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Smart Water flooding: Part 1

Laboratory workflow for screening EOR potential

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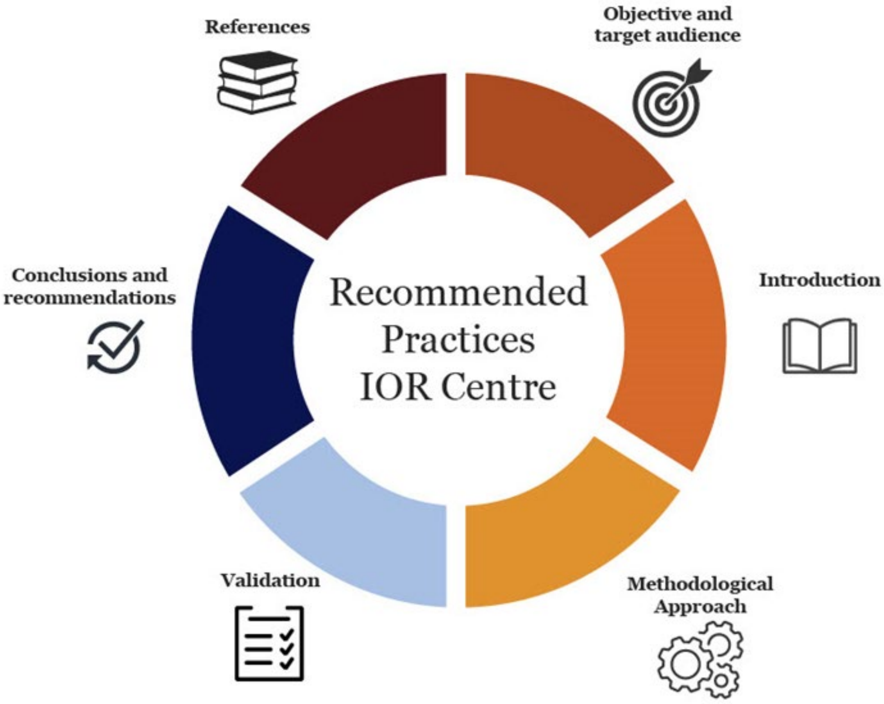

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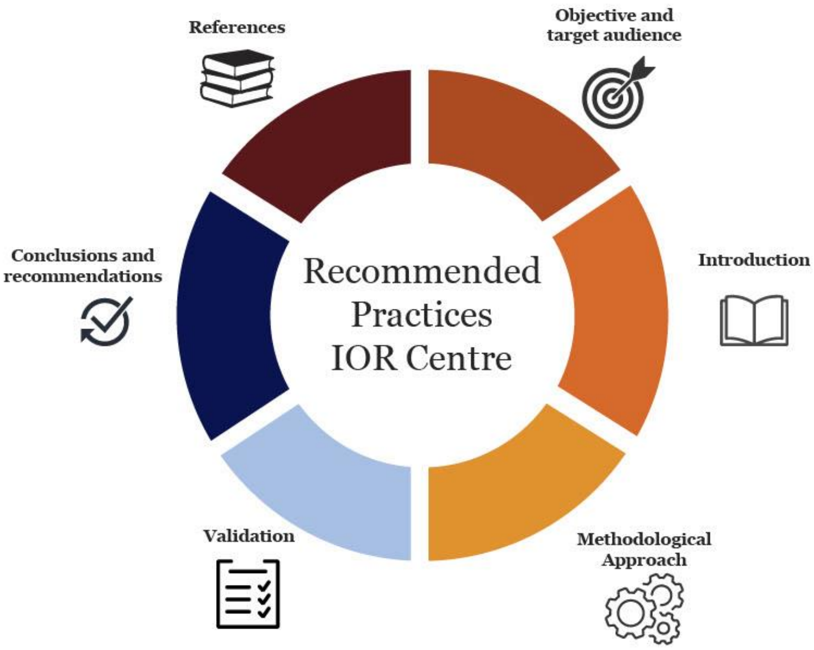

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Objectives

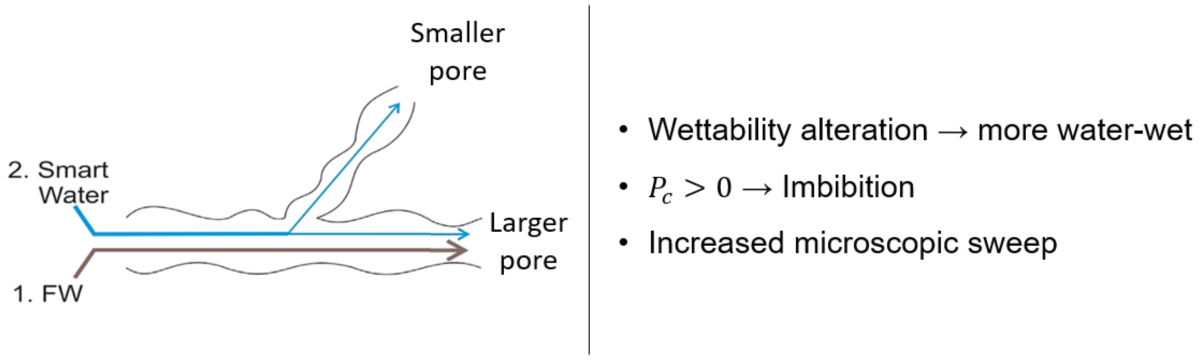
This report aims to provide guidance on the type of analyses to be performed to screen Smart Water EOR potential for various Crude Oil-Brine-Rock (COBR) systems. The objective of the report is to highlight the most important screening parameters and provide recommendations for laboratory tests. The recommended methodological approach is based on practical and fundamental knowledge gained during the lifetime of the National IOR Centre of Norway.

The document describes the main steps of the Smart Water EOR workflow with a simplified description of the experimental procedures. These guidelines can be addressed to both laboratory engineers/researchers and project managers. The authors hope that the recommendations presented will ultimately help facilitate the implementation of Smart Water technology in real reservoir systems including the Norwegian Continental Shelf (NCS).

Introduction

"Smart Water" technology implies the selection of a "smarter" injection brine with optimized ionic composition to improve oil recovery beyond standard waterflooding. The technology itself does not include the addition of chemicals (polymers, surfactants, etc.) and thus can significantly reduce operational costs and environmental impact. Previously published laboratory investigations have confirmed that increased oil recovery can be obtained by introducing ionically modified brines to various types of rock material (RezaeiDoust et al., 2009). For sandstone rocks, the Smart Water EOR effect is usually observed by reducing the salinity of the injected brine, often referred to as "low salinity (LS) waterflooding" (Morrow & Buckley, 2011). On the other hand, for carbonate rocks, the salinity of Smart Water brine is less important than the ionic composition, namely the presence of potential determining ions, Ca^{2+}, SO_4^{2-} (Fathi et al., 2010; Zhang et al., 2007). The growing interest in the technology in recent years has led to several field trial tests showing positive Smart Water EOR effect (Al-Qattan et al., 2018; Erke et al., 2016; Yousef et al., 2012). Studies by Smalley et al. (2020), Smalley et al. (2018) showed that Smart Water/low salinity (LS) injection has also a large potential for implementation on NCS as an EOR method.

Despite the apparent simplicity of ionic optimization approach, the underlying mechanism(s) is very complex and being studied in recent decades by a number of research groups around the globe (Austad et al., 2010; Lager et al., 2008; Ligthelm et al., 2009; RezaeiDoust et al., 2009; Tang & Morrow, 1999). Most of the proposed mechanisms agree that the physical basis for the observed EOR effect is rock wettability alteration towards a more water-wet state, which contributes to better capillary oil displacement and improved microscopic sweep, **Figure 1**.



- Wettability alteration → more water-wet
- $P_c > 0$ → Imbibition
- Increased microscopic sweep

Figure 1: Increased microscopic sweep efficiency by Smart Water injection in a simplified pore model (Strand et al., 2016).

Understanding of reservoir wetting is a challenging task and an important part of a successful Smart Water application. The main difficulties lie in the complex interactions between components in the COBR system. This report presents proposals for a Smart Water EOR screening methodology with an emphasis on physicochemical interactions in the COBR system, restoration of core wettability in laboratory conditions and conduction of wettability alteration studies.

Methodological Approach

This chapter contains an overview of laboratory studies, performed at the University of Stavanger and NORCE. The main goal of these studies was to determine a reliable methodological approach to estimate Smart Water EOR potential for certain COBR systems. The following recommendations are based on practical core flooding experience and supported by fundamental research on initial reservoir wetting and wettability alteration processes.

Characterization of the COBR system

The laboratory assessment of Smart Water EOR potential is based on restoring the initial core wettability and determining the reactivity of rock minerals towards contacting fluids. Both processes are directly dependent on the physicochemical properties and interactions within the COBR system. Therefore, a detailed characterization of the COBR system is a crucial part of the Smart Water EOR workflow.

Mineralogical analyses. Interactions in COBR systems mainly occur near the rock surface i.e., in contact zones between minerals and pore fluids. To assess the intensity of COBR interactions and Smart Water EOR potential, a detailed mineralogical analysis can be highly beneficial. The following combination of analyses is preferred for a comprehensive assessment of core mineralogy:

1. X-ray powder diffraction technology (XRD). XRD is the most widely used mineralogy assessment technique in industry. The result of the XRD analysis is a quantitative assessment of the specific minerals that make up the core matrix.
2. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS). SEM/EDS techniques allow for a qualitative assessment of the minerals that make up the pore surfaces. SEM/EDS results in combination with XRD data are often sufficient to provide a preliminary estimate of core reactivity towards saturating fluids.
3. QEMSCAN. QEMSCAN technology provides both quantitative and qualitative assessment of rock mineralogy. The outcome is a digitized rock surface map with different zones corresponding to different groups of minerals. Conducting QEMSCAN analysis can be an alternative and replace (or complement) the individual XRD and SEM/EDS tests.
4. BET (Brunauer-Emmet-Teller) surface area. BET is a technique which can evaluate the gas adsorption data and convert it to a specific surface area. The surface area of the studied core system is an important petrophysical characteristic of the mineral structure that can be correlated with SEM/EDS data. It is recommended to perform BET measurements on unmilled core pieces to obtain more reliable data.

As mentioned earlier, of interest for Smart Water EOR potential estimation is the minerals that make up the porous structure and are in direct contact with pore fluids. Therefore, in the Smart Water EOR workflow, it is recommended to conduct a thorough quantitative and qualitative assessment of core mineralogy using the above methods as examples.

Crude oil analyses. Crude oil is another contacting phase in the COBR system that determines the wettability state of the core and also interacts with the brine phase. In the Smart Water EOR workflow, it is important to detect the type and amount of polar organic components in the crude oil as they are in contact with the mineral surfaces and determine the wetting state. Recommended analyses of the crude oil phase can be summarized as follows:

1. Acid Number/Base Number (AN/BN). Acid number (AN) and base number (BN) quantify the amount of polar organic components (POC) in crude oil that exhibit acidic and basic behaviour. Acidic and basic POC with different intensities can adsorb on the core mineral surfaces, thereby changing the wettability. Thus, for a particular COBR system, measured AN/BN data combined with core mineralogy can provide a strong indication of the initial wetting and wettability alteration potential.
2. SARA. SARA is a type of analysis that quantifies four chemical crude oil groups: saturates, aromatics, resins and asphaltenes. For the Smart Water EOR workflow, SARA data can provide valuable information on asphaltene and resin content, as the presence of these components in crude oil can affect its physical properties and wettability of the COBR system.
3. Physical properties. It is also recommended to measure the standard physical properties of crude oil, such as density and viscosity at ambient temperature/atmospheric pressure and at reservoir conditions.

For reliable assessment of rock wettability, it is necessary to consider crude oil as chemically reactive phase containing polar organic components, which may be charged depending on pH in the contacting water phase. The above methods are examples of analyses that provide information on crude oil composition sufficient for further estimation of Smart Water EOR potential.

Analyses of brines. The brine phase is present in the pore space as irreducible water and as oil displacing agent in water-based EOR. From a chemical point of view, the brine phase can interact with the oil phase and rock minerals due to the presence of charged molecules: cations and anions. For the Smart Water EOR workflow, it is important to know the chemical properties of formation water (FW) in order to assess the initial wetting and select the optimal composition of Smart Water. Recommended analyses of the brine phase can be summarized as follows:

1. Ionic composition. Ionic composition reflects the type and concentration of certain ions in the brine. Positively and negatively charged ions in the brine phase can be involved in ion-exchange processes, as well as affect the reactivity of surface-active organic components of crude oil. In addition, it is important to consider the compatibility of the FW and the injected water in order to avoid the precipitation of insoluble compounds and the formation of scale. Thus, it is recommended to measure the ionic composition of all investigated brines involved in the Smart Water EOR workflow.
2. pH. pH is a measure of the acidity/basicity of the brine. pH can also be an indicator of chemical interactions in COBR system when brine is flooded through the core. It is recommended to perform pH measurements on bulk brines as well as on effluent samples during core flooding operations.
3. Physical properties. It is also recommended to measure physical properties of the brine phase, such as salinity, density and viscosity at ambient temperature/atmospheric pressure.

The described characterization guidelines are a set of relatively simple and quick analyses that provide comprehensive data about the main reacting components of the COBR system. The presented COBR characterization data, together with reservoir temperature, are sufficient to conduct an analytical desk evaluation of Smart Water EOR potential and select the most optimal coreflooding experimental plan.

Core restoration

The next step in Smart Water EOR workflow is to evaluate COBR interactions on representative core material. The main goal here is to develop experimental protocols that can ensure reproducibility of results, as well as restoration of rock wettability conditions in the laboratory, close to real reservoir conditions. The restoration of core samples consists of a number of processes:

1. Core cleaning – involves the removal of fluids retained in the preserved core plugs. The choice of the cleaning method largely depends on the experimental goals i.e., achieving the required state of rock wettability. To restore the core wettability, a "mild cleaning" can be performed, which aims to preserve adsorbed POC, before establishing initial water and oil saturations.
2. Restoration of initial water saturation (S_{wi}) – involves saturation of the core sample with representative formation water and establishment of required S_{wi}. Significant differences in the initial water saturation values for different cores can lead to a greater scatter of subsequent experimental data and difficulties in interpreting the results. Stable S_{wi} can be obtained by using desiccation technique or porous plate.
3. Restoration of initial oil saturation (S_{oi}) – involves saturation of the core sample with crude oil. Experimental observations show that upon contact of crude oil with mineral surfaces, adsorption of polar organic components occurs, which can lead to a significant reduction in the water-wetness degree. Therefore, strict control of the amount of injected oil is required to achieve representative rock wetting state. To restore the wettability state close to real reservoir conditions after mild cleaning, it is recommended to limit the amount of crude oil exposure to ~1PV.
4. Aging – involves soaking the core sample with established S_{wi} and S_{oi} in crude oil for a certain period of time. The main purpose of the aging process is allowing diffusion and even distribution of polar crude oil components within the pore space of the core to achieve more realistic rock wettability. Experimental observations show that the most significant changes in core wettability occur at an early stage of the aging process and decrease over time (Puntervold et al., 2021). Redistribution of POC can also occur during subsequent experiments on the core. Typical aging time in Smart Water EOR experiments is 2 weeks.

There are several experimental parameters involved at each stage, and it is important to have control of them and take into account their impact on the restoration process. More details can be found in the Recommended Practice: "Core restoration – a guide for improved wettability assessment". In addition, the physical parameters of the core, such as porosity, absolute/relative permeability, pore size distribution, etc., can also be measured during the restoration process.

Evaluation of capillary forces

In Smart Water EOR, one of the most important characteristics of COBR system is the state of initial wettability. The term "initial wettability" is intended to assess the wettability state of the core prior to surface reactivity and oil recovery tests, which include the use of Smart Water brine as a wettability modifier. At laboratory conditions, the initial wettability of the core can be estimated by the action of capillary forces, which directly depend on the rock wetting state. A direct measurement of capillary forces can be obtained by performing spontaneous imbibition (SI) tests:

1. SI with mineral oil. Mineral oil can be used in SI process as a non-wetting oil phase, which does not affect the wettability of the core. It is recommended to perform SI on a cleaned core sample with restored S_{wi}. To avoid wettability alteration during the SI test, it is advised to imbibe the core with the brine already saturating the pores of the core as irreducible water (S_{wi}), commonly FW. SI can be performed at reservoir temperature and pressure support at temperatures above 70°C to prevent boiling.

2. SI with crude oil. An alternative way of conducting the SI test is to use crude oil instead of mineral oil. The advantage of this method is the assessment of capillary forces closer to real reservoir conditions. Mildly cleaned core sample restored with S_{wi} (FW) and S_{oi} can be spontaneously imbibed with FW at reservoir temperature and pressure support. In addition, it is advised to use a limited amount of crude oil exposure (~1 PV) for core saturation in order to obtain reliable initial wetting conditions.

Improving capillary forces by changing wettability is the main driving mechanism in Smart Water EOR process. Thus, the assessment of capillary forces is an important indicator of initial core wetting state, which provides the baseline for further estimation of Smart Water EOR potential.

Surface reactivity evaluation

Evaluation of surface reactivity implies the assessment of the brine-rock interactions in a crude oil-free system. The main idea is to determine the most optimal ionic composition of the injected brine with the highest reactivity to the mineral surfaces of the studied core material. Due to the chemical properties of the rock minerals, the surface reactivity tests on silicate and carbonate-based cores are different. Test guidelines can be summarized as follows:

1. pH screening. A pH screening test can be performed on core material composed of silicate minerals (e.g., sandstones). Silicate mineral surfaces are generally *negatively* charged and can therefore adsorb positively charged cations and be involved in ion exchange reactions with the injected brine. The difference between the pH values of bulk and effluent brine samples (ΔpH) can serve as an indicator of ion exchange processes in the core. The goal of the test is to select the brine with the highest ΔpH compared to other injected brines.
   Recommended experimental procedure:
   - Saturate the core 100% with the first injecting brine (usually FW) and subsequently flood with the same brine until the effluent pH plateau is reached.
   - Replace the first injected brine with ion-modified water and repeat the procedure.
   - Conduct the test at reservoir T and injection rate representative for the frontal velocity in the reservoir (~1 ft/day equivalent to 4 PV/day in coreflooding).
2. Chromatographic Wettability Test (CWT). A CWT test can be performed on core material composed of *positively* charged carbonate minerals (e.g., chalk, limestone). The main principle behind the test is the chromatographic separation of ions with different affinities towards the water-wet regions of the carbonate surface. The ion with high affinity is sulphate (SO_4^{2-}), which can adsorb onto hydrophilic sites on carbonate rocks, thereby delaying the appearance of SO_4^{2-} in effluent samples. The non-adsorbing tracer ion (usually thiocyanate, SCN^- or lithium, Li^+) passes through the pores of the core and appears in effluent samples without delay. The separation between tracer and SO_4^{2-} concentration curves is proportional to the water-wet sites contacted by water during the core flooding process (Strand et al., 2006). CWT can be conducted before and after the injection of Smart Water brine as an indicator of wettability alteration. The increase in water wetness will cause longer delay in the appearance of SO_4^{2-} and thus larger separation between tracer and SO_4^{2-} curves. The experimental procedure and examples of CWT tests can be found in Strand et al. (2006) and Fathi et al. (2010).

Based on the results of surface reactivity tests, the most optimal Smart Water brine composition for a specific COBR system ca be selected. Further studies include verification of Smart Water EOR potential by core flooding tests involving crude oil.

Wettability alteration

The final stage in the laboratory Smart Water EOR workflow is to verify the most optimal ionic composition of the injected brine for the COBR system under study. The main objective of this step is to determine the effectiveness of the selected Smart Water brine in altering wettability and mobilizing additional oil. Verification is carried out by performing oil recovery tests, implying spontaneous imbibition and viscous flooding on restored core samples. Recommended options for conducting oil recovery tests are presented below:

1. SI oil recovery test. Spontaneous imbibition oil recovery test allows a direct assessment of the wettability alteration process through the action of capillary forces. Mildly cleaned core sample restored with S_{wi} (FW) and S_{oi} can be spontaneously imbibed with FW and then with Smart Water brine when oil recovery plateau with FW is reached. The additional oil recovered during Smart Water imbibition is a quantitative measure of the change in capillary forces due to wettability alteration towards more water-wet state. The SI oil recovery test is especially relevant for fractured reservoirs. The test is recommended to perform at reservoir temperature and with pressure support.
2. Smart Water EOR in tertiary mode. Tertiary mode implies the injection of Smart Water brine after secondary oil displacement by FW. In the restored core sample, FW is in chemical equilibrium with rock minerals and crude oil. Thus, the injection of formation water allows to obtain base oil recovery with brine, which does not change the wettability of the core. Further injection of Smart Water allows to estimate the possibility of wettability alteration and obtaining the EOR effect. Recommended experimental procedure:
   - Primary oil displacement with FW on the restored core until reaching the oil recovery plateau.
   - Replacing FW injected brine with Smart Water and repeating the procedure.
   - The test is recommended to conduct at reservoir T and injection rate representative for the frontal velocity in the reservoir (~1 ft/day equivalent to 4 PV/day in coreflooding).
   - Upon reaching oil recovery plateau with FW and before Smart Water flooding, the injection rate can be increased by 4 times (~16 PV/day) to evaluate potential for additional oil mobilization.
   - It is advised to measure pH of effluent brine samples to monitor ion exchanges during FW/Smart Water injection resulting in acidic or alkaline conditions.
   - The pressure drop across the core should also be monitored throughout the flooding experiment to detect possible flow restrictions and provide data for relative permeability calculations.
3. Smart Water flooding in secondary mode. Several experimental observations indicate faster and increased oil recovery response in Smart Water flooding tests in secondary mode i.e., direct injection of Smart Water brine into the restored core (Hamon, 2016). The reason for the improved response compared to that in tertiary mode is that in tertiary mode the first injected FW must be displaced by Smart Water, which leads to a delayed wettability alteration process, a lower EOR effect and a lower ultimate oil recovery factor. Therefore, it is recommended to perform Smart Water flooding in secondary mode as an additional oil recovery test. The experimental procedure is identical to the above-described Smart Water EOR in tertiary mode.
4. Hybrid Smart Water EOR. The use of ion-modified water has also shown high efficiency in laboratory studies of hybrid EOR (Lee & Lee, 2019; Piñerez Torrijos et al., 2018). The basic principle is to obtain a synergistic effect in a hybrid Smart Water EOR process by improving both sweep and displacement efficiencies. Thus, additional hybrid oil recovery tests can be performed in accordance with the project plans.

The described methodological approach can give a sufficient laboratory assessment of Smart Water EOR potential for the specific COBR system. The following steps prior to field tests include upscaling of laboratory data and modelling of Smart Water EOR processes. More information can be obtained from the Recommended Practice: "Smart Water flooding: Part 2 – Important input parameters for modeling and upscaling workflow".

Validation

This chapter contains an overview of the Smart Water EOR workflow following the above-described methodological approach. An outcrop sandstone material (hereinafter, T-sandstone) was selected as an example, as it has previously shown high reproducibility in repeated core flooding experiments (Piñerez Torrijos et al., 2017; RezaeiDoust et al., 2011). The laboratory data presented is a compilation of various research projects that were part of the National IOR Centre of Norway.

Material characterization

Mineralogical analyses. Quantitative mineralogical composition of the studied outcrop material was determined by XRD analysis performed on several core samples. The average percentage (weight percent, wt%) of the main minerals is shown in **Table 1**. XRD results show that the studied cores are mainly composed by quartz (~60%), Na-feldspar/albite (~30%) and illite clays (~8%). The presence of quartz, feldspars and clay minerals in the rock composition is typical for sandstone reservoirs, including oil fields on Norwegian Continental Shelf (NCS) (Bjørlykke et al., 1992).

Table 1 – Average mineralogical composition of the T-sandstone core material measured by XRD.

Mineral composition (wt%)						
Quartz	Albite	Chlorite	Illite	Calcite	Others	Total
59	30	2	8	0.3	0.7	100

Quartz minerals usually dominate in sandstone composition; however, their chemical reactivity is low due to their relatively small surface area, low cation-exchange capacity (CEC) and weak surface charge (Allard et al., 1983; Deer et al., 2013). Thus, the main reactive minerals in sandstone composition are feldspars and clays, which are involved in ion exchange processes and adsorption/desorption of polar crude oil components (Mamonov et al., 2020; Puntervold et al., 2018). To estimate Smart Water EOR potential for a specific rock system, it is important to know the distribution of reactive minerals within the porous structure, which can be determined using SEM/EDS analyses. The SEM image of the T-sandstone core material is shown in **Figure 2**. The minerals in the SEM image identified by EDS analysis are presented in **Table 2**.

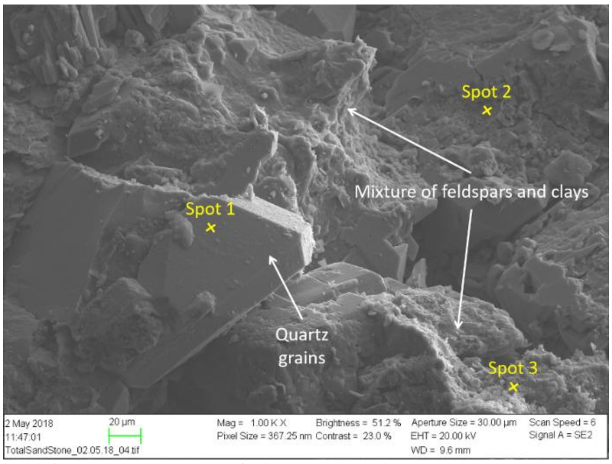


Figure 2: An example of SEM image of the T-sandstone core material (Mamonov, 2019).

Table 2 – EDS analysis of the rock sample presented in **Figure 2**.

	Atomic %			
Element	Spot 1	Spot 2	Spot 3	Avg.
Si	97	66.85	32.08	75.44
Al	1.75	18.19	13.15	13.76
Na	<1	11.65	10.36	6.52
Ca	<1	<1	41.09	<1
Fe	<1	<1	<1	<1
Mg	<1	<1	2.24	<1
K	<1	2.66	<1	1.97

The results of SEM/EDS analyses show that the porous structure of T-sandstone material is mainly composed by quartz grains, covered with a mixture of reactive albite and illite minerals. Generally, the presence of reactive minerals in rock-fluid contact zones results in a high Smart Water EOR potential, since the Smart Water brine should induce ion exchange interactions to change rock wetting and mobilize additional oil. Average physical properties of the T-sandstone material, measured during core restoration processes, are shown in **Table 3**.

Table 3 – Average physical properties of the T-sandstone core material.

Physical properties			
PV, ml	Porosity, %	k_{abs}*, mD	BET, m^2/g
20	20	30-130	1.8

*k_{abs} – absolute permeability, measured at 100% water saturation

Crude oil analyses. The degree of initial wetting is mainly determined by the adsorption of polar organic components (POC) from the crude oil phase onto charged mineral surfaces of the rocks (Puntervold et al., 2021). POC are naturally present in crude oils and are normally divided into acidic and basic components, quantified by the acid number (AN) and base number (BN) (Buckley & Morrow, 1990). AN and BN can be determined in the laboratory by potentiometric titration, and both characteristics have the unit mg KOH/g. AN/BN and properties of the crude oil used in core experiments on the T-sandstone are presented in **Table 4**.

Table 4 – Composition and properties of crude oil used in core experiments on the T-sandstone.

Crude Oil	AN mg KOH/g	BN mg KOH/g	Density g/cm^3	Viscosity cP @20 °C
T-oil	0.10	1.80	0.846	17.6

AN/BN titration show that T-oil predominantly contains basic components (BN=1.8 mg KOH/g). Previously published studies indicated more pronounced adsorption of crude oil bases over acids onto negatively charged silicate mineral surfaces (Mamonov et al., 2019; Puntervold et al., 2021). Thus, when T-sandstone core material is saturated with T-oil, a mixed initial wetting state is expected, favourable for observing Smart Water EOR effect. In addition, T-oil has low asphaltenic content (<1%) thus no SARA analysis is required.

Analyses of brines. When assessing the wettability of a porous medium, it is necessary to take into account the ionic composition and properties of the brine phase. The composition, salinity and pH of the FW have a large influence on the initial wetting because it determines the reactivity of surface active organic components towards mineral surfaces, especially towards clays (Strand et al., 2016). Further selection of the optimal ionic composition of Smart Water brine is aimed at disrupting the chemical equilibrium in the COBR system and inducing the wettability alteration process. The ionic compositions and properties of the brines used in core experiments on the T-sandstone material are presented in **Table 5**.

Table 5 – Composition and properties of brines used in core experiments on the T-sandstone.

	Ion concentration, mM						Brine properties			
Brine	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	Bulk pH	Salinity, ppm	μ @25°C, cP	μ @60°C, cP
T-FW	1540	-	90	-	1720	-	5.5	100 000	1.18	0.63
LS	17.1	-	-	-	17.1	-	5.7	1000	1.01	0.60

Brine analyses results indicate that T-FW has a high salinity of 100 000 ppm and contains 90 mM of Ca^{2+} ions, which can suppress FW pH during core restoration process. Slightly acidic conditions are favourable for establishing mixed initial wetting state (Strand et al., 2016). Variations in FW composition/salinity may also result in alkaline conditions and too water-wet initial state for observing sufficient Smart Water EOR effect (Aghaeifar et al., 2015; Reinholdtsen et al., 2011). Low salinity brine (LS, 1000 ppm NaCl) was selected as Smart Water for core flooding experiments on T-sandstone. Brines with salinity well below the salinity of FW have previously shown significant EOR potential on a variety of outcrop and reservoir sandstone core materials (Batias et al., 2009; Cissokho et al., 2010; Jerauld et al., 2008; Lager et al., 2008).

Spontaneous imbibition with crude oil

Performing a spontaneous imbibition test on a core sample evaluates the action of capillary forces, which are a function of rock wettability, interfacial tension (IFT) and pore size distribution. An example of a SI test performed on a mildly cleaned T-sandstone core saturated with T-FW (S_{wi}=20%) and T-oil is presented in **Figure 3**.

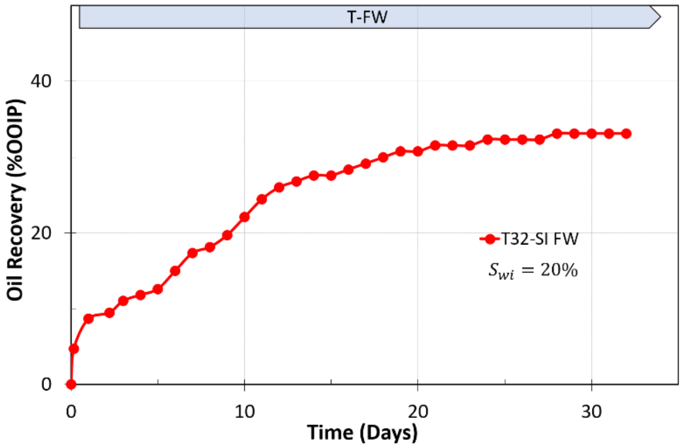


Figure 3: SI test with T-FW at 60°C on restored T-sandstone core with S_{wi}=20% (Piñerez Torrijos et al., 2017).

The amount of crude oil recovered by FW indicates the initial wettability state of the core sample since no chemically induced change in wettability is expected using the FW brine as an imbibition fluid. The results in **Figure 3** show that the oil production increased slowly up to a plateau of 33 %OOIP after 32 days, a behaviour consistent with a mixed core wetting. More water-wet behaviour will normally result is a steeper recovery curve and reaching the production plateau faster (Piñerez Torrijos et al., 2020).

Surface reactivity test

The reactivity of sandstone mineral surfaces towards injected brine can be evaluated by performing pH screening test on an oil-free core sample. The test allows estimating the potential for ion exchange reactions, which will be reflected in the difference between effluent and bulk brine pH. An example of a pH screening test performed on a T-sandstone core is shown in **Figure 4**. The core was successively flooded with T-FW→LS until the effluent pH plateau was reached for each brine.

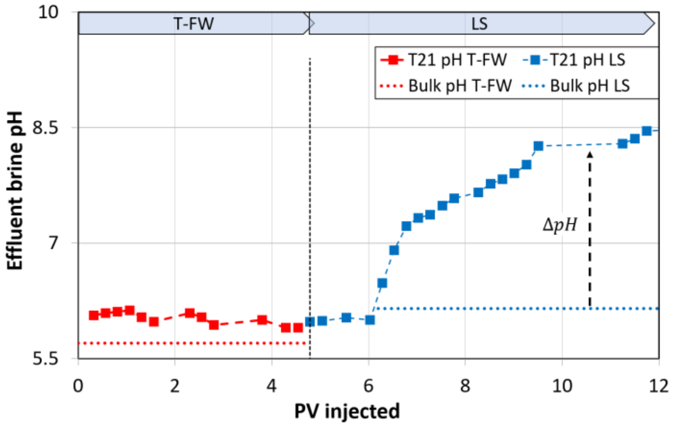


Figure 4: pH screening test on T-sandstone core at 60°C (Piñerez Torrijos et al., 2016). The core was successively flooded with T-FW → LS at a rate of 4 PV/D.

The results show a significant increase in the effluent brine pH when switching from FW to LS injection brine. The effluent pH shifts from initial acidic with T-FW to alkaline with LS injection, confirming favourable conditions for creating mixed wetting and the potential for wettability alteration with LS Smart Water.

Smart Water EOR potential

Smart Water EOR in tertiary mode. The efficiency of Smart Water application can be confirmed by performing viscous flooding oil recovery tests under simulated reservoir conditions. An example of an oil recovery test on T-sandstone material with LS Smart Water injection in tertiary mode is presented in **Figure 5**. The core was restored with T-FW (S_{wi}=20%) and T-oil, aged for 2 weeks, and successively flooded with T-FW→LS until an oil recovery plateau was reached with each brine injected.

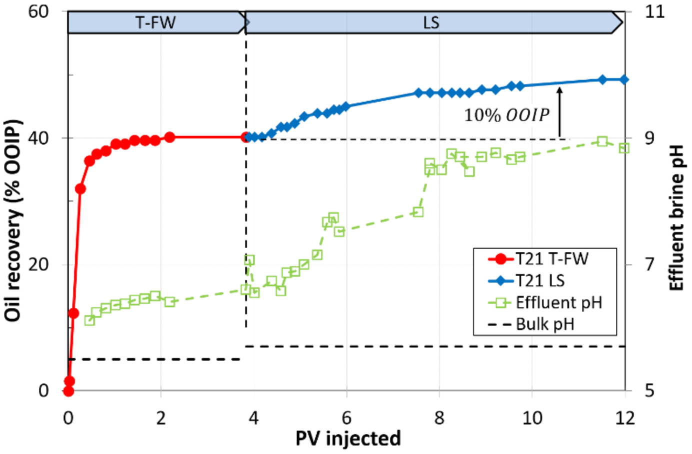


Figure 5: Oil recovery test performed on restored T-sandstone with S_{wi}=20% (Piñerez Torrijos et al., 2017). The core was successively flooded with T-FW→LS at 60°C and at a rate of 4 PV/D.

The results show that an oil recovery plateau of 40 %OOIP was reached within 4 PV injection of T-FW, confirming mixed-wet behaviour of the restored core. Changing the injection brine to LS Smart Water resulted in a gradual increase in oil recovery with a final EOR effect of ~10 %OOIP of extra oil produced. Note that effluent pH values shifted from slightly acidic to more alkaline as the injected brines changed, following the same trend as that observed earlier in pH screening test, **Figure 4**.

Smart Water EOR in secondary mode. An additional oil recovery test on T-sandstone was conducted to evaluate the efficiency of LS Smart Water injection in secondary mode, **Figure 6**. The core was restored with T-FW (S_{wi}=20%) and T-oil, aged for 2 weeks, and flooded with LS Smart Water brine until an oil recovery plateau was reached.

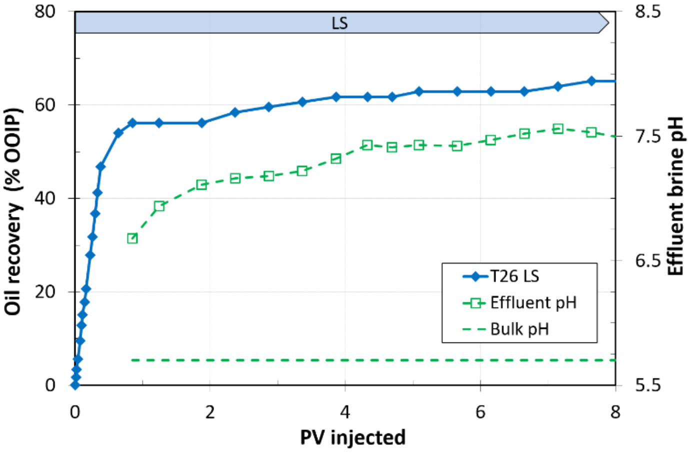


Figure 6: Oil recovery test performed on restored T-sandstone core with S_{wi}=20%. The core was flooded with LS at 60°C and at a rate of 4 PV/D (Piñerez Torrijos et al., 2017).

The ultimate oil recovery plateau reached about 60 %OOIP, which is 20 %OOIP higher than the recovery results obtained with T-FW injection, **Figure 5**. It confirms that LS Smart Water injection can be highly beneficial in secondary mode and therefore should be considered when choosing an injection strategy.

The above-described methodological approach for screening Smart Water EOR potential can be used for both outcrop and reservoir core material. For reservoir samples, particular attention should be paid to core restoration processes to create representative rock wettability conditions (see Recommended Practice “Core restoration – a guide for improved wettability assessment”). Examples of successful Smart Water EOR implementation for reservoir core material can be found in the following papers: Aghaeifar et al. (2018), Aghaeifar et al. (2019).

Conclusions and recommendations

Injection of Smart Water brine with optimized ionic composition is an environmentally friendly and relatively inexpensive IOR/EOR approach, which can be highly effective during both secondary and tertiary oil recovery stages. To facilitate the industrial application of Smart Water EOR, an understanding of underlying processes is crucial, as well as the establishment of a robust screening methodology. This report highlights the most important parameters for Smart Water screening with the aim to recreate initial core wetting and wettability alteration process in the laboratory representative of real reservoir COBR systems. The analyses and experimental procedures can be used as a guide to screen Smart Water EOR potential and can also be incorporated into existing screening workflows with different experimental protocols. The main stages and key parameters of the recommended Smart Water EOR workflow for sandstone and carbonate rocks are summarized in the flowchart, **Figure 7**.

Still, there are knowledge gaps, which should be filled. Starting from the first steps of the workflow and COBR characterization. All reservoirs are unique, but common denominators have been identified to a certain extent. However, carbonate rocks like dolomite and some outcrop limestones do not behave similarly as chalk. Reservoir limestones, however, have shown good agreement with chalk in experimental work. This knowledge gap should be filled. In addition, sandstones or siliciclastic reservoir rocks have very diverse mineralogy. The understanding of mineral effects on wettability and COBR- interactions has significantly improved over the last years, however, reservoirs like diatomite has not been covered. More fundamental studies to understand different behaviour from outcrop sandstones of varying compositions should be performed. The importance of clays in low salinity water flooding in sandstones has also been questioned in the literature lately and should be settled.

Core cleaning and restoration procedures in the laboratory have a big impact on resulting core, as described in the Recommended Practice “Core restoration – a guide for improved wettability assessment”. Although the topic is not extensively discussed in the present recommended practice, there are knowledge gaps to be filled, as to how to best recreate representative reservoir wettability in cores in the laboratory.

When it comes to selecting the optimal Smart Water composition for improved oil recovery for a field, the understanding is that low salinity brine is Smart Water in sandstone reservoirs, and that seawater and modified seawater are Smart Water in carbonates. Smart Water for more complex reservoirs like dolomite, diatomite, mixed mineralogy and tight reservoirs are yet to be fully understood.

Lastly, progress has been made in modelling of the geochemistry in the reservoir (see Recommended Practice “Smart Water flooding: Part 2 – Important input parameters for modeling and upscaling workflow”, however, correctly catching wettability alteration and increased positive capillary forces is still a challenge.

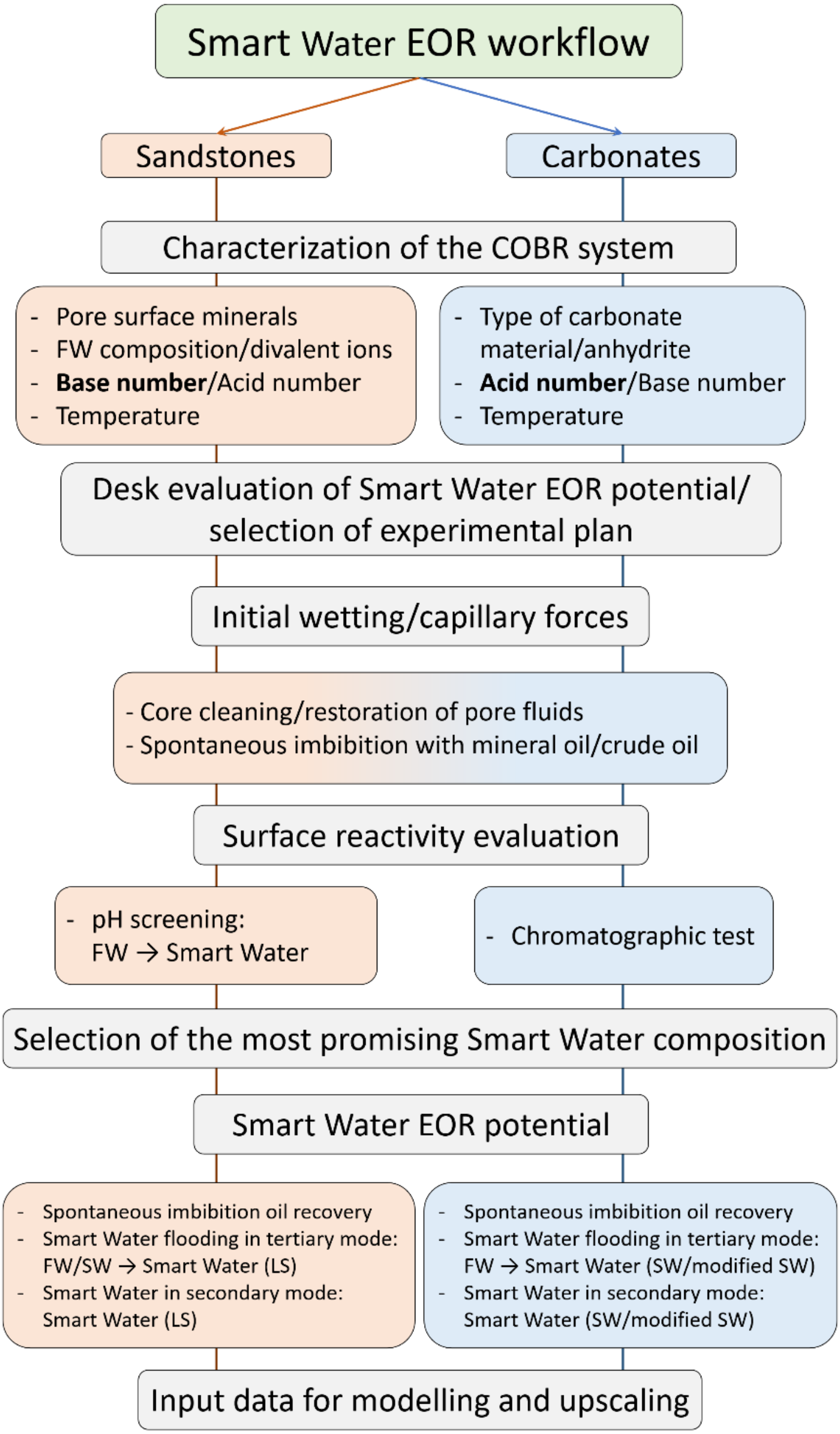


Figure 7: Flowchart of the recommended Smart Water EOR workflow. Low salinity (LS) and sea water (SW)/modified SW are listed as Smart Water brines for sandstones and carbonates respectively.

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