Effect of KCl/NaCl Composition on Fines Migration Initiation: Experimental Study and DLVO Analysis

by

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ORIGINALITY STATEMENT

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ABSTRACT

Fines migration is a major cause of formation damage in sandstone reservoirs. During water injection, changes in brine chemistry can destabilize naturally occurring fines such as kaolinite, clay fragments, and fine quartz. As a result fines detach, migrate with the fluid, and accumulate in pore throats. This accumulation leads to reductions in permeability, increase in pressure drop, and decline in injectivity and hydrocarbon recovery. Since sandstone reservoirs account for a large share of global hydrocarbon production, controlling fines migration remains an important reservoir engineering challenge. The onset of fines migration depends on the physicochemical stability of the sand-fine-brine (SFB) system. Grain surfaces and fines are usually negatively charged in quartz-rich sandstone, and their interaction is governed by the balance between attractive van der Waals and repulsive electrical double-layer (EDL) forces. Fines tend to detach from the rock surface when repulsion becomes dominant over attraction forces. This behavior is described by DLVO theory which connects this interaction energy to salinity, brine composition, zeta potential, and particle size. Among these factors, salinity and brine composition are especially important as they control EDL thickness. Lower salinity increases repulsion, and below the critical salt concentration (CSC), fines migration starts.

This study investigates the effect of NaCl/KCl brine composition on the critical salt concentration (CSC) for fines migration initiation in Berea sandstone. Approach used combines zeta potential measurements, machine learning prediction, DLVO modelling, and coreflooding validation. Zeta potential was measured for mixed NaCl/KCl brines using a Malvern Zetasizer, while the 100% KCl case was predicted using machine learning approach. TabM model was chosen to predict zeta potential values for KCl as it has the best performance among nine tested models (test R^2 = 0.6983, test RMSE = 7.79 mV). These values were used as inputs to a low-rate DLVO model, which predicted a CSC of 0.03 M for KCl brines.

Coreflooding experiments on a Berea sandstone core samples using KCl brines of decreasing concentration (0.20 M-0.01 M) were carried out to validate the DLVO prediction for 100% KCl brines. UV-Vis absorbance analysis of the effluent and pressure drop analysis indicated that a significant increase in fines concentration occurred between 0.03 M and 0.04 M KCl, placing the experimentally observed CSC in the range between 0.03 and 0.04 M. Using the midpoint of the experimental CSC range (0.035 M), the percentage error between the DLVO-predicted CSC of 0.03 M and the experimental result is approximately 14.3%. This relatively low error

confirms close agreement between the model and coreflooding results, supporting the reliability of the DLVO approach for predicting CSC in KCl brines. Since 100 % KCl case validated DLVO Model predictions, further models with different compositions of NaCl/KCl brines were constructed. DLVO modeling predicted CSCs of 0.05 M for 80/20 NaCl/KCl, 0.045 M for 50/50, and 0.04 M for 20/80, revealing a clear decrease in CSC with increasing KCl content.

The findings show that brine ion composition, even within monovalent systems, has a strong effect on fines stability. Systems dominated by KCl are more likely to experience fines mobilization than systems dominated by NaCl at the same salinity, which has practical importance for injection water design and formation damage control in sandstone reservoirs.

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1. INTRODUCTION

1.1 Background/Problem Definition

Fines migration is one of the most frequent causes of formation damage in sandstone reservoirs. During water injection, changes in brine chemistry can destabilize naturally occurring fine particles such as kaolinite, clay fragments, and fine quartz, causing them to detach from pore surfaces, move with the flowing fluid, and accumulate at narrow pore throats. This process reduces permeability, increases pressure drop, and can significantly reduce injectivity and hydrocarbon recovery (Khan et al., 2025). Since sandstone reservoirs account for a large part of global hydrocarbon production, understanding and controlling fines migration is still an important challenge in reservoir engineering.

The initiation of fines migration is closely connected to the physicochemical stability of the sand-fine-brine (SFB) system. In quartz-rich sandstone, both the grain surfaces and the fine particles typically have negative surface charge under reservoir conditions. Their interaction is governed by a balance between attractive van der Waals forces and repulsive electrical double-layer forces. When the repulsive force becomes sufficiently strong, attached fines destabilize and may detach from the rock surface. This behavior is commonly described by using DLVO theory, which provides a quantitative model for evaluating the total interaction energy between fines and pore surfaces as a function of salinity, ionic composition, zeta potential, and particle size (Muneer et al., 2020, 2022, 2023).

DLVO theory, developed by Derjaguin and Landau (1941) and Verwey and Overbeek (1948) provides a theoretical framework capable of relating surface chemistry to outcomes such as permeability decline and formation damage. This theory offers a quantitative basis for predicting whether fine particles will remain attached to grain surfaces or detach and migrate under given brine conditions. This done by describing the total interaction energy between two approaching surfaces as the sum of attractive van der Waals forces and repulsive electric double-layer (EDL) forces (Agmo Hernández, 2023).

Salinity and brine composition are among the most important factors affecting fines migration because they directly influence the electrical double layer. A decrease in brine salinity expands the diffuse double layer, increases repulsion, and can shift the interaction energy from attractive to repulsive. This threshold is referred to as the critical salt concentration (CSC), below which fines release begins. The CSC concept, first established in classical sandstone studies, remains

one of the most useful ways of defining the onset of chemically induced fines migration. However, the CSC is not universal, it depends on the mineralogy of the rock, the size and type of fines, and the composition of the surrounding brine (Khan et al., 2025; Muneer et al., 2022; Sadeghein et al., 2024). For example, based on series of research done by Muneer, CSC for NaCl is around 0.11 M (Muneer et al., 2022, 2024), which was first predicted by DLVO Modelling and then validated by coreflooding experiments. For $MgCl_2$ and $CaCl_2$ CSC is less than 0.0001M, which was in case also predicted by DLVO Modelling. For KCl he predicted that CSC is around 0.04 M, although no coreflooding validation was available for this case.

Besides single salt cases, complex brine systems were also tested in Muneer et al. (2024). According to his work for different scenarios of combined NaCl+$CaCl_2$ brines in proportions of 9:1, 8:2, 7:3, and 4:6, the DLVO model predicted CSCs of 0.01M, 0.003M, 0.001, and 0.0004M, respectively (Muneer et al., 2024). This exploration showed that CSC for this type of systems is not linear, and for other types of salts modelling alone is not enough, coreflooding validation is necessary to find CSC at which fines migration initiates.

Previous studies have shown that ion identity matters as much as overall salinity. Divalent cations such as Ca^{2+} and Mg^{2+} strongly compress the electrical double layer and stabilize fines more effectively than monovalent cations such as Na^+ and K^+. This explains why sandstone systems containing divalent ions generally have much lower CSC values than those where monovalent salts dominate (Muneer et al., 2020, 2022). At the same time, even within monovalent systems, different salts do not necessarily behave in the same way. NaCl and KCl both have monovalent cations, but specific ions like Na^+ and K^+ may have different surface charge, which can also differently affect fines stability. That's why composition of monovalent brines is an important variable in fines migration analysis, which is still not fully understood.

This gap is important both scientifically and practically. Scientifically, mixed NaCl/KCl brines give guide to understand the effect of monovalent cation composition on fines stability. This approach makes it easier to understand the role of Na^+ and K^+ fractions brine systems, rather than only comparing ions based on their valence number. Practically, both NaCl and KCl are widely used in brine preparation and formation damage control. If they lead to different CSC values, so assuming they are same based on their valence could result in inaccurate predictions for fines migration risk.

This study was done to address this gap by examining how NaCl and KCl compositions affects fines stability in Berea sandstone. Berea sandstone was chosen as the model rock because it is

rich in quartz, well characterized, and also commonly used in fines migration studies (Muneer et al., 2020). The work focused on the low-rate regime, where physicochemical detachment mechanisms dominate over hydrodynamic ones. So it makes possible to evaluate how changes in salt composition affect fines stability through surface force interactions.

In addition, this study makes a methodological contribution by combining experimental zeta potential measurements with DLVO-based prediction while considering for brine composition. Rather than relying only on literature data, it provides new surface charge measurements for mixed NaCl/KCl brines and uses them directly in the modeling. This strengthens the connection between measured interfacial behavior and predicted reservoir response. As a result, the study offers a more detailed and composition-based approach for prediction of CSC.

Overall, this thesis addresses an important unresolved question in fines migration research: how does the NaCl/KCl ratio influence the critical salinity at which fines become unstable in sandstone? By examining this issue, the study contributes new insight into sandstone formation damage and offers a practical foundation for improving fines migration control through brine composition design.

1.2 Objectives of the Thesis

1.2.1 Main Objectives

The main objective of this thesis is to investigate the effect of NaCl/KCl brine composition on the start of fines migration in Berea sandstone. It also aims to determine how variations in monovalent brine composition influence the critical salt concentration (CSC). To do this, the study employs an integrated approach that combines experimental zeta potential measurements, machine learning-based zeta potential prediction, DLVO-based interaction energy modelling, and coreflooding validation. The broader objective is to improve understanding of composition-dependent fines stability and to provide a more dependable basis for predicting fines migration risk in sandstone reservoirs under low-rate injection conditions

1.2.2 Specific Objectives

The specific objectives of this thesis are as follows:

1. To investigate the effect of brine salinity and NaCl/KCl composition on the zeta potential of the SFB system in Berea sandstone.

2. To experimentally measure zeta potential values for selected NaCl/KCl mixed brines over a range of salinities that is relevant to fines migration initiation.
3. To develop and apply machine learning model for predicting zeta potential in the 100% KCl case where direct experimental data are limited.
4. To construct a DLVO-based model for calculating the total interaction energy between fines and sandstone surfaces under different brine compositions.
5. To identify the critical salt concentration for 100% KCl and mixed NaCl/KCl brines by determining the salinity at which the total interaction energy shifts from attractive to repulsive.
6. To validate the DLVO-predicted CSC for the KCl system through coreflooding experiments, supported by pressure drop monitoring and UV-Vis effluent analysis.
7. To compare the predicted CSC values for different NaCl/KCl compositions and evaluate the effect of increasing KCl fraction on fines stability.
8. To assess the practical implications of monovalent brine composition for injection-water design and fines migration control in sandstone reservoirs.

1.3 Scope of Work

This thesis focuses on the initiation of fines migration in a quartz-rich Berea sandstone system under low-rate flow conditions. Under these conditions physicochemical interactions are expected to dominate over hydrodynamic forces. Study is limited to monovalent brine systems composed of NaCl and KCl. Main variable investigated is brine composition, which is expressed through variations in NaCl/KCl ratio, together with salinity as the controlling parameter for fines stability.

The work includes experimental measurement of zeta potential for selected mixed systems by using a Malvern Zetasizer, as well as machine learning-based prediction of zeta potential for the 100% KCl case. These zeta potential values are then used as inputs in a low-rate DLVO model to calculate van der Waals attraction, electrical double-layer repulsion, and Born repulsion, and to predict the critical salt concentration for each brine composition. Coreflooding experiments are carried out for the KCl system to validate the DLVO-predicted CSC, with UV-Vis absorbance and pressure drop analysis used to identify the point at which fines migration starts.

The scope of this study does not include divalent brines, high-rate hydrodynamic detachment, wettability alteration, temperature variation, or detailed mineral-specific surface complexation

modeling. Instead, the research is limited to evaluating how changes between NaCl and KCl brines affect fines stability and CSC prediction in a controlled sandstone system. The findings are expected to improve understanding of monovalent ion effects on fines migration and to support improved brine design for sandstone reservoir applications.

2. LITERATURE REVIEW

2.1 Sandstone reservoirs and fines migration

Sandstone reservoirs are sedimentary rock formations composed primarily of quartz and feldspar grains. They have sufficient porosity and permeability to store and transfer fluids: oil, natural gas, and water. They are formed in different depositional environments such as fluvial, aeolian, and coastal settings, and account for about half of the world's petroleum accumulations, which makes them one of the most significant storage systems for hydrocarbons (Greb et al., 2021; Tiab & Donaldson, 2016; Weimer & Tillman, 1982). Structure of sandstones consists of sand grains cemented by minerals such as silica, calcite, and clay, and have intergranular pores that act as primary flow paths. Size, shape, and connectivity of these pores strongly affect fluid movement through the rock. Porosity in sandstone reservoirs typically in a range between 10% to 35%, while permeability can vary from a few millidarcies in tight formations to several hundreds of millidarcies in high quality reservoirs (Civan, 2007). Berea sandstone which is used as a laboratory analog has porosity of 18-25% and permeability of 50-500 mD. It provides a reliable representative model for controlled studies of rock and fluid interactions (Khilar and Fogler, 1998).

A major challenge in management of sandstone reservoir is formation damage caused by fines migration. "Fines" are small particles which naturally present in the reservoir rock and generally have diameter less than 37-40 μm. They include clay minerals: kaolinite, illite, montmorillonite, and chlorite, and fine quartz fragments, feldspathic detritus, and other silicates (Muecke, 1979; Khilar and Fogler, 1998; Muneer et al., 2020). Under stable conditions between water and formation these particles remain attached to grain surfaces and system is stable. But any disturbance in the physicochemical equilibrium of the SFB system: changes in salinity, pH, or fluid composition, can lead to mobilization of these particles. Mobilized fines are carried by the flowing phase and accumulate at pore throats, which may reduce permeability and increase pressure drop (Khilar and Fogler, 1984; Kia et al., 1987; Muneer et al., 2022; Dalabayeva et al., 2025).

The effects of fines migration are important from both operational and economic perspectives. Worldwide, at least 10% of the estimated $100 billion annual expenditure on formation-damage prevention and remediation is associated with fines migration (Bedrikovetsky et al., 2011).

Permeability reductions can be as high as two orders of magnitude, and in some cases up to 500 times, which reduces well productivity and injectivity and increases operational costs related to workovers, acid stimulation, and sand control. Although reversing the flow may move some part the blocking fines, the permeability usually does not fully return to its original value (Gruesbeck & Collins, 1982).

2.2 Mechanisms of fines migration in porous media

Fines migration in porous media is usually described as a sequence of four linked events. Fines initially present on the pore surface become unstable and detach from the rock, then move with the flowing fluid and as a result accumulate at narrower pore paths. Figure 1 illustrates the main mechanisms of fines migration in porous media, including attachment, detachment, suspension, straining, and re-attachment during water flow through the pore network. The first step alone does not necessarily create serious damage, permeability loss becomes significant when detached particles are retained in pore throats. Khilar and Fogler (1984) interpreted the strong permeability decline in Berea sandstone in exactly this way, arguing that released clay particles migrate only a limited distance before blocking narrower passages. Vaidya and Fogler (1990) and Zhou et al. (2022) describe the same sequence in different sandstone settings, while Ines et al. (2023) used NMR and SEM observations to show how deposited particles can form pore-blocking structures during transport in porous media.

The driving force behind detachment is most often explained using colloidal interaction theory. In the classical interpretation that is developed by Khilar and Fogler (1984) and expanded by Kia et al. (1987) and Vaidya and Fogler (1990). Stability of fine particle on a pore wall depends on the balance between attractive van der Waals forces and repulsive electrical double-layer forces. Particle remains attached when attractive forces dominate. But when repulsive forces increase enough so that it overcomes that attraction, particle start to detach. Later studies by Muneer et al. (2021, 2022, 2023) and Dalabayeva et al. (2025) followed the same concept but described it more explicitly using DLVO modeling. In this approach, the total interaction energy is calculated from van der Waals attraction, double-layer repulsion, and Born repulsion, while hydrodynamic and gravitational effects are included when necessary.

This interpretation is especially useful because it links chemical changes directly to reservoir damage. For example, a decrease in salinity expands the electrical double layer around both the sand grain and the fine particle and increases the repulsive interaction between them. A change in pH alters surface charge and can also shift the force balance toward particle detachment.

After particle release, transport and retention become the main factors controlling the extent of damage. During this stage, particles may become trapped in narrow pore throats, form bridges across constrictions, or deposit on grain surfaces in other parts of the pore system. Ines et al. (2023) identified surface deposition and pore bridging as major clogging mechanism. Keykhosravi et al. (2025) described fines detachment, transport, and straining during two-phase CO2-brine displacement. These studies show that fines migration involves more than particle release, as particle transport and retention also play important roles.

A further development in the mechanism discussion is the understanindg that detachment is not controlled only by electrostatic interactions. At low flow rates, hydrodynamic forces may be weak enough for surface chemistry to become the dominant factor. At higher flow rates, however, drag and lift forces acting on the particle become increasingly important. Muneer et al. (2023) combined electrostatic, gravitational, and hydrodynamic forces in one model to predict the critical flow rate. Tangparitkul et al. (2020) used force and torque balance to show that drag, lift, buoyancy, and electrostatic forces together influence particle detachment. In two-phase systems capillary forces may also become significant. Keykhosravi et al. (2025) showed that moving gas-water interface can produce detaching forces on particles during CO_2 injection. This broader understanding is important because it helps explain why low-rate and high-rate regimes should be treated differently in analysis of fines migration.

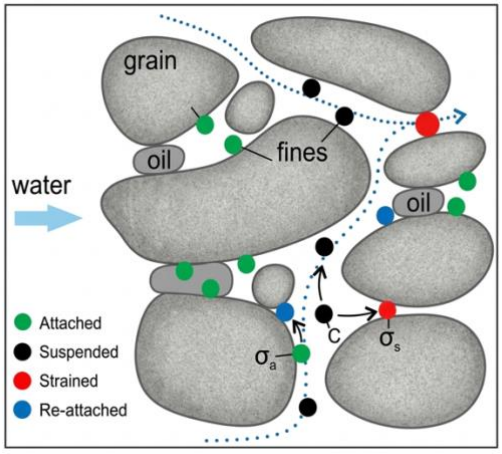


Figure 1. Conceptual diagram of fines behavior in porous media during water flow

2.3 Parameters affecting fines migration initiation

The initiation of fines migration is generally not gradual. Most studies describe it as a threshold event in which the system remains stable until a critical condition is exceeded, after which fines release begins. These conditions may include salinity, ionic composition, pH, temperature, and

flow rate. In sandstone reservoirs, this concept is useful because it allows fines migration to be understood not simply as a general risk, but as a process that begins at specific critical values. Khilar and Fogler (1984) established this approach for salinity, Kia et al. (1987) for pH, and more recent work by Muneer et al. (2022, 2023) and Dalabayeva et al. (2025) extended it to broader DLVO-based prediction of initiation conditions.

2.3.1 Salinity and CSC

Salinity is the most thoroughly studied controlling parameter in the fines migration literature. Khilar and Fogler (1984) introduced the concept of critical salt concentration (CSC), defined as the salinity below which fines detach from the rock surface and a sudden decline in permeability occurs. Their results showed that when the salinity of the injection fluid remains above the CSC, fines stay attached and no major permeability loss is expected. This concept was important because it gave a clear threshold for when fines migration begins and directly linked permeability decline to brine chemistry.

Later studies confirmed and further developed the CSC concept. Khilar et al. (1990) extended it from single-salt systems to mixed-salt systems. For brines containing both monovalent and divalent ions, critical total ionic strength (CTIS) was introduced as a more appropriate threshold. More recently, Muneer et al. (2021) and Muneer et al. (2022) applied DLVO modeling to predict CSC for several salts, and their predictions were consistent with experimental results. Dalabayeva et al. (2025) also treated CSC as a key threshold parameter for evaluating fines release under changing chemical conditions, particularly pH.

The importance of salinity is also demonstrated in low-salinity waterflooding studies. Snosy et al. (2020) reviewed many coreflood experiments and showed that changing water salinity that is injected into reservoir affects sandstone behavior in different ways based on clay content, clay type, and flooding stage. Hassan et al. (2020) linked successful low-salinity flooding in an Egyptian sandstone reservoir to favorable rock-fluid compatibility and kaolinite-bearing mineralogy, while Cesarian (2019) reported the existence of an optimum salinity for recovery in laboratory sandstone flooding. These studies are more recovery-oriented than fines-migration-focused, but they still support the idea that salinity changes can shift the stability of sandstone systems and therefore influence fines behavior.

According to Muneer et al. (2022), CSC for NaCl is approximately 0.1 M, which corresponds to the point where fines begin to detach from the pore walls. This value is determined experimentally by coreflooding, and it is supported by DLVO modeling. Muneer et al. (2022)

also predicted CSC for KCl brines, according to DLVO model fines detach from the pore walls at 0.044 M. For divalent salts like $CaCl_2$ and $MgCl_2$ according to (Khilar & Fogler, 1984), CSC is lower to orders of magnitude than for monovalent salts as divalent cations strongly stabilize fines, CSC for these salts is less than 0.0001 M. In summary, fines mobilization is highly sensitive to brine salinity. CSC values are highest for NaCl, lower for KCl, and extremely low for divalent salts such as $CaCl_2$ and $MgCl_2$.

2.3.2 Ionic composition and monovalent ion effects

Salinity alone does not fully define fines stability, the identity and valence of ions in solution matter more. Khilar and Fogler (1984) showed that CSC exists mainly in monovalent systems and becomes virtually nonexistent for cations of valence greater than one. They also reported that even among monovalent ions the CSC is not constant but decreases as the ion-exchange affinity of the counterion for clay increases. This indicates that sandstone sensitivity is controlled not only by salt concentration, but also by the type of ion present.

This effect becomes clearer in studies that compare monovalent and divalent ions directly. Khilar et al. (1990) demonstrated that in mixed NaCl/$CaCl_2$ systems the threshold for fines release depends strongly on the amount of calcium ions present in solution. Muneer et al. (2022) reached the same conclusion by DLVO modeling, predicting much lower CSC values for $CaCl_2$ and $MgCl_2$, CSC less than 0.0001 M, than for NaCl and KCl, 0.11 M and 0.004 M respectively by DLVO Modelling. Their results indicate that divalent ions lower the electrical double layer more effectively, reduce repulsion, and therefore reduce fines release more strongly than monovalent ions. From a practical point of view, sandstone systems with mainly monovalent ions are more sensitive to fines migration than systems that include divalent ions.

Among monovalent ions, differences are also important. Muneer et al. (2022) predicted different CSC values for NaCl and KCl, showing that these salts cannot be treated as equivalent stabilizers. This is highly relevant to the present thesis because it shows that monovalent ion effects are not governed by valence alone, mineralogical structure can change the critical threshold significantly.

2.3.3 pH

Kia et al. (1987) showed that pH plays an important role in the initiation of fines migration, as the pH of the injected fluid was found to either increase or reduce fines release in Berea sandstone. Their results showed there is no fines release below a critical pH. They explained this by showing that, at low pH, fines release happens slowly enough for multivalent ion

exchange to occur on the clay surface, which stabilizes the particles and prevents them from detaching. But once pH is raised to enough level, that stabilizing effect becomes weaker and fines release is more likely to be initiated.

Vaidya & Fogler (1990) developed this idea further by showing that pH and salinity often vary together during water shock. They found that replacing brine with fresh water not only lowers salinity, but also raises pH of the effluent, it is probably because of ion exchange involving surface cations and protons. This is important because it shows that pH should not be studied separately from salinity in sandstone damage analysis. A system that becomes unstable during low-salinity flooding may be reacting to both electrical double-layer expansion and pH-related changes in surface potential at the same time.

This interpretation is continued in some recent studies. Dalabayeva et al. (2025) developed a DLVO model to predict critical pH and used coreflooding experiments to validate it. Muneer et al. (2023) also noted in his works that even at low flow rate cases fines migration may be initiated if system has high pH. It is concluded that under conditions where hydrodynamic forces are weak, pH can still initiate fines migration by changing the electrostatic balance between the fines and the rock surface. This makes pH especially important in alkaline flooding and in systems where mineral reactions gradually raise the pH of the flowing fluid.

Both Dalabayeva et al. (2025) and Muneer et al. (2023) measured the zeta potential of sand-brine systems over a wide pH range, typically from pH 2 to 12 by using Malvern Zetasizer. Sand samples were cleaned, acid treated, and equilibrated in brine prior to measurements. Results revealed that the zeta potential became more negative with increase in pH. The reason for that is increased electrostatic repulsion which promoted detachment of fines. For monovalent salts such as NaCl and KCl, fines began to mobilize at around neutral pH, approximately 6-7. In contrast, for divalent cations such as Mg^{2+} and Ca^{2+}, fines remained stable at similar pH values because stronger double-layer compression required much lower concentrations for detachment. These findings show that the critical pH for fines migration depends on both cation type and brine ionic strength, and fines start migration when repulsive forces become stronger than attractive forces.

2.3.4 Temperature

Temperature has received less direct attention than salinity or pH, but it still considered important factor to control stability of fines. Khilar & Fogler (1984) reported that CSC depends on temperature, which indicates thermodynamic sensitive nature of fines. As DLVO

interactions depend on properties such as dielectric behavior and double-layer characteristics, temperature effect is physically reasonable and also agrees with their interpretation. Higher temperatures mobilize attached fines from grain surfaces which leads to pore clogging and permeability decline. Main mechanism here is increased EDL repulsion between kaolinite and quartz, which overcomes adhesion. Permeability can decrease to 35-90% of initial values at 80-180°C (Rosenbrand & Fabricius, 2012; Yang et al., 2022).

You et al., 2019) also showed that temperature influences fines mobilization through three main mechanisms. As temperature increases, dielectric permittivity decreases, which weakens the electrical double layer (EDL), lowers repulsion between clay particles and sand surfaces, and may reduce fines detachment. Viscosity decrease at higher temperature lowers drag force, and slows particle lifting and potentially decreases fines transport. Increase in negative surface charge of clay and sand enhances electrostatic repulsion, which can promote fines detachment at high temperatures (up to 129 °C). At 129 °C and ionic strength below 0.2 M NaCl, nearly all fines were mobilized, showing that in high-temperature geothermal conditions, fines mobilization is more pronounced than at room temperature (25 °C) (You et al., 2019).

Later studies usually include temperature as one of the variables affecting fines migration without focusing on it as the main parameter for experiments. Muneer et al. (2022) identified reservoir temperature as one of the factors that can influence fines detachment. Dalabayeva et al. (2025) also included temperature among the conditions affecting critical pH and fines release. In addition, Snosy et al. (2020) reported that temperature plays a role in the low-salinity response during sandstone waterflooding. These findings suggest that temperature does affect the critical conditions for fines migration, but its role is usually secondary rather than dominant in most sandstone systems.

2.3.5 Flow rate and low-rate regime

Flow rate influences fines migration because it controls the hydrodynamic forces acting on particles attached to the rock surface. Khilar and Fogler (1984) reported that CSC depends on temperature rather than flow rate. This result is often interpreted to mean that under low-flow conditions the start of fines migration is controlled more by the balance of surface forces than by hydrodynamic drag. This interpretation is especially relevant studies which focus on low flow rate and on physicochemical destabilization rather than mechanical removal. Once flow rate increases sufficiently, however, hydrodynamic forces cannot be neglected. Muneer et al. (2023) predicted critical flow rates for fines migration initiation and showed that drag and lift

forces become important to release fines from the rock surface. (Tangparitkul et al., 2020) also identified velocity as one of the main variables controlling detachment in torque and balance model. These studies do not contradict the early findings for low rate cases, rather, they are important to define the boundary of their applicability. At higher rate, hydrodynamic detachment becomes an additional trigger.

As shown in Figure 2, smaller fines require greater hydrodynamic force for detachment because the attractive van der Waals force is stronger. In contrast, when the fine particle radius exceeds 1000 nm (1×10^{-6} m), the required detachment force increases due to the influence of gravity. Therefore, the critical velocity can be estimated based on particle size. Muneer et al. (2023) predicted critical flow rate for different salinities of NaCl, for example, in the 0.15 M and 0.25 M cases, fine particles with a radius of 400 nm (4×10^{-7} m) are detached at injection velocities of 1×10^{-3} m/s and 6×10^{-2} m/s, respectively. The model estimated critical flow rates of 0.9, 2.6, and 3.8 cc/min for 0.15 M, 0.20 M, and 0.25 M NaCl, respectively. These predictions were validated through coreflooding experiments, which gave comparable critical flow rates of 1, 3, and 4 cc/min for the same brines. The results show that higher salinity leads to a higher critical flow rate for fines detachment, because stronger attractive forces require greater hydrodynamic force to initiate particle movement (Muneer et al., 2023).

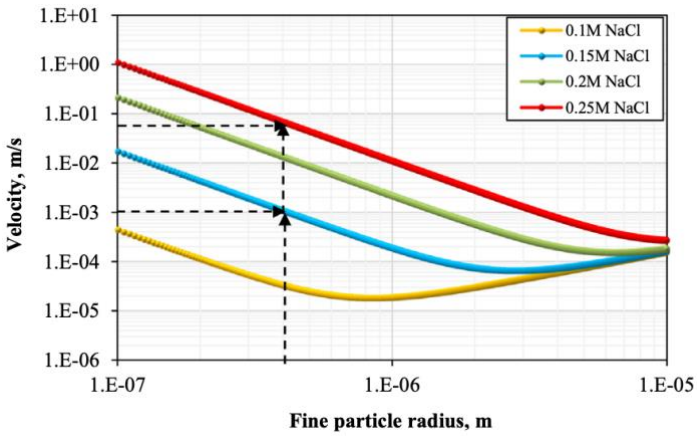


Figure 2. Effect of brine salinity on velocity profiles, (Muneer et al., 2023)

Other recently published studies support this interpretation. Askar et al. (2023) listed flow rate as one of the variables contributing to CSC and the extent of fines migration, especially when combined with wettability and phase distribution. Zhou et al. (2022) described kaolinite, illite, and mica as velocity-sensitive minerals in reservoirs with low permeability. These findings are useful for the present thesis because they justify the focus on the low-rate regime, and also show

that a different detachment mechanism may develop when velocity or multiphase effects become strong enough.

2.4 Experimental and modeling approaches for predicting fines migration

The prediction and characterization of fines migration draw on a range of experimental techniques and mathematical models, from classical coreflooding to advanced surface-force measurements and machine learning. The choice of approach depends on the level of investigation, available resources, and the specific outputs required for engineering decision-making.

2.4.1 Coreflooding and effluent analysis

Coreflooding is the gold-standard experimental technique for characterizing migration in reservoir rocks. In a typical coreflooding experiment, a cylindrical core plug is placed in a flow-through apparatus and saturated with brine. Brines of decreasing salinity are then injected in sequence at controlled flow rates, and the pressure drop is monitored continuously to calculate the instantaneous permeability. The effluent is collected and analyzed for turbidity, absorbance, or particle concentration to quantify the amount of fines released at each salinity step (Khilar & Fogler, 1984; Muneer et al., 2022)

A characteristic coreflooding signature for fines migration is a permeability decline as salinity is reduced, with the most dramatic drop occurring at the CSC. In experiments on Berea sandstone, Khilar & Fogler (1984) observed permeability reductions from approximately 500 mD to less than 1 mD over a salinity reduction from 20000 ppm to distilled water, confirming the existence of a threshold value for salinity. Muecke (1979),Zeinijahromi et al. (2013), and (Bedrikovetsky et al., 2011) all reported that Berea and Bentheimer cores with high kaolinite content showed permeability reductions of 70-95% following salinity reduction below the CSC. X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy dispersive X-ray spectroscopy (EDS) are then applied to characterize the mineralogy of collected fines and changes in pore structure before and after flooding.

2.4.2 Zeta potential measurements as a surface-charge indicator

Zeta potential (ζ) is a fundamental electrokinetic parameter that quantifies the electrostatic charge at the slipping plane of a particle suspended in a liquid medium. Specifically, it represents the potential difference between the surface of the particle's diffuse electrical double layer (EDL) and the bulk fluid at the boundary of the slipping plane (Muneer et al., 2020, 2022). In the context of sandstone reservoirs, zeta potential is an important indicator of the surface

charge carried by fine particles and sand grains, and it is directly used to quantify the electrostatic repulsive energy that governs whether fine particles remain attached to or detach from pore surfaces (Muneer et al., 2020). Therefore, zeta potential measurement is one of the most useful practical tools for studying fines migration because it reduces complex surface chemistry to a single value that is easier to interpret.

Relationship between zeta potential and salinity is very important for understanding fines migration. Under typical reservoir conditions, both silica sand grains and fine clay particles have negative surface charges because of deprotonation of silanol and aluminol groups on their surfaces. As brine ionic strength increases, cations in brine compress the electrical double layer (EDL), then tend to reduce the magnitude of the negative zeta potential, and decrease the electrostatic repulsion between fines and sand surfaces. So EDL expands with salinity decrease, zeta potential becomes more negative, and the repulsive interaction between the fine particle and the sand grain surface becomes stronger (Muneer et al., 2020). This expansion of the EDL is the main mechanism by which low-salinity waterflooding can trigger fines migration.

In their subsequent study, Muneer et al. (2022) systematically measured and collected zeta potential data for SFB systems with four different monovalent and divalent brines such as NaCl, KCl, $CaCl_2$, and $MgCl_2$, and then used these values as the primary input to DLVO models to predict the CSC for each salt system. The zeta potentials were measured using a Zetasizer on dispersed sand particles in brine, and data from previous literature were also integrated for machine learning prediction. The DLVO models that were built using average fine particle sizes and the corresponding zeta potentials predicted CSCs of 0.11 M for NaCl, 0.04 M for KCl, 0.0001 M for $CaCl_2$, and 0.0001 M for $MgCl_2$, all of which were found to be in close agreement with experimental CSCs reported in the literature (Muneer et al., 2022).

In summary, zeta potential is a useful and practically measurable indicator of surface charge in SFB systems in sandstone reservoirs. Muneer and co-workers developed a clear framework in which zeta potential values measured by Zetasizer instruments over a range of salinities, ionic compositions, and pH values are directly applied in DLVO models to predict CSC, critical pH, and critical flow rates. The numerical zeta potential values reported in their studies form the quantitative basis for DLVO-based fines migration prediction in sandstone reservoir systems.

2.4.3 Machine learning approaches

Machine learning (ML) can be a useful addition to physics based models such as DLVO theory. It is especially helpful when experimental data are limited, many variables must be considered,

and the relationships between them are complex and not always linear. In studies of fines migration and sandstone brine interactions, ML has been applied to predict important interfacial properties, reservoir parameters, and signs of formation damage that are often difficult, time consuming, and expensive to measure experimentally. By learning from existing laboratory results and published data, ML models can detect patterns under different conditions and provide fast estimates for cases where no direct experiments are available.

Muneer et al. (2023) developed and compared three ML models such as multiple regression analysis (MRA), support vector machine (SVM), and artificial neural network (ANN), to predict the zeta potential of silica nanofluids and related colloidal systems relevant to SFB interactions. The training dataset was collected from multiple published literature sources and included 249 data points across a wide range of experimental conditions. The input variables of the models included nanoparticle size, nanoparticle concentration, pH, temperature, brine salinity, monovalent ion type, and the presence of sand, limestone, or nano-sized fine particles. Target output parameter was zeta potential in millivolts. This ML-based zeta potential model is practically important for fines migration prediction. Since zeta potential is the main surface-charge parameter in DLVO modeling, a reliable value predicted by an ML model can replace direct experimental measurement in the DLVO framework.

In the context of this thesis, the work of Dalabayeva et al. (2025) is directly relevant. Her work applied the DLVO modeling framework to predict the pH above which fines detach in sandstone formations by using zeta potential as the key input. The study further developed and confirmed the link between experimentally measured or model-predicted zeta potential values and the conditions that lead to fines release. It also showed that this predictive framework can be applied not only to salinity, but also to the pH of injection water. The study closely follows the broader research direction of using surface-force analysis, supported by zeta potential data, to improve fines migration control strategies (Dalabayeva et al., 2025). Therefore, combining ML-predicted zeta potential with DLVO-calculated interaction energies is a effective approach for building a more complete and data-based framework for fines migration prediction (Larestani et al., 2022; Muneer et al., 2023).

2.5 Sand-fine-brine system as a colloidal system

Sandstone reservoirs are naturally colloidal environment. Fine clay particles, including kaolinite, illite, chlorite, montmorillonite, and fine quartz grains, are dispersed in the formation or injection brine and continuously interact with the surfaces of larger sand grains (Muneer et

al., 2020; 2022). Colloidal systems involve at least one phase with dimensions between about 1 nm and 10 μm and reservoir fines fall within this size range. SEM measurements of Berea sandstone fines showed average particle sizes of 800–900 nm (Muneer et al., 2022). At this size range, particle behavior is controlled mainly by surface interactions rather than gravity.

DLVO theory provides the main framework for describing particle interactions in this system. According to this theory, the total interaction energy (V_T) is determined by the combined effects of van der Waals attraction (V_{LW}) and electrical double-layer (EDL) repulsion (V_{EDL}), and sometimes include Born repulsion (V_B) and hydration forces (Muneer et al., 2020). In SBF systems Hamaker constants is between 0.8×10^{-20} and 1.3×10^{-20} J, which indicates that the attractive component remains relatively stable and not strongly affected by brine composition.

Electrical double layer (EDL) changes the most strongly with brine chemistry. The Debye length (k^{-1}), which shows how far the repulsive ion layer extends from the surface, becomes smaller as ionic strength increases. In high salinity brine the EDL is compressed, so fines are remained close to grain surfaces, and van der Waals attraction helps to keep them attached. As salinity drops, the EDL expands, so that the repulsive energy barrier grows, and at the CSC fines detach and migrate. This transition explains the colloidal mechanism that causes formation damage in sandstone reservoirs (Muneer et al., 2022).

Ion type is just as important as total salinity. Divalent cations such as Ca^{2+} and Mg^{2+} compress electrical double layer much more strongly than monovalent ions such as Na^+ and K^+. They can also attach to clay surfaces and lower the surface charge. DLVO modeling showed that the CSC for $CaCl_2$ and $MgCl_2$ around 0.0001 M, , which is about three orders of magnitude lower than the predicted NaCl CSC of 0.11 M. This clearly shows the strong effect of ion valence on colloidal stability (Muneer et al., 2022).

pH of the system is also important, as under alkaline conditions, silanol groups lose protons, make the surfaces more negatively charged and increase the chance of fines detachment. But under normal reservoir flooding conditions, both quartz and kaolinite surfaces are negatively charged, so repulsive electrical double layer forces are present. DLVO modeling showed that the critical pH is about 8 in untreated systems, but it increases to around 11 after treatment with silica nanoparticles (Muneer et al., 2022).

Once fines detach, they become part of a dilute colloidal suspension in the flowing brine and move through the pore network. When they reach pore throats smaller than the particles, they can become trapped, block the flow path, and cause irreversible permeability loss (Muneer et

al., 2022). Nanoparticles may address this issue by adsorbing onto grain surfaces and shifting zeta potentials to less negative values so that EDL repulsion is reduced and system is restabilized (Muneer et al., 2022; 2024).

Colloidal basis is based on EDL repulsion, van der Waals attraction, zeta potential, and Debye length. This basis can provide both a physical explanation of fines behavior and a quantitative way to predict it. The reported particle sizes (800-900 nm), interaction distances (1-100 nm), and zeta potential values (-27 to -35 mV for NaCl brines) show that this colloidal explanation is not only theoretically appropriate but also practically useful for to predict fines behavior (Muneer et al., 2022).

2.6 DLVO theory and its application to fines migration

A theoretical framework is required to connect surface chemistry with larger-scale reservoir effects such as permeability reduction and formation damage in sandstone formations. DLVO theory developed by Derjaguin, Landau, Verwey and Overbeek provides this framework. It describes the total interaction energy between two approaching surfaces approaching as the combined result of attractive van der Waals forces and repulsive electric double-layer (EDL) forces. Theory provides quantitative evaluation whether fine particles are likely to remain attached to grain surfaces or detach and migrate under specific brine conditions. The following subsections discuss each of these interaction components separately before addressing the assumptions and limitations that affect the application of the theory in real porous media.

2.6.1 General concept

DLVO theory describes the stability of colloidal dispersions by representing the total interaction energy between two surfaces as the algebraic sum of attractive van der Waals forces and EDL forces (Agmo Hernández, 2023; Missana & Adell, 2000; Trefalt & Borkovec, 2014). For classical DLVO theory, the total interaction energy V_T corresponds for the sum of the London-van-der-Waals (LVW) potential V_{LW}, the electrical double layer potential V_{EDL}, and the Born potential V_B (Yang et al., 2022). Formula 2.6.1 below gives this total energy expression in equation form. According to this theory attractive component tends to pull particles into contact, while the repulsive component works to keep them apart (Trefalt & Borkovec, 2014). The balance between these forces determines whether a colloidal system remains stable, with particles staying dispersed, or becomes unstable, resulting in aggregation or, in porous media, the detachment and migration of fine particles.

$$V = V_{LW} + V_{EDL} + V_B \quad (2.6.1)$$

In sandstone reservoirs, DLVO theory is highly relevant for understanding fines migration. Clay minerals such as kaolinite, illite, and montmorillonite are naturally found on grain surfaces. Response of these clay minerals to different brine conditions determines whether they remain attached or detach and as a result move through pore throats. This theory is useful for interpreting the impact of salinity reduction during waterflooding or low-salinity injection, since changes in ionic strength strongly affect EDL repulsion while having only a negligible effect on van der Waals attraction (Agmo Hernández, 2023; Israelachvili, 2010). The critical salt concentration (CSC) is defined as the salinity below which fines begin to detach, and according to DLVO analysis it is a point where the repulsive energy barrier in V_T disappears, which allows particles to overcome adhesion and become mobile. This theory offers a physically based and mathematically manageable framework to predict fines stability as a function of brine composition, pH, and ionic strength.

2.6.2 Van der Waals attraction

The van der Waals interaction in the SFB system less affected by changes in brine ionic strength or composition, since it depends primarily on the dielectric properties of the materials rather than the solution chemistry (Israelachvili, 2010). This is in stark contrast to the EDL interaction, which is highly sensitive to ionic strength. As a result, the van der Waals term acts as a fixed attractive baseline against which the salinity-dependent EDL repulsion must compete, it is the modulation of the EDL repulsion by ionic strength that determines whether the net interaction is attractive or repulsive, and thus whether fines remain attached or are mobilised (Muneer et al., 2020).

Van der Waals forces arise from electromagnetic fluctuations between molecular dipoles and are present between all materials regardless of their surface charge or chemical composition (Israelachvili, 2010) At the molecular scale, these forces originate from three distinct mechanisms: orientation interactions between permanent dipoles, induction interactions between permanent and induced dipoles (Debye forces), and dispersion interactions arising from instantaneous, correlated fluctuations in the electron clouds of neighbouring atoms (London forces). Of these, dispersion forces are generally dominant, occurring universally between all atoms and molecules, including those with no permanent dipole moment (Agmo Hernández, 2023; Israelachvili, 2010). Because they are always present and always attractive between two identical materials in a medium, van der Waals forces constitute the baseline

attractive term in DLVO theory that holds fine particles against grain surfaces in reservoir conditions.

For macroscopic bodies such as colloidal particles interacting across a liquid medium, the van der Waals interaction energy is characterised by the Hamaker constant, A_H. In DLVO modelling of the CSC, the Hamaker constant is typically held constant while ionic strength is varied, with the CSC identified as the ionic strength at which the energy barrier first vanishes. This constant encapsulates the material-specific contribution to the interaction and depends on both the composition of the interacting surfaces and the properties of the intervening medium (Israelachvili, 2010). For two spherical particles of radius r separated by distance d, the van der Waals interaction energy can be expressed as shown in formula 2.6.2, which shows that the interaction increases in magnitude as separation decreases (Agmo Hernández, 2023; Trefalt & Borkovec, 2014). Typical values of A_H for insulating condensed phases lie in the range of approximately 10^{-21} to 10^{-19} J, with the specific value for silica-water-silica systems of relevance to quartz-rich sandstone reservoirs (Israelachvili, 2010).

$$V_{LW} = -\frac{A_H r}{12d} \tag{2.6.2}$$

An important implication of the Hamaker approach is that van der Waals forces between two identical materials remain attractive regardless of the intervening medium (Agmo Hernández, 2023; Israelachvili, 2010). In sandstone systems, where both fine clay particles and sand grains are siliceous, the van der Waals attraction between them remains a consistent force and is relatively insensitive to changes in brine salinity. This differs from EDL repulsion, which is highly responsive to variations in ionic strength and ion valence. In practical terms, van der Waals forces provide the baseline attractive force responsible for fine particle attachment. As a result, when EDL repulsion becomes sufficiently weak, overall interaction becomes attractive, which allows the fines to enter the primary energy minimum at contact.

2.6.3 Electric double-layer repulsion

When a surface is immersed in an aqueous electrolyte solution, it commonly develops a net electrical charge through processes such as dissociation of surface functional groups or specific adsorption of ions (Agmo Hernández, 2023). This surface charge attracts oppositely charged ions from the solution, leading to the formation of the electric double layer (EDL). The EDL consists of a compact Stern layer of tightly bound oppositely charged ions located directly next

to the surface, followed by a diffuse layer in which ion concentration gradually decreases with distance from the surface. The thickness of this diffuse layer is described by the Debye screening length, k^{-1}, which is inversely proportional to the square root of the ionic strength of the solution (Trefalt and Borkovec, 2014; Agmo Hernández, 2023).

When two similarly charged surfaces approach one another, their diffuse layers start to overlap, and generate a repulsive force that is primarily entropic in origin. These overlap constrains the spatial freedom of the counter-ions between the surfaces, increasing the osmotic pressure in the gap and pushing the surfaces apart (Agmo Hernández, 2023). The magnitude of this repulsion depends on the surface charge density (or zeta potential), the ionic strength of the solution, and the valence of the ions present. At high ionic strength, the Debye length is short, the diffuse layers are compressed, and the surfaces can approach closely before their EDLs overlap significantly, and under these conditions, the van der Waals attraction is largely unopposed at short range and fines remain attached to grain surfaces. As the ionic strength is reduced, for example, during fresh water or low-salinity brine injection, the Debye length increases, the repulsive energy barrier in V_T grows, and at the CSC this barrier is sufficient to enable fine particle detachment(Agmo Hernández, 2023; Dalabayeva et al., 2025; Missana & Adell, 2000; Trefalt & Borkovec, 2014). According to Sourani et al. (2014), EDL can be described by using formula 2.6.3 below:

$$V_{EDL} = \frac{\partial r_p}{4}\left[2\omega_{01}\omega_{02}\left(\frac{1+e^{-kx}}{1-e^{-kx}}\right) + (\omega_{01}^2 + \omega_{02}^2)\ln(1-e^{-2kx})\right] \tag{2.6.3}$$

$$k = \sqrt{\frac{e^2 I}{\varepsilon k_B T}} \tag{2.6.4}$$

where, r_p is particle radius, I is ionic strength, k_B is Boltzmann's constant, e is electron potential, ω_{01} and ω_{02} refer to surface potential of plate and sphere, and k is the reciprocal Debye length.

Since surface charge varies with ionic strength and pH, the electrical forces and double-layer characteristics are also governed by these two parameters. As a result, the likelihood of fines being released from the pore wall is highly dependent on ionic strength and pH (Sourani et al., 2014).

However, because surface potentials are difficult to determine experimentally, an alternative expression as shown in formula below based on constant potential can be used:

$$V_{EDL} = 2\pi\varepsilon_m\varepsilon_0 r z^2 \ln(1 + \mathrm{e}^{-\frac{h}{k^{-1}}}) \quad (2.6.5)$$

where ε_m represents the dielectric constant of water, ε_0 is the vacuum permittivity, z denotes the zeta potential, r is the particle radius, h is the separation distance between the particle and the surface, and e is the electron charge.

The role of ion valence in modulating EDL repulsion is particularly important in reservoir settings where brines contain mixtures of monovalent and divalent cations. Divalent cations such as Ca^{2+} and Mg^{2+} are considerably more effective than monovalent cations such as Na^{+} at compressing the EDL at equivalent molar concentrations, in accordance with the Schulze–Hardy rule (Trefalt & Borkovec, 2014). This is because the ionic strength, which governs k^{-1}, scales with the square of the ionic valence, so divalent ions contribute disproportionately more to the screening of surface charges. As a result, the critical coagulation concentration (CCC) for divalent salts is much lower than that for monovalent salts, which means that fine particles can remain stable at considerably lower total salinities when divalent cations are present. This has direct implications for reservoir engineering decisions related to injection water composition, since replacing divalent ions with monovalent ions during low-salinity flooding can destabilize fines at concentrations that would otherwise be too low to trigger their release.

2.6.4 Born repulsion

At very small surface separations, the classical DLVO expression for van der Waals attraction predicts interaction energies that become infinitely large as the distance approaches zero, which is not physically realistic. In practice, when two surfaces approach atomic contact, the overlap of electron clouds generates a strong repulsive force that prevents the surfaces from penetrating one another (Israelachvili, 2010). This is known as Born repulsion, and its presence in the DLVO energy profile determines the depth of the primary energy minimum, which represents the well into which particles must fall to be regarded as irreversibly attached to a surface.

In the context of fines migration, its principal significance is that it prevents particles from collapsing to zero separation with the grain surface, thereby ensuring that an energy minimum of finite depth is used in quantitative predictions of fine particle adhesion. The Born repulsive energy for the sphere-plate configuration is given by:

$$V_{BR} = \frac{A_H}{7560}\left(\frac{\sigma}{r}\right)\left[\frac{8 + H}{(2 + H)^7} + \frac{6 - H}{H^7}\right] \quad (2.6.7)$$

For reservoir engineering applications, Born repulsion is therefore not a dominant term in controlling fines release under varying salinity, this role belongs to the EDL repulsion, but it is a necessary component of a physically consistent interaction energy model (Israelachvili, 2010).

2.6.5 Other forces affecting fines migration

Fluid flow through pore spaces generates several forces that can influence the movement of fine particles in the porous medium as shown in Figure 3. These forces are electrical forces (F_e), lift or buoyancy force (F_l), drag force (F_d), and gravity force (F_g) (Sourani et al., 2014).

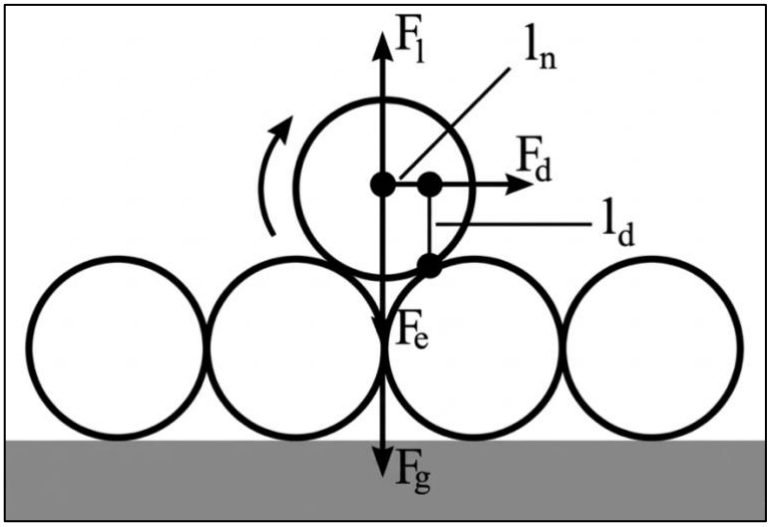


Figure 3. Forces acting on a nano-sized particle because of fluid flow through porous media, (Sourani et al., 2014).

Following formulas 2.6.8, 2.6.9, and 2.6.10 are used to calculate these forces(Sourani et al., 2014).

$$F_d = \frac{\pi \mu \omega r_p U}{\varphi (H - h_c)} \tag{2.6.8}$$

$$F_L = 89.5\, r_p^3 \sqrt{\frac{\rho_w \mu U^3}{(H - h_c)^3}} \tag{2.6.9}$$

$$F_g = \frac{4}{3} \pi r_p^3 g (\rho_p - \rho_w) \tag{2.6.10}$$

where μ is the water viscosity, ω is a proportionality factor ranging from 10 to 60, H and h_c are the height of the pore and the height of particles deposited on the pore wall, respectively, with h_c assumed to represent a single layer of fine particles, that is $2r_p$, U and φ are the fluid velocity

and porosity, respectively, ρ_w is the water density, g is the gravitational constant, and ρ_p is the particle density.

Figure 3 presents the force and torque balance that controls fine particle detachment, including electrical force, drag force, lift or buoyancy force, and gravitational force, and shows how particle deposition and later movement are governed by this balance. Fines migration begins once the detachment forces overcome the attachment forces. A clear understanding of these interactions is important for predicting fine particle behaviour in applications such as sediment transport, oil and gas reservoirs, and filtration processes.

Under low injection-rate conditions, lift force can be neglected because its effect is minor compared with drag force. Thus, the critical flow rate in the DLVO-based model was obtained from a simplified low-rate force balance involving only the principal attachment and detachment forces, equation for which is given below(Dalabayeva et al., 2025; Muneer et al., 2020):

$$v = \left(F_g + F_e\right)\left[\frac{2r_f\left(2r_p - r_f\right)\left(17.75\pi\mu r_f\right)}{r_p^2}\right]^{-1} \tag{2.6.11}$$

2.6.6 Assumptions and limitations

Classical DLVO theory is based on several simplifying assumptions that make it easier to analyze mathematically, but also reduce its quantitative accuracy in real systems. Most importantly, the theory treats both the particles and the liquid between them as continuous and structureless media. The surfaces are assumed to be perfectly smooth, uniform, and infinitely large, while the solvent is considered a uniform dielectric medium described only by its permittivity (Agmo Hernández, 2023; Trefalt & Borkovec, 2014). In this theory, ions in solution are treated as point charges, so their actual size and the steric effects that appear at high ionic concentrations are neglected. The Poisson-Boltzmann equation used for EDL calculation also assumes that ions in the diffuse layer behave independently, meaning that ion-ion correlations are ignored (Agmo Hernández, 2023).

Assumptions mentioned above sometimes not valid for real sandstone cases. Fines typically characterized to have irregular, plate-like shapes rather than the ideal spherical shape assumed in standard DLVO calculations. Their surfaces are also structurally and chemically heterogeneous. Structural heterogeneity arises from the presence of face and edge sites with different charge characteristics, while chemical heterogeneity come from mixed mineral

composition. This behavior is observed in clay minerals such as montmorillonite and kaolinite. Due to isomorphic substitution on their basal planes, they generally carry a permanent negative and charge at their edge sites is pH-dependent (Missana & Adell, 2000). Studies on montmorillonite colloids shows that classical DLVO theory cannot fully explain how stability changes with pH, because this theory does not consider the fact that faces and edges can have opposite charges. As a results particles tend to aggregate even if ionic strength is not considered as controlling factor. Because at low pH attractive interactions are formed between positively charged edges and negatively charged faces (Missana & Adell, 2000).

At reservoir conditions, in addition to the surface charge complexity of clays, some forces may contribute to interactions between a surface and particle. Hydration forces that come from the structured organization of water molecules near hydrophilic surfaces, can produce additional short ranged repulsion that standard EDL terms do not consider (Agmo Hernández, 2023; Israelachvili, 2010). Hydrodynamic forces also provide mechanical driving force for fines detachment. These forces usually arise from because of brine flow through pore throats and must be incorporated into extended models to predict critical flow rates for fines mobilization (Israelachvili, 2010).

Hamaker constant and the surface potential introduces additional uncertainty. Different studies on clay colloids have used Hamaker constants that vary by more than one order of magnitude which alone can produce completely opposite stability predictions (Missana & Adell, 2000). Double layer theory predicts that zeta potential of some clays does not vary with ionic strength, However, significant errors may arise from these predictions if zeta potential is used as approximation of surface potential (Missana & Adell, 2000).

To understand interactions between particle and surface in sandstone reservoirs DLVO theory, despite limitations mentioned above, can provide a useful and widely applied framework. It captures the main mechanism for fines mobilization driven by salinity, especially the balance between the relatively less sensitive van der Waals attraction and the strongly salinity-dependent EDL repulsion, which makes it a practical first-step predictive tool. Later extensions of the theory, including extra interaction forces, non-spherical particle shapes, and hydrodynamic effects, have improved its relevance to real porous media. So the core idea of an energy barrier remains fundamental to quantitative modeling of fines migration and formation damage.

2.7 Key input parameters for DLVO-based CSC prediction

Accurate prediction of the CSC using DLVO theory requires a set of well-characterized input parameters that describe the physical and chemical state of the SFB system. The most important inputs are ionic strength, Debye length, Hamaker constant, zeta potential, particle size, and surface separation distance. Each of these parameters is discussed in following sections.

2.7.1 Ionic strength and Debye length

Debye length is the characteristic distance over which the electric potential of a charged surface decays in the surrounding electrolyte solution. It describes the thickness of the diffuse part of the electric double layer and indicates how far the influence of surface charge extends into the liquid. A larger Debye length means that electrostatic interactions act over a greater distance, whereas a smaller Debye length indicates that the surface charge is screened more rapidly (Agmo Hernández, 2023; Sourani et al., 2014).

This parameter is strongly affected by both ionic strength and ion valence. As shown in Figure 4, as ionic strength increases, the Debye length decreases because a greater number of dissolved ions are available to accumulate near the charged surface and neutralize its electric field. This causes the diffuse layer to become more compressed and reduces the range of electrostatic interactions between the particle and the surface. Ion valence has a similar effect: multivalent ions are more effective than monovalent ions at screening surface charge, and therefore compress the electric double layer more strongly. As a result, solutions containing higher-valence ions generally produce a shorter Debye length and weaker long-range electrostatic repulsion. Consequently, increasing salinity and ion valence both reduce the electric double-layer repulsive force, although under certain low-concentration conditions the interaction may become attractive depending on the electrolyte type and solution chemistry (Agmo Hernández, 2023; Sourani et al., 2014).

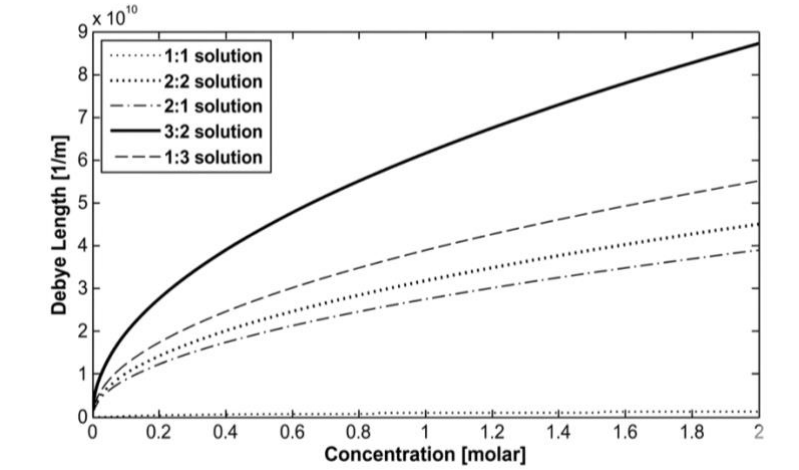


Figure 4. Effect of electrolyte concentration and ion valence on the inverse Debye length (k), (Sourani et al., 2014)

Ionic strength plays an important role in DLVO analysis because it controls the thickness of the electrical double layer and, therefore, the interaction distance between particles. When the distance between fines becomes comparable to or smaller than the Debye length, electrostatic interactions become significant and can influence whether particles remain attached or detach from the surface (Dalabayeva et al., 2025; Muneer et al., 2022; Sourani et al., 2014). In general, van der Waals attraction is more important at very short and very long separation distances, while double-layer repulsion is more influential at intermediate distances. As ionic strength increases, the electrical double layer becomes compressed, reducing the range of repulsive forces. Under such conditions, attractive interactions become more dominant, which can favor particle attachment(Dalabayeva et al., 2025; Sourani et al., 2014; Trefalt & Borkovec, 2014). Ionic strength is commonly calculated as:

$$I = \frac{1}{2}\sum cz^2 \tag{2.6.12}$$

where c is the ion concentration and z is the ion valence(Sourani et al., 2014)(Sourani et al., 2014).

2.7.2 Hamaker constant

The Hamaker constant (A_H) is a parameter that quantifies the strength of the van der Waals dispersion interaction between two bodies and is a fundamental material parameter in DLVO theory. In DLVO theory, it is the constant used to quantify the attractive part of the interaction between particles, or between a particle and a surface. A larger Hamaker constant means

stronger van der Waals attraction. Simple Hamaker approach is defined by Israelachvili (2010) by formula below:

$$A_H = \pi^2 C \rho_1 \rho_2 \quad (2.7.1)$$

where C is the coefficient in the atom–atom London interaction potential, and ρ_1 and ρ_2 are the number densities of atoms or molecules in the two-interacting media.

For most condensed materials, its magnitude is typically in the range of 10^{-20} to 10^{-19} J, although lower values may occur in liquid media and higher values are possible for metals (Israelachvili, 2010). Although the Hamaker constant is often treated as a fixed material parameter in DLVO-based calculations, it may vary with system conditions. For example, Yang et al. (2022) reported that the Hamaker constant that governs van der Waals attraction increases to about 20% when temperature rises from 25 to 129°C for a kaolinite-water-quartz system. However, temperature was not interpreted as a variable in the present study, and all calculations were conducted at ambient temperature. Therefore, the Hamaker constant was treated as unchanged with respect to temperature.

2.7.3 Zeta potential

The zeta potential ζ is the most important variable in DLVO-based CSC prediction, because it enters the EDL energy formula as a squared term in the exponent, making the interaction energy highly sensitive to its value. For silica and kaolinite surfaces in NaCl brines, zeta potential typically ranges from approximately -5 mV at high salinity (> 0.5 M NaCl) to -40 mV or more at low salinity (less than 0.01 M NaCl) and moderate pH (6-8) (Muneer et al., 2022; Walker & Glover, 2018). (Sadeghein et al., 2024) measured zeta potential for kaolinite in low-salinity brine (1,000 mg/L) as -40 mV and in high-salinity brine (250,000 mg/L) as near-zero, demonstrating the pronounced salinity dependence. In the absence of pH adjustment, the zeta potential of quartz in typical reservoir brines (10,000-50,000 ppm NaCl) is around -15 to -25 mV (Nasralla & Nasr-El-Din, 2014).

In mixed brine systems, divalent cations reduce the magnitude of the zeta potential relative to equivalent-ionic-strength monovalent brines, through both EDL compression and specific adsorption (Alarouj et al., 2021). Alarouj et al. (2021) reported that natural formation brines rich in divalent ions produced zeta potentials that were less negative than those obtained with simple NaCl solutions of the same ionic strength, and in some cases positive zeta potentials were recorded for dolomite-bearing samples. For DLVO-based CSC prediction, the zeta

potential must therefore be measured at the specific brine composition relevant to the injection scenario, rather than extrapolated from single-salt measurements (Muneer et al., 2022; Nasralla & Nasr-El-Din, 2014).

2.8 DLVO-based prediction of CSC in sandstone systems

The application of DLVO theory to predict the CSC in sandstone systems has progressed from qualitative mechanistic explanations to quantitative predictive models that are validated against experimental data. The general approach involves: (i) measuring or estimating the zeta potential of the SFB system as a function of ionic strength and brine composition; (ii) measuring or estimating the Hamaker constant for the system; (iii) characterizing the average size of in-situ fines by SEM; (iv) computing the van der Waals, EDL, and Born interaction energies as functions of separation distance for a range of ionic strengths; and (v) identifying the ionic strength at which the total interaction energy transitions from net-negative (attractive-dominated) to net-positive (repulsive-dominated), which is defined as the CSC (Muneer et al., 2020; Muneer et al., 2022).

Muneer et al. (2022) applied this methodology to predict the CSC for four individual salts and several mixed NaCl–$CaCl_2$ brines. Their DLVO models predicted CSC values of 0.11 M (approximately 6,400 ppm) for NaCl, 0.04 M for KCl, and 0.0001 M for both $CaCl_2$ and $MgCl_2$, all in close agreement with experimentally measured values from coreflooding. Overall, these results demonstrate that DLVO modeling can provide a practical and reasonably accurate tool for predicting CSC in sandstone systems when the key input parameters are properly characterized.

2.9 Effect of brine composition on fines stability

Brine composition has a direct influence on stability of fines. As zeta potential value of brine solutions differ from each other based on their composition, brine composition became the target controlling parameter mitigating fines migration. As it was described by Agmo Hernández (2023), Missana & Adell (2000), and Muneer et al. (2022) brine composition strongly affects fines stability in sandstone reservoirs because it controls the electrical double-layer thickness, zeta potential, and the balance between attractive and repulsive surface forces. In DLVO terms, van der Waals attraction remains nearly constant for a given system, while double-layer repulsion changes significantly with electrolyte composition. Therefore, fines stability depends not only on total salinity, but also on the identity of the dissolved ions.

The effect of cations is most important because cation valence strongly influences charge screening. Khilar and Fogler showed that fines migration is highly sensitive to counterion type, with divalent cations stabilizing fines much more effectively than monovalent cations. Divalent ions such as Ca^{2+} and Mg^{2+} compress the electrical double layer more strongly, reduce electrostatic repulsion, and promote particle attachment. Muneer et al. (2022, 2024) confirmed this through DLVO-based prediction, reporting much lower CSC values for $CaCl_2$ and $MgCl_2$ than for NaCl and KCl. However, monovalent cations are not equivalent. Although both Na^+ and K^+ are singly charged, Muneer et al. (2022, 2024) showed that NaCl and KCl produce different zeta potential responses and different CSC values. This indicates that fines stability depends not only on ion valence, but also on specific ion effects. As a result, replacing NaCl with KCl can change the salinity at which fines become unstable and start migration.

The role of anions is less pronounced, but they still contribute to ionic strength and double-layer thickness. In the salt systems most studied for fines migration, chloride is the common anion in NaCl, KCl, $CaCl_2$, and $MgCl_2$. Because the anion is unchanged, most differences in fines stability are mainly attributed to the cation.

Overall, brine composition affects fines stability through ionic strength, charge screening, and surface potential. Previous studies established the difference between monovalent and divalent salts, but mixed monovalent systems remain less explored. For this reason, NaCl/KCl mixtures provide an important basis for improving the understanding and prediction of fines migration in sandstone reservoirs.

2.10 Research gap

Although fines migration in sandstone reservoirs has been studied for decades, important gaps remain in understanding how mixed monovalent brines affect fines stability and critical salt concentration. Early work by Khilar & Fogler (1998) established the CSC concept and showed that fines migration is strongly controlled by brine chemistry, especially ion valence and ionic composition. However, their studies focused mainly on individual salts and the general contrast between monovalent and multivalent systems, while composition-dependent behavior of mixed monovalent brines were not interpreted within their framework.

Later, Muneer et al. (2022, 2024) advanced this field by combining zeta potential measurements, DLVO modeling, and experimental validation to predict CSC in sandstone systems. His work examined individual salts such as NaCl, KCl, $CaCl_2$, and $MgCl_2$, and also

some mixed systems such as $NaCl/CaCl_2$ and $NaCl/MgCl_2$. These studies confirmed that fines stability depends not only on salinity but also on brine composition.

However, pure KCl and NaCl/KCl systems remain studied insufficiently by both experiments and DLVO-based predictions. Muneer et al. (2022) included KCl in DLVO prediction models, but main focus of his work was still individual salts not mixed systems. Previous studies did not develop CSC framework which is dependent on composition for mixtures of NaCl and KCl. CSC for pure KCl system was also not validated by coreflooding experiments. Here underlies the main issue, even though NaCl and KCl are considered as common monovalent salts, their electrostatic behavior were not same. So, its important to experimentally validate CSC for KCl systems and build models that can predict this thresholds for different compositions of NaCl/KCl brines.

3. METHODOLOGY

Accurate prediction of fines migration behavior and reliable estimation of critical salt concentration require combination of experimental measurements and modeling approaches. This chapter presents the materials, sample preparation procedures, experimental methods, and analytical framework used in the present study. It includes rock characterization, brine preparation, zeta potential measurements, machine learning model development, and DLVO-based calculations. These methods were chosen to obtain the main input parameters required for CSC prediction and to provide clear basis for evaluating how brine composition affects fines stability in sandstone systems.

3.1 Characterization of the rock sample

Upper Berea sandstone outcrop core sample was used in the coreflooding experiments. Before the testing, dimensions of the sample and dry weight were measured. The sample had a diameter of 37.38 mm, length of 73.47 mm, and dry weight of 172.42 g.

The pore structure of the sample was characterized using a helium porosimeter. Based on the porosimeter measurements, the pore volume was determined to be 15.94 mL, and porosity was 19.77%.

The sandstone sample used in this study was described using previously reported elemental, mineralogical, and morphological characterization available for the same material. As shown in Table 1, the reported XRF results indicated that the rock is dominated by silicon, with smaller amounts of iron, potassium, aluminum, and calcium. These results confirm the silica-rich nature of the sample. The XRD analysis given in Table 2 showed that quartz is the dominant mineral phase, while kaolinite is present as a minor clay component together with small amounts of metal oxides. This mineral composition is important for fines migration studies as quartz is considered to be the dominant mineral in the rock. Clay minerals such as kaolinite can have effect of surface charge and take a part in particle detachment process during low salinity interactions. Previously reported characterization data from Muneer et al. (2024) were used to support the interpretation of the experimental results obtained in this study.

Table 1. Elemental composition of the sandstone sample from XRF analysis

Element	Concentration (wt %)
Si	64.20
Al	3.62
O	2.02
Fe	12.78
Ca	3.37
K	6.70
Mn	0.37
P	1.05
Cr	2.20
Cl	0.23

Table 2. Mineralogical composition of the sandstone sample determined by XRD

Phase/component	Formula	Reported content
Quartz	SiO_2	87.14 ± 5.0 wt.%
Kaolinite	$Al_2Si_2O_5(OH)_4$	6.41 ± 0.5 wt.%
Aluminium oxide	Al_2O_3	3.97 ± 0.5 wt.%
Iron oxide	Fe_2O_3	1.67 ± 0.3 wt.%
Magnesium oxide	MgO	0.81 ± 0.5 wt.%

Figure 5 presents the previously reported SEM-EDS results for Berea sandstone sample. Based on the results from SEM-EDS, strong oxygen and silicon peaks are the confirmation for the silica rich nature of this sample. While smaller peaks of aluminum, potassium, iron, titanium, and calcium indicate the presence of minor mineral impurities. Results obtained from SEM-EDS were consistent with the mineralogical composition analysis identified from XRF and XRD.

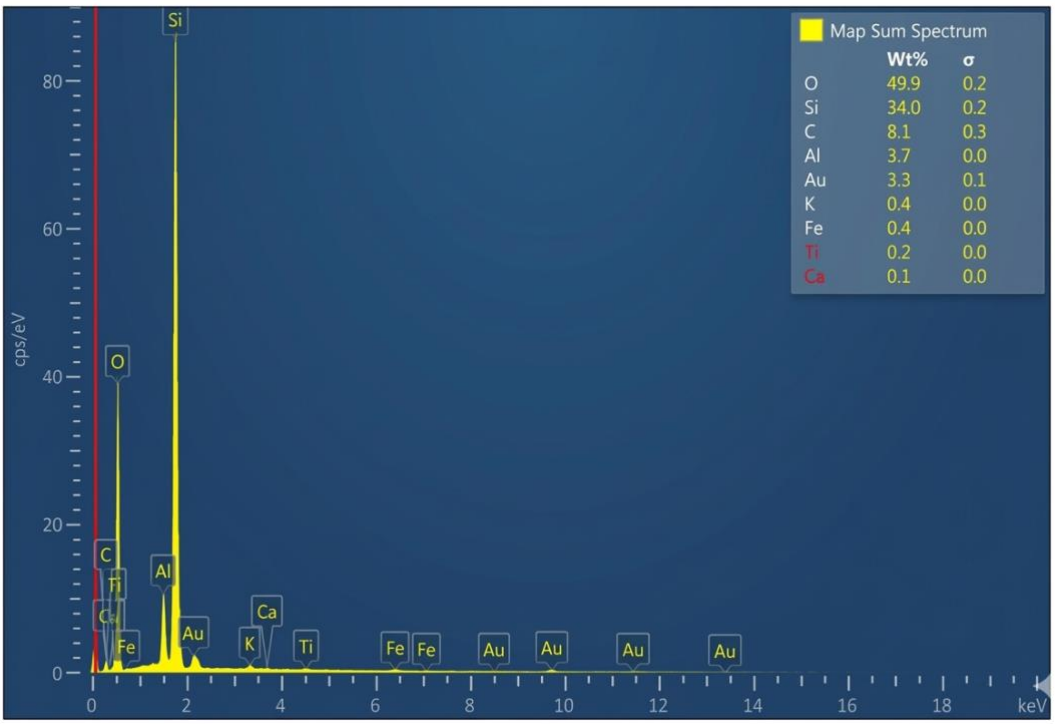


Figure 5. SEM–EDS elemental spectrum of the sandstone sample, (Muneer et al., 2024)

3.2 Brine preparation

Synthetic formation water was prepared for core saturation using reagent-grade salts dissolved in deionized water. The composition of the prepared brine is presented in Table 3 and Table 4. The final solution had a total dissolved salt concentration of 76.96 g/L, corresponding to a salinity of 76,955 ppm.

Table 3. Salt recipe used for preparation of synthetic formation water

Salt	Formula	Mass added (g/L)
Sodium chloride	$NaCl_3$	59.55
Calcium chloride dihydrate	$CaCl_2 \cdot 2H_2O$	12.32
Magnesium chloride hexahydrate	$MgCl_2 \cdot 6H_2O$	10.86

Table 4. Ionic composition of synthetic formation water used for core saturation

Ion	Concentration (ppm)
Na^+	23426
Ca^{2+}	4448
Mg^{2+}	1300
Cl^-	47781

To determine the critical salt concentration (CSC) for the SFB system, at which fines migration initiates, brines of different salinities were prepared so that it exceeds CSC. According to Muneer et al. (2024), CSC for KCl based on machine learning prediction is about 0.04 M. Salinity range for this work was chosen based on this prediction. Salinities of injection brines were selected in a range between 0.2 M KCl and in decreasing concentration order till 0.01 M.

To prepare different salinity KCl brines reagent grade KCl was dissolved in distilled water by using magnetic stirrer. Table 5 shows amounts of reagent grade KCl needed to prepare specific brine salinities in 1 liter volume.

Table 5. Composition of KCl brines prepared at different salinities

Brine (M)	KCl mass (g/L)	K^+ (ppm)	Cl^- (ppm)	Total Salinity (ppm)
0.20	14.91	7820	7093	14910
0.15	11.18	5865	5320	11185
0.10	7.46	3910	3547	7457
0.07	5.22	2737	2483	5220
0.04	2.98	1564	1419	2983
0.03	2.23	1172	1064	2236
0.02	1.49	782	709	1491
0.01	0.75	391	355	746

3.3 Zeta potential measurements

In the present study, zeta potential measurements were carried out to generate the input data required for predicting the critical salt concentration (CSC) of mixed NaCl/KCl brine systems. Although a CSC value for the 100% NaCl case was available from previous work presented in Muneer et al. (2024), comparable surface charge data for intermediate salt compositions were not available in the literature. To address this gap, zeta potential measurements were performed for Berea sandstone in 80/20, 50/50, and 20/80 NaCl/KCl mixtures over a range of salinities. Obtained results were used as the basis for machine learning-assisted estimation and DLVO modelling. This allowed the development of a clearer composition dependent picture of CSC across different NaCl/KCl ratios.

3.3.1 Preparation of sandstone powder for zeta potential measurement

For zeta potential measurements, the Berea sandstone core sample was first mechanically reduced to fine powder. The rock was first crushed using a jaw crusher to obtain smaller particles. These particles were then further milled by using a disk mill, which was followed by additional size reduction in a mixer mill to produce finer particles. Obtained finer particles then sieved using a 40 μm sieve placed on a sieve shaker, and the portion with particle size smaller than 40 μm was collected for further cleaning and zeta potential analysis.

The collected sandstone powder was then chemically cleaned before the measurement to remove surface impurities and residual contaminants. Powder with size less than 40 μm was divided into portions of approximately 2.1 g and then transferred into 50 mL Falcon tubes. Each portion was treated with approximately 30 mL of 0.1 M HCl that was prepared by diluting 33% hydrochloric acid to the required concentration. Approximately for 20-30 minutes these suspensions were manually mixed to allow full acid contact with particle surface.

After manual mixing, suspensions treated with acid were centrifuged at 6000 rpm for 10 minutes. Then supernatant was decanted, and tubes were filled with distilled water. Particles were resuspended by gentle inversion, which is followed by centrifugation and decanting. This washing procedure was repeated eight times until the pH of supernatant reached neutral pH of 6.8, which was verified by pH meter. During decanting after pH verification, a small residual liquid layer was intentionally left in the tube to minimize the loss of fine particles during drying process. Following the final washing step, cleaned samples with small liquid layer left were dried in an oven at 50-60°C for 12 hours with the tube caps removed. The dried powder was then collected, and further used for preparation of particle suspensions for zeta potential measurements.

3.3.2 Brine preparation for zeta potential measurement

For zeta potential measurements, mixed NaCl/KCl brines were prepared at molar ratios of 80/20, 50/50, and 20/80. Two stock solutions, 0.2 M NaCl and 0.2 M KCl, were first prepared separately in 1 L volumes using deionized water. The required brine solutions were obtained by volumetric dilution of the stock solutions to a final volume of 30 mL. For each composition, brines were prepared at total salinities of 0.01, 0.02, 0.03, 0.04, 0.07, 0.10, 0.15, and 0.20 M. The volumes of NaCl stock solution, KCl stock solution, and deionized water that were used for each preparation are given in Table 6.

To prepare sandstone particle suspensions in the brine solutions, an initial solid concentration of 0.033 wt% was used, equal to 0.01 g of sandstone powder in 30 mL of brine. However, signal quality obtained at at this concentration was low, which indicated that the particle concentration was too low for reliable detection by the Zetasizer. Therefore, the solid loading was increased to 0.05 wt % (0.015 g in 30 mL) in order to obtain stable and measurable suspensions for zeta potential analysis. For reproducibility, zeta potential measurements for each condition were repeated at least four times, and the average value was used for further analysis. Malvern Zetasizer Nano ZS shown in Figure 6 was used to perform zeta potential measurements in these experiments.

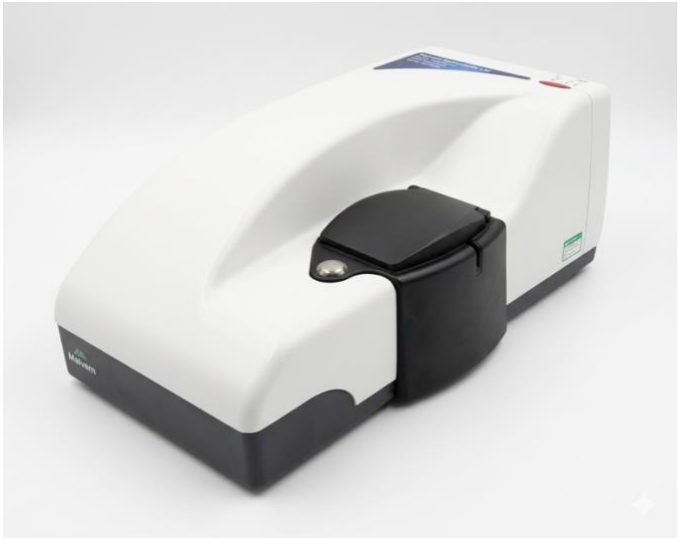


Figure 6. Malvern Zetasizer Nano ZS used for zeta potential measurements

Table 6. Volumes of stock solutions used for preparation of NaCl/KCl brines at different salinities

Composition (NaCl/KCl, molar)	Total salinity (M)	NaCl stock (mL)	KCl stock (mL)	DI water (mL)	Final volume (mL)
80/20	0.01	1.2	0.3	28.5	30
80/20	0.02	2.4	0.6	27	30
80/20	0.03	3.6	0.9	25.5	30
80/20	0.04	4.8	1.2	24	30
80/20	0.07	8.4	2.1	19.5	30
80/20	0.1	12	3	15	30
80/20	0.15	18	4.5	7.5	30
80/20	0.2	24	6	0	30

50/50	0.01	0.75	0.75	28.5	30
50/50	0.02	1.5	1.5	27	30
50/50	0.03	2.25	2.25	25.5	30
50/50	0.04	3	3	24	30
50/50	0.07	5.25	5.25	19.5	30
50/50	0.1	7.5	7.5	15	30
50/50	0.15	11.25	11.25	7.5	30
50/50	0.2	15	15	0	30
20/80	0.01	0.3	1.2	28.5	30
20/80	0.02	0.6	2.4	27	30
20/80	0.03	0.9	3.6	25.5	30
20/80	0.04	1.2	4.8	24	30
20/80	0.07	2.1	8.4	19.5	30
20/80	0.1	3	12	15	30
20/80	0.15	4.5	18	7.5	30
20/80	0.2	6	24	0	30

3.4 Machine learning model development

A literature-based dataset was compiled to support the machine learning analysis of zeta potential behavior in KCl brines. Since zeta potential for the 100% KCl system was not measured experimentally in this study, machine learning was used to predict its behavior based on data collected from published literature. The collected raw dataset contained 105 data points, with each record consisting of temperature, salt type, salinity, pH, type of media, and zeta potential. Because the data were collected from different sources, before the analysis all variables were first standardized into consistent units. Temperature values were converted to °C, salinity values to ppm, and zeta potential values were recorded in mV. This standardization to same unit makes the data points from different publications and experimental conditions comparable and uniform.

The initial dataset covered a relatively broad range of conditions. Temperature values ranged from 22 to 25°C, salinity values ranged from very low conditions up to approximately 407000 ppm, and pH values ranged from 0.91 to 8.99. Four different types of media such as sandstone, glass beads, borosilicate, and artificial ceramic were represented in the collected data. However, as the objective of the present study was to model the zeta potential behavior of sandstone particles relevant to fines migration, data collected for non-sandstone media were excluded from the analysis.

A large number of literature data points were excluded during preprocessing because the present study focused specifically on zeta potential behavior in sandstone media under conditions relevant to Berea sandstone. So only data corresponding to sandstone systems were remained, while measurements obtained for other media were removed. In addition, only KCl brine conditions were considered and data points for NaCl were removed during this stage. This was done since these were the most consistent with the assumptions and target conditions of the present study. This filtering reduced the size of the dataset but improved its relevance and consistency for model development.

After media-based filtering, the dataset was then cleaned to remove points considered unsuitable for the present study. This preprocessing step included the removal of outliers and data points that are considered to be unreliable or not representative of Berea sandstone. As a result, the final dataset used for model development consisted of 37 sandstone data points, which were considered the most relevant and reliable for the present study. They were reliable in all terms considering media type, salinity range, brine type, ph and temperature.

The cleaned dataset was then used for machine learning model development. The selected input parameters were temperature, salinity, and pH, target output was zeta potential. Before the training, the final dataset was randomly divided into training and testing groups. 80% of the data used for training and the remaining 20% used for testing. Approximately 30 data points were used for training and 7 data points were used for testing. This split made it possible to fit the model using the larger group, while keeping a separate part of the data for evaluating predictive performance.

Several machine learning regression models were tested to identify the most suitable model for predicting zeta potential from the cleaned sandstone dataset. The models evaluated included Linear Regression, Decision Tree (DT), TAB M, Random Forest (RF), Support Vector Regression (SVR), Gradient Boosting Regressor (GBR), XGBoost, and CatBoost. Their performance was assessed using the coefficient of determination (R^2) and root mean square error (RMSE) across the cross-validation, training, and testing datasets. TAB M was selected to predict zeta potential values for this study as it delivered relatively good performance without pronounced overfitting and also offered a simple, stable, and physically interpretable relationship between zeta potential and salinity. Based on this and taking both predictive performance and interpretability into account, TAB M was used to generate the zeta potential values required for constructing the DLVO model.

3.5 DLVO modeling

3.5.1 Input data and parameters used

The low-rate DLVO model applied in this study followed the approach used by Muneer et al., (2024) and Dalabayeva et al., (2025). Physicochemical constants were kept constant: fluid temperature, Boltzmann constant, dielectric constant of water, vacuum permittivity, electron charge, Avogadro's number, and atomic collision diameter were kept unchanged. For each NaCl/KCl brine case, the varying inputs were the brine salinity, ionic strength, Debye length, and zeta potential. Debye length was not treated as a fixed constant; instead, it was calculated separately for each brine case from the corresponding ionic strength, since the thickness of the electrical double layer varies with electrolyte concentration. Since the studied systems consisted only of monovalent salts, the main effect of changing NaCl/KCl proportion was reflected through recalculated ionic strength and experimentally determined zeta potential values, while the remaining constants were kept fixed.

The constant parameters used in the low-rate DLVO model are given in Table 7.

Table 7. Input parameters used for low-rate DLVO modeling

Constant parameters	Symbol	Value	Unit
Particle radius	ap	450	nm
Fluid temperature	T	298.15	K
pH of solution	pH	7	-
Boltzmann constant	k_B	1.38E-23	JK^{-1}
Hamaker constant	A_H	1.52E-20	J

Dielectric constant for water	ε_m	80	-
Vacuum permittivity	ε_o	8.85E-12	Fm^{-1}
Electron charge	e	1.60E-19	C
Avogadro's number	N_A	6.02E+23	mol^{-1}
Pi	π	3.1416	-
Atomic collision diameter	σ	5.00E-10	m
pH of the system	pH	7	-

3.6 Coreflooding procedure

Core flooding experiments were conducted using the CFS series core flood system by Vinci technologies, specifically CFS 700 core flooding system, which is designed to perform single-phase and multiphase flow studies under controlled pressure and temperature conditions representative of subsurface reservoirs. Scientific diagram of the core flooding system used for carrying out core flooding experiments is shown in Figure 7. In this study, the system was used specifically to investigate the effect of KCl brine salinity on fines migration in sandstone core samples and to determine the critical salt concentration (CSC). The apparatus allows accurate control of injection conditions, including flow rate, confining pressure, and backpressure, while continuously monitoring the system response during flooding.

All experiments were performed at an ambient laboratory temperature of 24°C, with the confining pressure maintained at 1000 psi and the backpressure fixed at 300 psi. Since the previously determined critical flow rate for fines migration was 2 cc/min, the brine was injected lower constant rate was chosen for coreflooding experiments, 1 cc/min was injection rate selected for all tests. This low injection rate was selected to avoid flow rate as a triggering factor for fines detachment and migration. As a result, brine salinity was the main variable affecting the system during the experiment, so it makes it possible to evaluate the effect of salinity reduction on fines mobilization more clearly.

Step-by-step salinity reduction was chosen as injection strategy for KCl brines for coreflooding experiments. The experiment began with injection of 0.20 M KCl to determine initial conditions and collect in-situ fines as a baseline. Then, the salinity was step-by-step reduced in several stages. At each stage, the core sample was contacted with the selected brine concentration and then soaked for 1 hour before the next injection step. Soaking period provided enough time for interaction between the rock surface, attached fines, and the injected brine before further salinity reduction. Such a procedure made it possible to observe the onset of fines migration under progressively less saline conditions and to identify the concentration range at which the

rock-brine system became unstable. The detailed step-by-step flooding procedure used in this study is presented in the Table 8 below.

Table 8. Experimental core flooding sequence for evaluation of CSC using KCl brine

Constant rate from 0.2 M till 0.01 M	Collect in-situ fines (baseline)
1	0.20 M KCl → 1 hour soaking → 0.15 M KCl
2	0.15 M KCl → 1 hour soaking → 0.15 M KCl
3	0.10 M KCl → 1 hour soaking → 0.10 M KCl
4	0.07 M KCl → 1 hour soaking → 0.07 M KCl
5	0.04 M KCl → 1 hour soaking → 0.03 M KCl
6	0.03 M KCl → 1 hour soaking → 0.02 M KCl
7	0.02 M KCl → 1 hour soaking → 0.1 M KCl

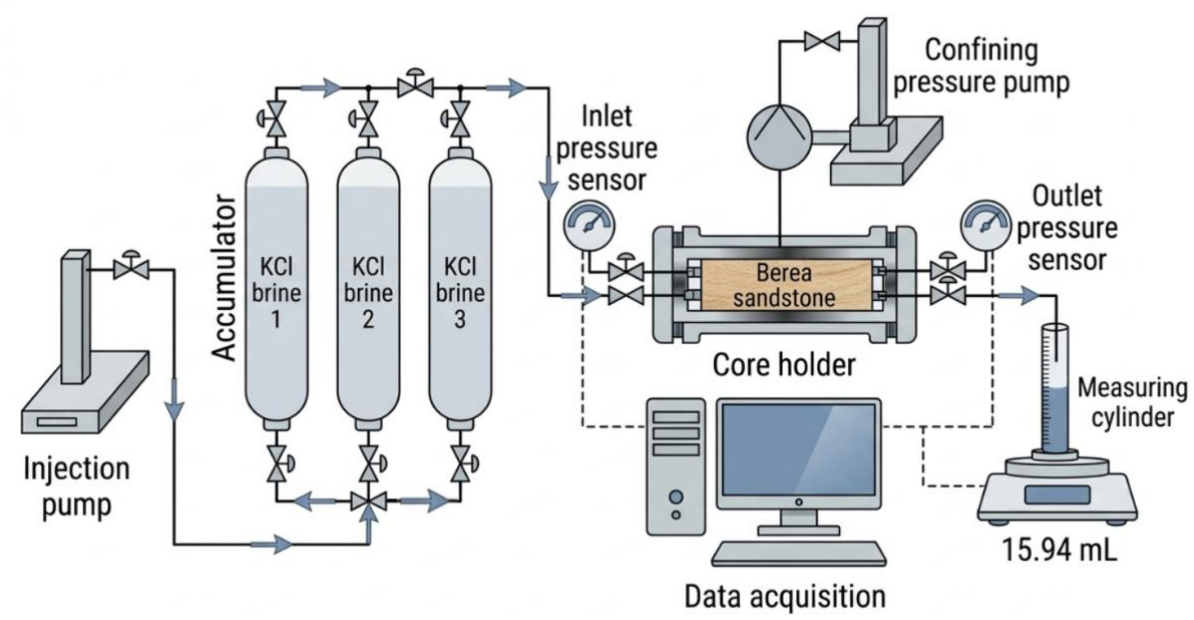


Figure 7. Scientific diagram of the coreflooding system (CFS 700) used to perform coreflooding experiments

3.7 Effluent turbidity analysis

Ultraviolet-Visible (UV-Vis) spectroscopic analysis was performed on the effluent samples collected after each coreflooding experiment in order to identify the salinity at which fines migration was initiated. A Thermo Scientific Evolution 300 UV-Vis spectrophotometer was used for this purpose. The instrument is equipped with a xenon flash lamp, silicon photodiode detectors with an extended wavelength range up to 1100 nm, and a stable optical design suitable for routine quantitative analysis. It can be operated through local or PC control and is supported

by VISION software for data collection, storage, and analysis. For each of the 8 coreflooding experiments, 3 pore volumes (PV) of effluent were collected and analyzed. Prior to sample measurement, a baseline test was conducted using distilled water, since all brine solutions were prepared by dissolving salts in distilled water. To ensure that measured absorbance is mainly due to suspended fines in tested effluent samples, baseline test was entered as a reference sample. Absorbance results from UV-Vis for different samples were then collected for further analysis to determine the salinity at which possible fines migration started. Figure 8 shows the UV-Vis spectrophotometer used to provide experiments.

Figure 8. Thermo Scientific Evolution 300 UV-Vis spectrophotometer used for effluent sample analysis

4. RESULTS&DISCUSSION

To have reliable interpretation of fines migration behavior prediction alone is not enough. Modelled trends must be validated by experimental analysis. This section presents the main results obtained from zeta potential measurements, machine learning analysis, and DLVO modeling. It discusses the variations of zeta potential with salinity and brine composition obtained from Mavern Zetasizer, performance of the selected predictive model for ML, resulting CSC values obtained from DLVO calculations, and results from coreflooding experiments that validate predictions from DLVO Model. Obtained results were analyzed to evaluate fines stability and to understand how changes in brine composition affect the risk of formation damage in sandstone reservoirs.

4.1 DLVO-based prediction of CSC for the KCl system

4.1.1 Zeta potential prediction for KCl brines

A comparative analysis was performed to evaluate the predictive ability of several machine learning models for zeta potential estimation. Linear Regression (LR), Decision Tree (DT), Random Forest (RF), Support Vector Regression (SVR), Gradient Boosting Regressor (GBR), XGBoost, CatBoost, LightGBM, and TabM. Model performance was assessed using cross-validation, training, and testing metrics, specifically the coefficient of determination (R^2) and root mean square error (RMSE). Among all evaluated models, TabM showed the strongest predictive performance, achieving CV R^2 of 0.6457, training R^2 of 0.8801, and test R^2 of 0.6983. In addition, it produced a training RMSE of 5.0803 mV and a test RMSE of 7.7931 mV, indicating the lowest prediction error on new data among the tested models. Although some tree-based models achieved very high training accuracy, their clearly lower test performance indicated overfitting. In contrast, TabM provided a more favorable balance between model fit and generalization, which made it the most suitable model for the present dataset.

Since zeta potential is a critical input parameter in DLVO modeling, the accuracy of its prediction directly affects the reliability of the calculated interaction energy profiles. Therefore, the zeta potential values predicted by the best-performing TabM model were selected for the subsequent DLVO calculations. These predicted values were used as input in the electrostatic component of the DLVO model to examine fines-surface interactions and to support the

estimation of critical salt concentration under different brine compositions and salinity conditions. The zeta potential values predicted by TabM are presented in the Table 10 below.

Table 9. Performance comparison of machine learning models for zeta potential prediction

Model	CV_R2	Train_R2	Train_RMSE	Test_R2	Test_RMSE
LinearRegression	0.2224	0.3405	11.9158	0.6273	8.6617
DT	0.2981	0.9951	1.0253	0.2208	12.5232
RF	0.6443	0.9625	2.8404	0.3495	11.4428
SVR	-0.0331	0.2288	12.8856	0.3586	11.3620
XGBoost	-0.0609	0.9951	1.0253	0.6519	8.3705
CatBoost	0.3456	0.9918	1.3277	0.2934	11.9258
TAB M	0.6997	0.8801	5.0803	0.6983	7.7931
GBR	0.3098	0.9948	1.0581	0.2279	12.4664

Table 10. Predicted zeta potential values from Tab M

Salinity	TabM_Predicted
0.01	-49.94
0.015	-40.71
0.02	-30.79
0.025	-25.65
0.03	-23.36
0.035	-19.99
0.04	-18.21
0.045	-16.84
0.05	-15.77
0.055	-14.95
0.06	-14.34
0.065	-14.01
0.07	-13.98
0.1	-14.35
0.15	-14.71
0.2	-15.01

4.1.2 DLVO interaction energy profiles for the KCl system

To predict zeta potential values for a range of salinities for KCl brines machine learning approach was used. Among all evaluated models Tab M showed the best performance, and its predicted values for zeta potential were used to construct DLVO Model for 100% KCl brine case. All input parameters that were used to construct DLVO Model were listed in section 3.5.1.

Figure 9 shows the total interaction energy profiles calculated by the DLVO model for the 100% KCl system over a range of brine salinities. In these profiles, negative interaction energy represents net attraction between the fine particle and the rock surface, meaning that fines are

likely to remain attached. In contrast, positive interaction energy represents net repulsion, indicating that fines may become unstable and detach from the surface. Therefore, the salinity at which the interaction energy begins to shift from negative to positive is important, because it marks the condition at which fines migration may start.

Based on constructed model as shown in Figure 9, at 0.03 M brine case, the DLVO calculations showed that the total interaction energy shifted from the negative region to the positive region as the separation distance increased by indicating the dominance of repulsive forces in this system. At this salinity, the calculated Debye length was 1.77×10^{-9} m, indicating an expansion of the electrical double layer compared with higher-salinity systems. Although van der Waals attraction remained dominant at very short separation distances, the electrostatic double-layer repulsion increased with distance and eventually overcame the attractive forces. As a result, the total interaction energy became positive at a separation distance of approximately 1.40 nm, where overall interaction energy between the fine particle and the rock surface changed from -0.815 to +0.483. This transition indicates the formation of an energy barrier in the system and suggests that fines detachment or migration could occur under these conditions.

The behavior observed at 0.03 M therefore reflects a system in which the lower ionic strength causes double-layer expansion and increases the repulsive interaction between the fines and the rock surface. With a predicted zeta potential of -23.36 mV, the repulsive contribution became sufficiently strong to offset the London-van der Waals attraction, which results in a net positive interaction energy. This positive energy region is typically interpreted as favorable for fines release, as attractive adhesion between particles and the pore surface becomes weaker. So, DLVO results for the 0.03 M system suggest that this salinity lies in the region where fines migration may be initiated.

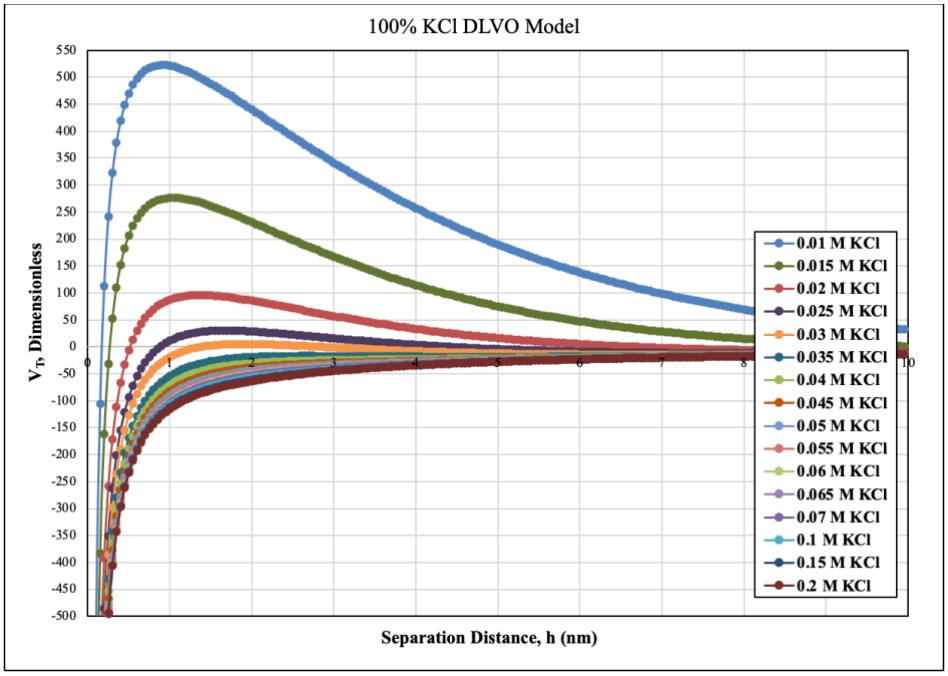


Figure 9. DLVO interaction energy profiles for the KCl–sand system at different salinities

4.2 Coreflooding validation of the predicted CSC for KCl

4.2.1 UV-Vis absorbance results

The UV-Vis absorbance measurements of the effluent samples collected at each salinity step directly indicate the amount of suspended fines released from the core during the coreflooding experiment. Because absorbance is proportional to effluent turbidity, a higher absorbance at a given salinity step means that more fine particles were mobilized and transported to the core outlet.

Figure 11 presents the UV-Vis absorbance results of the effluent samples collected at each salinity step during the coreflooding experiments. The measured absorbance values were 0.463 at 0.20 M KCl, 0.609 at 0.15 M, 0.186 at 0.10 M, 0.281 at 0.07 M, and 0.064 at 0.04 M. Below this point, absorbance increased sharply to 1.321 at 0.03 M, 1.519 at 0.02 M, and 1.708 at 0.01 M. So, results show that there is relatively low absorbance values at salinities from 0.20 to 0.04 M, which was followed by strong increase between 0.04 and 0.03 M KCl.

At high salinity values of 0.20 M and 0.15 M KCl, moderate absorbance values of 0.463 and 0.609 were measured, respectively. Values considered to be moderate, the reason for that can be the release of small amount of loosely attached in-situ fines. This can be considered as baseline fine production at the initial stages, so there is no reason to say that these salinities represent the CSC for this system. At 0.10 M and 0.07 M KCl, the absorbance values dropped

to 0.186 and 0.281, which supports previous statement, and proves system's stability in these ranges of salinities.

Clear shift in absorbance is observed at 0.04 M KCl, where the absorbance dropped strongly to 0.064, the lowest recorded value in the entire experiment. This low reading indicates that only a small amount of fines was present in suspension during 0.04 M flooding, which means that the system remained stable and the particles stayed attached. Major change occurred below this value. The absorbance increased to 1.321 at 0.03 M KCl and continued to rise to 1.519 at 0.02 M and 1.708 at 0.01 M. Clear increase in effluent turbidity strongly suggests that fines migration began within this salinity range of at or below 0.03 M.

This agrees with the behavior predicted by DLVO theory, according to which fines remain attached to pore surfaces when attractive van der Waals forces dominate. When salinity is reduced, electrostatic double-layer repulsion increases, and once it becomes strong enough to generate a net positive interaction energy, fines become destabilized (Muneer et al., 2020; 2022). The sharp transition in absorbance between 0.04 M and 0.03 M KCl identifies the beginning of chemically induced fines detachment in the KCl system and places the CSC in the range 0.03 M < CSC < 0.04 M.

Table 11. UV-Vis absorbance results

Salinity, M	Absorbance, a.u
0.01 M KCl	1.708
0.02 M KCl	1.519
0.03 M KCl	1.321
0.04 M KCl	0.064
0.07 M KCl	0.281
0.1 M KCl	0.186
0.15 M KCl	0.609
0.2 M KCl	0.463

4.2.2 Pressure drop behavior /observed onset of fines migration

Pressure drop across the core is a macroscopic indicator of permeability change and serves as a complementary diagnostic for fines migration. When fine particles detach from pore surfaces and move through the pore network, they can accumulate at pore throats and cause partial or complete blockage. As a result, more pressure is needed to maintain a constant flow rate (Muecke, 1979; Bedrikovetsky et al., 2011).

At high salinities (0.20 M KCl) relatively low pressure drop of 1.2 psi was recorded, which is consistent with a stable core with good permeability. As salinity was reduced to 0.15 M, the pressure drop increased slightly to 2.5 psi, and to 2.4 psi at 0.10 M KCl. These relatively small values suggest that slight pore-throat bridging or compaction may have occurred, but overall permeability was still not significantly affected.

At 0.07 M KCl, the pressure drop remained at 4.1 psi, while values of 4.6, 4.3, 4.4, and 4.2 psi were recorded at 0.04, 0.03, 0.02, and 0.01 M KCl, respectively. The observation that pressure drop was already elevated at 0.04 M, despite the UV-Vis data showing near-zero absorbance at this salinity is significant. This observed difference may be explained by the possibility that some early-stage fines detachment occurred at 0.04 M and caused local pore-throat bridging, but not enough fines reached the outlet to produce measurable turbidity in the effluent. Such internal trapping of mobilized fines without breakthrough is a common during coreflooding experiments (Zeinijahromi et al., 2013).

The continued rise in pressure drop above 0.04 M, together with the strong increase in effluent absorbance at 0.03 M, indicates that the CSC is possibly between 0.03 M and 0.04 M KCl. The pressure drop trend is consistent with the UV-Vis data, and both results indicate that fines migration began within this salinity interval. This also agrees with the classical description of formation damage caused by fines migration, where permeability decreases after the critical salt concentration is exceeded and particles start to detach from rock surface (Khilar & Fogler, 1984; Muneer et al., 2022).

Table 12. Pressure drop analysis

Salinity, M	Pressure drop, psi
0.01 M KCl	4.2
0.02 M KCl	4.4
0.03 M KCl	4.3
0.04 M KCl	4.6
0.07 M KCl	4.1
0.1 M KCl	2.4
0.15 M KCl	2.5
0.2 M KCl	1.2

4.2.3 Verification of DLVO-predicted CSC

The DLVO model constructed for the 100% KCl system using machine-learning-predicted zeta potential values indicated that the total interaction energy transitioned from net-negative (attractive-dominated) to net-positive (repulsive-dominated) at a salinity of 0.03 M. At this concentration, the Debye length was calculated to be 1.77×10^{-9} m, and the predicted zeta potential was -23.36 mV. The total interaction energy changed sign at a separation distance of approximately 1.40 nm, where it shifted from -0.815 to +0.483 indicating the formation of a repulsive energy barrier sufficient to promote fines detachment. The DLVO model therefore predicted a CSC of 0.03 M for the 100% KCl system.

The coreflooding experiments placed the experimental CSC in the range 0.03 M < CSC < 0.04 M, based on the combined evidence from UV-Vis absorbance and pressure drop data.

Average pressure drop results are given in Figure 10. Pressure drop graph shows two clear trends, first trend shows increasing pressure drop, which can be associated with the onset of fines release and partial pore throat plugging. The second is a region of continuously high pressure drop, showing continuous fines transport and blockage in the porous medium.

Average absorbance results obtained from UV-Vis analysis is shown in Figure 11. The absorbance profile shows two clear trends. The first trend, observed from 0.20 to 0.04 M KCl, is a general decrease in absorbance, indicating that the amount of suspended fines remained low and the system was relatively stable over this salinity range. The second trend observed below 0.04 M KCl shows a significant increase in absorbance, which shows continuous fines production and increasing effluent turbidity as salinity decreased. This change between 0.04 M and 0.03 M suggests the start of chemically induced fines migration and places the CSC in the range between 0.03 and 0.04 M KCl. This behavior is consistent with DLVO theory, which says that decreasing salinity increases electrostatic repulsion and leads to fines detachment once it reaches the critical value.

The lower limit of 0.03 M corresponds to the point at which both increased effluent turbidity and a clear rise in pressure were clearly observed. 0.04 M represents the transition stage where the pressure drop started to increase before any measurable fines were observed in the effluent. Therefore, the modeled value of 0.03 M shows close agreement with the experimentally identified range of 0.03-0.04 M and falls within the experimental uncertainty .

The close correspondence between the DLVO prediction and the experimental result validates both the machine learning zeta potential prediction step and the DLVO modeling framework as applied to pure KCl brines. It also confirms that the critical transition in fines stability for KCl-based injection water in Berea sandstone occurs at lower salinity than for NaCl (0.03 M versus 0.11 M), a difference that has direct implications for injection water design in sandstone reservoirs.

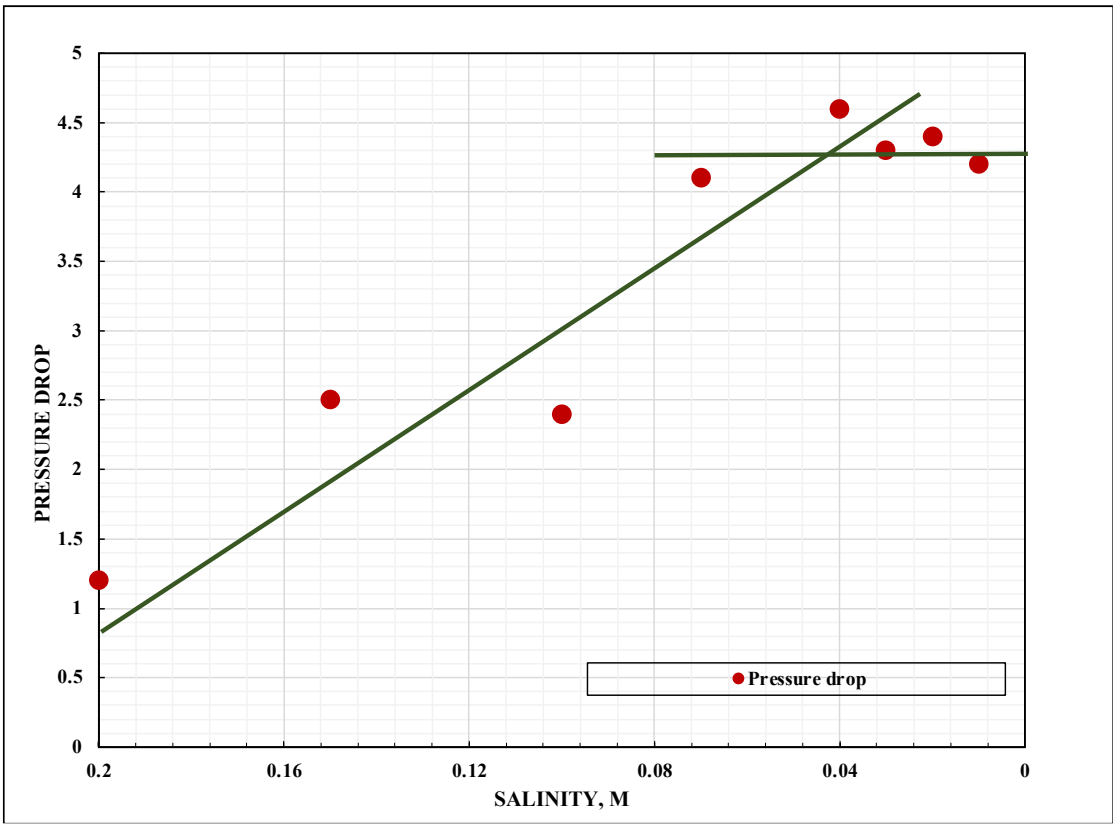


Figure 10. Pressure drop results obtained from coreflooding (CFS 700)

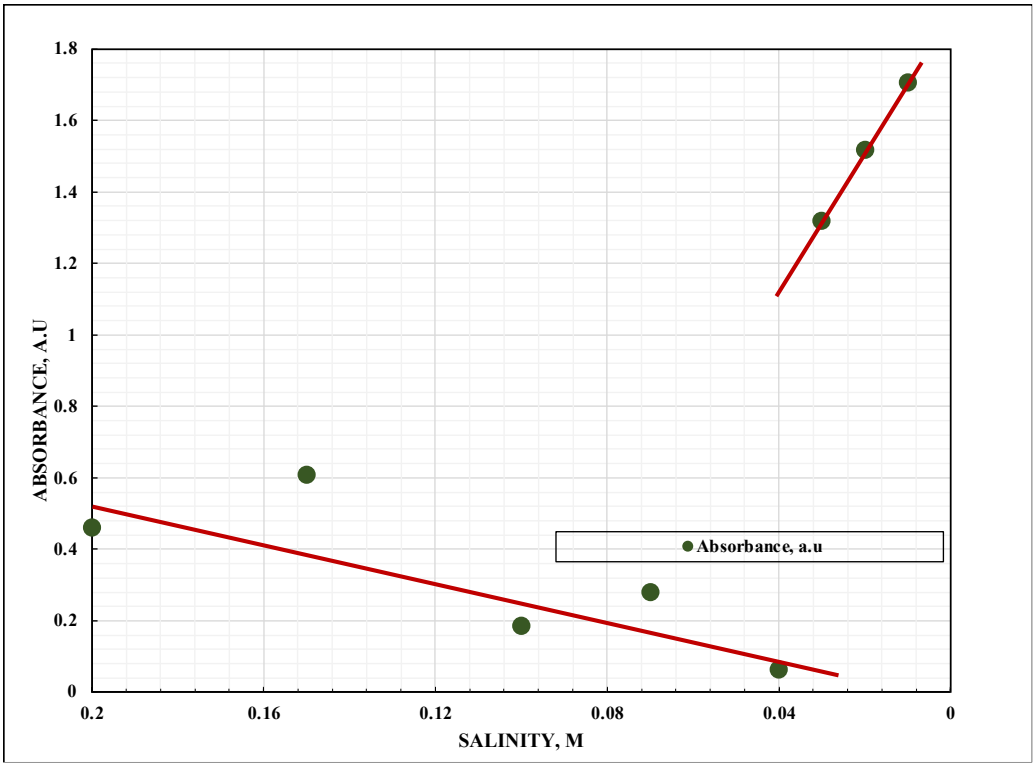


Figure 11. UV-Vis absorbance results

The close agreement (which shows 14.3% error) between the DLVO-predicted CSC and the experimentally observed CSC for the 100% KCl system verifies the validity of the modelling approach used in this study. The model predicted a CSC of 0.03 M, while coreflooding and UV-Vis results showed that fines migration began in the range between 0.03 and 0.04 M KCl. This agreement indicates that the model is sufficiently accurate for describing fines stability under the investigated conditions. So, validated model can be applied to mixed NaCl/KCl brine systems, where direct experimental verification was not performed for every composition. In this way, the model provides a practical tool for estimating CSC values across different NaCl/KCl ratios.

4.3 Application of the DLVO approach to NaCl/KCl mixed-brine systems

4.3.1 Experimental zeta potential results for mixed systems

Due to the lack of data in the literature for NaCl/KCl mixtures Machine Learning method was unable to predict CSC. For this reason, zeta potential measurements were carried out experimentally for the NaCl/KCl mixtures used in the present study. The zeta potential results obtained for the NaCl/KCl brine systems indicate a clear effect of salinity on the electrostatic behavior of the sand-brine system. In general, the zeta potential values became less negative with increasing salinity, which indicates progressive compression of the electrical double layer

at higher ionic strength. Following Figure 12 present experimentally measured zeta potential values that were used as input parameters in the low-rate DLVO model.

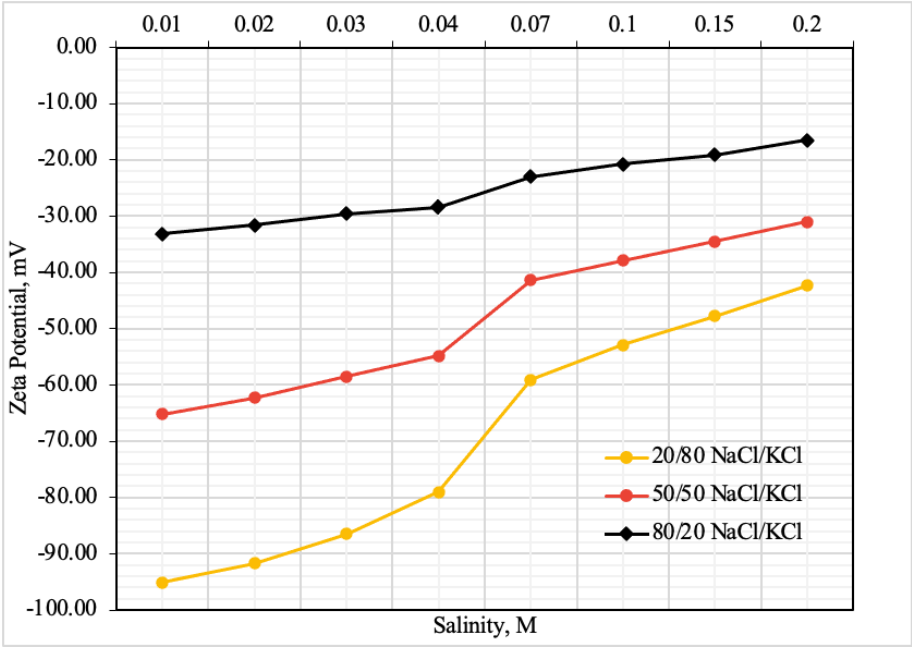


Figure 12. Zeta Potential for different compositions of NaCl/KCl obtained from Malvern Zetasizer

Figure 12 shows that both salinity and brine composition affected the zeta potential of the sandstone-brine system. For all investigated NaCl/KCl mixtures, the zeta potential became less negative with increasing salinity, which is consistent with the expected compression of the electrical double layer at higher ionic strength. In addition to salinity, the NaCl/KCl ratio also had a clear influence on surface charge behavior. The 20/80 NaCl/KCl system showed the most negative zeta potential values over the whole salinity range, followed by the 50/50 mixture, while the 80/20 system showed the least negative values. This indicates that increasing the KCl fraction made the surface charge more negative and therefore increased electrostatic repulsion between fines and the sandstone surface. Since zeta potential is a key input parameter in DLVO-based fines migration analysis, this trend suggests that KCl-rich systems are more prone to fines detachment at lower salinities.

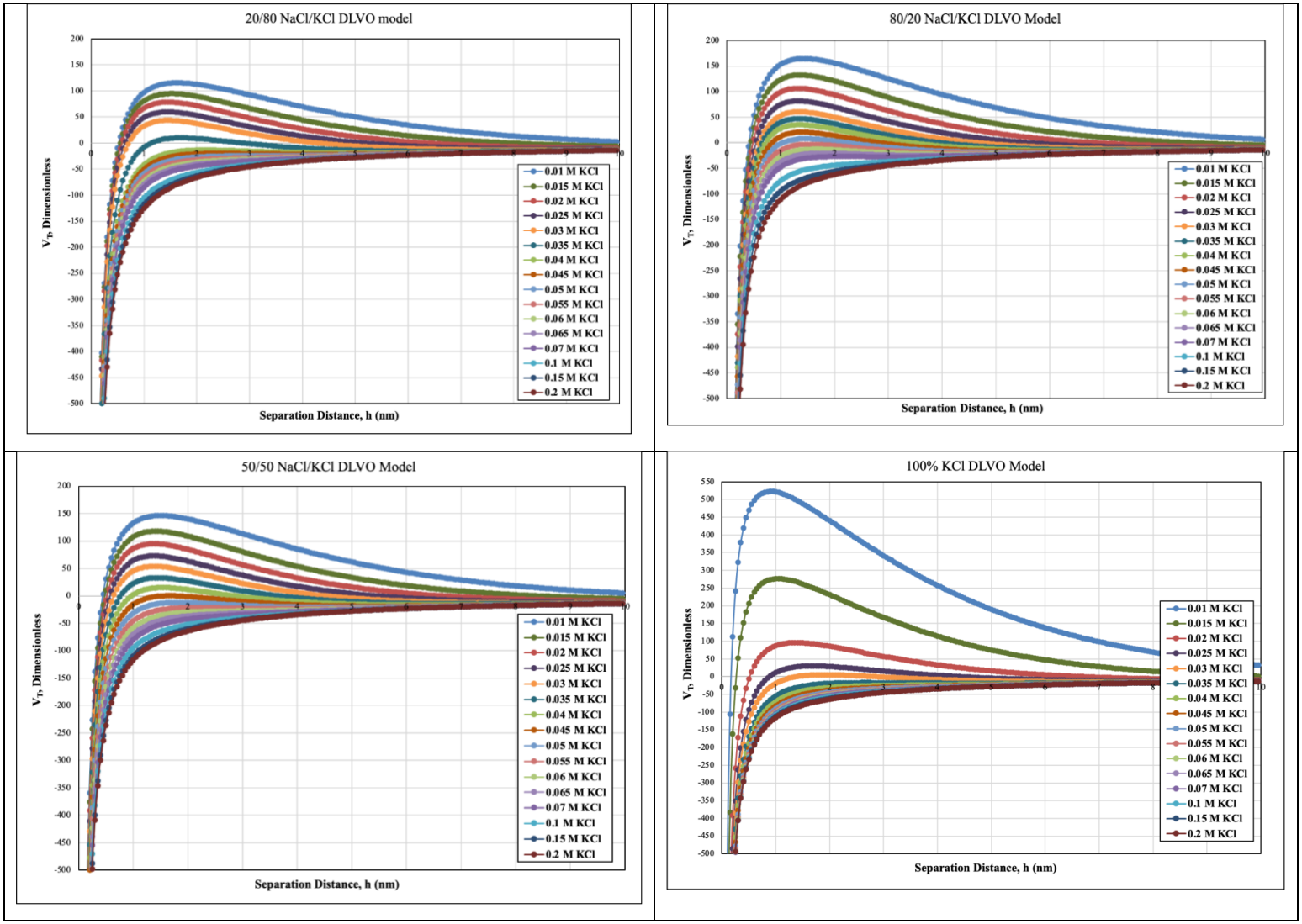
4.3.2 DLVO-based CSC prediction for NaCl/KCl mixtures

Different compositions of NaCl/KCl mixtures, specifically 80/20, 50/50, and 20/80 NaCl/KCl brines, were prepared and zeta potential values were measured by using Malvern Zetasizer (Nano ZS). For each combination zeta potential values were measured for salinity range between 0.2-0.01 M. Since the experimental values were measured only at selected salinity points, logarithmic fitting was applied to find a continuous relationship between salinity and

zeta potential for each brine composition. Following approach made it possible to interpolate intermediate zeta potential values between the measured data points and generate complete dataset for DLVO Modelling. All values were used as input parameters in the low-rate DLVO model, and the following Table 13 presents the constructed DLVO model for all investigated cases, including the 100% KCl system, for which the zeta potential values were obtained from machine learning predictions. For each combination DLVO Model was constructed and CSC values were predicted. CSC was 0.05 M for the 80/20 NaCl/KCl mixture, 0.045 M for the 50/50 NaCl/KCl mixture, and 0.04 M for the 20/80 NaCl/KCl system. For 100 % KCl system DLVO Model was constructed by using Machine Learning predicted zeta potential values and CSC for this case was 0.03 M.

These results show a clear trend, the higher the KCl content, the lower the CSC value. This means that fines release is predicted to start at a lower salinity in KCl-rich systems than in NaCl-rich systems. In other words, the 100% KCl case was the most sensitive to salinity reduction, while the 100% NaCl case required a much larger drop in salinity before the total interaction energy became positive. This trend suggests that changing the salt composition had a strong effect on fines stability in the modeled systems. Even though CSC lowers with increase in KCl content, important to note that this trend is not linear. This indicates that the effect of brine composition on fines stability is composition-dependent and cannot be described by a simple proportional relationship. Therefore, for each specific brine composition, experimental measurements or modelling are needed to determine the corresponding CSC accurately. Summary of DLVO model for different NaCl/KCl brine compositions is shown in Table 13.

Table 13. Summary of DLVO model for different NaCl/KCl brine compositions



4.4 Effect of NaCl/KCl ratio on CSC

Based on results obtained from DLVO Modelling for different compositions of NaCl/KCl, including 100% KCl case in the framework of this research and following graph was constructed. CSCs for all cases are given in Table 14.

Table 14. CSCs for different compositions of NaCl/KCl

Composition of salt	CSC (M)
100 % NaCl	0.11
80% NaCl	0.05
50 % NaCl	0.045
20 % NaCl	0.04
100 % KCl	0.03

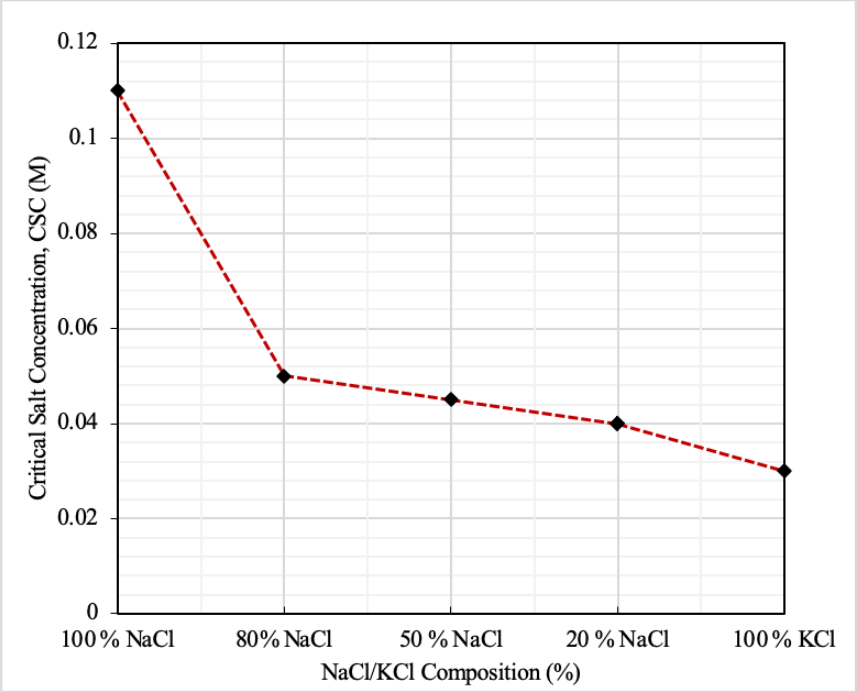


Figure 13. Critical Salt Concentration (CSC) as a function of NaCl/KCl composition

The DLVO modeling results obtained across the full range of NaCl/KCl compositions show a clear and consistent trend. CSC decreases monotonically as the proportion of KCl in the brine increases. Table 14 summarizes the predicted CSC values for all investigated compositions. The CSC for the 100% NaCl case (0.11 M) was taken from the validated reference work of Muneer et al. (2022), while CSCs for 80/20, 50/50, and 20/80 NaCl/KCl were predicted using

experimentally measured zeta potential values, and the 100% KCl CSC (0.03 M) was obtained using machine learning-predicted zeta potentials which is then validated by coreflooding.

Moving from 100% NaCl to 100% KCl, the CSC dropped from 0.11 M to 0.05 M (80/20 NaCl/KCl), then to 0.045 M (50/50), 0.04 M (20/80), and finally 0.03 M (100% KCl). The CSC decreased by almost four times across the full composition range, indicating that KCl is a much stronger promoter of fines instability than NaCl at the same total molar concentration. As shown in Figure 13, the CSC-composition relationship is non-linear, which suggests that the effect is not simply additive. The most pronounced decrease occurs when moving from NaCl-rich brines to intermediate mixtures, while the trend becomes flatter at higher KCl contents. This behavior may indicate a critical response in electrostatic interactions, where even moderate amounts of K^+ change surface charge behavior more strongly than expected from a simple replacement of Na^+.

The underlying mechanism for this compositional effect lies in the different interactions of Na^+ and K^+ ions with silica and clay surfaces. As documented in the zeta potential results (given in section 4.3.1), increase in KCl fraction consistently shifted the zeta potential to more negative values, which indicates that K^+ ions are less effective than Na^+ ions at compressing the electrical double layer at equivalent ionic strengths. This is consistent with the known differences in hydrated ion radius and charge density between the two cations. Na^+ with a smaller ionic radius and larger hydration shell interacts more strongly with the diffuse layer near charged silica surfaces, and effectively screens surface charge to a greater degree and reduces the magnitude of the zeta potential. K^+, by contrast, has a slightly larger radius and smaller hydration shell, which results in weaker electrostatic screening and as a result more negative zeta potentials at the same ionic strength (Sadeghein et al., 2024; Nasralla & Nasr-El-Din, 2014).

From a DLVO perspective, a more negative zeta potential means a stronger electrostatic repulsive energy component in the total interaction energy. At the same salinity, a KCl-dominated system therefore shows a higher repulsive energy barrier than a NaCl-dominated one, which makes fines detachment energetically more favorable and reduces the salinity threshold at which the net interaction energy changes sign. This interpretation agrees well with the decreasing CSC trend observed across the composition series.

The result also has implications for how the CSC concept generalizes to mixed brine systems. Unlike the case of mixed monovalent-divalent systems studied by Muneer et al. (2024), where CSC decreased dramatically even at very small divalent fractions due to the extreme

compressive effect of Ca^{2+} and Mg^{2+}, the NaCl/KCl series shows a more gradual and predictable progression. This makes it potentially easier to model the compositional effect within the DLVO framework using measured or predicted zeta potential values specific to each mixture, as was done in the present study.

5. CONCLUSION AND RECOMMENDATIONS

This study investigated the effect of NaCl/KCl brine composition on the initiation of fines migration in Berea sandstone. Framework focuses on an integrated approach that combines zeta potential measurement, ML prediction, DLVO modeling, and coreflooding validation. The main conclusions are given below:

1. The TabM machine learning model demonstrated the best generalization performance among 9 evaluated models for predicting zeta potential of the sand-brine system (test R^2 of 0.6983 and a test RMSE of 7.79 mV). Its predictions were used as input value to the DLVO model, which predicted CSC of 0.03 M for KCl.

2. Experimentally measured zeta potential values for the mixed NaCl/KCl brine compositions (80/20, 50/50, 20/80) showed that increasing the KCl fraction in composition resulted in pronounced negative zeta potentials at all salinities. It reveals that K^+ ions are less effective than Na^+ ions in compressing EDL, which leads to stronger electrostatic repulsion and reduced fines stability in systems rich in KCl fractions.

3. DLVO modeling predicted a consistent decrease in CSC with increasing KCl content: 0.05 M (80/20 NaCl/KCl), 0.045 M (50/50), 0.04 M (20/80), and 0.03 M (100% KCl). This demonstrates that brine ion composition, even within monovalent systems, show a significant control on fines stability.

4. Coreflooding experiments using stepwise KCl brine dilution identified the experimental CSC for the KCl system in the range 0.03 M < CSC < 0.04 M, based on UV-Vis absorbance and pressure drop measurements. This is in close agreement with the DLVO-predicted value of 0.03 M, validating both the machine learning prediction and the DLVO modeling framework (14.3% error).

5. The results confirm that KCl-dominated brines have a significantly lower CSC than NaCl-dominated brines. The CSC for pure KCl is approximately 3.7 times lower than that for pure NaCl, indicating that KCl-rich systems remain stable until lower salinity conditions are reached. Therefore, the NaCl/KCl ratio must be considered in injection water design and fines migration risk assessment.

Based on the findings and limitations of this study, the following recommendations are proposed for future research:

1. It is recommended that future work consider hydrodynamic forces by performing high-rate injection experiments, since the present study was limited to low-rate conditions, where fines detachment is governed mainly by surface interaction forces. Extending the analysis to higher injection rates would make it possible to evaluate the combined influence of fluid drag and physicochemical interactions on fines migration.
2. The experimental and modeling framework should be repeated at elevated temperatures representative of actual reservoir conditions, as temperature has effect on both zeta potential and the Hamaker constant (Yang et al., 2022). This would broaden the applicability of the results from laboratory to field scale.
3. Future work should consider extending the modeling approach to account for the different size distribution of in-situ fines, rather than using a single average particle size. DLVO calculations performed over a range of particle sizes would show more realistic picture of the range of salinities over which fines of different sizes become unstable.
4. The DLVO-based framework for mixed brine composition should be tested with additional brine systems beyond NaCl/KCl, which includes mixtures with divalent ions to find how specific is the ion effects transition from monovalent brine to brine with mixed valence for CSC control.

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