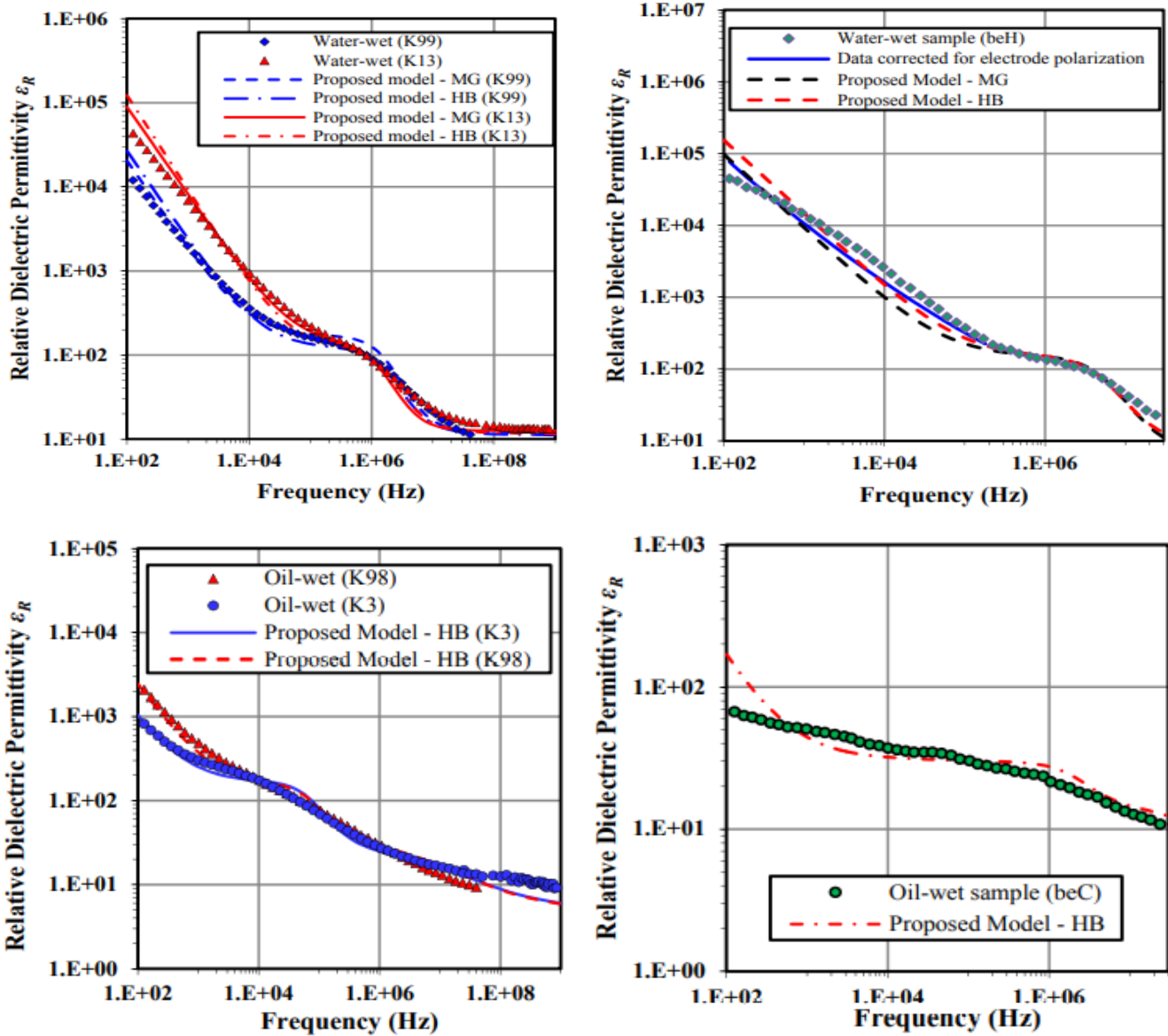


Figure 22 The plots representing the model outputs and comparing them with Bona et al., (2002) lab measurements (after Garcia and Heidari, 2018).

Another study related to this topic was published by Garcia et al., in 2022. They proposed a numerical iterative model based on gradient descent to find porosity, water saturation and wettability index from dielectric measurements (see **figure 20**). The model was generated by applying a forward model on the

pre-known mentioned petrophysical properties (from Bona et al., 2002) to find the corresponding dielectric measurements. Then, the obtained dielectric measurements were compared against the correct values from Bona et al., 2002. If there is no match, a reverse model, based on gradient descent, was applied to update the estimated petrophysical properties. Afterwards, the forward model was applied again on the updated estimates in the same way to obtain the dielectric measurements. This cycle was repeated till a good match between the dielectric measurement generated by the model and the data present in the literature is obtained and the final estimate of petrophysical properties were reported.

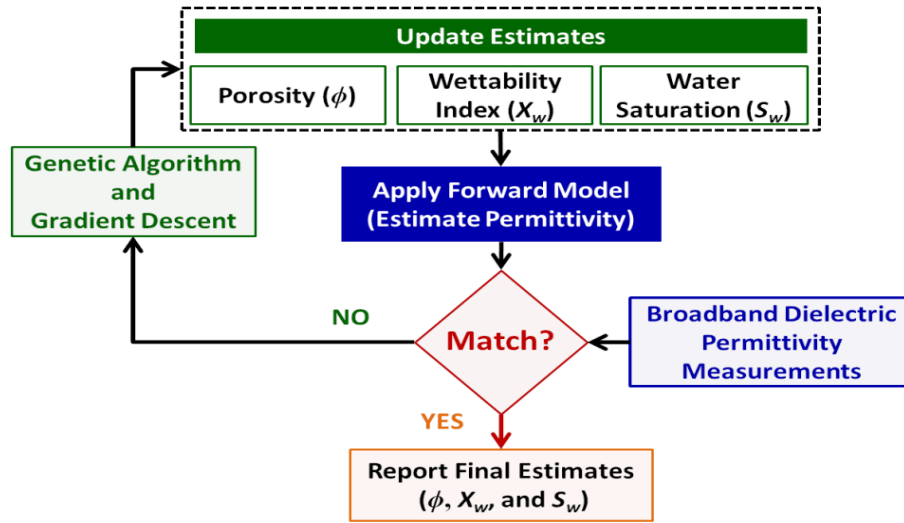


Figure 23 The process flow map of the model applied by Garcia et al., 2022.

Recently, another work has been published which proposed some modification on the conventional bimodal-like model, which was designed to petro-physically interpret the dielectric measurements for the water wet samples, to qualitatively evaluate the wettability conditions (Hou et al., 2023). Originally, the bimodal-like model consists of several parameters which are related to water phase tortuosity, water saturation exponent and water salinity. An additional model parameter has been incorporated, called trapped water fraction, which is sensitive to wettability conditions. The trapped water fraction is designed such that it approaches zero when the sample is strongly water wet whereas it drops to zero when the sample is fully oil wet. However, the new fraction can provide qualitative information about wettability, whether it is more likely to be water wet, oil wet or mixed wet, but it is not capable of determining the wettability index precisely.

Although there has been significant work in the literature to explore the possibility of using dielectric as a wettability indicator, no quantifiable wettability index was obtained using the dielectric measurements to evaluate the wettability directly. Instead, different models were developed to estimate the dielectric permittivity based on different pre-defined petrophysical properties including the wettability. In addition, these models involved different parametric assumptions that depend on wettability, which is not defined yet, such as non-wetting phase shape inclusion factor and depolarization factor. Yet, there has not been a direct method to determine wettability index from dielectric dispersion directly without either making multiple parametric assumptions or requiring more petrophysical information which are, mostly, unavailable, or significantly expensive. In **table 4**, a summary of the gaps found in the previously discussed studies are presented which can form a potential area to be fulfilled to achieve our goal of obtaining a dielectric wettability index.

Table 4 Summary of the studies investigated and the gaps which can be further investigated.

Authors, Year	Study Outcomes	Gaps could be improved
Bona et al., 1998	Qualitative analysis of dielectric measurements, including real and imaginary permittivity, some type of permittivity derivatives, and loss tangent response to wettability. (Curves behavior)	- Used Only Berea sandstone and Glass filter samples. - Used only brine and deionized water to saturate the samples. - No wettability index correlation obtained. - Only low to med. frequency bandwidth (100 Hz to 50 MHz)
Bona et al., 2002	Incorporated dielectric-related parameters, such as relaxation time, relaxation strength, and DC conductivity, and studied their behavior in response to different dielectric measurements	- No wettability index obtained. - Single dielectric measurement for each sample at partial water saturation.
Venkataramanan et al., 2014	Qualitative analysis of Dielectric and NMR response on 3 oolitic limestone samples while altering wettability.	- No wettability index correlation was developed. - Involved only oolitic limestone. - Comparison was done at Swirr only.
Al-Ofi et al., 2017 and 2018	Numerical model to estimate the dielectric measurement based on fluid content and distribution. The model involves fluid inclusion shape factors which depend on wettability. The model was then inverted back to obtain those geometrical factors and have a qualitative conclusion on the wettability condition. In 2018 study, linear correlations between dielectric parameters and wettability were developed using 3 points.	- No direct wettability index relationship from dielectric was obtained. - Based on CRIM model which relies on the volumetric contribution and applies only to high frequency. - Single dolomite sample with limited number of saturation values.

Neogord et al., 2018	Used Archi, 1942 equation to calculate water saturation using the resistivity index. Then, obtained triangular diagrams to correlate water saturation and critical water saturation to wettability.	- Only qualitative analysis of wettability. No wettability index obtained - The separation between the curves at high water saturation values, is very small which makes the judgement on the wettability condition difficult.
Garcia and Heidari, 2018	Analytical model with sensitivity analysis to predict dielectric measurement based on predefined petrophysical properties.	- Based on HB and MG mixing model that are not developed for porous media. - Not considering pore structure and tortuosity. - No wettability index correlation was developed. - Involved several parametric assumptions.
Garcia et al., 2022	Forward and reversed numerical model to evaluate S_w , ϕ and X_w	- Only Berea Sandstone. - Sophisticated model based on many assumptions and costly inputs. - The model depends on iterative evaluation to optimize multiple fitting parameters. Need to further investigation on larger population of data
Hou et al., 2023	Modified the Bimodal-Like model to incorporate a new parameter, called effective trapped water fraction (ETWF) which correlates with wettability. Theoretically, ETWF should approach zero for water-wet while it should reach 1 for oil-wet condition.	- Qualitative assessment of wettability using ETWF value. - Only carbonate samples; Edwards Limestone and Baker Dolomite. - The wettability index of the samples was unknown. - No wettability index correlation.

CHAPTER 4

RESEARCH OBJECTIVES AND METHODOLOGY

4.1. Problem statement:

The traditional methods to measure the wettability index in the oil and gas industry are complicated, time consuming and expensive. Therefore, utilizing the dielectric logging tool to perform this task in real time will be significantly rewarding in terms of both time and cost. On the other hand, although there have been several studies to investigate the response of dielectric to wettability changes, there is no wettability index developed using the dielectric measurements.

4.2. Thesis Objectives

This study aims to closely investigate the dielectric response toward wettability alteration at different endpoint water saturations ($S_w = 1$, S_{wirr1} , S_{or} , and S_{wirr2}). A detailed experimental work consisting of wettability alteration and wettability index measurements combined with conventional petrophysical analysis, NMR and dielectric measurements will be conducted on 3 pairs of core samples which belong to 3 rock types: Berea and Fontainebleau sandstone and Indiana limestone. The ultimate goal of the study is to develop an empirical correlation to calculate the wettability index from dielectric measurements ($WI_{dielectric}$). One of the core samples among each pair will go directly for wettability index measurement while taking NMR and dielectric measurements whereas the other sample will be subjected to full wettability alteration process before measuring its wettability index along with NMR and dielectric measurements. The wettability alteration process was designed in a way that prevents compromising the pores' structure. The dielectric wettability index to be developed will be benchmarked with the industry-known USBM wettability index (WI_{USBM}), validated with Al-Garadi et al., (2022) NMR wettability index (WI_{NMR}). After concluding the experimental work, the data will be analyzed, and the dielectric wettability index will be formulated.

4.3. Sample Preparation and Initial Core Analysis

Three pairs of standard sandstone (Berea and Fontainebleau) and carbonate (Indiana) samples were considered in the study. Separately, a chip and powder for each rock type were prepared for X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) surveys. The XRD was planned to define the mineral composition while the SEM was acquired to explore the pores structure of the samples used. The core samples were cut into 1.5" diameter and 2" length. Then, they were cleaned with methanol in the Soxhlet

and dried out in the vacuumed oven under 80 degC. After that, the porosity was measured using the inert Helium gas for all the samples. The mineralogical composition and pore structure were surveyed using X-Ray Diffraction analysis (XRD) and Scanning Electron Microscope (SEM), respectively. Then, the samples were saturated fully with 3% KCl while measuring the absolute liquid permeability. Finally, the first pair of the samples, called (master samples), went to wettability index measurement using USBM and NMR while the other pair of the samples, called (sister samples), went through the wettability alteration process before measuring their wettability index in a similar fashion as the master samples after treatment. **Figure 24** shows the flowchart for sample preparation and the initial core analysis.

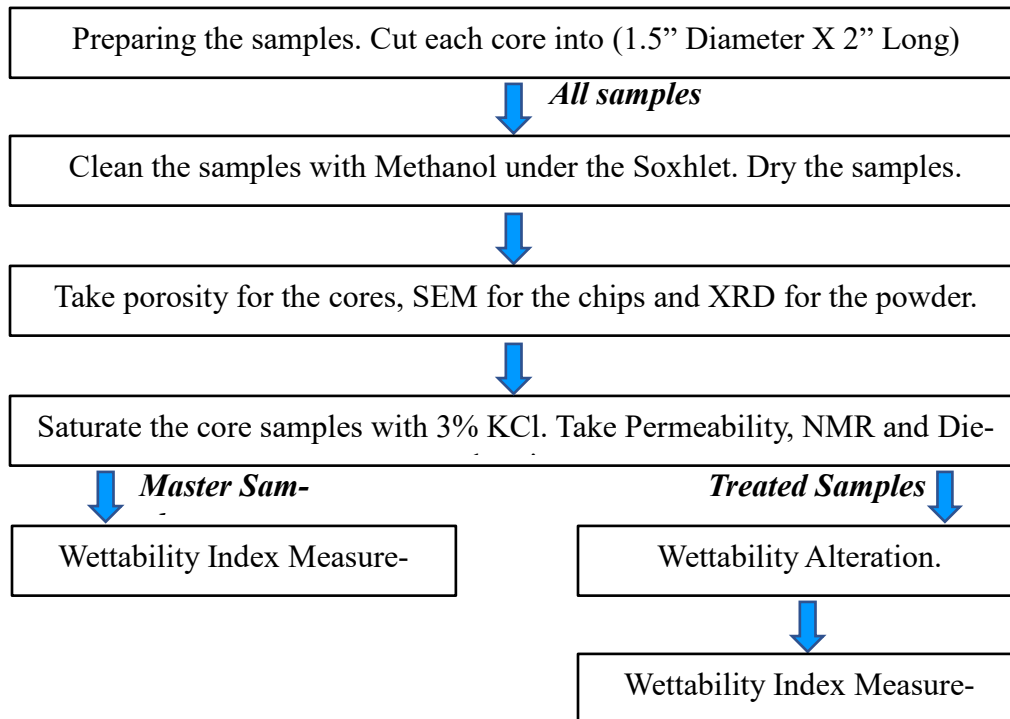


Figure 24 Workflow for sample preparation and initial core analysis.

4.4. Wettability Index Measurement

The wettability of the core samples was measured using USBM and Al-Garadi et al., 2021 NMR T-2 wettability indices. The drainage and imbibition cycles were conducted using the Beckman Coulter Optima XPN-90K centrifuge machine at several rotational speeds (in RPM). The cycles were carried out under elevated RPM speeds in which each speed was operated for 8 hours. However, the last RPM speed was extended for 60 hours to drive the saturation to the maximum saturation endpoint. The drainage cycles were executed using a model oil (Dodecane - $C_{12}H_{26}$) while the imbibition was performed using 3 % KCl

brine. To make the model oil visible during the centrifuge flooding, a small amount of oil-soluble color dye, called methylene dye blue, has been added. The dye solubility was tested in brine and oil separately as well as in a mixture of both. The dye showed solubility only in the oil phase, not the brine. A minimum dye concentration of 0.08 wt. % resulted in a visible color segregation and complete stability under agitation, hence, it was used as an optimum dye concentration. **Figure 25** shows a comparison between the optimum minimum concentration (0.08%) and a lower concentration (0.05%).

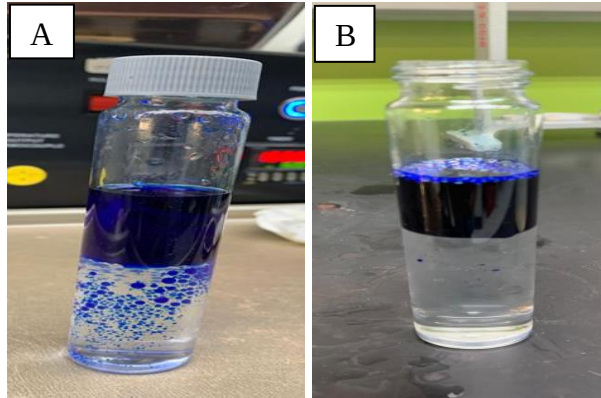


Figure 25 The optimization of the methylene dye blue under agitation. The 0.08% in (B) showed a more stable color than 0.05% in (A).

Initially, the primary drainage cycle was performed on the brine-saturated samples in the presence of the dyed dodecane till the first irreducible water saturation (S_{wirr1}). Then, the samples at (S_{wirr1}) were centrifuged in the presence of 3% KCl brine till the residual oil saturation (S_{or}), in which the process is called imbibition. Finally, the drainage process was repeated on the samples at S_{or} , in what is called a secondary drainage until reaching the second irreducible water saturation (S_{wirr2}). At the end of each cycle, the NMR and dielectric surveys were taken to cover all the saturation endpoints; $S_w = 1$, S_{wirr1} , S_{or} and S_{wirr2} . **Figure 26** demonstrates the workflow for acquiring the dielectric and NMR measurements.

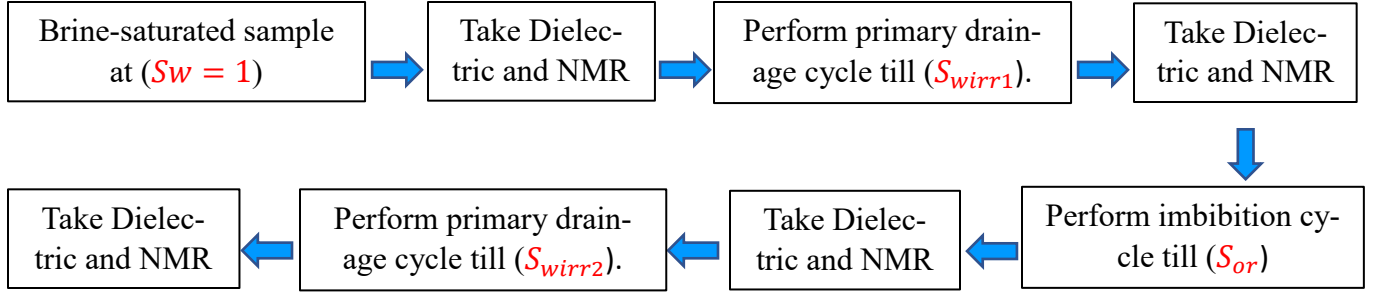


Figure 26 The workflow of wettability index experiment and the related NMR and dielectric measurements.

4.4.1. USBM Wettability Index

Donaldson et al. (1969) developed the USBM technique to assess the wettability of reservoir rocks. This method relies on quantifying the area under the capillary pressure curves obtained by multiple cycles of drainage and imbibition. Initially, the core sample is fully saturated with water. Then, the primary drainage is carried out, where the dodecane displaced the brine in the fully brine-saturated sample ($S_w = 1$) till the first irreducible water saturation (S_{wirr1}) under elevated capillary pressures while recording the volume of the water collected. This displacement can be performed using either centrifuge with varying RPM or core flooding with varying capillary disks. After the primary drainage, the oil is displaced by the water with the same procedure until reaching the residual oil saturation (S_{or}) under what is called the imbibition process or oil drive. Finally, we repeat the same procedure as the primary drainage till we reach the second irreducible water saturation (S_{wirr2}), which is called the secondary drainage or the brine drive cycle. After collecting the data of all displacement cycles, we plot the capillary pressure versus the water saturation for the imbibition and secondary drainage cycles. **Figure 27** shows the capillary pressure plot for only the imbibition and the secondary drainage. Then, the areas under both curves shown in **Figure 27** are evaluated. Finally, the USBM wettability index (WI_{USBM}), which ranges from -1 for oil-wet condition to +1 for water-wet condition, can be computed as the following:

$$WI_{USBM} = \log \frac{A_1}{A_2} \quad (30)$$

Where,

- A_1 is the area below the secondary drainage curve (oil drive).
- A_2 is the area below the imbibition curve (brine drive).

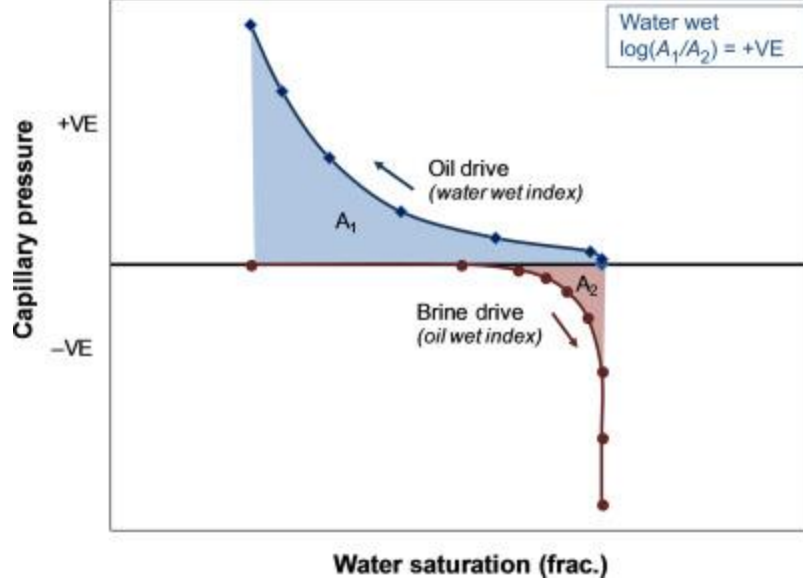


Figure 27 The capillary pressure curves for the secondary drainage (oil drive) and imbibition (water drive) cycles (After Donaldson et al., 1969).

4.4.2. NMR Wettability Index

As mentioned earlier, K. Al-Garadi et al. (2022) NMR wettability index, WI_{NMR} , was used in our study as a secondary wettability index measurement for benchmarking the dielectric wettability index correlation. This index can be obtained by recording the NMR T_2 at different water saturation end points, S_{wirr} and S_{or} . The expression for K. Al-Garadi et al. (2022) NMR wettability index can be written as follows:

$$I_{NMR} = I_w - I_o \quad (31)$$

$$I_w = \frac{T_{2Bw} - T_{2Sor}}{T_{2Bw}} \quad (32)$$

$$I_o = \frac{T_{2Bo} - T_{2Swirr}}{T_{2Bo}} \quad (33)$$

Where,

- I_w and I_o are the NMR water and oil wettability indices, respectively.
- T_{2Bw} and T_{2Bo} are the bulk water and bulk oil T_2 values, respectively.
- T_{2Swirr} and T_{2Sor} are the NMR T_2 values at S_{wirr} and S_{or} , respectively.

4.5. Wettability Alteration

For the sake of the maximum preservation of the pore structure while shifting the wettability towards oil wetness, the sister samples were aged in stearic acid diluted in light crude oil and then cleaned with an aliphatic solvent, hexane. The treatment fluid was prepared by adding 1% stearic acid to light crude oil under stirring at 45 degC. Initially, the sister cores were cleaned with methanol under the Soxhlet for 2 days and dried under 80 degC in a vacuumed oven for 3 days. Afterwards, samples were placed in a saturation cell and vacuumed for over a night. Then, the treatment fluid was introduced using the vacuum force to the cell. After that, the cell was hooked to the actuated transfer cell filled with the same fluid and 2500 psi of pressure was applied using a hydraulic pump. After pressurizing the saturation cell, the valves were shut closed, and the cell was left pressurized. After 5 days, the cell was depressurized, and samples were left to be aged in the treatment fluid for 3 weeks. To remove the oil, samples were retrieved and placed in the Soxhlet for cleaning with hexane for 5 days. Finally, the samples were dried in the vacuumed oven under 80 degC for 3 days which brought the samples back to dry condition. **Figure 28** shows the process flow map for the wettability alteration process.

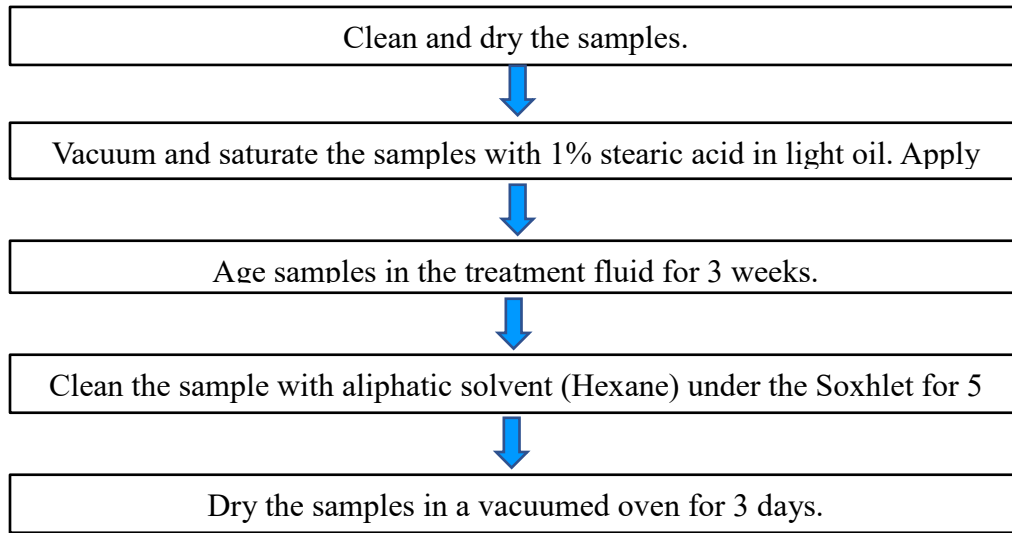


Figure 28 Process flow map for wettability alteration.

4.6. NMR and Dielectric Measurements

The Geospec NMR spectrometer was used to measure the ^1H NMR T_2 at different saturation conditions. The device has parallel plates with permanent magnets installed, which provide a magnetic field strength (B_0) of 0.05 T, or 2.2 MHz, as the Larmor frequency. To obtain the transverse relaxation (T_2) values, the radio frequency (RF) is then applied in a series of 90° and 180° pulses using a Carr-Purcell-Meiboom-Gill

(CPMG) sequence pattern. **Figure 29** shows the CPMG sequence, where n denotes the number of echoes and t_e denotes the time delay between pulses.

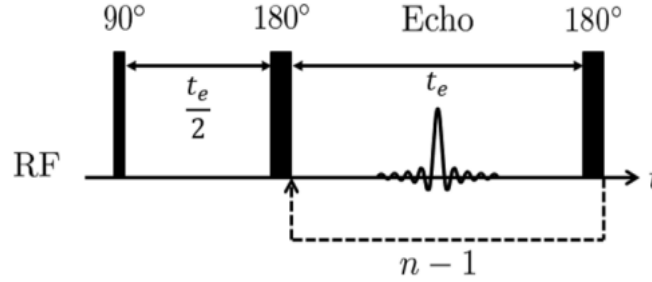


Figure 29 CPMG pulse sequence (After Elsayed et al., 2022).

On the other hand, a coaxial probe attached to an impedance analyzer made by Keysight, which can produce an electrical field with a frequency range of 1 MHz to 3 GHz, was used to carry out the dielectric tests. In the frequency range of 10 MHz to 1 GHz, the measurements were taken for the samples at different saturation conditions. The amplitude and phase shift that represent the instrument's raw output are transformed into real and imaginary permittivity using an open-ended coaxial EM reflection model, as described in Baker-Jarvis et al. (1994). Next, the following formulas are used to calculate the conductivity, σ , while the loss tangent, $\tan \delta$, is calculated using equation (10):

$$\sigma = 2\pi f \epsilon_0 \epsilon'' \quad (34)$$

Where,

- $\tan \delta$ is the loss tangent, dimensionless.
- ϵ' and ϵ'' are the real and imaginary permittivity obtained by inverting the instrument's raw data, dimensionless.
- σ is the conductivity, S/m.
- f is the frequency, Hz.
- ϵ_0 is the dielectric constant (permittivity) of the air ($8.854 \times 10^{-12} \text{ F/m}$).

Figure 30 shows the instruments used for both NMR and dielectric measurements.



Figure 30 The NMR rock analyzer (A) and the multifrequency dielectric instrument (B) used in the study.

CHAPTER 5

RESULTS AND DISCUSSION

5.1. Initial Core Analysis

Prior to any wettability treatment, different measurements were acquired for the core samples, chips, and powders at dry and fully brine-saturation conditions. At dry condition, gas porosity and dielectric were collected for the cores, XRD was taken for the chips and the chips were scanned with the SEM. At $S_w = 1$, NMR and dielectric were acquired for core samples as well as their permeabilities were determined.

5.1.1. Dry Core Samples Measurements

Both master and sister samples were taken from the same 12” length core except the Fontainebleau which is supplied usually in a 3” length cores by different vendors. Therefore, the Berea sandstone and the Indiana limestone showed a close match in terms of porosity in both the master and the sister whereas the Fontainebleau showed a 1.50 p.u. difference in the porosity between the master and the sister samples.

Table 5 shows the porosity measurements of all samples before the treatment.

Table 5 'He' gas porosity results for the core samples.

Sample	Diameter (cm)	Length (cm)	'He' Gas Porosity (%)
Berea – Master (BS-1)	3.823	5.035	19.50
Berea - Sister (BS-2)	3.824	5.123	19.75
FB – Master (FB-1)	3.813	5.059	9.50

FB – Sister (FB-2)	3.836	4.774	8.00
Indiana – Master (IL-1)	3.763	4.859	17.46
Indiana – Sister (IL-2)	3.769	4.885	18.86

A small fragment of each rock type has been grinded into powder to define the mineral composition. The findings of the XRD mineralogy analysis are presented in **Figure 31**. The FB sample had a composition of pure quartz, whereas the Berea sample had 90% quartz with minor amounts (5.8%) of the potassium-rich alkali feldspar known as microcline, 1.1% of potash mica known as muscovite, and 2.8% of some kaolinite. On the other hand, the Indiana's XRD results revealed pure calcite composition.

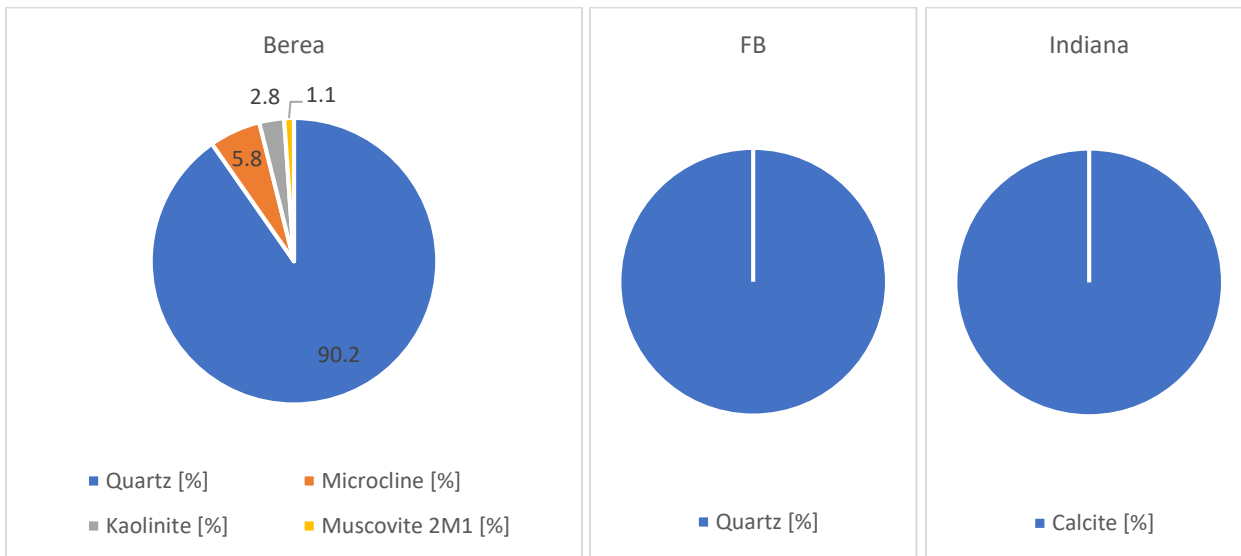
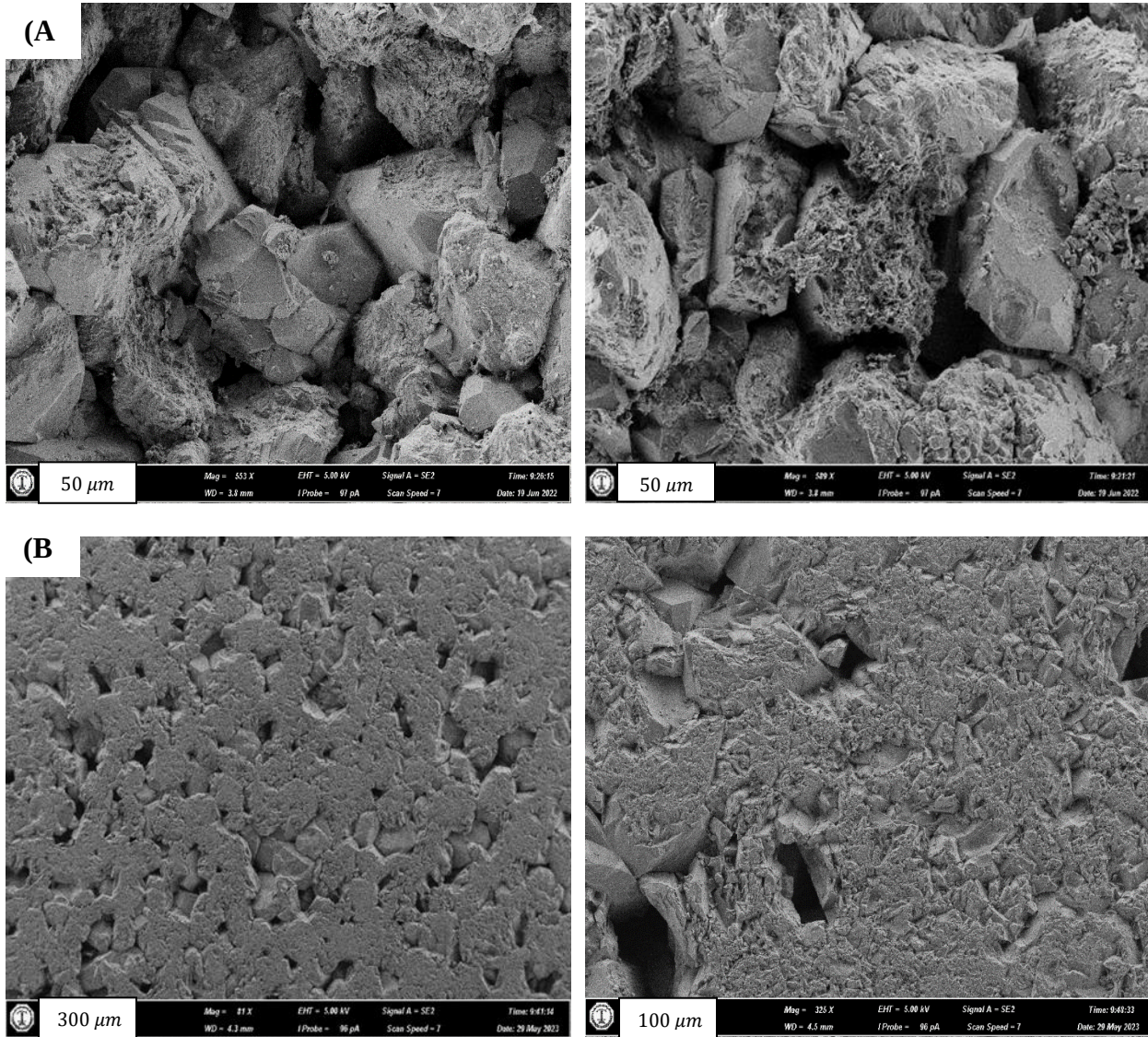


Figure 31 The XRD results of the samples in the study.

To explore the pores network, the SEM was conducted on a small chip which was prepared for each rock type. The SEM images showed that the Berea sandstone had almost a single large pore system and big effective with good connectivity. Another finding is the existence of kaolinite flake-like patches on the quartz grain surface without compromising the pores; as a result, neither the permeability nor the porosity was impacted. On the other hand, the Indiana sample showed a dual porosity system which consist of large and small pores. This was confirmed later with the NMR measurement. The FB sample's images demonstrated well-sorted pore system with good connectivity, which was supported by the sample's comparatively high permeability (74 mD) measured later. The literature has thoroughly examined the connection between the porosity and the permeability of the pores in the Fontainebleau rocks. It was discovered that a crossover porosity value of about 9% corresponds to a power law-like increase in the connectivity

of the Fontainebleau's pores, which causes their permeability to rise (Oshaish et al., 2023^a; Jacquin, 1964 and Bourbie and Zinszner, 1985). Given that the FB has a porosity of 10.12%, good permeability is anticipated. The SEM pictures for the Berea, FB and Indiana samples are shown in **Figure 32**, respectively.



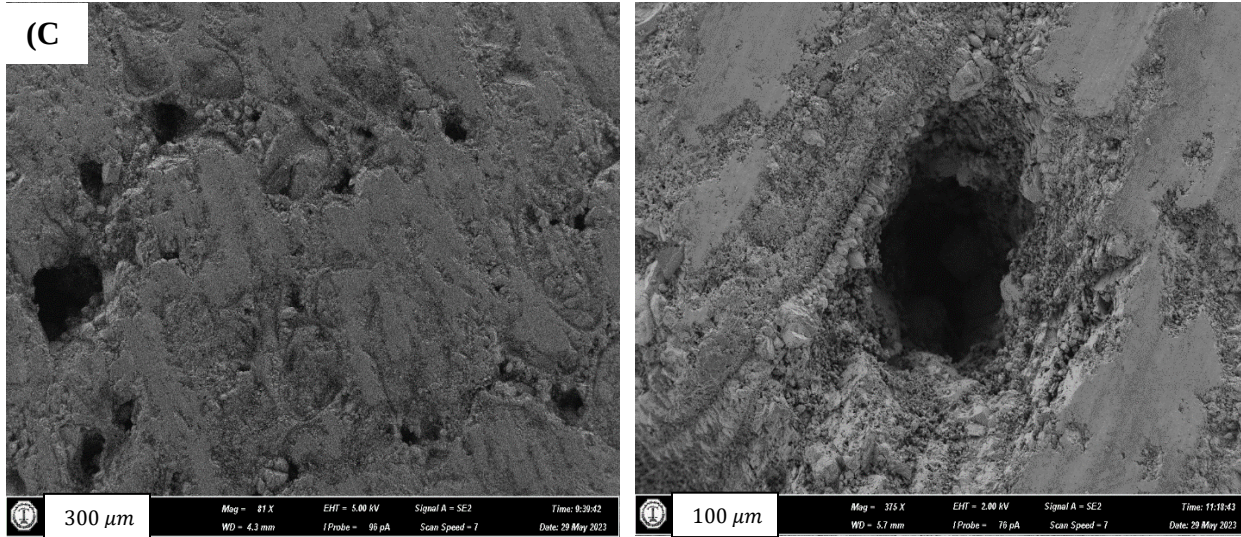


Figure 32 The SEM images of the samples presented in rows. Each row corresponds to one sample with the right image of zoom-in focus. (A) Berea, (B) FB. (C) Indiana.

The dielectric measurements were taken for the master and sister samples before any treatment. As mentioned earlier, real permittivity, imaginary permittivity, loss tangent and conductivity are the dielectric measurements that will be considered in our study. The results showed a real permittivity ranging between 3.2 and 3.7 for the sandstone samples whereas the limestone samples showed a value ranging between 5 and 5.5 which is consistent with the mineral composition of the samples and the recorded values in the literature. However, the Berea samples showed a clear dispersion (slope change) in all the dielectric measurements and higher conductivity across the frequency range investigated which indicates the presence of clay minerals. **Figure 33** shows the dielectric measurements of the dry samples. BS, FB and IL denote Berea sandstone, Fontainebleau Sandstone and Indiana limestone, respectively. Also, subscript 1 indicates the master samples while 2 represents the sister samples which are going to be treated later.

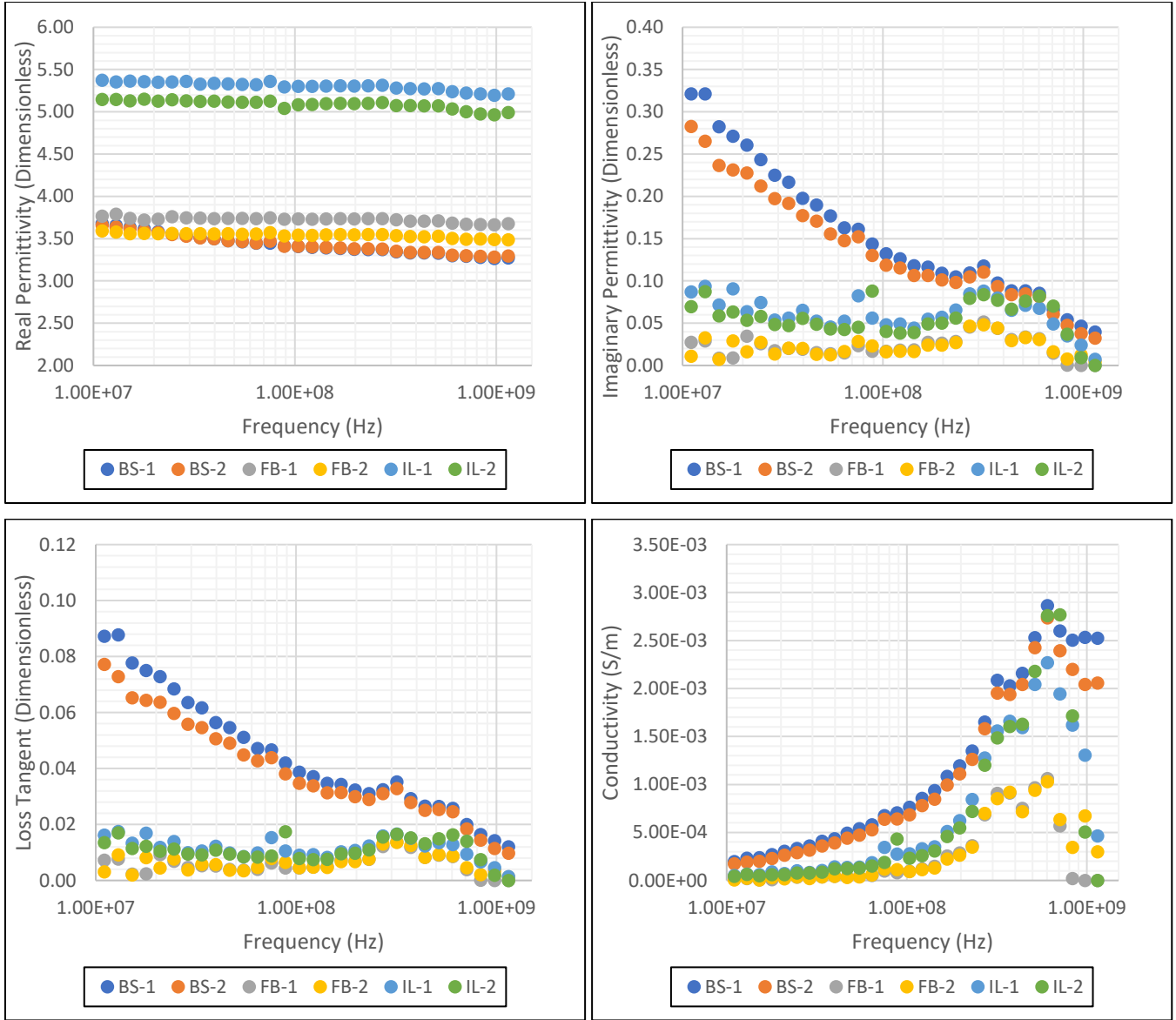
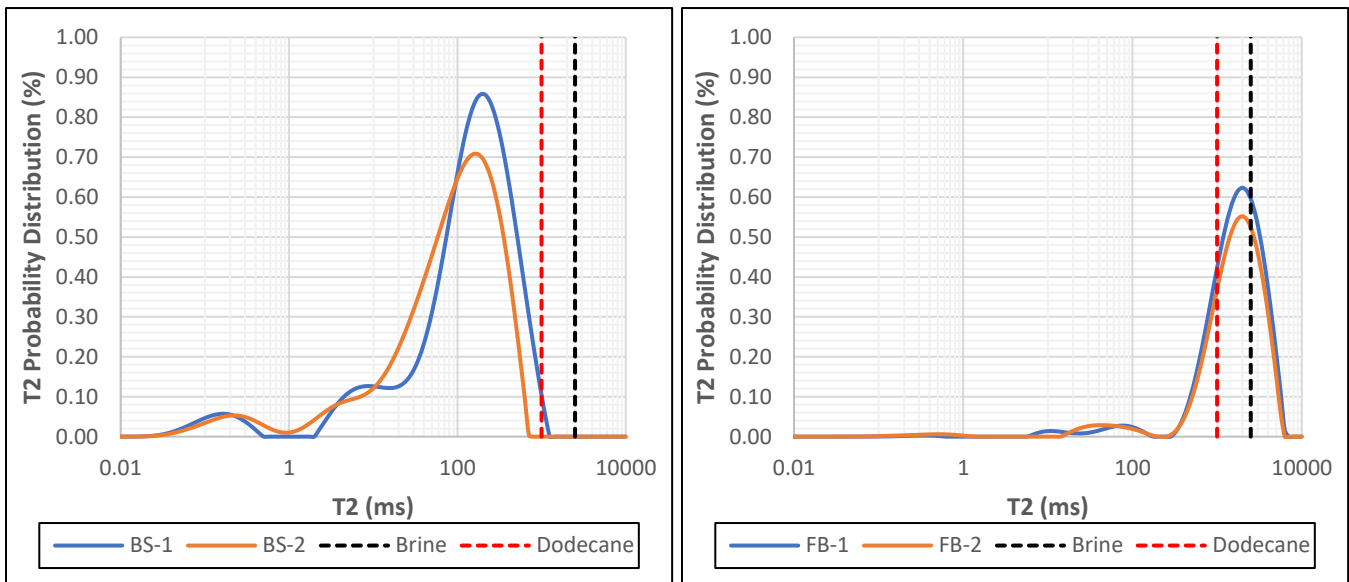


Figure 33 The dielectric measurements for all the samples before treatment at dry conditions.

5.1.2. Initial Core Analysis at $S_w = 1$

After acquiring the primary core analysis at dry conditions, the samples were vacuumed and saturated with 3% KCl brine solution. Then, the liquid permeability was measured for the master samples using the same brine at three different flow rates. The permeability results showed that the Berea sample has the highest value (101 mD) while the Indiana and the FB samples showed an average permeability of 92 mD and 74 mD, respectively. Furthermore, the NMR T_2 was taken for all the samples before engaging them in any treatment or fluid displacement which makes the baseline for the NMR measurements. In general, the NMR T_2 profiles of the sample presented in **Figure 34** agree with the information comprehended about

the pores structure by the SEM images. The Berea samples showed that the majority of the pores follows single pore size distribution with the presence of minor amounts of smaller pores whereas FB samples showed more distinctly single pore size network. On the other hand, the Indiana limestone sample showed clear dual porosity system with smaller pores are dominating the pore size distribution. In addition, the Indiana samples showed more heterogeneity than the other samples which was reflected by the slight mismatch of the NMR T_2 peak of the smaller pores. Moreover, the porosity obtained from the accumulation of the probability values over the range of T_2 investigated showed a close agreement with the He gas porosity measured.



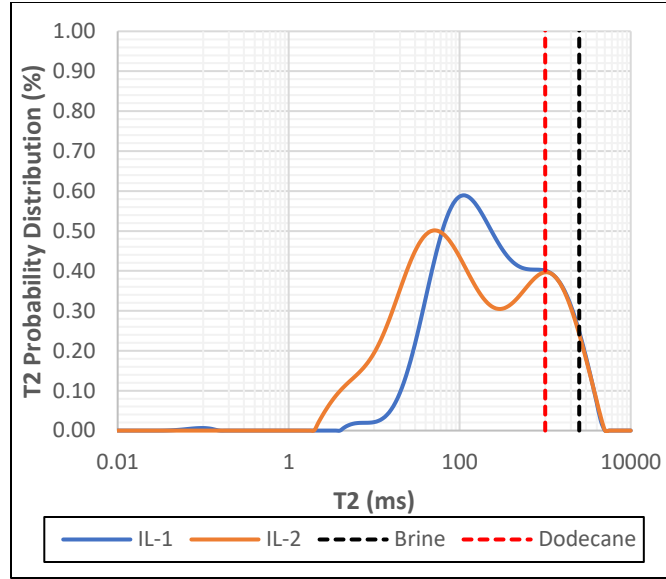


Figure 34 Initial NMR T_2 measurements at $S_w = 1$ for the master samples and the sister samples prior to treatment.

The last measurement conducted on the brine-saturated samples was the dielectric measurements which are presented in **Figure 35**. The Berea samples (BS-1 and BS-2) showed some variation in the real and imaginary permittivity values over the swept low frequency range which also impacted the loss tangent and the conductivity values. This indicates different tortuosity across the samples' pores. However, the real and imaginary values are matching on the high frequency range which indicates similar pore volume which agrees with the gas porosity measurements (19.50% for BS-1 and 19.03% for BS-2). On the other hand, the FB samples showed the lowest dielectric measurements without significant variation due to the low porosity values of the sample and the homogeneous well-sorted pore size distribution which was observed by the SEM. For the Indiana samples, the real permittivity showed variation across the whole frequency bandwidth which indicates both different tortuosity and some variation in the pore volume. This observation was supported by the NMR T_2 profile which showed some variation in the pore structure of both samples. Moreover, the BS-2 sample showed higher real permittivity over the high frequency range and higher conductivity over the whole frequency bandwidth than BS-1 which correlates well with their porosity values (17.46% for BS-1 and 18.47 for BS-2).

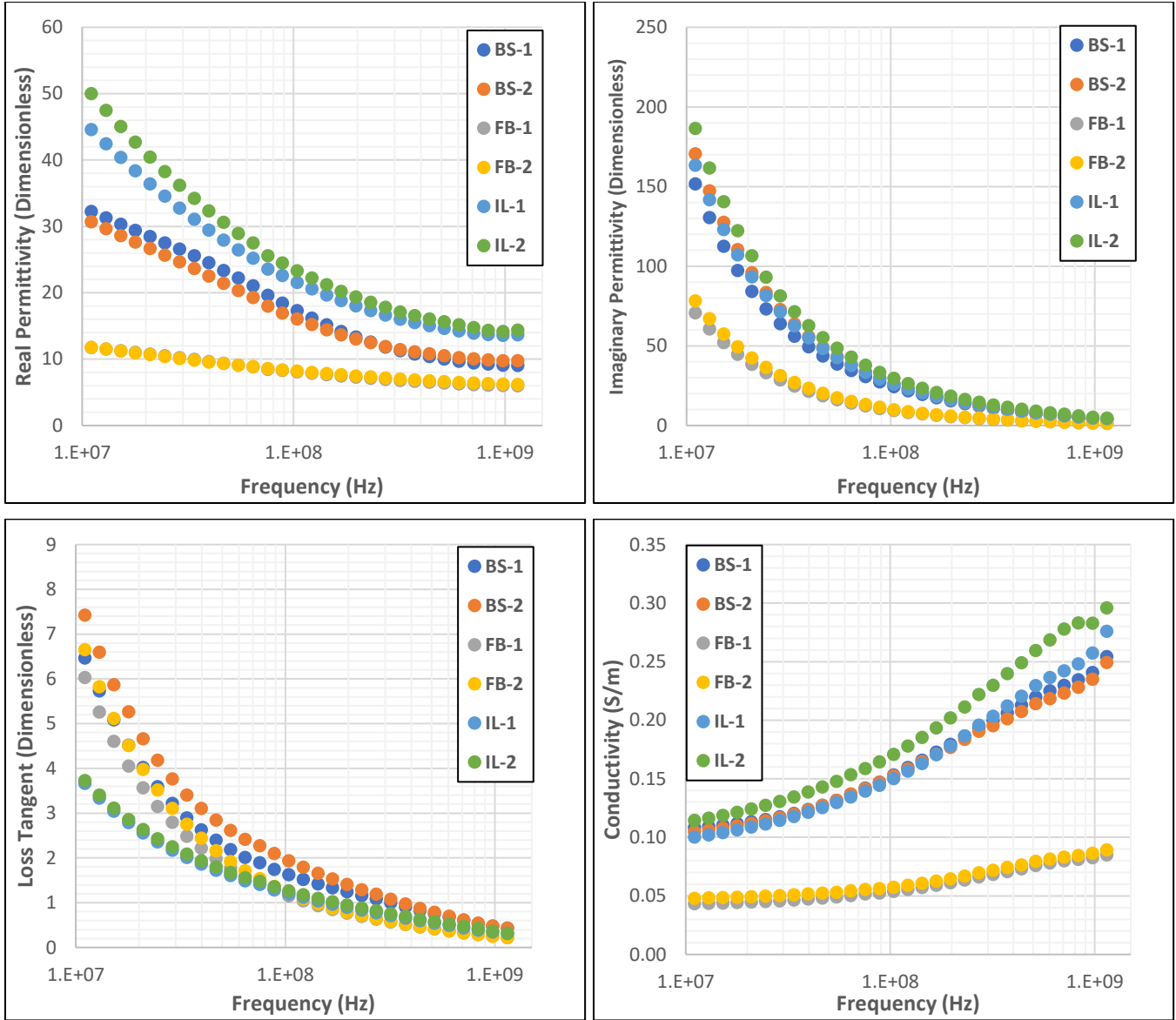


Figure 35 The initial dielectric measurements of all the samples at $S_w = 1$.

5.2. Wettability Alteration Results

The wettability alteration was performed on the sister samples BS-2, FB-2 and IL-2 using 1% stearic acid dissolved in light crude. The objective of this process is to reach the maximum shift of the wettability from water-wet towards the oil-wet condition without compromising the pore structure. Therefore, we relied on the small amount of asphaltene in the light crude oil along with the 1% stearic acid to achieve that objective. Saturates, Aromatics, Resin and Asphaltene analysis (SARA) was performed on the crude oil in 4 runs for validation. On average, the asphaltene content was 6.41% while the saturates, aromatics and resin contents were 22.86%, 64.56% and 6.17%, respectively. **Figure 36** shows the SARA results of

the 4 runs while **Table 6** summarizes the average content of the 4 components over the 4 runs. **Figure 37** shows the samples before and after wettability alterations.

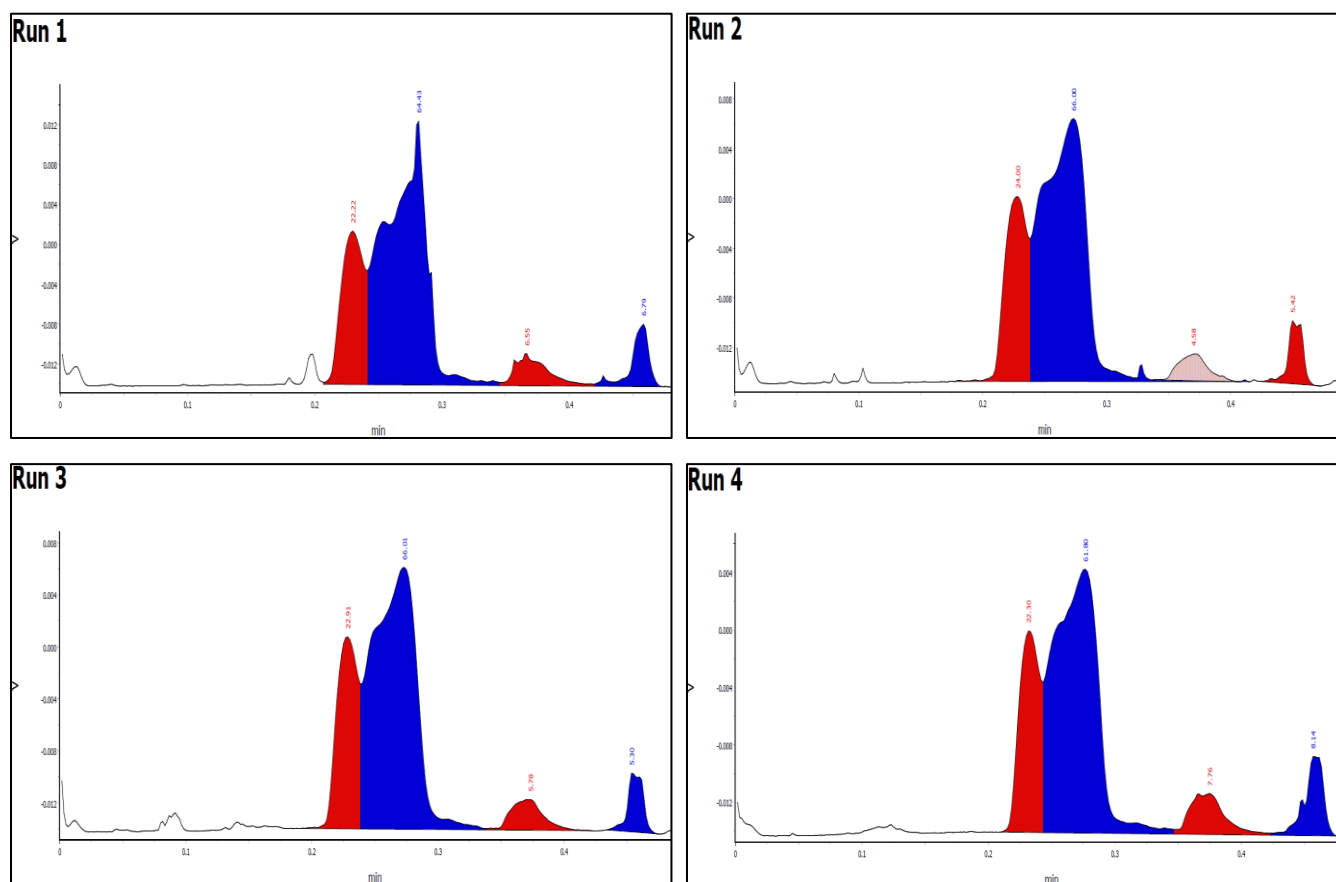


Figure 36 The SARA analysis results of the 4 runs for the light crude used in the treatment.

Table 6 Summary of the SARA analysis results of the 4 runs for the light crude used in the treatment.

Component / Run	Run 1	Run 2	Run 3	Run 4	Average
Saturates (%)	22.22	24.00	22.91	22.30	22.86
Aromatics (%)	64.43	66.00	66.01	61.80	64.56
Resins (%)	6.55	4.58	5.78	7.76	6.17
Asphaltene (%)	6.79	5.42	7.76	8.14	6.41

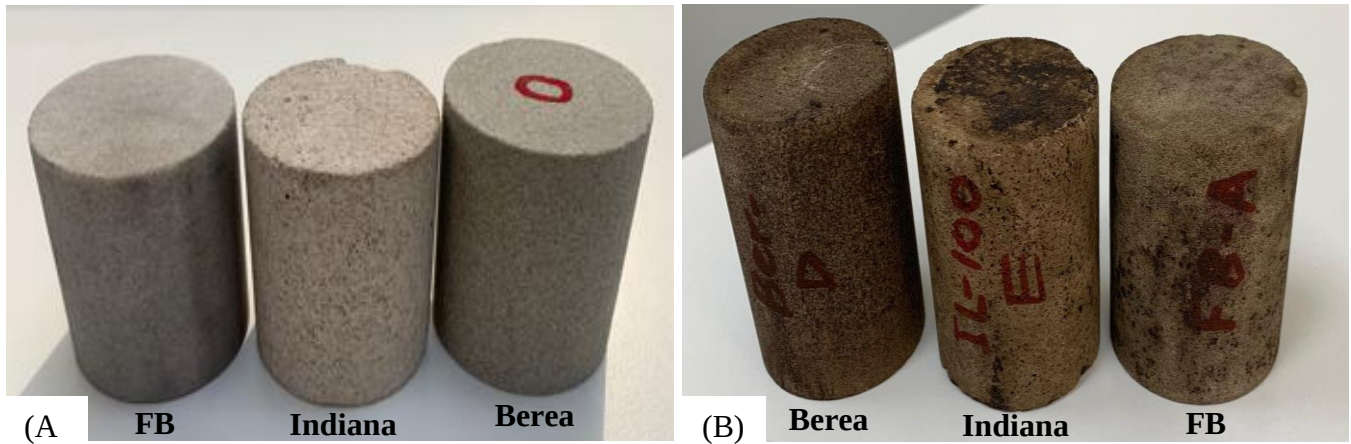
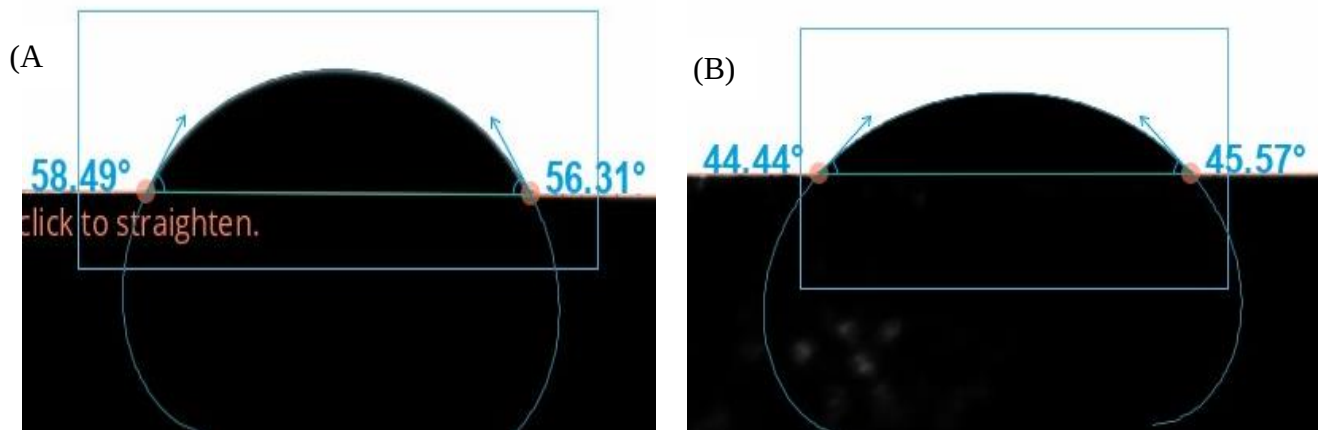


Figure 37 The sister samples before (A) and after (B) the wettability alteration.

To investigate the contact angle changes due to the wettability alteration, a small chip of pure quartz and calcites have been prepared for contact angle measurement. The chips were cut and fine polished for the test. The contact angle measurements were performed before and after the wettability alteration using a drop of the 3% KCl brine in ambient conditions. Before the treatment, the quartz showed a contact angle of 57.40° , on average, while the calcite showed a contact angle of 45.01° , on average. This indicates that both ships are close to water-wet condition. After treatment, the contact angle has been shifted to 98.04° and 86.59° for both quartz and calcite chips, respectively. **Figure 38** shows the contact angle measurements for both quartz and calcite samples before and after wettability alteration.



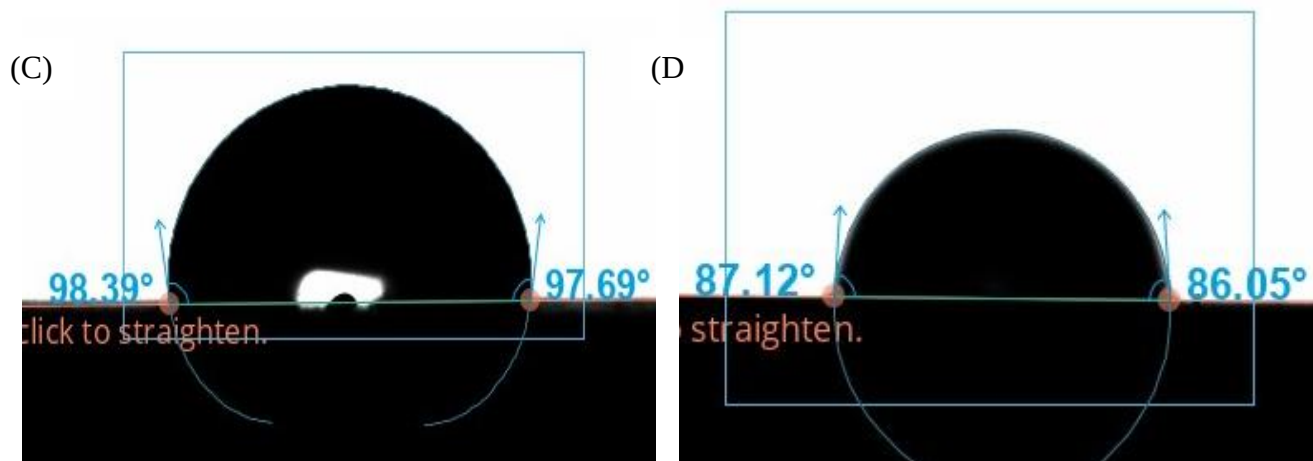
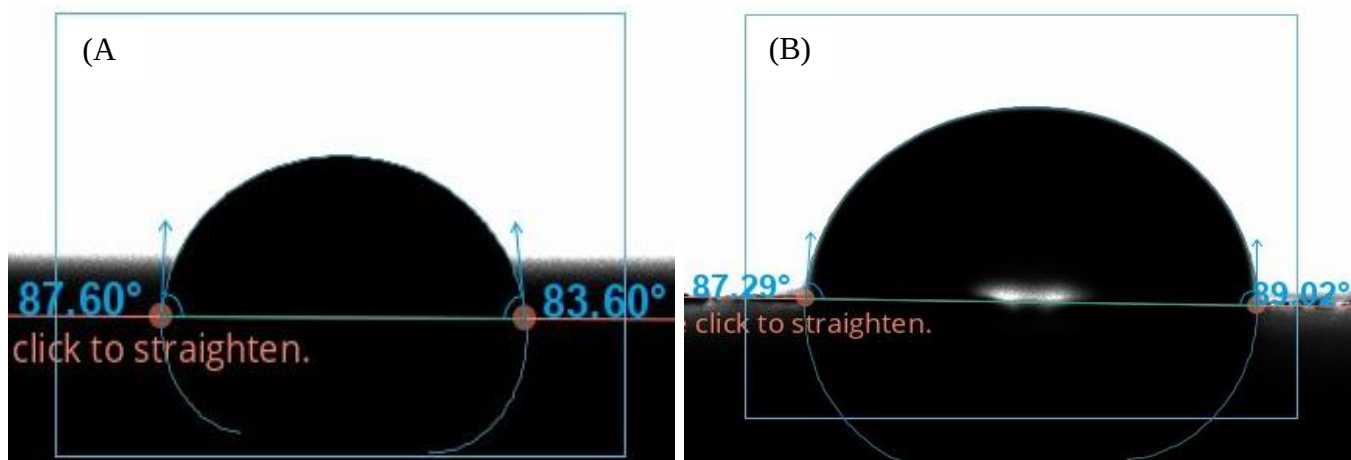


Figure 38 Contact angle measurements for the quartz and calcite chips before and after wettability alteration. (A) Quartz before treatment, (B) Calcite before treatment, (C) Quartz after treatment, (D) Calcite after treatment.

After performing the wettability alteration on the core sister samples, the contact angle was measured on the top of the inlet face to compare them with the contact angle measured on the chips. The measurements showed mixed wet contact angle values, close to 90° , which agrees with measurements on the chips. A contact angle of 85.6° was observed in the Berea, 88.16° for the FB and 79.82° for the Indiana. **Figure 39** illustrates the contact angle measurements performed on the sister samples after wettability alteration.



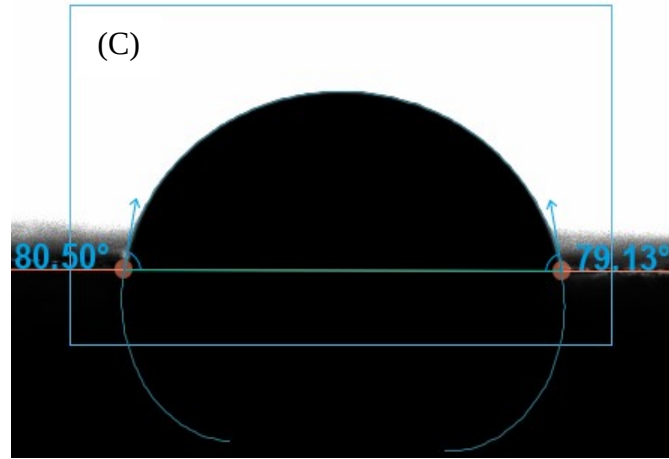


Figure 39 The contact angle measurements performed on the sister samples after wettability alteration; (A) BS-2, (B) FB-2 and (C) IL-2.

After treatment, the porosity was investigated using NMR and ‘He’ gas porosity measurements for all the treated sample. The samples showed a slight reduction in porosity in response to the wettability alteration. **Table 7** shows a comparison of the porosity measurement, before vs after treatment, using both measurement techniques.

Table 7 Porosity comparison for all treated samples before and after wettability alteration.

Sample	‘He’ Gas Porosity			NMR Porosity		
	Before Treatment (%)	After Treatment (%)	Difference (%)	Before Treatment (%)	After Treatment (%)	Difference (%)
BS-2	19.75	18.48	6.43%	19.70	18.30	7.11
FB-2	8.00	7.85	1.875%	8.40	7.60	9.52
IL-2	18.86	18.46	2.12%	20.10	19.70	1.99

Furthermore, the pore structure has been investigated in the treated sample using NMR T_2 measurement. As mentioned earlier, the NMR T_2 was collected for all the samples (at $S_w = 1$) before applying the wettability treatment or introducing any other fluids which was presented in figure 34. After altering the wettability of the sister samples, they were saturated again with the same brine and investigated under the NMR T_2 acquisition. The NMR data showed slight shift in the peaks which indicated a change in the wettability but without change in the overall profile which reveals that there are no changes in the pore

size distribution. Dielectric is very sensitive to the changes in the structure of the water inclusion sizes which can be induced by large asphaltene distribution. However, we followed a careful procedure in altering the wettability without compromising the pore structure which was confirmed by the NMR measurements. **Figure 40** shows the comparison of NMR results before and after wettability alteration for the sister samples (at $S_w = 1$).

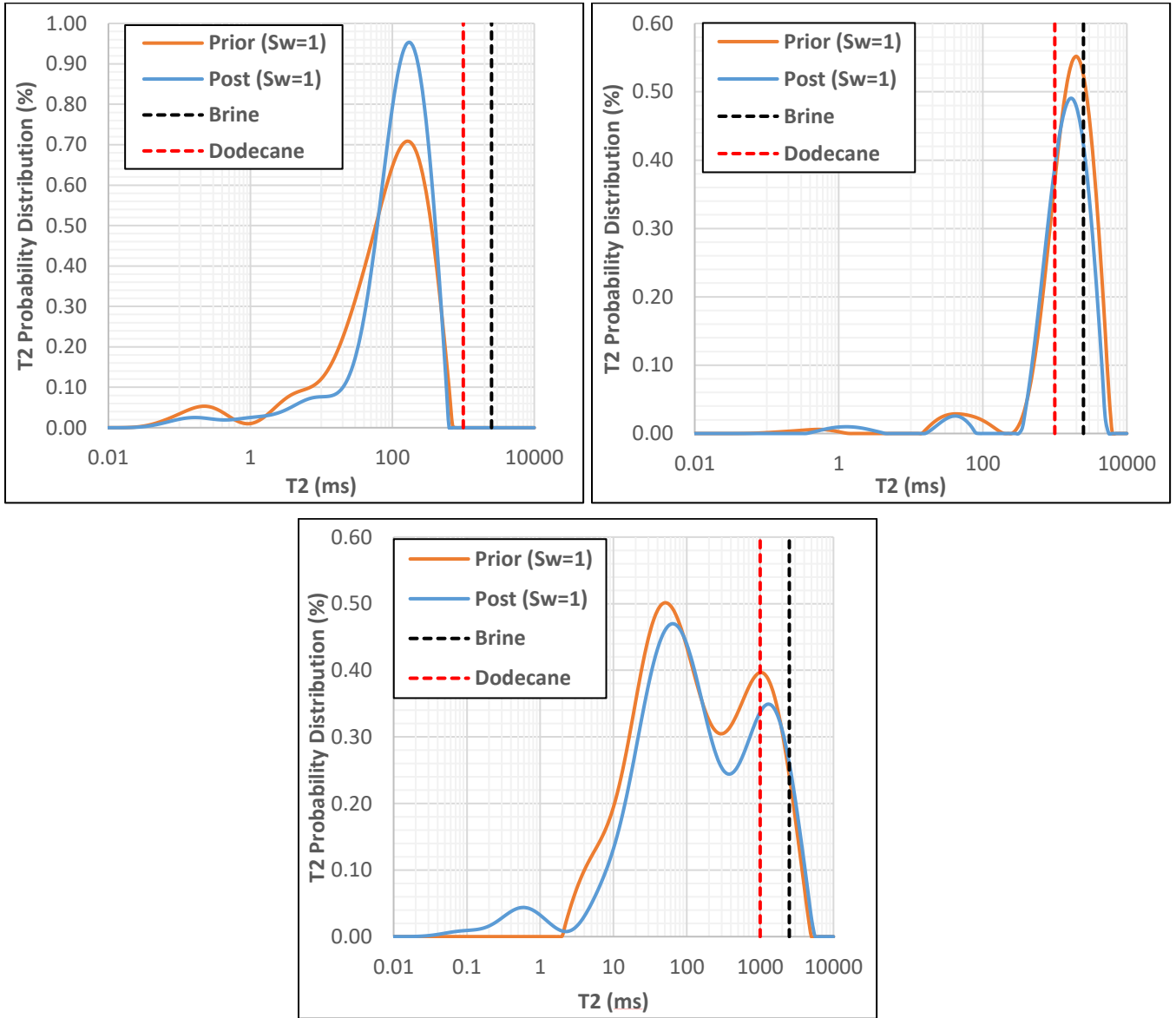


Figure 40 The comparison of NMR results before and after wettability alteration for the sister samples (at $S_w = 1$).

5.3. Wettability Index Calculations

As mentioned previously, the wettability indices used for benchmarking the dielectric wettability index correlation are the USBM wettability index, WI_{USBM} , developed by Donaldson et al. (1969) and K. Al-Garadi et al. (2022) NMR wettability index, WI_{NMR} . The wettability index calculations were performed on the master samples which represent the wettability index before wettability alteration and the sister samples after they have been exposed to wettability alteration process, called treated samples.

5.3.1. USBM Wettability Index

To induce the capillary forces which are responsible for fluid displacement, the centrifuge method has been implemented. The setup of the centrifuge is demonstrated in **Figure 41**. As mentioned earlier, the displacement cycles included primary drainage, imbibition and secondary drainage. The RPM can be converted to capillary pressure, P_c , using Hassler- Brunner (1945) expression:

$$P_c = 7.953 \times 10^{-8} (\Delta\rho) \omega^2 (r_o^2 - r_i^2) \quad (35)$$

Where,

- $\Delta\rho$ is the difference between the densities of the displacing and the displaced fluids (in g/cc). The brine density is 1.0132 g/cc while the density of the dyed dodecane is 0.7345 g/cc.
- $\omega = 2\pi \frac{RPM}{60}$ is the rotational speed (in rad/s).
- r_o is the distance from the center of the rotor to the outlet end faces of the sample (in cm).
- r_i is the distance from the center of the rotor to the inlet end faces of the sample (in cm).

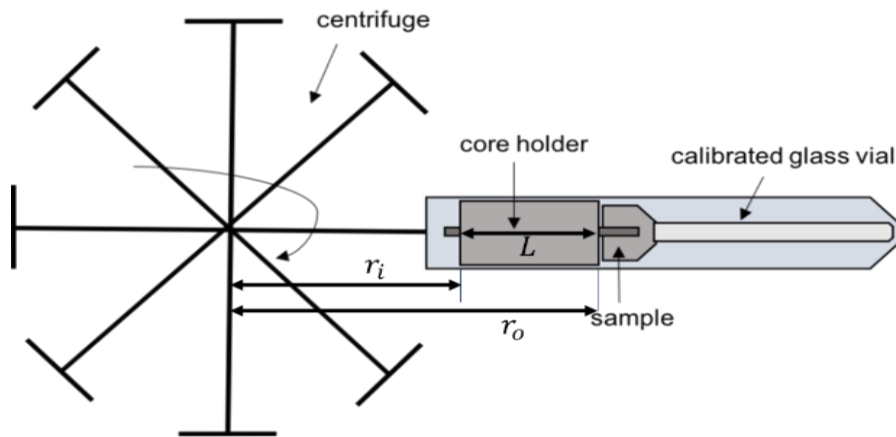


Figure 41 A Schematic of the classical centrifuge setup (After Shikhov et al., 2017).

The wettability index results showed a shift towards the oil wetness direction and ended up in mixed wettability conditions. The shift has been observed by the centrifuge displacement at low rotational speed (1000 RPM) and very low capillary pressure. During primary drainage, the master Berea and Indiana samples expelled only 2% and 16.70% of the brine in the pores, respectively, while the master FB expelled 53.88%. This indicates stronger water wetness in the Berea and Indiana samples compared to the FB. This has been confirmed by the wettability index results which will be discussed later. However, after wettability alteration, the amount of displaced brine at the same speed has spiked in the Berea sister sample to reach 36.18% and relatively increased in the FB to 62.34% and Indiana to 26.84%. On the other hand, the displaced amount of the dodecane at the same speed during the imbibition cycle showed a reduction in response to the wettability treatment in all the samples. The master Berea expelled 44.36% of the dodecane while the sister treated sample expelled 34.02%. For the FB samples, 68.42% of the dodecane was displaced by the brine in the master sample compared to 40.40% in the sister treated sample. And finally, the Indiana sample showed the strongest response toward the treatment in which 43.47% of the dodecane was expelled in the master sample compared to 24.84% in the treated sister sample. **Figure 42** illustrates these observations at 1000 RPM.

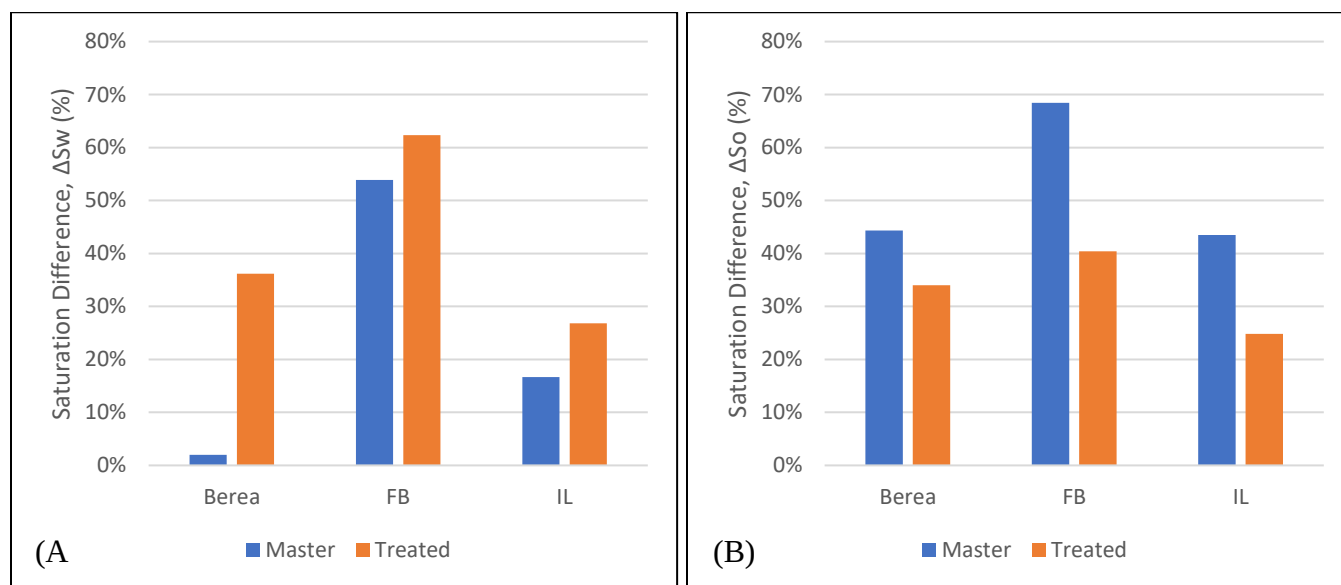
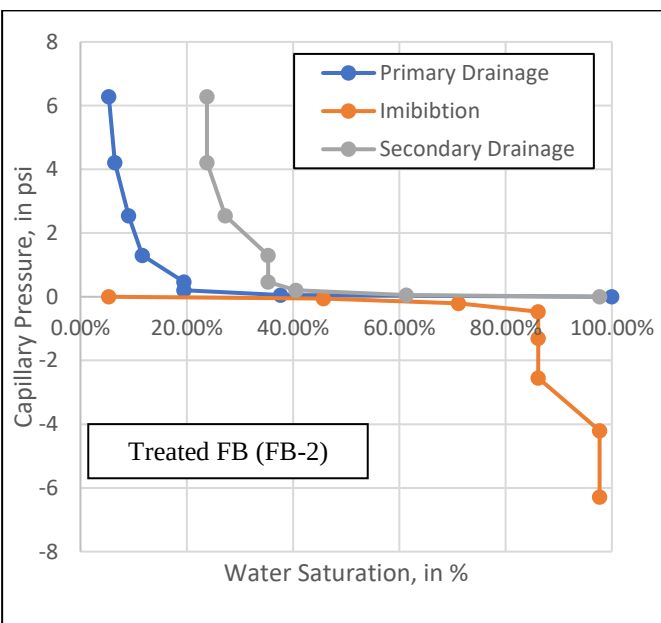
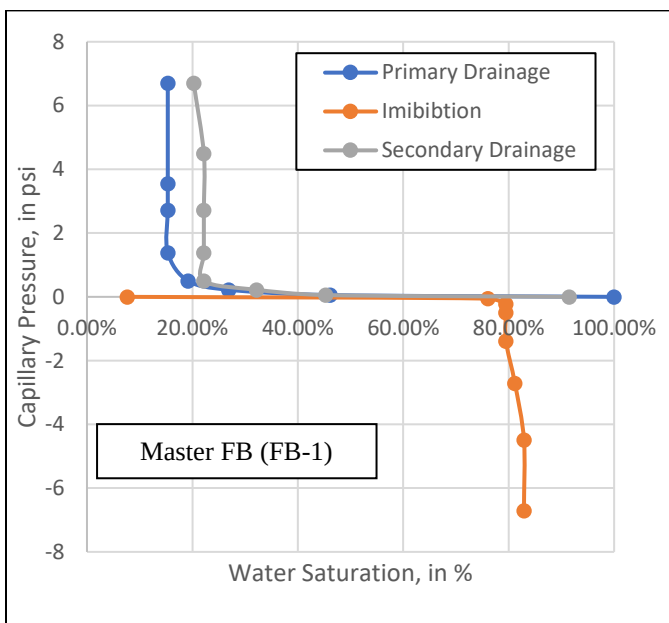
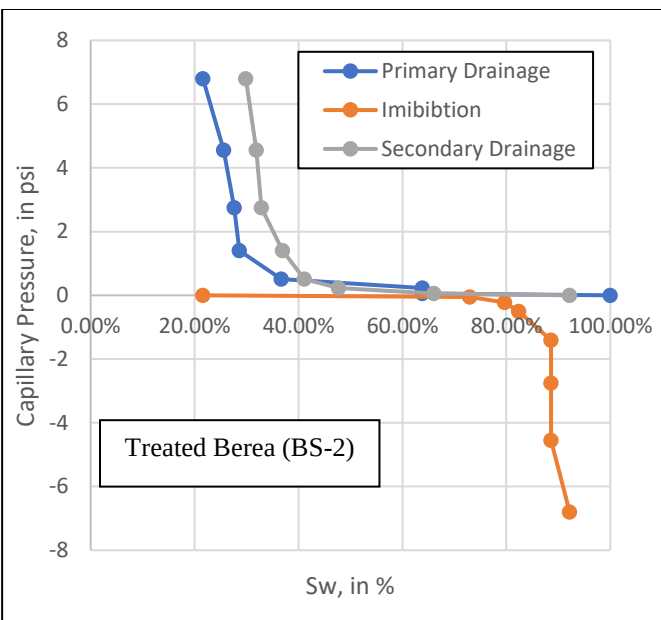
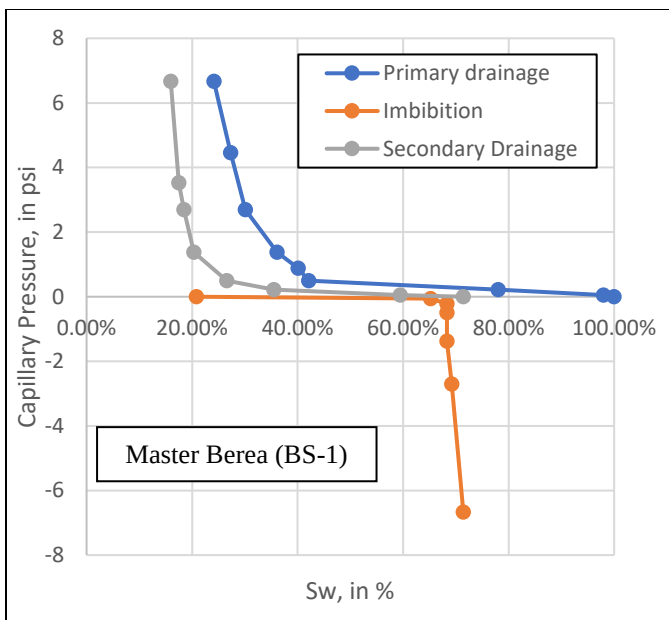


Figure 42 Comparison between the displaced amount of the fluids in the samples at 1000 RPM during (A) Primary Drainage and (B) Imbibition.

After completing all the drainage and imbibition cycles for all the samples, the USBM wettability index was evaluated. Without wettability alteration, the Berea and Indiana master samples showed stronger water wetness than the FB. The wettability index for the Berea and the Indiana master samples was found to

be 0.73 and 0.63, respectively, which agrees with water-wet nature known for quartz and calcite. However, although FB is composed of quartz only, the sample showed a USBM wettability index of 0.16 which falls in the mixed wettability index range. This can be attributed to well sorted grains and uniform and homogeneous pore size distribution that were seen by the SEM images and depicted from the relatively high permeability compared to the significantly low porosity. Moreover, the FB sample showed the least S_{wirr1} and S_{or} values (7.63% and 6.63%, respectively) which indicated equally efficient primary drainage and imbibition displacement cycles reflecting an equal affinity to both oil and water. From this observation, it can be deduced that the USBM wettability index measurement is different than the contact angle which measures solely the surface interfacial interaction between the grain surface and fluids. The USBM wettability index is a dynamic measurement which is affected by the ease of the fluid flow controlled by several factors other than grains surface interactions including pore size distribution, pores connectivity and tortuosity.

On the other hand, the USBM wettability index for the treated sister samples showed lower values than the master untreated samples indicating a shift in the wettability to the oil wetness. All the treated samples showed a USBM wettability index close to the mixed wettability index, zero. The USBM wettability index for the treated Berea, FB and Indiana was obtained to be 0.16, -0.17 and 0.14, respectively, which indicates an effective wettability alteration process. **Figure 43** shows the capillary pressure, P_c , versus the water saturation curves for different drainage and imbibition cycles. The areas included in the USBM wettability index calculations are the area below the secondary drainage (A_1) and the area above the imbibition cycle (A_2) which have been computed using the trapezoidal method. In table 8, the areas computed, and the USBM wettability index results are presented.



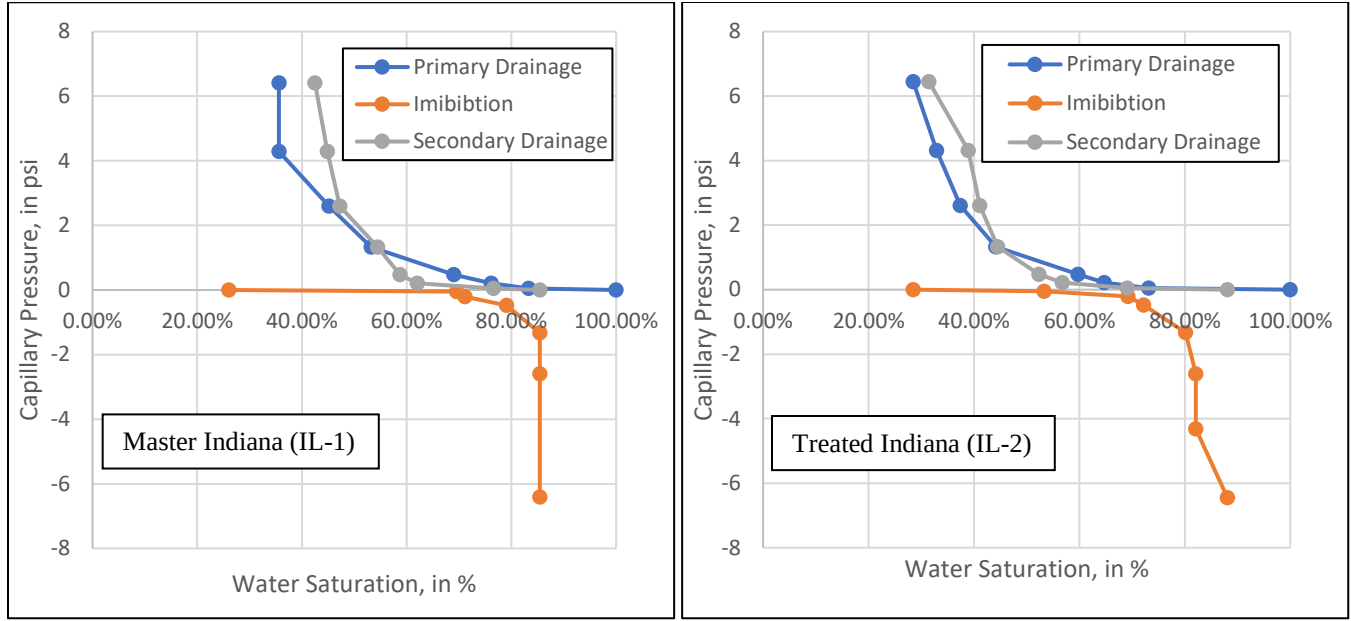


Figure 43 The capillary pressure, P_c , versus the water saturation curves for primary drainage, imbibition and secondary drainage cycles used in the USBM wettability index calculations for all master and treated samples.

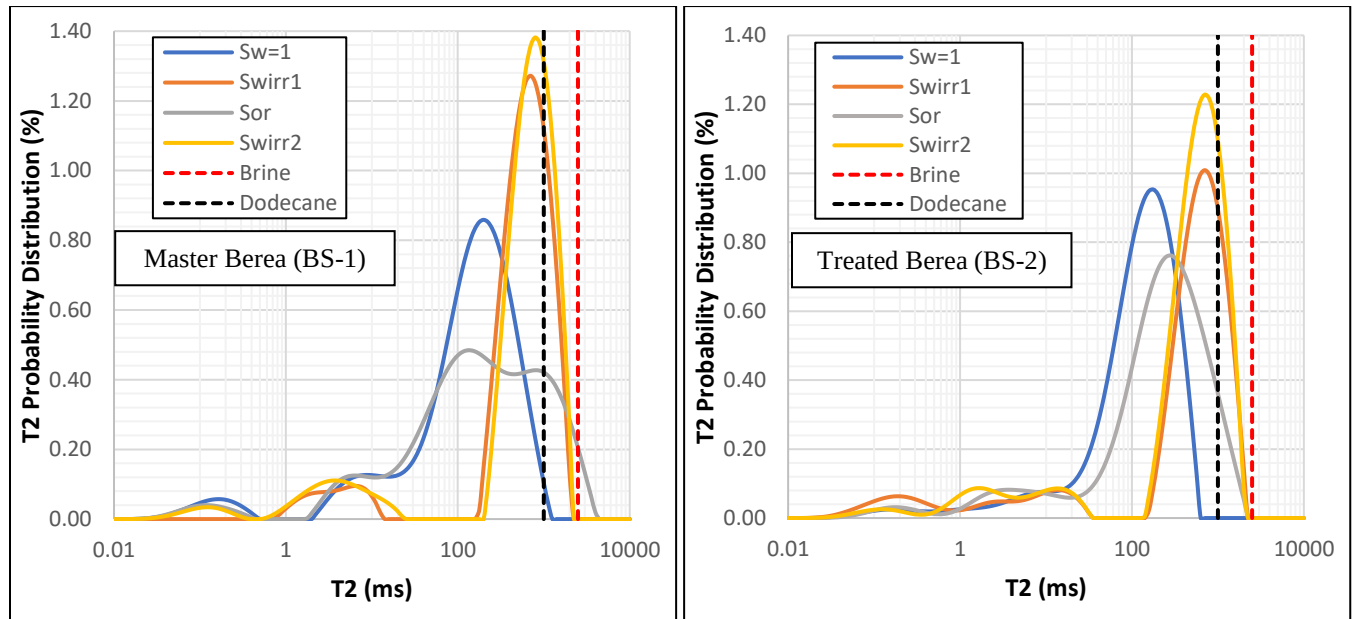
Table 8 USBM wettability index results for all samples.

Sample	A_1	A_2	WI_{USBM}
BS-1	0.1841	0.0346	0.73
BS-2	0.4262	0.2962	0.16
FB-1	0.1747	0.1204	0.16
FB-2	0.3263	0.4840	-0.17
IL-1	0.4219	0.0983	0.63
IL-2	0.6524	0.4701	0.14

5.3.2. NMR Wettability Index

For comparison purpose, the NMR wettability index was calculated for the master samples and for the sister samples after wettability treatment using Al-Garadi et al., (2022) correlation. The NMR T_2 measurement was acquired for the samples at different endpoint saturation conditions, $S_w = 1$, S_{wirr1} , S_{or} and S_{wirr2} . In addition, the NMR T_2 was measured for the bulk brine and the bulk oil (dodecane) which were found to be 2500 ms and 1000 ms, respectively. As per equations 31-33, The required T_2 measurements for the wettability index calculation are the bulk brine T_2 (T_{2Bw}), the bulk oil T_2 (T_{2Bo}), T_2 at S_{wirr}

(T_{2Swirr}) and T_2 at S_{or} (T_{2Sor}). Overall, the NMR wettability index (WI_{NMR}) results showed good agreement for all samples with the USBM wettability index (WI_{USBM}). The master Berea sample showed WI_{NMR} value of 0.74 compared to the WI_{USBM} of 0.73 while the treated sample showed a WI_{NMR} of 0.48 compared to a WI_{USBM} of 0.16. Both USBM and NMR results showed a shift in the wettability towards oil wetness. For the other sandstone sample, FB, the master showed a WI_{NMR} of 0.15 compared to a WI_{USBM} of 0.16 whereas the sister sample a WI_{NMR} of -0.10 compared to a WI_{USBM} of -0.17. On the other hand, the Indiana master sample showed a WI_{NMR} of 0.42 compared to a WI_{USBM} of 0.63 while the treated sample showed a WI_{NMR} of 0.20 compared to a WI_{USBM} of 0.14. **Figure 44** demonstrate the NMR T_2 profiles for the master samples and the sister samples after treatment. **Table 9** summarizes the different parameters used in the NMR wettability index calculations and the WI_{NMR} results.



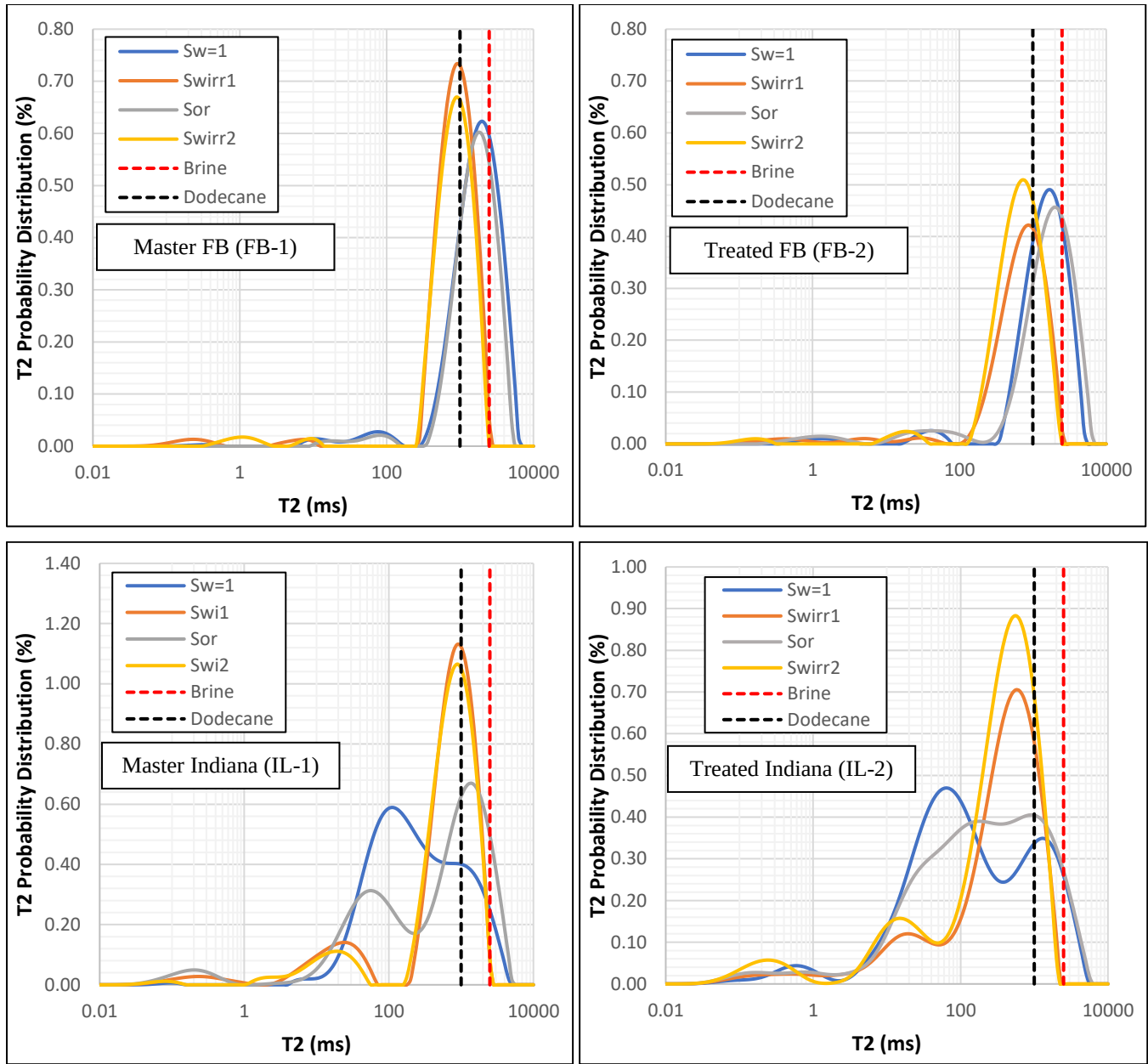


Figure 44 The NMR T_2 curves at different saturation endpoints for the master samples (without treatment) and the sister samples after treatment.

Table 9 Summary of the different parameters used in the NMR wettability index calculations and the WI_{NMR} results.

Sample	$T_{2Swirr'}$ in ms	$T_{2Sor'}$ in ms	I_w (Ratio)	I_o (Ratio)	WI_{NMR}
BS-1	800	150	0.94	0.20	0.74

BS-2	600	290	0.88	0.40	0.48
FB-1	950	1995	0.20	0.05	0.15
FB-2	700	2000	0.20	0.30	-0.10
IL-1	980	1412	0.44	0.02	0.42
IL-2	600	1000	0.60	0.40	0.2

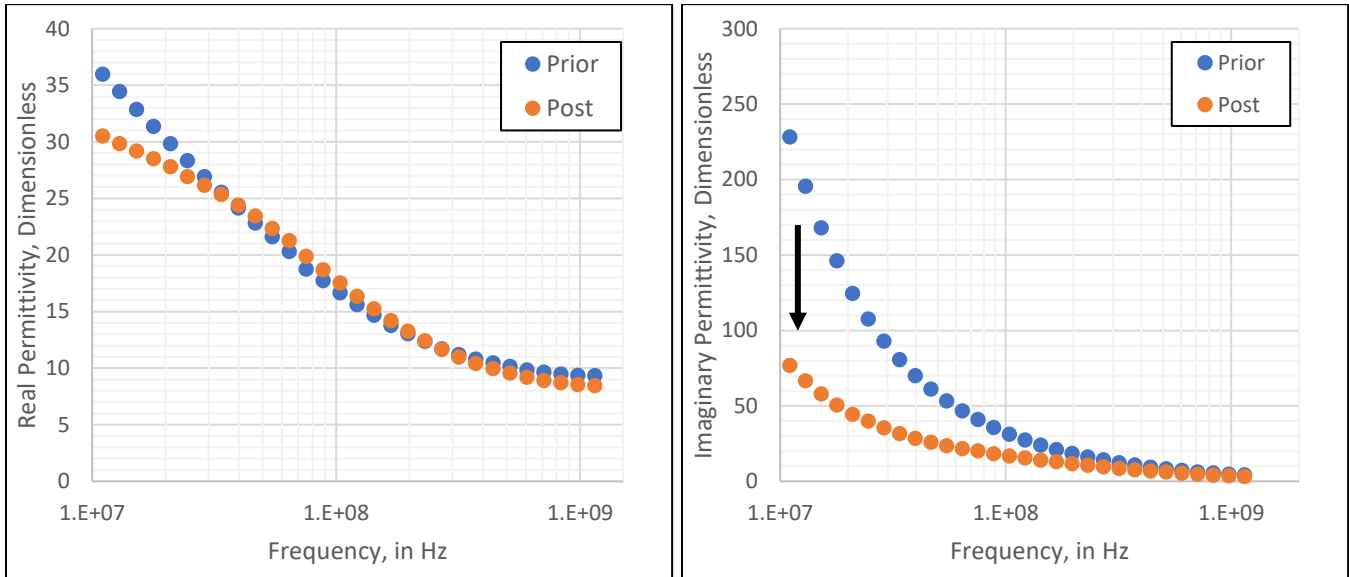
5.4. Dielectric Response to Wettability Alteration

The dielectric measurements were acquired under the previously mentioned endpoint saturations ($S_w = 1$, S_{wirr1} , S_{or} and S_{wirr2}) for all the samples (master samples with no treatment and sister samples after treatment). In addition, one extra dielectric measurement was conducted on the sister samples before treatment at $S_w = 1$ to use it as a base line and confirm wettability alteration on the same sample with same pore structure. The basic dielectric measurements obtained are the real and imaginary permittivity. Then, the loss tangent and conductivity were computed using equations (10) and (34), respectively. To investigate the impact of the wettability alteration on the dielectric comprehensively, we will discuss the dielectric results in 2 parts: comparing the dielectric results of the sister samples before and after treatment at $S_w = 1$ and comparing the dielectric results of the treated samples against the master samples at different endpoint water saturations.

5.4.1. Dielectric Comparison of the Treated Samples at $S_w = 1$ (Before vs After Treatment):

The study of the wettability effect of wettability on the dielectric results at the exact same fully water saturation conditions ($S_w = 1$) with almost the same porosity has not been studied before. Most of studies have investigated the dielectric response on partially saturated samples (Venkataramanan et al., 2014, Bona et al., 2002 and Al-Ofi et al., 2017 and 2018). The advantage of this analysis is to eliminate the effect of the water content variation and relate the changes in the dielectric response to wettability alteration only. According to the dielectric polarizations, the real permittivity dispersion is solely sensitive for the water filled porosity at high frequencies, hence, most of dielectric water saturation models, such as CRIM (Birchak, 1974), Rayleigh mixing formula (Rayleigh, 1892) and Seleznev et al. (2004) model, use the permittivity values at 1 GHz in the calculations. On the other hand, at medium and low frequency ranges, the dielectric dispersion exhibits other different polarizations which are controlled by rather than water content such as the shape of the water inclusions and the interfacial interactions between the fluids and between the fluids and the grains surface (Bona et al., 2002 and Garcia and Heidary, 2018). Therefore, the study of the wettability effect should be restricted to the low and medium frequency ranges.

The dielectric results showed a significant change in response to the wettability alteration. The imaginary permittivity and loss tangent decreases after treatment at lower frequencies while the conductivity decreases over the whole frequency range. As depicted from previous studies such as Garcia and Heidary (2018) and Bona et al. (2002), this trend is consistent with the fact that samples are shifted to the oil-wet status and the shape of the water phase becomes less continuous and more rounded. However, the real permittivity trend of the sandstone samples (BS-2 and FB-2) showed an opposite trend at lower frequencies. As a result of wettability alteration, the real permittivity for both sample increases at the frequency ranges, below 200 MHz for BS-2 and below 80 MHz for FB-2. This trend can be attributed to the increase in the tortuosity of the pore spaces which is confirmed by the reduction in the conductivity (Al-Ofi et al., 2018). However, the IL-2 sample showed a reduction in the real permittivity across the whole frequency range after treatment. Furthermore, the real permittivity showed a very minor decrease at high frequency range indicating a slight reduction in porosity which was confirmed by ‘He’ gas porosity and NMR measurements. **Figures 45, 46 and 47** present the comparison between the dielectric measurements of the sister Berea, FB and Indiana samples, respectively, before and after treatment at $S_w = 1$.



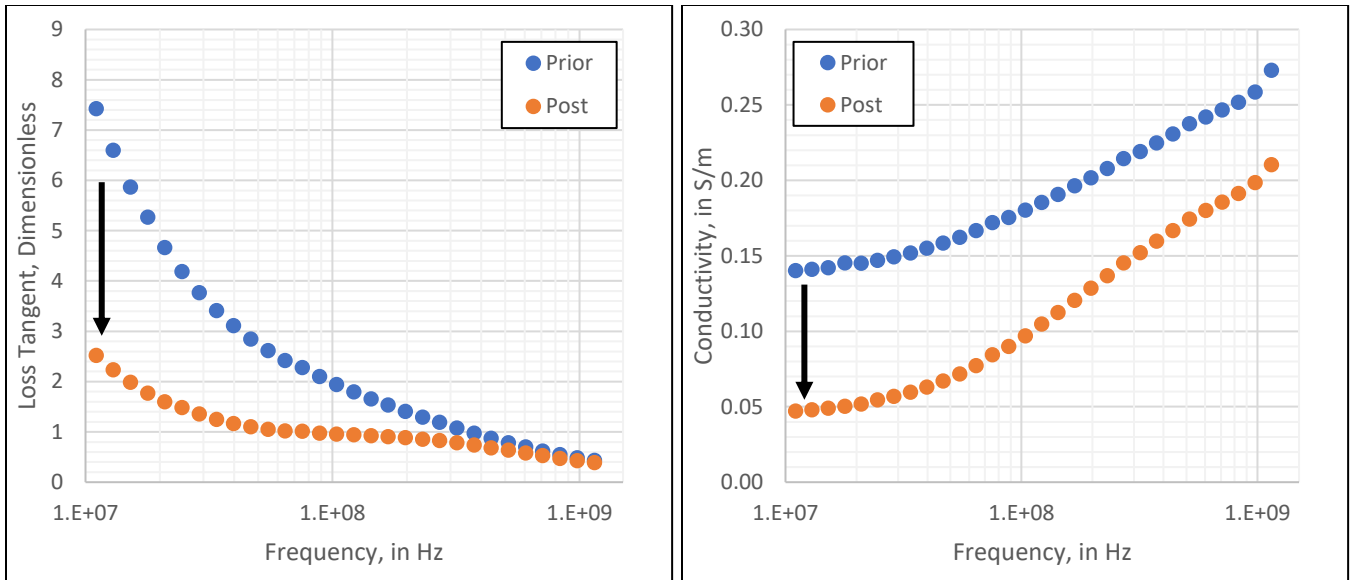
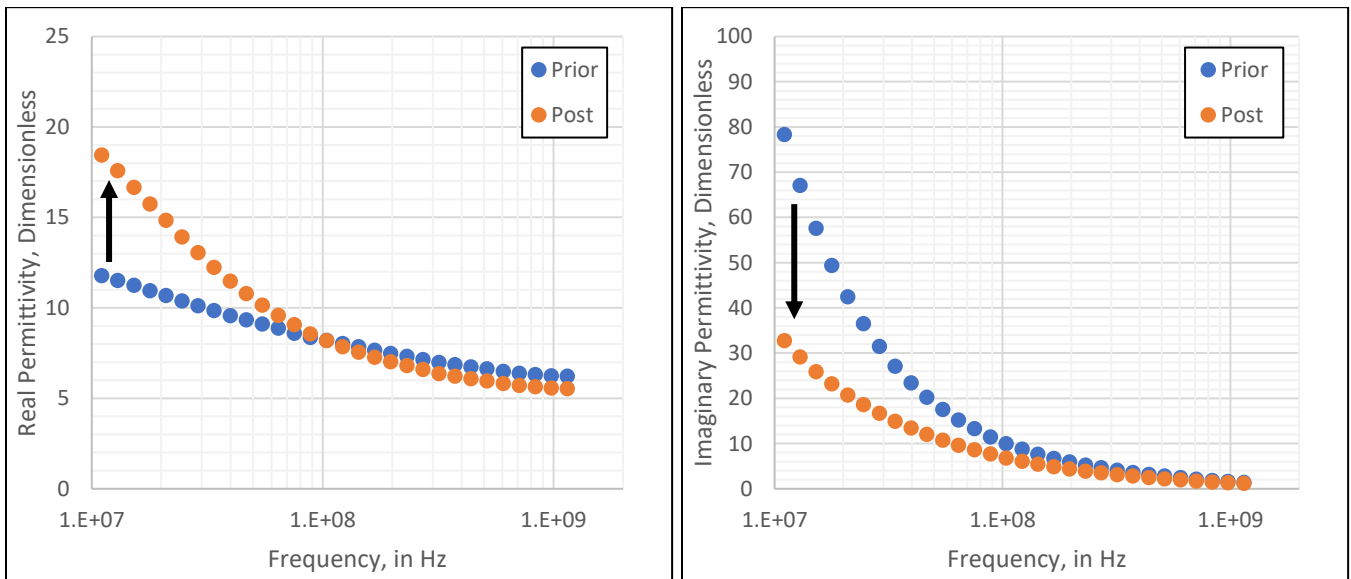


Figure 45 Comparing the dielectric results of the sister Berea sample (BS-2) before the treatment against the results after treatment at $S_w = 1$.



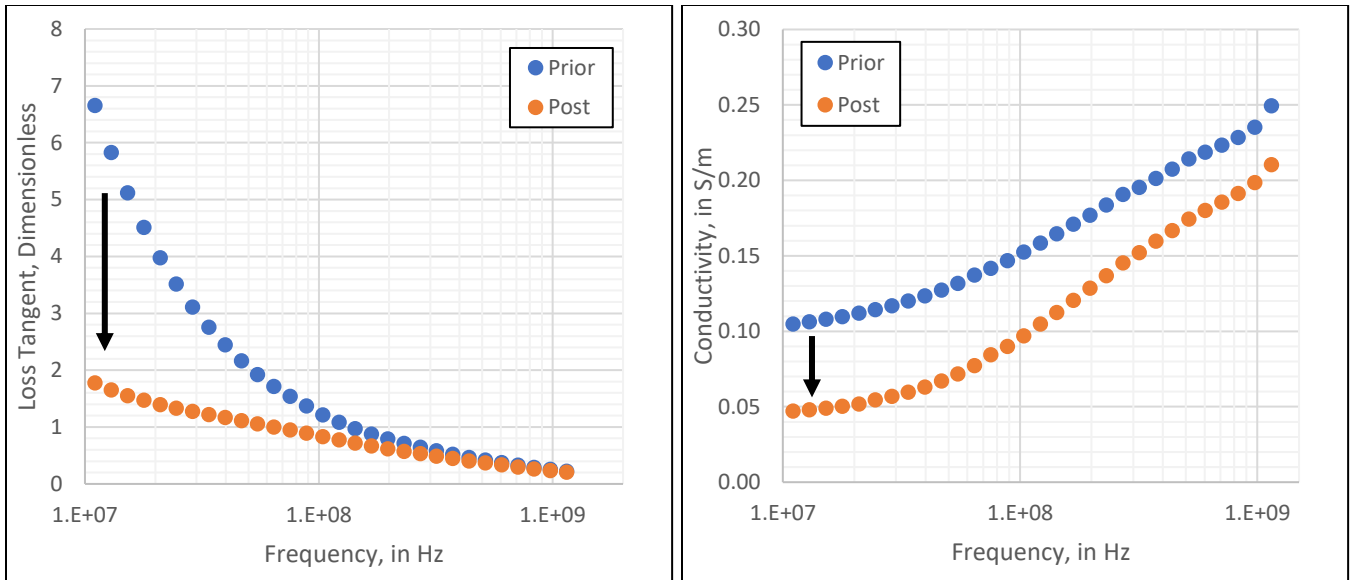
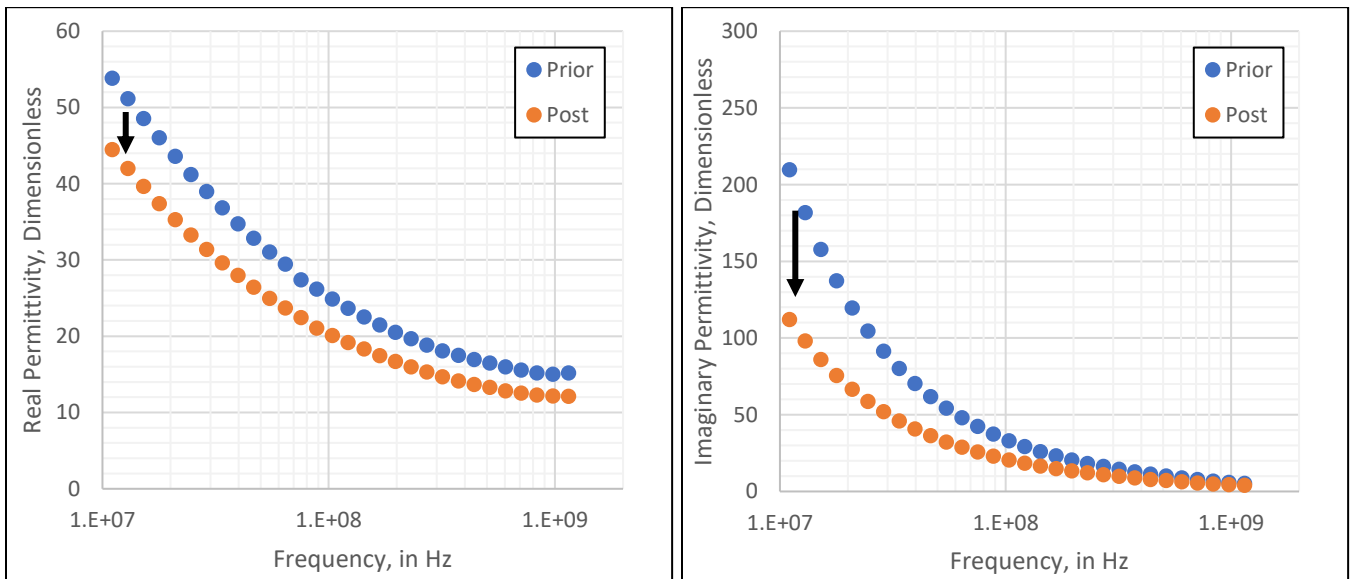


Figure 46: Comparing the dielectric results of the sister FB sample (FB-2) before the treatment against the results after treatment at $S_w = 1$.



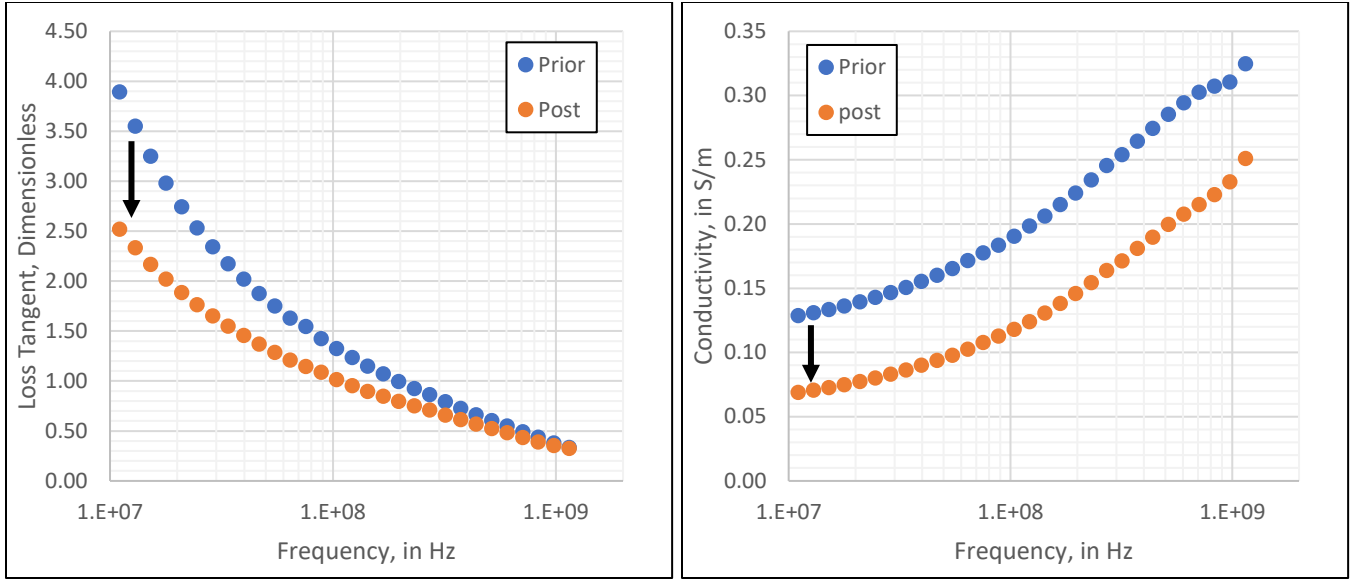


Figure 47 Comparing the dielectric results of the sister Indiana sample (IL-2) before the treatment against the results after treatment at $S_w = 1$.

According to some studies, the dielectric relaxation time is another parameter which showed a strong correlation with wettability conditions. For instance, Bona et al. (1998 and 2002), who used a combination parallel plate and coaxial probe, deduced that wet samples can experience larger relaxation times than oil wet ones. The relaxation time can be defined by the time it takes for a molecule to reach 63% of its return from an organized state to randomized chaos after an applied microwave field is turned off (Neas and Collins, 1988). There are several methods to calculate the relaxation time such as Debye and Cole-Cole. However, as discussed in section 2.2 (Cao and Gerhardt, 1990). However, evaluating relaxation times requires acquiring the real and imaginary permittivity at lower frequencies than what the open-ended coaxial probe is capable of to allow the molecules to achieve to the relaxation required for the measurement. Although we have utilized the open-ended probe, the real versus the imaginary plot for the treated samples before and after treatment, which is used by the Cole-Cole relationship to evaluate the relaxation time, showed consistent trends. Before treatment, plots showed larger imaginary permittivity values with larger slopes than the curves after the wettability alteration which reveals significant change in relaxation times. **Figure 47** shows the plots of the imaginary permittivity versus the real permittivity for the treated samples before and after wettability alteration at the same water saturation ($S_w = 1$).

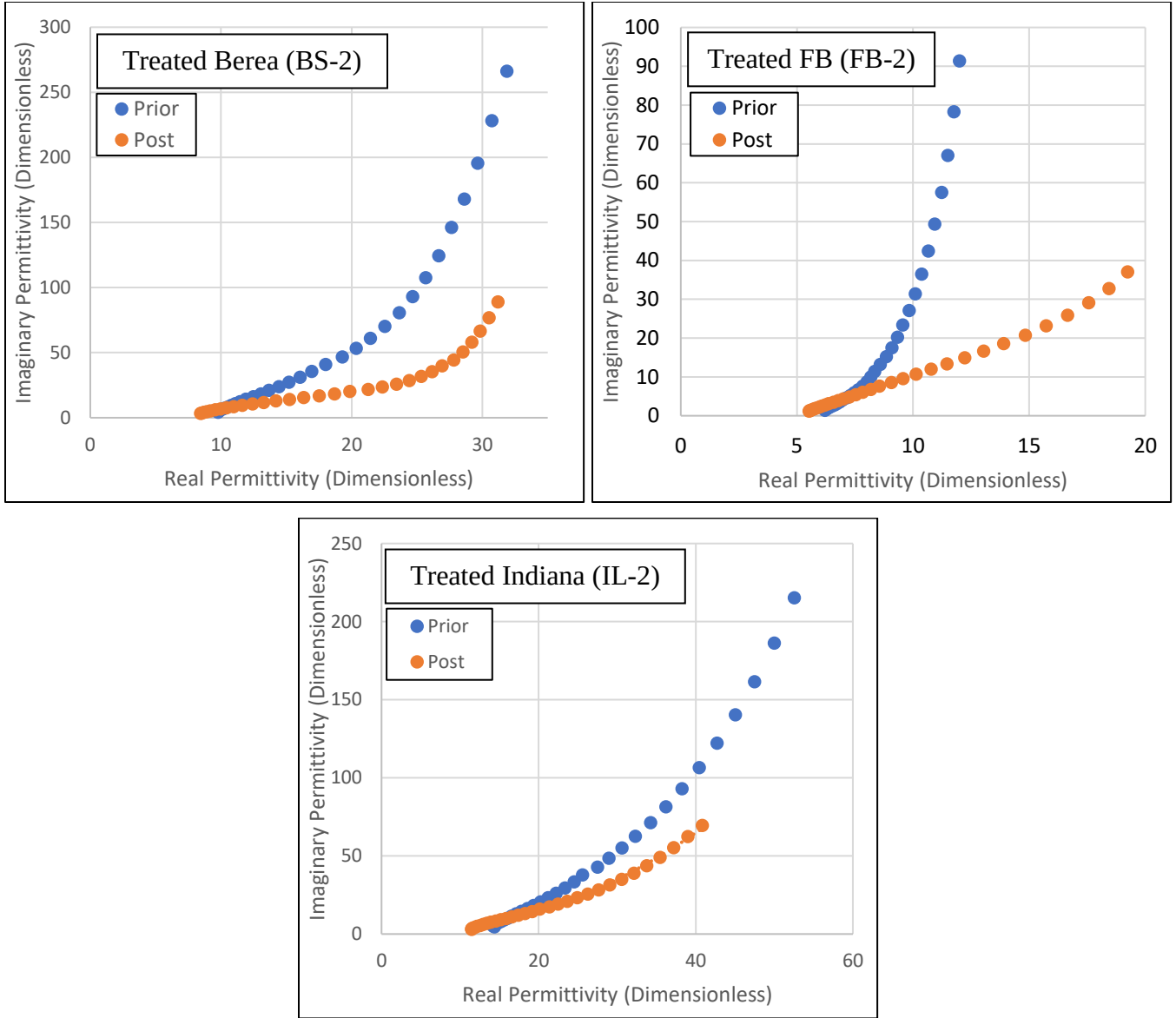


Figure 48 The imaginary permittivity vs the real permittivity for the treated samples prior and post wettability alteration at the same water saturation ($S_w = 1$).

As can be seen from the previous results, the imaginary permittivity and the other parameter relying on it, the conductivity, are the best correlating parameters with the wettability alteration. Moreover, as was explained earlier, the impact of the shape of water inclusions and the interfacial interaction between both oil and water, which are controlled by the wettability conditions, on the dielectric dispersion can be observed in the lower frequency ranges. Therefore, we have analyzed the relationship between the reduction in the

imaginary permittivity ($\epsilon''_{prior} - \epsilon''_{post}$) and the conductivity ($\sigma''_{prior} - \sigma''_{post}$) due to treatment and the change in the USBM wettability index (ΔWI_{USBM}) at the lowest frequency value available, 10 MHz. **Table 10** shows the results obtained by the analysis while **Figure 49** shows the plots of (ΔWI_{USBM}) on one side versus ($\epsilon''_{prior} - \epsilon''_{post}$) and ($\sigma''_{prior} - \sigma''_{post}$) at 10 MHz on the other side. From the plots, a linear relationship is observed for the difference in both the imaginary permittivity and the conductivity before and after treatment at 10 MHz with respect to the change in the wettability index with a coefficient of determination (R^2) of 0.9619. Both plots showed the same straight line but with different slopes. The slope of the conductivity relationship is the same as the slope of the imaginary trendline multiplied by a constant. According to equation (34), this constant equals to $2\pi f \epsilon_0$ where f is the frequency (10 MHz) and ϵ_0 is defined in (34).

Table 10 The analysis results of the reduction in the imaginary permittivity and conductivity in response to wettability index changes.

Sample	Imag. Permittivity before treatment (ϵ''_{prior}) at 10 MHz	Imag. Permittivity after treatment (ϵ''_{post}) at 10 MHz	Reduction in imag. permittivity ($\epsilon''_{prior} - \epsilon''_{post}$) at 10 MHz	Conductivity before treatment (σ''_{prior}) at 10 MHz	Conductivity after treatment (σ''_{post}) at 10 MHz	Reduction in Conductivity ($\sigma''_{prior} - \sigma''_{post}$) at 10 MHz	The change in USBM wettability index (ΔWI_{USBM})
	Dimensionless	Dimensionless	Dimensionless	in S/m	in S/m	in S/m	Dimensionless
Berea	228.080	76.845	151.235	0.1401	0.0472	0.0929	0.57
FB	78.270	32.734	45.536	0.0481	0.0201	0.0280	0.33
Indiana	209.523	111.968	97.555	0.1287	0.0688	0.0599	0.49

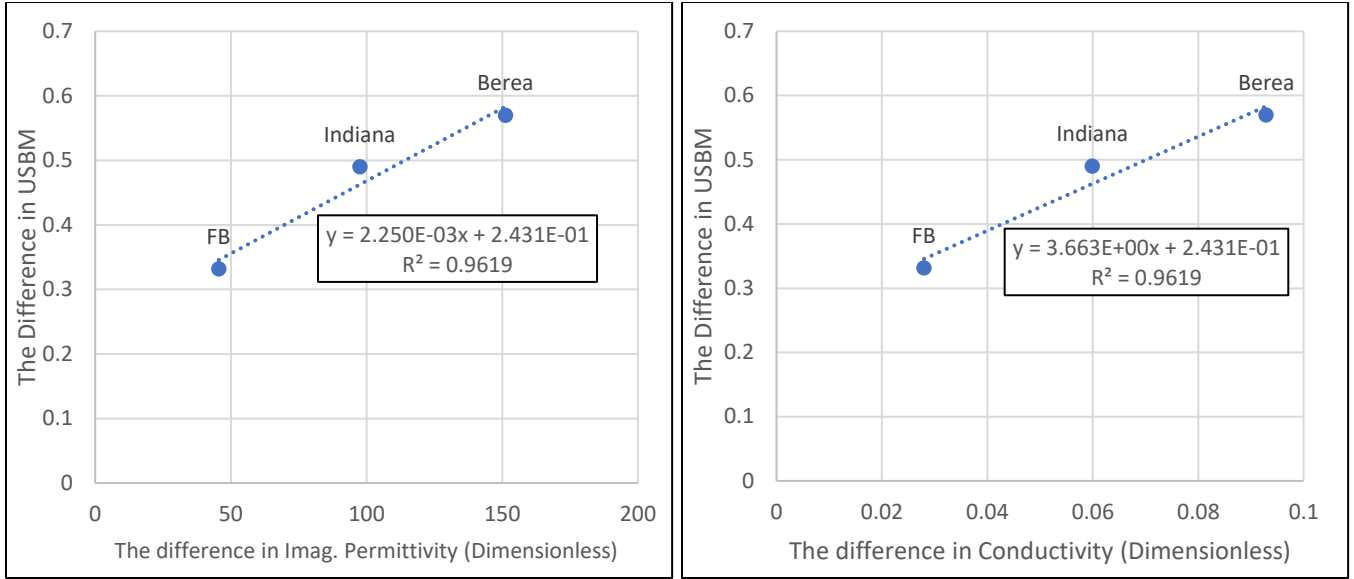


Figure 49 The plots of (ΔWI_{USBM}) versus $(\epsilon''_{prior} - \epsilon''_{post})$ at 10 MHz (A) and (ΔWI_{USBM}) versus $(\sigma''_{prior} - \sigma''_{post})$ at 10 MHz (B).

5.4.2. Dielectric Measurements for the Master and the Treated Sister Samples at Different Water Saturations ($S_w = 1$, S_{wirr1} , S_{wirr2} and S_{or}):

To explore the impact of wettability alteration on the dielectric measurements at different water saturations, the dielectric measurements were acquired on the fully brine-saturated master and treated samples (at $S_w = 1$) and after each centrifuge displacement cycle, after primary drainage (at S_{wirr1}), after imbibition (at S_{or}) and after the secondary drainage (at S_{wirr2}). The objective of the measurements is to analyze the shift in the dielectric response from one saturation to another at different wettability conditions, water-wet and mixed-wet. First, we will analyze the trend of each dielectric measurement at different saturations.

5.4.2.1. Berea Sandstone Samples:

The dielectric results for the Berea samples are presented in **Figure 50**. At $S_w = 1$, both master (BS-1) and treated (BS-2) samples showed similar overall real permittivity trends with almost the same values at large frequencies (greater than 200 MHz). The similarity in the samples' trends indicates similar pore structure while the equal values of real permittivity for both samples at large frequencies indicate very close porosity values for both samples which was confirmed by porosity measurements. At S_{wirr1} and S_{wirr2} , we can see a significant drop in the real permittivity values with minimal dispersion (change in slope) due to the drastic drop in water saturation. However, the treated master samples showed slightly

lower values than the master samples which indicates a higher degree of oil wetness in the treated sample. Furthermore, similar trend of real permittivity at S_{or} was observed for both samples with higher values at large frequency for the treated sample due to the higher water saturation in the treated sample (71.41% in BS-1 compared to 92.18% in BS-2).

For the imaginary permittivity and loss tangent, we can see higher values for the master sample at $S_w = 1$ than the treated one at lower frequency which agrees with the analysis discussed in 7.4.1, higher values for strong water wetness. Moreover, the conductivity showed differences in the values which is almost consistent over the whole frequency bandwidth. Like real permittivity, significant drop in imaginary permittivity and loss tangent can be seen at S_{wirr1} and S_{wirr2} compared to $S_w = 1$ at lower frequencies. However, more drop is observed in the treated sample than the master due to the wettability shift towards the oil wetness. This drop can also be seen in the conductivity but over the whole frequency range. For the last saturation condition, S_{or} , the imaginary permittivity and loss tangent was reading higher than the $S_w = 1$. Since the imaginary permittivity is a measure of how dissipative or the lossy the material is and sometimes is called the loss factor, this trend is expected at S_{or} . Under that saturation, the continuity of water phase is disrupted which makes the phase more dissipative, accelerating the loss of the dielectric polarization, and amplifies the loss magnitude at certain frequency. This explains that increase in the imaginary permittivity at S_{or} compared to the values at $S_w = 1$.

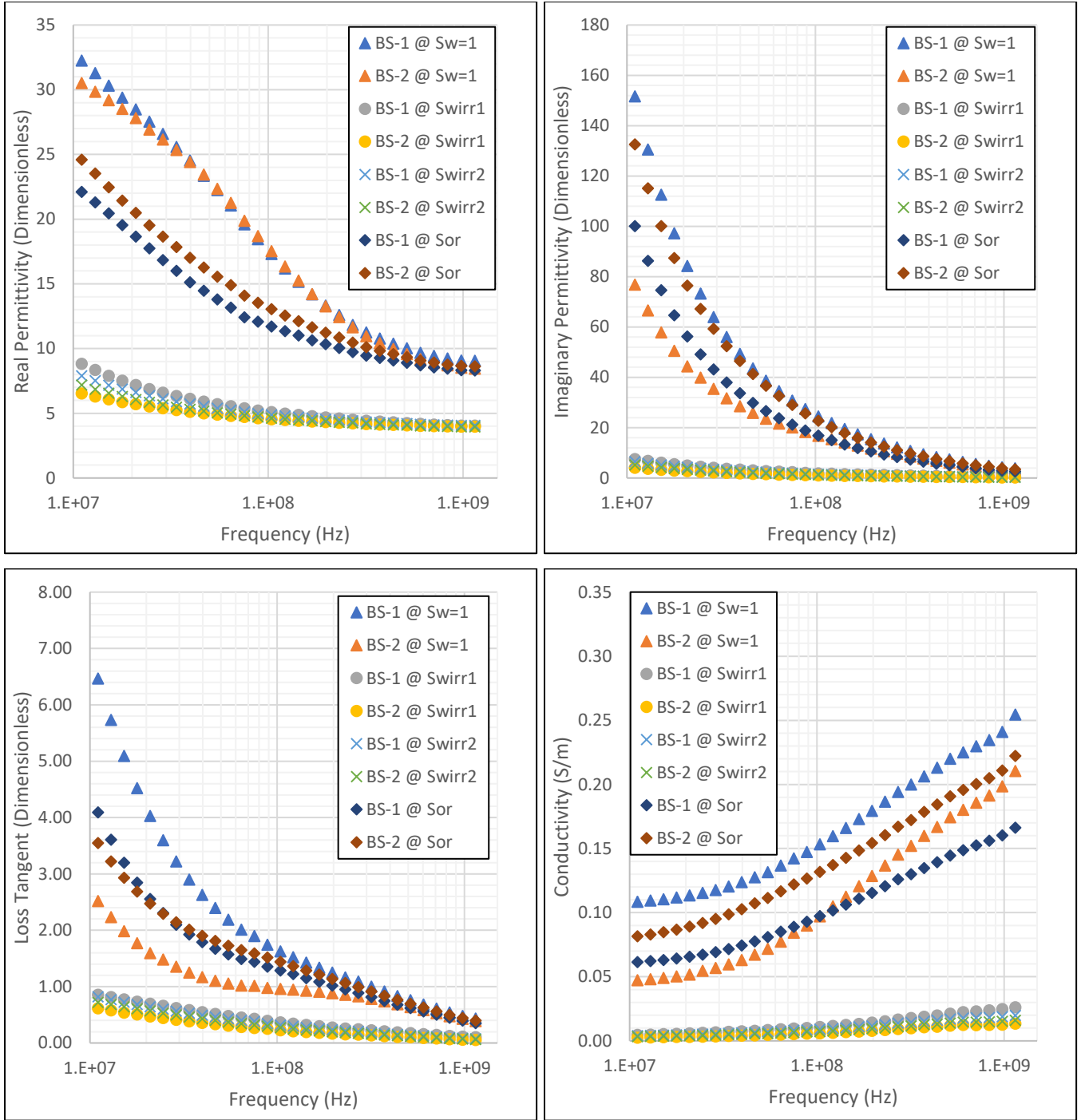


Figure 50 The dielectric measurements for the master untreated Berea sample (BS-1) and the sister Berea sample (BS-2) after wettability alteration at different saturations ($S_w = 1$, S_{wirr1} , S_{wirr2} and S_{or}).

5.4.2.2. Fontainebleau Sandstone Samples:

Overall, both master and treated FB samples (FB-1 and FB-2) showed similar dielectric responses to the Berea samples, as illustrated in **Figure 51**. However, the real permittivity of the treated sample was reading higher than the readings of the master sample at frequencies lower than 100 MHz which indicates more tortuosity in the water phase residing in the treated sample pores due to the wettability alteration, compared to the master sample. For the frequency range greater than 200 MHz, a flip in the trend is observed where the master sample showed higher real permittivity than the treated sample which reveals higher porosity in the master sample (9.50%) compared to the sister sample after the treatment (7.85%). Moreover, the real permittivity measurement profiles for the master and the treated samples at $S_w = 1$ and S_{or} are different due to the wettability alteration. One more observation, the real permittivity of each sample at S_{or} was reading very close to the values at $S_w = 1$ which indicate a very low residual oil saturation and a water saturation close to 1 after the imbibition. Furthermore, large differences in the imaginary permittivity are observed at lower frequency between the master and treated sample at $S_w = 1$ due to wettability alteration which reveals similar results to the Berea and the comparison performed in 7.4.1. for all the sister samples. However, to confirm that the slight variation in the porosity does not influence the pore structure, which should induce a change in the overall trend of the dielectric profile, and ensure that any change occurs in the dielectric profile is a result of the wettability alteration process solely, the dielectric measurements were compared for the master (FB-1) and the sister sample (FB-2) before treatment at $S_w = 1$. The comparison showed equivalent dielectric results for both samples as illustrated in **Figure 52**. Furthermore, among all the core samples, FB exhibited the best displacement performance during the drainage and imbibition cycles. As a result of this, low values of S_{wirr1} (7.63% for FB-1 and 5.34% for FB-2) and S_{or} (8.55% for FB-1 and 2.31% for FB-2). Therefore, FB samples' dielectric measurements showed lower values and less dispersion than the other samples at S_{wirr} while they showed closer values of dielectric measurement to the measurements at $S_w = 1$.

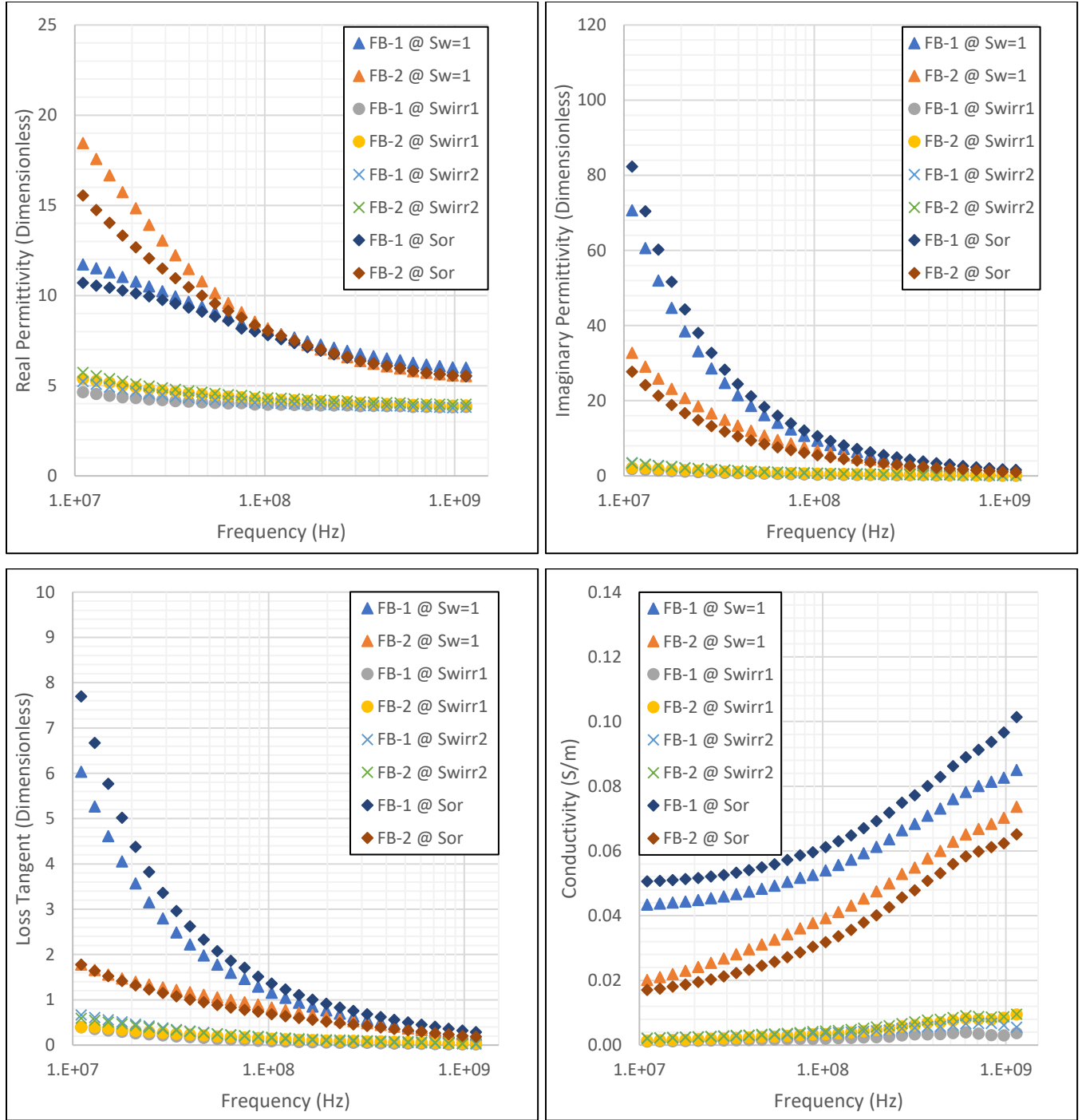


Figure 51 The dielectric measurements for the master untreated Berea sample (FB-1) and the sister Berea sample (FB-2) after wettability alteration at different saturations ($S_w = 1$, S_{wirr1} , S_{wirr2} and S_{or}).

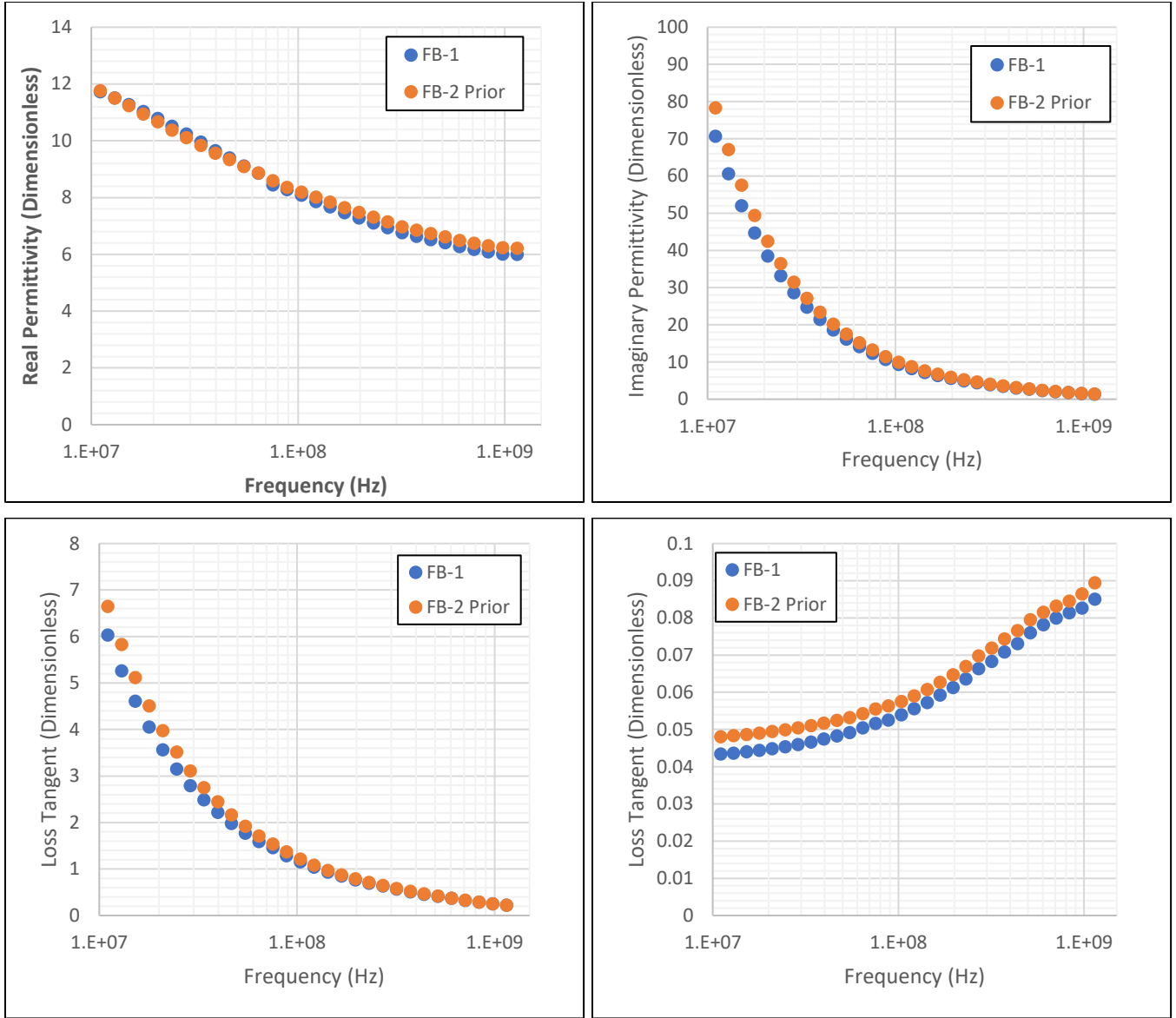


Figure 52 Comparison of the dielectric measurements for the master FB sample (FB-1) and the sister sample (FB-2) before treatment.

5.4.2.3. Indiana Limestone Samples:

The dielectric measurements for the master (IL-1) and the treated (IL-2) samples are presented in **Figure 53**. Overall, the dielectric measurements showed similar profiles as the Berea samples. At $S_w = 1$, both IL-1 and IL-2 showed similar real permittivity trend over the whole frequency range. Similar to the other samples, the imaginary permittivity and the loss tangent showed lower values for IL-2 than IL-1 at lower frequencies due to the wettability alteration. On the other hand, the conductivity showed the same reduction in IL-2 compared to IL-1 over the whole frequency range for the same reason. At S_{wirr1} , S_{or} and

S_{wirr2} , the dielectric results showed the exact same trend discussed for the Berea samples, BS-1 and BS-2.

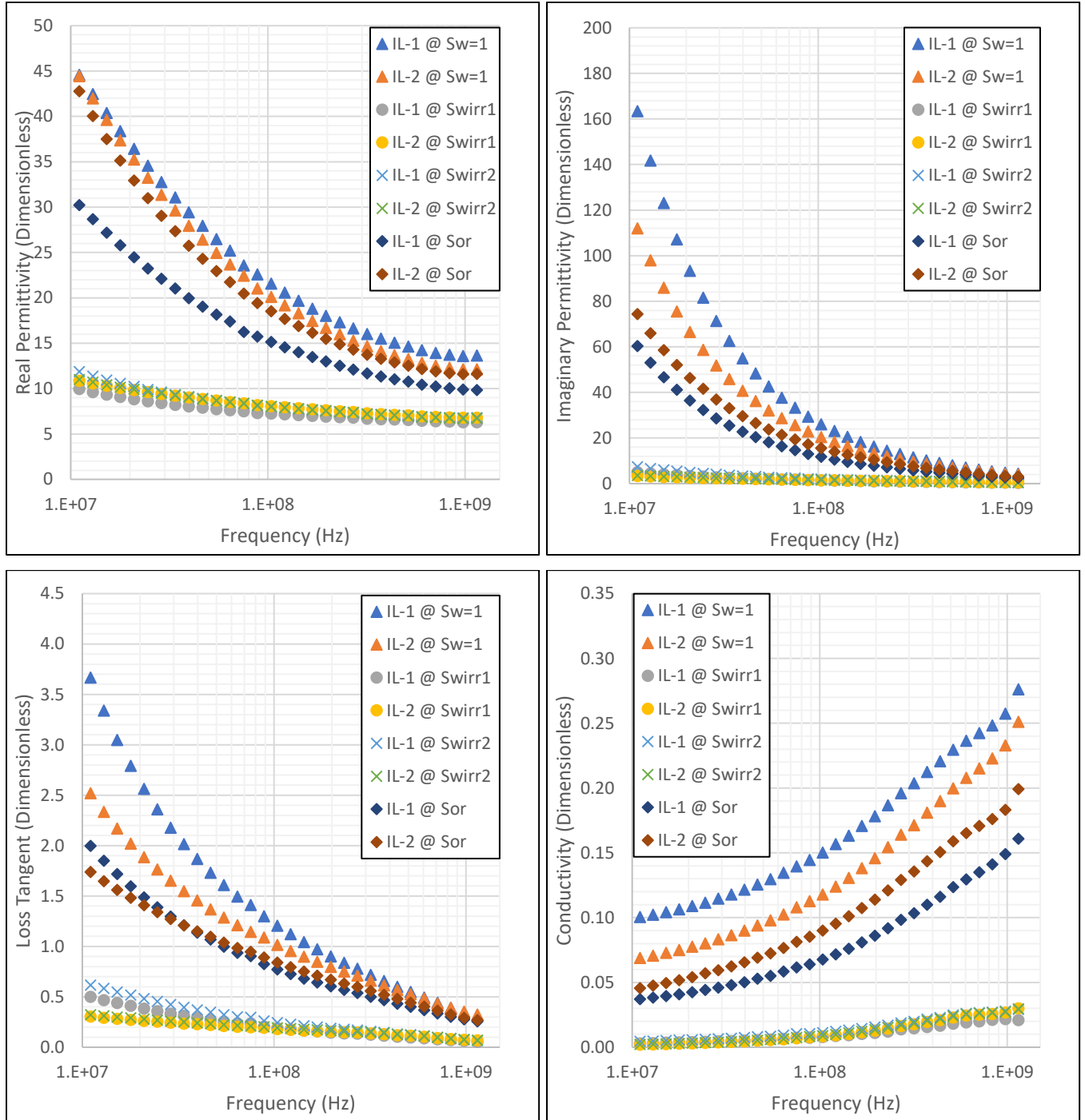


Figure 53 The dielectric measurements for the master untreated Berea sample (IL-1) and the sister Berea sample (IL-2) after wettability alteration at different saturations ($S_w = 1$, S_{wirr1} , S_{wirr2} and S_{or}).

5.5. The Correlation between Dielectric Measurements and Wettability Index

From the previous analysis of the dielectric responses at different saturations for originally water-wet master samples and mixed wet sister samples, the impact of the wettability alteration can be clearly seen on the imaginary permittivity and the other measurement relying on it, loss tangent and conductivity, at the lower frequency range. On the other hand, the real permittivity is affected by the changes in the tortuosity of the water phase inside the pores, hence, it cannot conclusively describe the changes in the wettability condition. This most dominated response on the imaginary permittivity in response to the wettability treatment is observed at low frequency bandwidth whenever the sample is shifted from $S_w = 1$ to S_{wirr1} or S_{wirr2} . The master water wet samples showed a higher reduction in the imaginary permittivity than the treated samples at frequencies less than 200 MHz. At S_{or} , when the water saturation is relatively high (close to $S_w = 1$), the dielectric dispersion is masked by the water response due to its high sensitivity of to water phase which does not allow us to see the minor changes in inclusions shapes induced by wettability changes at relatively large water saturations. This has caused the dielectric measurements at S_{or} to show similar values to the ones corresponding to $S_w = 1$.

Therefore, to analyze the correlation between the wettability index and dielectric dispersion, the amount of reduction in the imaginary permittivity at the minimum frequency available (10 MHz) while moving from $S_w = 1$ to S_{wirr1} or S_{wirr2} is analyzed for the master sample and compared against the measurements of sister treated samples. The dielectric measurement showed equivalent imaginary permittivity values at S_{wirr1} and S_{wirr2} , hence, any of them can be used for the analysis. Initially, the reduction in the imaginary permittivity at 10 MHz, $\Delta\epsilon''$, can be calculated as expressed by equation (36). Then, the results are plotted against the USBM and NMR wettability indices, WI_{USBM} and WI_{NMR} , respectively.

$$\Delta\epsilon'' = (\epsilon''_{S_w=1} - \epsilon''_{S_{wirr}}) \quad (36)$$

Where,

$\epsilon''_{S_w=1}$ is the imaginary permittivity at $S_w = 1$ and $\epsilon''_{S_{wirr}}$ is the imaginary permittivity at S_{wirr} , both at 10 MHz. **Table 11** lists the results obtained by equation (36) and **Figure 54** shows the plot of WI_{USBM} and WI_{NMR} versus $\Delta\epsilon''$. Since the WI_{USBM} is the most used wettability index in the industry, the fit line was constructed using it.

Table 11 The results for applying equation (36) to find the relationship between the wettability index and the difference in the imaginary permittivity at $S_w = 1$ and S_{wirr} .

Sample	Imaginary Permittivity at $S_w = 1$ ($\epsilon''_{S_w=1}$) at 10 MHz	Imaginary Permittivity at S_{wirr} ($\epsilon''_{S_{wirr}}$) at 10 MHz	Reduction in imaginary permittivity ($\Delta\epsilon''$) at 10 MHz	USBM Wettability Index (WI_{USBM})	NMR Wettability Index (WI_{NMR})
	Dimensionless	Dimensionless	Dimensionless	Dimensionless	Dimensionless
BS-1	151.630	7.553	144.077	0.73	0.74
BS-2	76.845	4.031	72.814	0.16	0.48
FB-1	70.708	1.823	68.885	0.16	0.15
FB-2	32.734	2.121	30.613	-0.17	-0.10
IL-1	163.458	4.969	158.489	0.63	0.42
IL-2	111.968	3.294	108.674	0.14	0.2

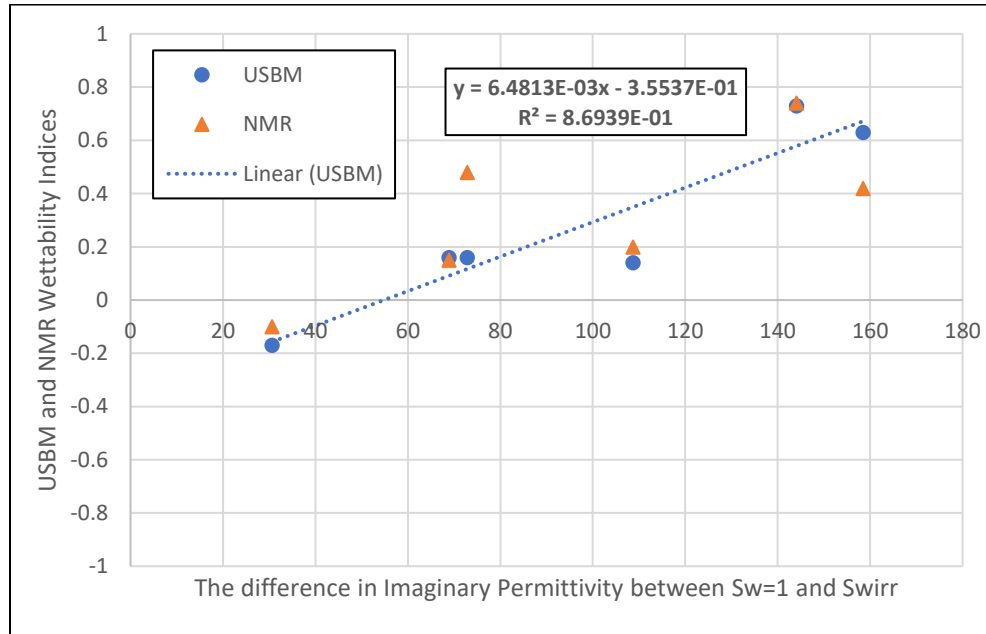


Figure 54 The correlation between the WI_{USBM} and WI_{NMR} versus the difference in the imaginary permittivity between $S_w = 1$ and S_{wirr} .

From **Figure 54**, a linear relationship can be observed between the USBM wettability index and the difference in the imaginary permittivity at $S_w = 1$ and S_{wirr} with a coefficient of determination (R^2) of 0.8694. This deduces that a strong relationship does exist between WI_{USBM} and the variation in the imaginary permittivity while shifting the sample's water saturation from $S_w = 1$ to S_{wirr} . This relationship can be converted into an empirical dielectric wettability index. Based on the correlation obtained from the plot and by involving the endpoint saturations, S_{wirr} and S_{or} , and the dielectric constants for the 3% KCl brine and the dodecane, 75 and 2 respectively, a simplified empirical correlation has been developed. The proposed dielectric wettability index can be expressed as the following:

$$WI_{dielectric} = \frac{S_{wirr}}{1 - S_{or}} \left(\frac{\epsilon_o^*}{\epsilon_w^*} \Delta\epsilon'' - 1 \right) \quad (37)$$

Where,

- S_{wirr} is the average irreducible water saturation, (ratio). This can be calculated from S_{wirr1} and S_{wirr2} as

$$S_{wirr} = \frac{S_{wirr1} + S_{wirr2}}{2}.$$
- S_{or} is the residual oil saturation (ratio).
- ϵ_o^* is the dielectric constant for the oil phase (dimensionless).
- ϵ_w^* is the dielectric constant for the water phase, (dimensionless).
- $\Delta\epsilon''$ is the difference between the imaginary permittivity at $S_w = 1$, $\epsilon''_{S_w=1}$, and the imaginary permittivity at S_{wirr} , $\epsilon''_{S_{wirr}}$, computed by equation (36).

The correlation introduced produced a good estimation of wettability index which results in a Pearson coefficient of correlation (r) of 0.9867 and coefficient of determination (R^2) of 0.9735. **Figure 55** shows the plot of the dielectric wettability index, $WI_{dielectric}$, versus the USBM wettability index, WI_{USBM} , on the one-to-one line.

Table 12 The results of applying equation (37) on the dielectric measurements to obtain the dielectric wettability index correlation.

Sample	Average Ir-reducible Water Saturation, S_{wirr}	Residual Oil Saturation, S_{or}	Imaginary Permittivity at $S_w = 1$ ($\varepsilon''_{S_w=1}$) at 10 MHz	Imaginary Permittivity at S_{wirr} ($\varepsilon''_{S_{wirr}}$) at 10 MHz	Reduction in imaginary permittivity ($\Delta\varepsilon''$) at 10 MHz	USBM Wettability Index (WI_{USBM})
	(%)	(%)	Dimensionless	Dimensionless	Dimensionless	Dimensionless
BS-1	23.06	18.82%	151.630	7.553	144.077	0.73
BS-2	25.74	7.82%	76.845	4.031	72.814	0.16
FB-1	13.94	6.63%	70.708	1.823	68.885	0.16
FB-2	13.42	2.31%	32.734	2.121	30.613	-0.17
IL-1	34.27	14.58%	163.458	4.969	158.489	0.63
IL-2	30.35	11.92%	111.968	3.294	108.674	0.14

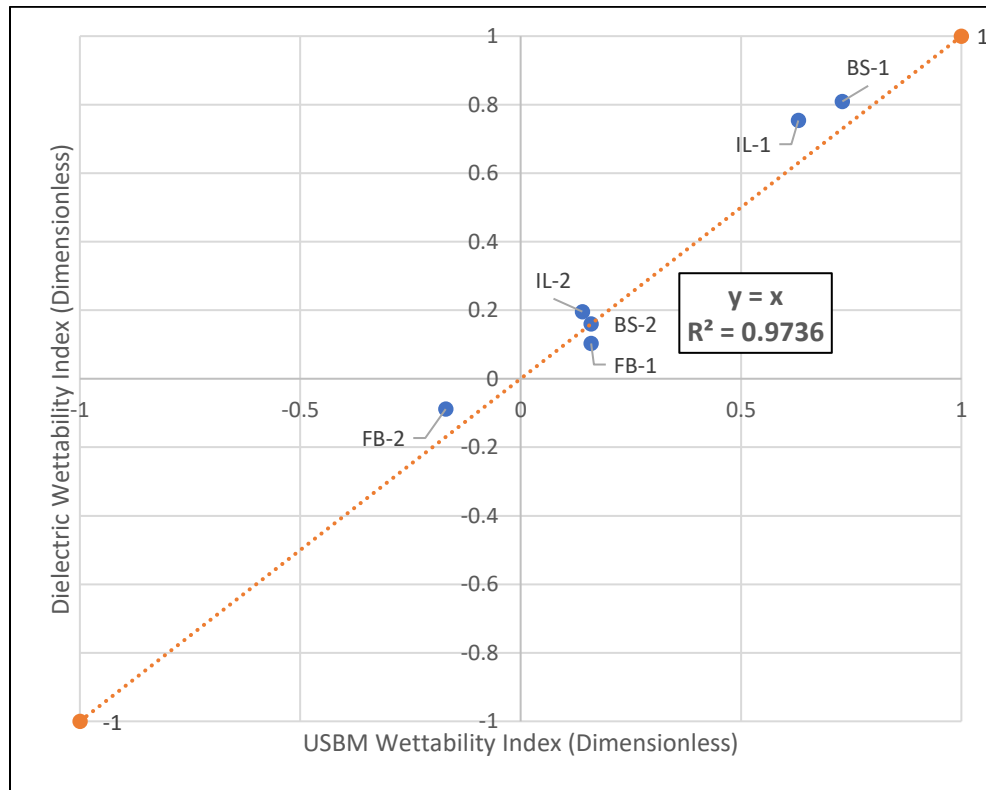


Figure 55 The plot of the dielectric wettability index, $WI_{dielectric}$, versus the USBM wettability index, WI_{USBM} , on the one-to-one line ($y = x$).

CHAPTER 6

CONCLUSIONS

In this study, we have investigated the dielectric response toward wettability alteration with detailed experimental work conducted on 3 rock types, Berea and Fontainebleau sandstone and Indiana limestone. The objective of this work is to develop an empirical correlation to calculate the wettability index based on basic dielectric measurements. For wettability index benchmarking, the industry-known USBM wettability index (WI_{USBM}) validated with Al-Garadi et al., (2022) NMR wettability index (WI_{NMR}) was used to develop the dielectric wettability index ($WI_{dielectric}$). The advantage of this study over the others available in the literature can be summarized in the following:

- 1- Dielectric dispersion is very sensitive to water filled porosity, hence, any discrepancy in the porosity resulting because of the treatment, such as asphaltene precipitation, will contribute to the overall dielectric measurements. Therefore, a cautious wettability alteration procedure was followed to mitigate significant alterations in the pore structure. This was achieved by aging the to-be-treated sister samples in 1% stearic acid dissolved in light crude with minimum asphaltene content to avoid asphaltene precipitation on the pore's walls. After the treatment, the sample was cleaned using an aliphatic solvent, hexane, under Soxhlet and dried under 80 degC to bring the sample back to the dry conditions. The porosity was measured before and after the alteration and showed low differences (6.43% for Berea, 1.88% for FB and 2.12% for Indiana).
- 2- Dielectric comparison was carried out on the same sample at $S_w = 1$ before and after the wettability alteration which has not been done before. This was affordable due to the careful wettability treatment and cleaning process explained before which brought the sample back to the completely dry condition after treatment. Consistent dielectric measurements trend was observed for all three treated samples.
- 3- We have relied on the pure dielectric measurements, real and imaginary permittivity, loss tangent and conductivity, while avoiding the use of different models available in the literature which was designed for water wet samples only, involves fitting parameters that induces uncertainties and are incapable of fully describing the wettability condition or consistently detecting any wettability changes.

A pair of each rock type was used in the study; the first sample in the pair, called the master sample, was used to calculate the original wettability index while the other sample, called the sister samples, is used

for wettability alteration and calculating the wettability index after the treatment. During the wettability index calculation process, both dielectric and NMR measurements were acquired for the master and sister samples at the different saturation endpoints, $S_w = 1$, S_{wirr1} , S_{or} , and S_{wirr} . Initially, basic petrophysical analysis was conducted on the dry samples including porosity, permeability, XRD and SEM. Then, all the pairs were saturated with brine to take their original NMR and dielectric measurements at $S_w = 1$. Next, the master samples were sent for USBM and NMR wettability index measurements directly while the treated samples were sent to cleaning (with methanol), drying and then to the wettability alteration. After the wettability was altered, the treated samples were sent for cleaning (with hexane) and drying processes. Then, the treated samples were saturated again with brine and their NMR and dielectric were acquired and compared against the previous measurements before treatment at $S_w = 1$. Finally, the treated samples were sent to USBM and NMR wettability index measurements in the same way as the master samples while acquiring NMR and dielectric.

The USBM wettability index measurements for the master samples showed that the Berea and Indiana samples were almost water-wet initially, with WI_{USBM} of 0.73 and 0.63, respectively, while the FB sample showed mixed wet conditions, with WI_{USBM} of 0.16. However, the treated samples showed a shift in the wettability towards the oil wetness and became ultimately mixed wet, with WI_{USBM} values of 0.16, -0.17 and 0.14 for Berea, FB and Indiana samples, respectively. For the NMR wettability index, the results showed an agreement with USBM measurements. Separately, the performance of wettability alteration was investigated on pure calcite and quartz chips as well as on the top of the inlet face of the sister samples after treatment using contact angle measurements. Prior to treatment, the contact angle of the chips showed water-wet contact angles (less than 90°) whereas they showed mixed wettability contact angles (close to 90°) after the treatment. Like the treated chips, the contact angles showed values close to 90° on the inlet face of the treated samples.

For the dielectric measurements obtained for the treated samples before and after wettability alteration at $S_w = 1$, the results showed a significant drop in the values of imaginary permittivity and loss tangent at lower frequencies (less than 200 MHz) due to the wettability shift towards oil wetness. On the other hand, a similar drop was also observed in the conductivity but over the whole frequency range. In contrast, the real permittivity showed minor and non-conclusive changes toward wettability alteration. Therefore, the reduction in the imaginary permittivity and the conductivity at frequency of 10 MHz were plotted against the difference in the wettability index between the master and treated samples, assuming that the

wettability index of the master sample match with the wettability index of the sister sample prior to treatment. That plot and showed a linear relationship between the drop in the imaginary permittivity and the drop in the wettability index from water wetness ranges towards oil wetness with good correlation ($R^2 = 0.9619$).

For the comparison between the dielectric results at different saturations for both master and treated samples, the dielectric results showed a proportional correlation between the amount of the drop in the imaginary permittivity at frequencies lower than 200 MHz as the sample's water saturation moves from $S_w = 1$ to S_{wirr} and the USBM wettability index of the sample. When the sample is water-wet (master), the difference between the imaginary permittivity at $S_w = 1$ and S_{wirr} is higher than the same difference for less water-wet samples (treated). This trend coincides with the conclusion deduced earlier for the treated samples when we compared dielectric measurements at $S_w = 1$ before and after the treatment. At S_{or} , the dielectric measurements were reading very close to the measurements at $S_w = 1$, hence, these measurements would not prevail any improvement to the correlation between dielectric and the wettability index. Therefore, we have restricted the development of our correlation to the dielectric measurements at $S_w = 1$ and S_{wirr} . Like the analysis conducted for the treated samples previously, the USBM wettability index was plotted versus the difference between the imaginary permittivity values at $S_w = 1$ and S_{wirr} under 10 MHz frequency for each sample. Good linear correlation was observed in that plot with R^2 of 0.8694. Therefore, we have considered that difference in the imaginary permittivity along with endpoints saturations and the dielectric constants for the fluids used in the study to develop the dielectric wettability index correlation. The correlation between the USBM wettability index and the dielectric wettability index obtained by the correlation showed an excellent r of 0.9867 and R^2 of 0.9736.

Overall, this study provides an excellent insight into the response of dielectric measurements to the changes in the wettability index solely while isolating the other changes in porosity and pore structure which impacts the dielectric response. Moreover, it suggests a novel technique to alter the wettability efficiently without compromising the pores' structure. This study serves the expansion of dielectric dispersion applications in the petrophysical analysis and paves the road for more studies related to the impact of wettability and solid-fluid interactions such, as zeta potential, on the dielectric measurement. This study can be further improved through the following:

1. Relaxation time is a very important dielectric measurement which can be used to develop another dielectric wettability index correlation. However, it requires lower frequency ranges than what is available via the coaxial probe dielectric fixture.
2. Extreme oil wetness ranges can be included in the study which would improve the robustness of our wettability index correlation. However, reaching to maximum oil wettability is not feasible without using heavy crude oil with large asphaltene content which will certainly alter the porosity and the pores' structure. Moreover, it will be hard to reach to a water saturation value of $S_w = 1$ under that technique of wettability modification.
3. Consider more samples with larger diversity of mineralogical composition. This would help in ensuring the robustness of the correlation performance.

NOMENCLATURES

- P : The induced electric dipole moment per unit volume, in (Coulomb/m or C/m).
- D_e : The overall electrical displacement vector, in (Coulomb/m or C/m).
- E : The strength of the static electrical field applied between condenser plates (in Volt/m).
- I_t : The overall current generated by the electrical field.
- I_c : The conduction current generated by the electrical field.
- I_d : The displacement current generated by the electrical field.
- V : The potential difference between the condenser's plates, in (Volts).
- V_o : The peak voltage at time zero, in (Volts).
- ω : The angular frequency of the varying field applied, in (radian/s).
- ϵ_d^* : The complex dielectric permittivity resulting from polarization with excluding the conductivity part.
- ϵ_d'' : The magnitude of the imaginary part of ϵ_d^* (dissipation (loss) due to polarization).
- ϵ^* : The generalized complex dielectric permittivity.
- ϵ_w^* : The dielectric constant of 3% KCl brine.
- ϵ_o^* : The dielectric constant of dodecane.
- ϵ' : The generalized real permittivity value.
- ϵ'' : The magnitude of the imaginary part of ϵ^* .
- σ^* : The complex conductivity.
- f_c : The critical frequency value where relaxation time occurs, in (MHz).
- ϵ_s : The static DC value of dielectric permittivity where the frequency is minimum.
- ϵ_{cc} : The Cole-Cole permittivity.
- $\tan \delta$: loss tangent, or the tangent of the angle of dielectric loss. (Ratio)
- $\epsilon_p(\omega)$: The complex permittivity associated with polarization effects.
- $A_{\tan(\delta)}$: The amplitude of the little hump in $\tan \delta$ corresponding to MW polarization.
- D_1 : Dispersivity parameter related to the real part of permittivity curve = $\frac{\partial\{\log_{10}[\epsilon'(\omega)-\epsilon_\infty]\}}{\partial\{\log_{10}[\omega]\}}$
- D_2 : Dispersivity parameter related to the imaginary part of permittivity curve = $\frac{\partial\{\log_{10}[\epsilon''(\omega)]\}}{\partial\{\log_{10}[\omega]\}}$, in Farad/(m Hz)).
- I_o : The oil wettability index. (Ratio).

I_w : The water wettability index. (Ratio)
 $N_{HC,C}$: The hydrocarbon depolarization factor.
 N_f : The depolarization factor of the fluid.
 N_g : The depolarization factor (i.e., equal to 1/3 for spherical grains).
 N_j^i : The depolarization factor of i-th fluid phase and j-th inclusion.
 S_w : The saturation of water in the porous medium (Ratio)
 X_w : The fraction of the grains which is water wet. (Ranges from 0 to 1)
 f_j : The volumetric inclusion fraction of the j-th inclusion. ($f_m = (1 - \phi)$, $f_w = \phi S_w$, $f_{oil} = \phi (1 - S_w)$).
 f_{max} : The frequency value where MW Polarization occurs, in (MHz).
 ϵ_0 : The dielectric permittivity of the empty space (vacuum) = 8.854×10^{-12} Farad/m.
 ϵ_∞ : The unrelaxed dielectric constant, at very high frequency, in (Farad/m)
 ϵ_C : The dielectric permittivity of the inner layer
 $\epsilon_{HC,C}$: The effective dielectric permittivity of the hydrocarbon phase, in (Farad/m)
 ϵ_{HC} : The dielectric permittivity of the bulk hydrocarbon phase, in (Farad/m)
 $\epsilon_{MW}(\omega)$: The complex permittivity related to Maxwell-Wagner (MW) Polarization.
 $\epsilon_{PL}(\omega)$: The complex permittivity related to charge transport (PL).
 ϵ_R : The overall dielectric permittivity of rock sample, in (Farad/m)
 ϵ_{SC} : The relative dielectric permittivity of the grains coated with the electric double layer, in (Farad/m).
 ϵ_d : The relative permittivity of the dielectric material enclosed between the condenser's plates. (Ratio)
 ϵ_{fluid} : The fluid phase permittivity, in (Farad/m).
 ϵ_g : The dielectric permittivity of the solid grains, in (Farad/m).
 ϵ_m : The dielectric permittivity of the insulating phase (matrix and oil), in (Farad/m).
 ϵ_{solid} : The permittivity of the dry grains with certain mineralogy, in (Farad/m)
 ϵ_{static} : Static dielectric of the sample, in (Farad/m)
 ϵ_w : The dielectric permittivity of the dispersive water, in (Farad/m).
 σ_S : The grain surface conductivity, in (Coulomb/m).
 σ_{dc} : The sample's direct current (DC) conductivity, in (Siemens /m or S/m).
 $\Delta\epsilon$: $\epsilon_\infty - \epsilon_{static}$ Relaxation Strength from the curve of permittivity value's real part, in (Farad/m).

h : The thickness of the capacitive Electric-Double layer surrounding the oil drop. (in nm)
 $\varepsilon(\omega)$: Generalized complex permittivity, in (Farad/m).
 $\sigma'(\omega)$: The real part of the conductivity value, in (S/m)
 $\sigma''(\omega)$: The magnitude of the imaginary part of the conductivity value, in (S/m)
 g : Orientation factor
 v : The volume fraction of the inner layer compared to the total fluid inclusion volume = $\left(1 - \frac{h}{r_0}\right)^3$ (Ratio).
 β : Shape parameter of water inclusions.
 ε'' : The imaginary part of the generalized dielectric constant (dielectric loss factor).
 ε' : The real part of the generalized dielectric constant (dielectric constant of the material).
 σ : Charge density or conductivity, in (S/m).
 τ : Relaxation time, in (μs).
 φ : The porosity of rock sample, in (fraction).
 WI_{USBM} : USBM wettability index.
 WI_{NMR} : NMR wettability index.
 $WI_{Dielectric}$: Dielectric wettability index.

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VITAE

PERSONAL DETAILS

Name : Ali Abdulwahab Oshaish
Nationality : Yemeni
Date of Birth : 26 June 1987
Email : ali.oshaish87@gmail.com
Academic Background : Bachelor and Master of Science in Petroleum Engineering
Marital Status : Married
Residential Address : 6779 Al-Firdaws District, Dammam 32251, KSA

PROFESSIONAL PORTFOLIO AND CAREER OBJECTIVE

A petroleum engineer with 12 years' experience, working in the oil and gas industry. Starting from 2011 and for more than 4 years, I had worked with Schlumberger's formation evaluation team as a field engineer delivering the wireline services to Saudi Aramco. In Oct 2015, I joined the industry of surface production and completion systems working with Cameron, a Schlumberger company. I covered a couple of roles for 6 years, starting as a field engineer and then as a planning and manufacturing engineer. In 2021, I have started my MSc. degree as a part-time student besides my duties as a manufacturing engineer in Cameron. Later, in early 2022, I joined the college of petroleum engineering and geosciences at King Fahd University of Petroleum and Minerals as a laboratory engineer. In less than 2 years, a couple of patents were filed, multiple technical papers were published, and some publications are in progress. My vision is to exploit the field experience along with the excellent petroleum engineering background to work on research and development projects related to formation evaluation and reservoir engineering.

EDUCATION HISTORY

September 2021 – Present	MSc. Candidate in Petroleum Engineering at King Fahd University of Petroleum and Minerals, Dhahran 31261, KSA GPA (3.96 out of 4) Thesis Title: Quantification of Rocks Wettability Using Dielectric Measurements.
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January 2006 – August 2010	BSc. in Petroleum Engineering from King Fahd University of Petroleum and Minerals, Dhahran 31261, KSA. GPA (3.98 out of 4)Summer Training: Drilling and Measurement Segment, Schlumberger, Khobar, KSA. The only petroleum engineering student winning the College of Engineering Science Outstanding Student Award in 2009.
September 2002 – May 2005	High School in Natural Sciences from Al-Andalus High School, Taif, KSA (98.67%).

WORK EXPERIENCE

January 2022 – Present	Laboratory Engineer <i>College of Petroleum Engineering and Geoscience at King Fahd University of Petroleum and Minerals, Dhahran 31261, KSA</i> - Working on different research projects related to the areas of the applications of SIP, dielectric and NMR in oil and gas industry in designing the setups, conducting experiments, analyzing the data, and writing the technical publications. - Peer reviewer for ACS Omega Journal. - Delivering Techlog lab sessions and special lectures related to well logging for the graduate and undergraduate students.
December 2020 – January 2022	Planning and Manufacturing Engineer <i>Cameron – A Schlumberger Company, Khobar, KSA</i> - Design the process flow for the manufacturing and maintenance works of surface production systems. - Provide technical support to the surface aftermarket team through designing the required fixtures, preparing SOP's & conducting the training for shop operators.

- A member of Root Cause Analysis (RCA) team which runs the analysis for different nonconformance incidents.
- Participating in new and high-profile projects meetings to ensure services and products are delivered with the best industry-known quality standards.

October 2015 – October 2020

Field Service Engineer – Surface Systems

Cameron – A Schlumberger Company, Khobar, KSA

- Execute the installations, commissioning, and maintenance of different types of surface systems including spools, casing hangers, tubing spools, tubing hangers, production & hydraulic fracturing trees, Wellhead Isolation Tools (WHIT), gate valves, actuators, Back Pressure and 2-Way Check Valves, High Integrity Protection System (HIPS) and surface completions.
- Won the “Ibn Rimthan Award”, a Schlumberger's KSA Excellence Award branched in service quality in 2018.

May 2014 – May 2015

Senior Field Engineer – Wireline

Schlumberger, Khobar, KSA

- Promoted to Senior Field Engineer in May 2014.
- Assigned for high profile jobs and critical operations.
- Designated to run advanced logs and special services.

January 2011 – May 2014

Field Engineer – Wireline

Schlumberger, Khobar, KSA

- Run the formation evaluation logs including Resistivity, Density, Neutron, Formation Micro Imaging, Sonic Scanner, Natural GR Spectroscopy, Elemental Spectroscopy, Nuclear Magnetic Resonance, Dielectric Array and fluid sampling and pressure points through mini-well testing tools.

- Run Cased Hole logs for casing and cement evaluation such as Electromagnetic Pipe Imaging (EMIT), Multi-Finger Caliper Imaging, Ultrasonic Imaging and Cement Bond Logs.
- Working in one of the busiest locations worldwide associated with a variety of logging challenges such as highly deviated wells to run high tension setups and drill pipe conveyed logging (TLC).
- Active member of Loss Prevention and Service Quality Team.

TRAINING AND CERTIFICATIONS

November 2022 – November 2022

JewelSuit® Short Course, Baker Hughes's Geomechanics Software

College of Petroleum Engineering and Geosciences, KFUPM and Baker Hughes

- **Location:** Delivered by a Baker Hughes's expert in the college of petroleum engineering and geosciences at KFUPM.
- Covered the basics of the JewelSuit® geomechanics software.

April 2019 – April 2019

Fluted Mandrel Hanger (FMH) Stack Up Test

Cameron – A Schlumberger Company

- **Location:** Cameron Manufacturing Facility in Singapore.
- New wellhead system test for one of Aramco's projects.

October 2016 – October 2016

Techlog® Short Course, Schlumberger's Well Logs Interpretation Software

College of Petroleum Engineering and Geosciences, KFUPM

- **Location:** college of petroleum engineering and geosciences, KFUPM.
- Covered the basics of the Techlog® software.

October 2013 – November
2013

Wireline Advanced Training (PEPTEC-2-OH & PEPTEC-2-MDT)
Schlumberger Oilfield Services

- **Location:** Schlumberger's Kellyville Training Center (KLC), Oklahoma, USA.
- The courses covered Drill Pipe Convoyed Logging (TLC), Magnetic Resonance (MRI-CMR), Micro-Resistivity Imaging (FMI), Sonic Scanner (MSIP), Fluid Sampling (MDT) and Pressure Point (XPT).

May 2011 – August 2011

Wireline Basic Training (PEPTEC-0 & PEPTEC-1)
Schlumberger Oilfield Services

- **Location:** Schlumberger's Kellyville Training Center (KLC), Oklahoma, USA.
- The courses covered basic wireline services including equipment rig up and practical and theory of open hole logs including GR, Resistivity, Density, Neutron and Sonic Logs.

PUBLICATIONS

• **Journals**

- 1) **Oshaish, A.**, Hassan, A., Mahmoud, M., El-Husseiny, A., Al-Ofi, S., & Al-Yaseri, A. (2023). Evaluating the rock wettability using multi-frequency dielectric measurements: A review on the fundamental concept and experimental approach. *Journal of Petroleum Science and Engineering*, 220, 111177. <https://doi.org/10.1016/j.petrol.2022.111177>
- 2) Hassan, A., Mohammed, E., **Oshaish, A.**, Badhafere, D., Ayranci, K., Dong, T., ... & Mahmoud, M. (2023). Prediction of Total Organic Carbon in Organic-Rich Shale Rocks Using Thermal Neutron Parameters. *ACS omega*, 8(5), 4790-4801. <https://doi.org/10.1021/acsomega.2c06918>
- 3) Badhafere, D., Kirmizakis, P., **Oshaish, A.**, El-Husseiny, A., Mahmoud, M., Ntarlagiannis, D., & Soupios, P. (2023). Detection of Iron Disulfide Materials in Geological Porous Media Using Spectral Induced Polarization Method. *SPE Journal*, 28(06), 3409-3418. <https://doi.org/10.2118/217424-PA>

• Conferences

- 1) Oshaish, A., & Weijermars, R. (2023, October). Fracture Propagation-Rate and Fracture Half-Length Estimated for an Individual Fracturing Stage Using Dynamic Balancing of Fluid Pressures: Eagle Ford Case Study. In *ARMA/DGS/SEG International Geomechanics Symposium* (pp. ARMA-IGS). ARMA. <https://doi.org/10.56952/IGS-2023-0176>
- 2) Oshaish, A., Elsayed, M., Hassan, A., Al-Ofi, S., El-Husseiny, A., & Mahmoud, M. (2023, October). Integrating the Dielectric and NMR Techniques to Investigate the Petrophysical Properties of Sandstone and Carbonate Formations. In *Abu Dhabi International Petroleum Exhibition and Conference* (p. D011S027R006). SPE. <https://doi.org/10.2118/216091-MS>
- 3) Oshaish, A., Alnuaim, S., Hassan, A., & Mahmoud, M. (2023, October). A New Inflow Performance Relationship for Shale Gas Reservoirs Using Well Logs and Geochemistry Data. In *Abu Dhabi International Petroleum Exhibition and Conference* (p. D021S052R003). SPE. <https://doi.org/10.2118/216374-MS>
- 4) Hassan, A. M., Elsayed, M. K., Oshaish, A. A., Al-Ofi, S. M., El-Husseiny, A. A. H., Abu-Mahfouz, I. S., ... & Attia, H. M. (2022, October). A New Workflow to Study the Impact of Artificial Maturations on the Petrophysical Properties of Unconventional Shale Rocks. In *ADIPEC*. OnePetro. <https://doi.org/10.2118/211794-MS>

PERSONAL COMPETENCIES

- Strong adaptability to work in remote locations and harsh work environments.
- Excellent management skills for responsibilities in fast-paced workplaces.
- Proficient in MATLAB, Techlog®, Petrel® and Microsoft Office Software.
- Skilled in troubleshooting and detecting early signs of electronic and hydraulic malfunctions.
- Fast learner and eager to continuously improve.
- Excellent team work attributes while maintaining remarkable individual contribution.