

**IMPACTS OF INJECTION RATE, PORE
PRESSURE AND ROCK PERMEABILITY
ON WORMHOLE GENERATION DURING
CO₂ SEQUESTRATION IN LIMESTONE
AQUIFERS**

BY

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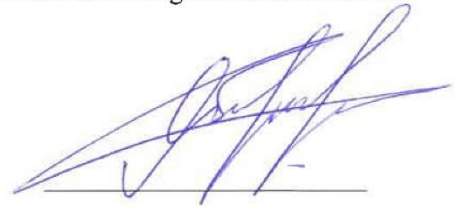
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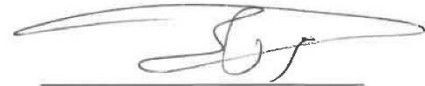
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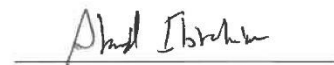
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To my family, whose unwavering support – from late-night talks to celebrating milestones – made this achievement possible.

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LIST OF ABBREVIATIONS

YM	:	Young's Modulus
PVBT	:	Pore Volume to Breakthrough
CO₂	:	Carbon Dioxide
CCUS	:	Carbon Capture, Utilization, and Storage
CCS	:	Carbon Capture and Storage
NMR	:	Nuclear Magnetic Resonance
XRD	:	X-ray Diffraction
IL	:	Indiana Limestone
N_{Da}	:	Damkohler Number

ABSTRACT

Full Name : Elvin Mirzayev

Thesis Title : Impacts of Injection Rate, Pore Pressure and Rock Permeability on
Wormhole Generation during CO₂ sequestration in Limestone Aquifers

Major Field : Petroleum Engineering

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The primary approach to reduce greenhouse gas concentrations in the atmosphere is through the capture and geological storage of carbon dioxide, with saline aquifers being the most used site for storage. However, once CO₂ is injected into saline aquifers, it reacts with the formation water to create carbonic acid. Despite being a weak acid, carbonic acid can still cause changes in the petrophysical and mechanical properties of the reservoir rock. This alteration in properties has the potential to weaken the rock, which poses a risk to the mechanical stability of a formation. In order to avoid the risk of rock failure, which could result from the reduction of rock strength, it is essential to comprehend the uncertainties surrounding the impact of carbonic acid on the rock. Unfortunately, few studies have explored the effect of carbonic acid on rock property deterioration and what injection parameters affect wormhole generation.

This study will examine the effects of CO₂-saturated brine injection on limestone, specifically analyzing how injection rate, pore pressure and rock permeability influences wormhole formation and subsequent changes in petrophysical and geomechanical properties. Indiana limestone samples (1.5 inches diameter, 3 inches length) with varying permeabilities (3, 10, 15, and 22 mD) were utilized throughout the experiments. Standard

conditions of the experiments were a constant pore pressure (2,000 psi) and temperature (60°C). A brine solution (120,000 ppm) mixed with CO₂ (70:30 ratio) was maintained at 1200 psi initially. An injection rate of 1 cm³/min was consistently employed for coreflooding experiments. Before and after coreflooding, various properties were assessed to understand the impact of the different injection parameters: Young's modulus, Poisson's ratio, porosity, permeability, and surface hardness. Micro-CT scans were employed to visualize and quantify the generated wormholes within the rock samples. The analysis of the injection rate revealed that among the tested rates (0.25 to 5 cm³/min), 1 cm³/min resulted in the lowest Pore Volume Breakthrough Time (PVBT). The study also identified the need to modify the Buijse and Glasbergen model for accurate prediction with CO₂-saturated brine. Investigating the impact of pore pressure (4,000, 3,000, 2,000, and 1,500 psi) did not yield a clear trend with regards to PVBT. However, a strong correlation emerged between higher pore pressure and increased mechanical damage in the cores, as evidenced by reductions in both surface hardness and Young's modulus. Finally, the rock permeability of the samples significantly influenced the results. The experiment with the lowest permeability core (3 mD) yielded the lowest PVBT. A clear trend emerged where PVBT increased significantly with increasing rock permeability. Interestingly, higher permeability resulted in less significant deterioration of the core samples due to lower dissolution effects.

ملخص الرسالة

الاسم الكامل : إلفين ميرزايف

عنوان الرسالة: آثار معدل الحقن وضغط المسام ونفاذية الصخور على توليد الثقوب الدودية أثناء عزل ثاني أكسيد الكربون في طبقات المياه الجوفية المالحة من الحجر الجيري

التخصص: هندسة البترول

تاريخ الدرجة العلمية: مايو 2024

يتمثل النهج الأساسي لتقليل تركيزات غازات الدفيئة في الغلاف الجوي في احتجاز ثاني أكسيد الكربون وتخزينه جيولوجيًا، حيث تعد طبقات المياه الجوفية المالحة هي الموقع الأكثر استخدامًا للتخزين. ومع ذلك، بمجرد حقن ثاني أكسيد الكربون في طبقات المياه الجوفية المالحة، فإنه يتفاعل مع ماء التكوين لتكوين حمض الكربونيك. على الرغم من كونه حمضًا ضعيفًا، إلا أن حمض الكربونيك لا يزال بإمكانه إحداث تغييرات في الخواص البتروفيزيائية والميكانيكية لصخور الخزان. هذا التغيير في الخصائص لديه القدرة على إضعاف الصخور، مما يشكل خطراً على الاستقرار الميكانيكي للتكوين. ومن أجل تجنب خطر انهيار الصخور، والذي يمكن أن ينجم عن انخفاض قوة الصخور، فمن الضروري فهم أوجه عدم اليقين المحيطة بتأثير حمض الكربونيك على الصخور. ولسوء الحظ، فقد استكشفت دراسات قليلة تأثير حمض الكربونيك على تدهور خصائص الصخور وما هي معلمات الحقن التي تؤثر على توليد الثقوب الدودي.

ستدرس هذه الدراسة تأثيرات حقن محلول ملحي مشبع بثاني أكسيد الكربون على الحجر الجيري، وتحلل على وجه التحديد كيفية تأثير معدل الحقن وضغط المسام ونفاذية الصخور على تكوين الثقوب الدودي والتغيرات اللاحقة في الخواص البتروفيزيائية والجيوميكانيكية. تم استخدام عينات من الحجر الجيري في ولاية إنديانا (قطر 1.5 بوصة وطول 3 بوصات (مع نفاذية متفاوتة) 3، 10، 15، و 22 مللي أمبير (طوال التجارب. كانت الظروف القياسية للتجارب هي ضغط مسام ثابت (2000 رطل لكل بوصة مربعة (ودرجة حرارة 60 درجة مئوية. (تم الحفاظ على المحلول

الملحي) 120.000 جزء في المليون (الممزوج بثاني أكسيد الكربون) نسبة 70:30 (عند 1200 رطل لكل بوصة مربعة في البداية. تم استخدام معدل حقن قدره 1 سم 3 / دقيقة بشكل ثابت في تجارب الفيضانات الأساسية. قبل وبعد الغمر المركزي، تم تقييم خصائص مختلفة لفهم تأثير معلمات الحقن المختلفة: معامل يونغ، ونسبة بواسون، والمسامية والنفاذية، وصلابة السطح. تم استخدام الأشعة المقطعية الدقيقة لتصوير وقياس الثقوب الدودية المتولدة داخل عينات الصخور. كشف تحليل معدل الحقن أنه من بين المعدلات التي تم اختبارها (0.25 إلى 5 سم³/دقيقة)، أدى 1 سم³/دقيقة Buijse وحددت الدراسة أيضًا الحاجة إلى تعديل نموذج (PVBT) إلى أقل وقت لاختراق حجم المسام، للتعقب الدقيق بالمحلول الملحي المشبع بثاني أكسيد الكربون. التحقيق في تأثير ضغط المسام (Glasbergen 4000 و PVBT. ظهرت 1500 رطل لكل بوصة مربعة (لم يسفر عن اتجاه واضح فيما يتعلق بـ 2000، 3000 وعلاقة قوية بين ارتفاع ضغط المسام وزيادة الضرر الميكانيكي في النوى، كما يتضح من التخفيضات في كل من صلابة السطح ومعامل يونغ. وأخيرًا، أثرت نفاذية الصخور للعينات بشكل كبير على النتائج. أسفرت التجربة ذات بشكل ملحوظ مع PVBT ظهر اتجاه واضح حيث زاد PVBT. النواة الأقل نفاذية (3 مللي د (عن أدنى مستوى من زيادة نفاذية الصخور. ومن المثير للاهتمام أن النفاذية الأعلى أدت إلى تدهور أقل أهمية في العينات الأساسية بسبب انخفاض تأثيرات الذوبان

CHAPTER 1

INTRODUCTION

1.1 General Information about CCUS

The ecological health of our world is in danger from airborne greenhouse gases or climatically unfavorable gases. In the atmosphere, carbon dioxide makes up around 82% of the warming gases. The vast amount of CO₂ emissions put into the atmosphere make it the most important greenhouse gas for effective climate regulation, despite the fact that it has a lower ability to cause climate change than other greenhouse gases. In order to lower the concentrations of greenhouse gases in the atmosphere, Carbon dioxide capture, consumption, and storage (CCUS) technology has emerged and is being used. The CCUS process involves removing carbon dioxide and its byproducts from energy-producing sources, compressing them for transportation, and using them in a variety of ways, like injecting them into active oil fields to boost hydrocarbon recovery or storing them in deep geological formations for the long term (Ajayi et al., 2019b).

CO₂ sequestration has been applied in a variety of ways all around the world. Natural and artificial storage can be used to generalize the different storage kinds. Terrestrial sequestration is an example of a natural kind of storage, whereas storage in geologic formations is an example of an artificial one. The following types of CO₂ storage and usage have been looked at:

1. The process of removing CO₂ from the atmosphere and storing it in soil and vegetation is referred to as terrestrial sequestration. Utilizing photosynthesis to

collect CO₂ and reducing CO₂ emissions from terrestrial sources are two methods used for terrestrial storage. According to some hypotheses, terrestrial sequestration may offer an effective method of CO₂ storage (Thomson, César Izaurralde, et al., 2008).

2. Due to its projected capacity to store up to 40,000 gigatons (Gt) of CO₂, which could handle more than 90% of the present CO₂ emissions, ocean sequestration is regarded as the most significant conceivable carbon dioxide sink for storage (Lal, 2008a). This sequestration technique includes injecting CO₂ into a body of water at a depth of one kilometer or more through either offshore rigs, floating ships, or stationary pipelines. The density of water has a lower density compared to that of the injected CO₂ at such depths. Over time, the CO₂ is anticipated to break down and diffuse into the water body (Metz, 2005). Nevertheless, due to the acidity of the seawater close to the injection site, CO₂ has a significant negative environmental impact on marine life (B. A. , & W. P. J. (2001). Seibel, 2001). This sequestration method is still in the development phase and has not yet undergone any pilot tests.
3. The most spread and utilized sequestration method is geological sequestration. As part of this process, CO₂ is stored in subterranean geological formations like saline aquifers, exhausted reservoirs, and impassible coal beds(J. Kaldi et al., 2009; Metz, 2005). Given below is a brief explanation of each storage location:
 - a) *Saline aquifer formations*: Due to their high storage capacity, saline aquifer formations stand out among all geological possibilities as the finest salted sink for storing CO₂ (Ajayi et al., 2019b). According to recent estimates for the Alberta

deep saline basin, the solubility entrapment technique could allow for the storage of about 103 gigatons (Gt) of CO₂ (Bachu & Adams, 2003). An additional instance that can be cited is the injection of CO₂ into the Utsira aquifer, located in the North Sea (Torp & Gale, 2004). Since it is unsuitable for use in industry, agriculture, or by humans, this sequestration technique requires a saline aquifer. Given that the CO₂ injection could have a negative impact on both the environment and people, it is seen to be crucial to make sure that it does not interfere with the aquifer's current uses. Therefore, the location's geological and hydrological qualities, its closeness to infrastructure and population centers, and any potential environmental effects of the injection must all be taken into consideration when choosing the best site for CO₂ sequestration. These factors are essential for ensuring that the sequestration process is effective, long-lasting, and secure (Aydin et al., 2010).

- b) *Drained gas and oil reserves*: Reservoirs that were formerly generating petroleum and now that have been labeled as economically unviable for continued extraction of hydrocarbons are prospects for geological sequestration. Because they offer the characteristics required for a storage site, these formations have been exploited for storage type, which is geological. The fact that they have historically been excellent for oil and gas storage is a significant benefit. These formations are also excellent prospects since they have a history of storing oil and gas and are secure. The formations have more confidence because there are already numerical computer simulations of these configurations that have been historically matched. These fields' original facilities and wells are suited for injecting CO₂ now as well. There is one fundamental disadvantage to depleted oil and gas reserves despite all of these

positive possibilities: their storage capacity. Due to the necessity to keep the pressure below fracture pressure, which might harm caprock and lead to a significant quantity of leakage, it is significantly lower. Leaks could also exist behind well casings (Ajayi et al., 2019b).

- c) *Deep unmineable coal beds*: In the process of enhanced coal bed methane (ECBM) recovery, methane is extracted from coal seams using CO₂ (Busch & Gensterblum, 2011; Mukherjee & Misra, 2018; Pan et al., 2018). Methane, which can be used as fuel, may be produced by this source. Large-scale fracture networks are present in coal beds, allowing gas molecules to permeate into the matrix and release methane that has been tightly adsorbed. According to studies, adding CO₂ can boost methane recovery from traditional methods from 50% to around 90%. The injected CO₂ is then kept in the formations after the methane has been removed. CO₂ adsorption on the coal surface, which can take place at deeper depths than other formation types, is what allows for storage in coal beds. The permeability of the coal, which can vary due to changes in depth and stress levels on coal fractures, is what determines how viable this storage strategy is though (Metz, 2005).
- d) *CO₂ storage during enhanced oil recovery*: Both the soluble and insoluble states of CO₂ can be used in EOR processes. Oil can expand, lose viscosity, and interfacial tension, and in some circumstances, the two substances can even become completely soluble, enabling single-phase movement, when CO₂ is added to the oil. Of these two miscibility states in CO₂ injection for EOR purposes, miscible CO₂ injection procures higher recoveries. The point at which CO₂ and oil become miscible at or above a particular pressure level is known as the minimum miscibility

pressure. This pressure level aids in determining whether CO₂ can mix with oil. While improved oil recovery (EOR) is the main goal of CO₂ injection in this process, it also has the additional benefit of CO₂ storage, which can lessen the risks associated with global warming (Ajayi et al., 2019b).

1.2 Storage of Carbon Dioxide in Saline Aquifers

Three essential criteria must be met before selecting a geological region for storage: capacity, injectivity, and containment. The capacity criterion guarantees that the selected site has sufficient pore volume to store sizeable amounts of CO₂. Choosing a site with a high degree of permeability or occupying a significant space are typical ways to satisfy this condition. In addition, a formation with high permeability meets the injectivity requirement, allowing for the utilization of reduced wellhead pressure levels to maintain the intended injection rate of CO₂. Because injected carbon dioxide has a lower density value than salty water that is resident in a reservoir and could therefore leak into groundwater, it is essential to have effective cap rocks and faults that seal the reservoir. The only way to store carbon dioxide effectively is to compress it to greater pressures and temperatures (about 89 °F and 7.4 MPa), which will cause it to enter a supercritical phase. CO₂ acts like a fluid but flows like a gas while in the supercritical stage. Therefore, it is essential to store CO₂ in this form because its higher density reduces the buoyancy difference between it and the other fluids already present in the formation (Grobe et al., 2010; Kane & Klein, 2002; Koide et al., 1992). Although the density of CO₂ increases as it is injected beneath the surface, it still has a lower density than in situ brine. Due to this disparity in densities, CO₂ tends to float upward when introduced underground, requiring the existence of cap rocks with limited permeability to cover the aquifer.

The chosen formation's geological and petrophysical characteristics determine the ability to store, restrict, and inject CO₂. Supercritical CO₂ is carefully pumped underground and is trapped by two primary entrapment techniques: physical and geochemical entrapment (**Figure 1**). The efficiency of the conservation procedure depends on the integration of both entrapment techniques to ensure long-term preservation (Metz, 2005)(Metz et al., 2005a).

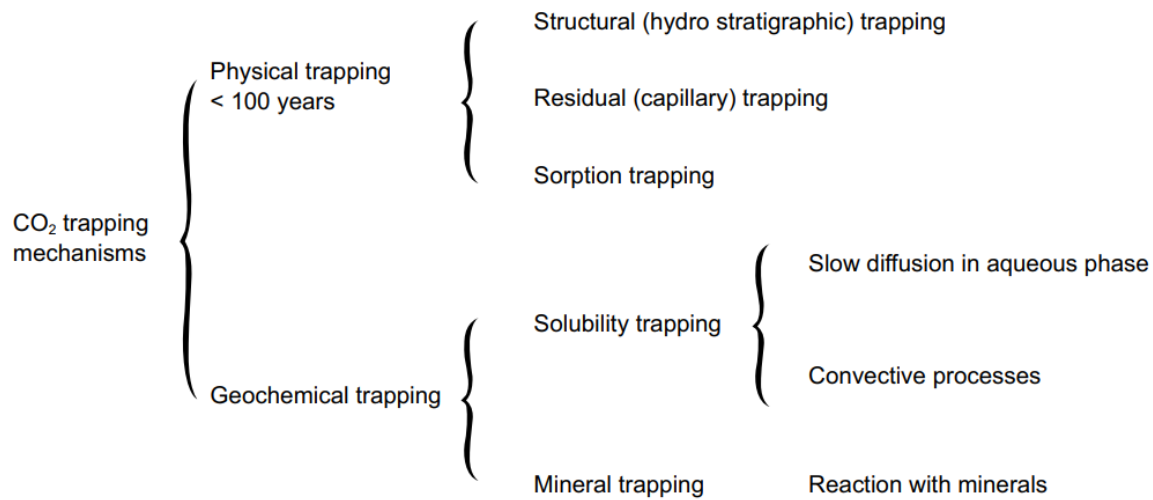


Figure 1.1. CO₂ Trapping mechanisms in geological storage (Ajayi et al., 2019b)

1.2.1 Physical Entrapment

When CO₂ is stored via the physical trapping technique, it keeps its original form after being injected into an aquifer. The two subcategories of this technique are structural (hydrostratigraphic) entrapment and residual (capillary) entrapment. Physical entrapment is typically thought to endure less than a century (Juanes et al., 2006).

Structural Entrapment: During geological sequestration, structural entrapment is frequently the first type of entrapment that is observed. Geological structures, such as anticlines surrounded by cap rocks or stratigraphic traps, regardless of the presence of sealed faults, are utilized for preserving CO₂ as a mobile phase or supercritical fluid, in a

manner similar to the process that has preserved oil and gas safely stored below for hundreds of thousands of centuries. It is crucial to optimize the storage mechanism of CO₂ injection to ensure the long-term retention of the injected CO₂ underground. During the injection process, CO₂ migrates primarily due to viscous forces. The storage of CO₂ occurs either in the supercritical or gas phase depending on the depth, pressure, and temperature of the targeted formation. After the injection is complete, the buoyancy of the supercritical CO₂ causes it to move upward through porous and permeable rocks until it reaches a cap rock, fault, or sealed discontinuity. The CO₂ can also migrate laterally through preferential pathways. Therefore, it is essential to identify and seal any discontinuities to prevent the upward or lateral migration of CO₂ and maximize its long-term storage in the targeted formation (Han, 2008). After being injected into geological formations, the goal is to stop CO₂ from traveling farther (**Figure 2**). The passage of CO₂ can be halted in exhausted oil and gas fields by plugging abandoned wells with cement. Nevertheless, the possibility of leaks via the plugs or from behind the casing must be considered. The assessment of the potential for CO₂ leakage through geological features and abandoned wells has been the subject of numerous research projects.

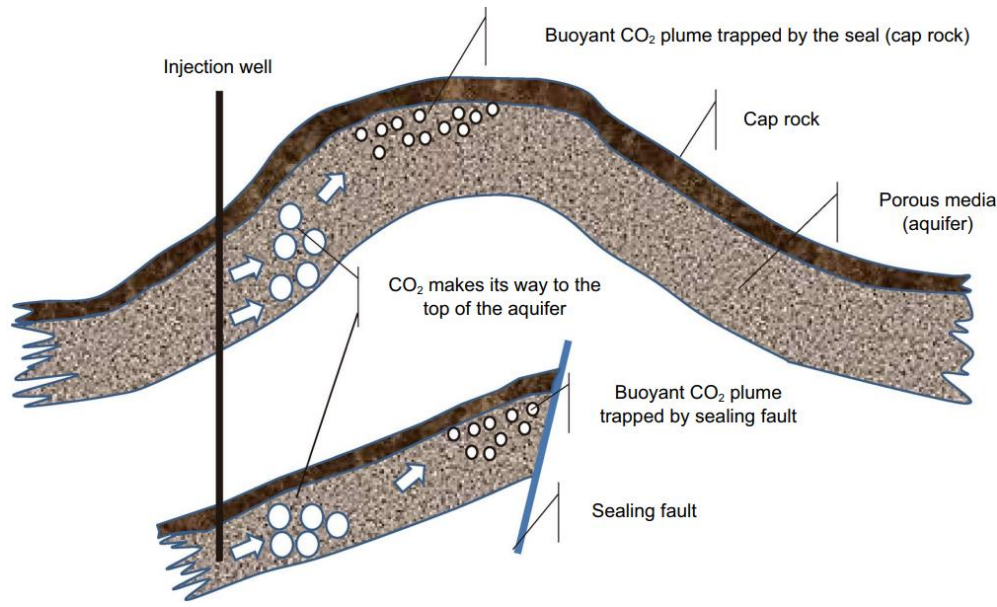


Figure 1.2. Physical entrapment of injected CO₂ (Ajayi et al., 2019b)

Residual or Capillary Entrapment: Fluids that are present in reservoir rock are moved by supercritical CO₂ as it passes through storage strata. Because of lateral viscous forces and variations in density, this shifting occurs in two orientations. The empty spaces left by the CO₂ are subsequently filled with reservoir fluid. Nevertheless, some CO₂ is still present in the porous spaces as unconnected or lingering droplets (**Figure 3**). The interaction between CO₂ and brine surface tension functions to stop the movement of CO₂, resulting in a capillary entry pressure that exceeds the average rock pressure. In other words, the surface tension of CO₂ and brine creates a barrier that prevents CO₂ from moving easily, leading to a capillary entry pressure that is higher than the pressure of the surrounding rock on average (Saadatpoor et al., 2010). At this stage, CO₂ reaches residual gas concentration and becomes trapped in the pores. Typically, it is seen in rocks with microscopic capillary heterogeneities. According to the latest research, capillary entrapment promises to be a more efficient technique than other short-term entrapment mechanisms for capturing CO₂ underneath (Burnside & Naylor, 2014)(Lamy et al., 2010). It works because it exhibits

stronger capillary forces than buoyant forces, which causes CO₂ to be seen as pore-scale air bubbles rather than being contained by a cap rock that has some degradation. It also has the advantage of eliminating the potential for a catastrophic failure brought on by structural traps in a short amount of time. (Jalil et al., 2012).

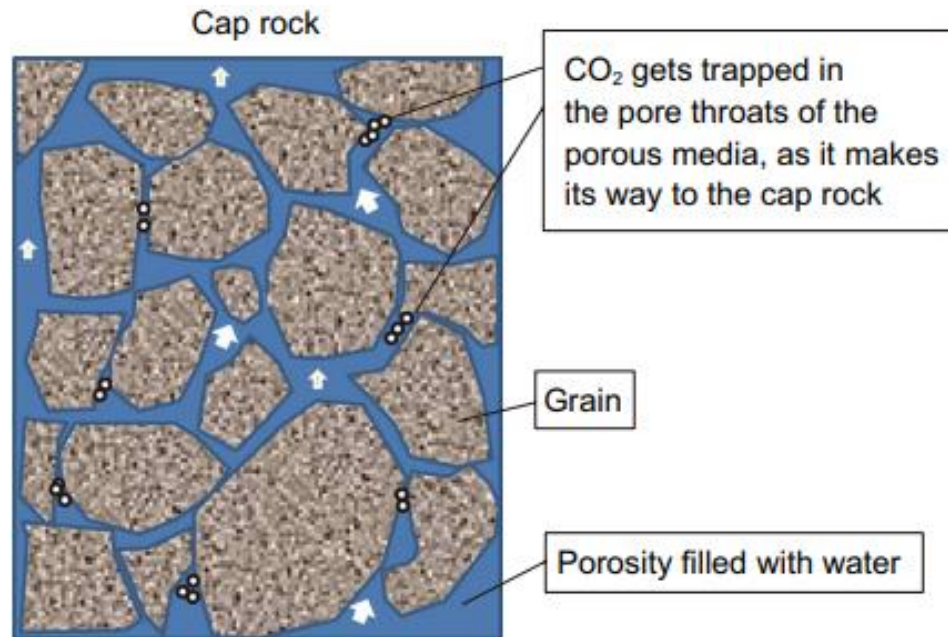


Figure 1.3. Representation of residual trapping. Diagram arrows represents the migration of CO₂ (Ajayi et al., 2019b)

1.2.2 Geochemical Entrapment

Geochemical entrapment is a procedure whereby carbon dioxide interacts with rock and formation fluid to modify their nature through a series of chemical and physical interactions and stop remaining in a mobile or immobile state. This interaction eliminates CO₂ as a discrete phase, enhances the capacity for storage, and makes the approach ideal for long-term storage.

Solubility Entrapment: No matter whether it is in the supercritical or gaseous state, CO₂ dissolves in other liquids, much like how sugar dissolves in tea. Dissolving the CO₂ in the

brine causes solubility entrapment, which results in concentrated CO₂-saturated brine. It stops being a distinct phase at this moment, which diminishes the buoyancy effect. As CO₂-saturated brine settles to the base of the formation as time passes, it becomes denser than the other reservoir fluids and provides more reliable CO₂ trapping (**Figure 4**).

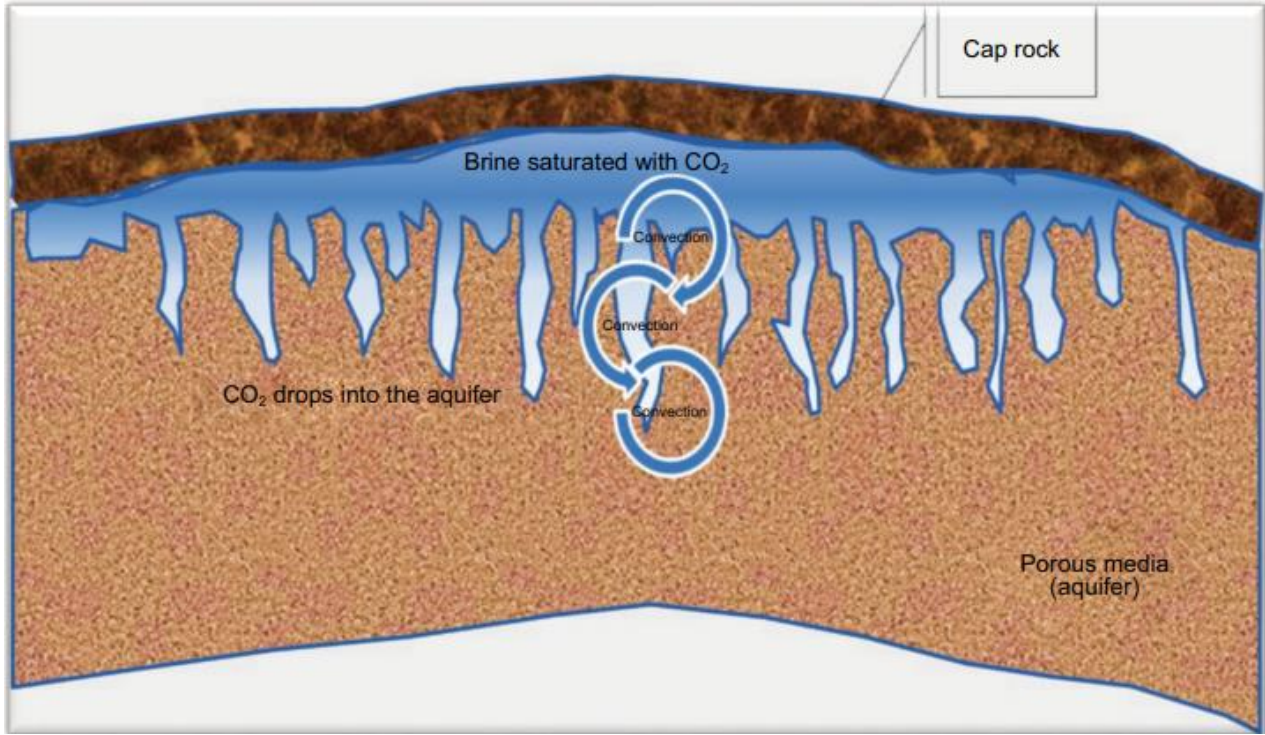
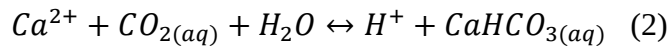
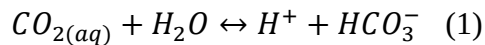
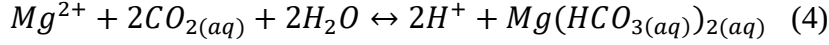


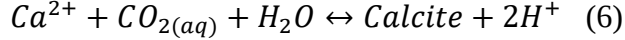
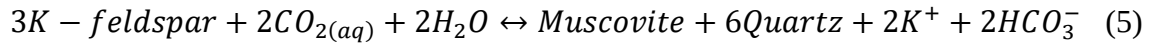
Figure 1.4. Illustration of solubility entrapment through convective mixing (Ajayi et al., 2019b)

Weak carbonic acid is generated when CO₂ dissolves in the water phase, and this acid eventually breaks down into H⁺ and HCO₃⁻ ions (**Eq. 1**). There is a possibility that it can interact with other available cations in the brine in order to generate ionic substances that are insoluble. Equations 1-4 demonstrate given phenomena.





Mineral Entrapment: Although it is a somewhat slow process that happens either during or following the solubility trapping, mineral entrapment, which is thought to be the most permanent storage mechanism, is caused by the transformation of CO₂ into calcite through interactions with minerals that are solid. According to the mineralogy of the formation, CO₂ in the aqueous phase combines with rock elements to generate ions of bicarbonate along with different cations. Below is an illustration of such a reaction using potassium basic silicate (**Eq. 5**) and calcium (**Eq. 6**) (Ajayi et al., 2019b).



Depending on the composition of the rocks, interactions with nearby structures of rock always serve as the catalyst for the production of carbon dioxide minerals. Consequently, geochemical simulation of these responses is essential for producing reliable estimates of the storage of CO₂. The nature of the material that rock is composed of, the pressure that gases provide, varied circumstances of temperature values, and different reservoirs with varied porosity values are only a few examples of the variables that affect how successful this entrapment mechanism is. In addition, it has been noted that this technique has the potential to modify the rock's permeability and porosity significantly (Benson & Cole, 2008; Kampman et al., 2014). Perkins(Perkins et al., 2005), using a simulation study, estimated that after 5000 years, the Weyburn Oil Field would experience the complete

transformation of all injected CO₂ into carbon dioxide minerals. In addition, they discovered that the cap rock and the underlying formation rock had greater mineralization potential, which is crucial knowledge for determining the danger of leakage. The capability of the mineral entrapment method is assessed by comparing the number of minerals accessible to CO₂ precipitation with the amount of CO₂ used in the reaction pathways. This approach has a number of advantages over others, but its main benefit is that it inhibits CO₂ from continuing as a distinct phase, essentially halting its upward migration and encouraging the development of stable precipitates (Xu et al., 2001)(Xu et al., 2003)(Xu et al., 2004). The calculation of storage capacity is impacted by the fact that many systems, which work concurrently and on various time periods, are responsible for storing CO₂. These systems interact in a complicated way that changes over time and is greatly influenced by regional circumstances. **Figure 5** illustrates how several mechanisms have changed in a deep saline formation over time.

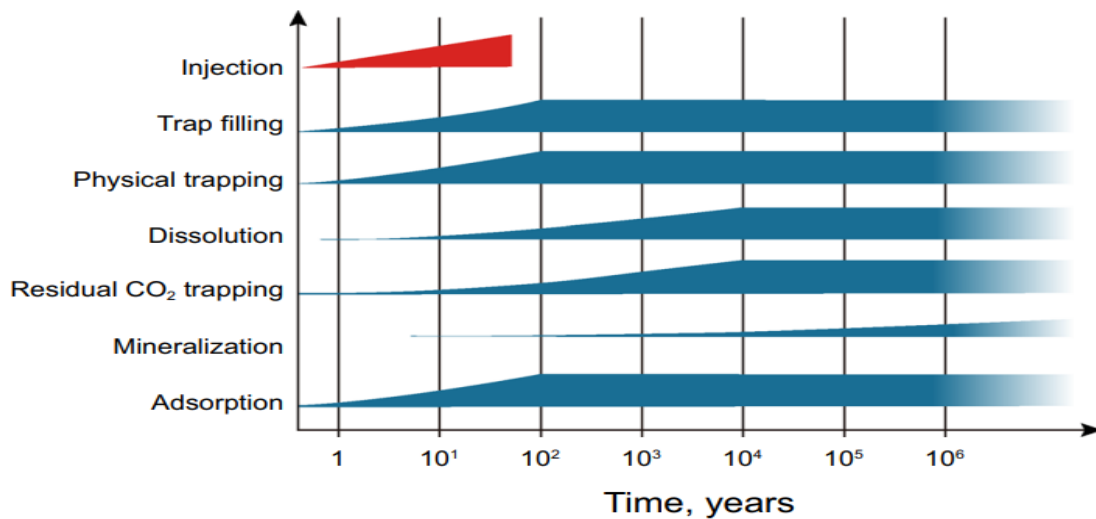


Figure 1.5. Period of time during and after injection where entrapment techniques in deep saline deposits can occur (Metz et al., 2005a)

1.2.3 Physical Procedures during CO₂ Sequestration

Both the injection stage and stage after the injection phase of carbon dioxide entail numerous physical reactions. Three main physical procedures help to store CO₂ in aquifers - buoyancy (gravity), capillary forces, and viscous forces (Kong et al., 2013). Viscous forces are mostly to blame for the vertical and lateral displacement of CO₂ during the injection phase into aquifers, driven by pressure gradients created during the injection. In addition, the formation fluid (brine) is displaced by the injection of CO₂ fluid in a manner similar to drainage.

CO₂ is held in place after the injection phase by a combination of buoyancy and capillary forces. Following injection into deep saline aquifers, buoyancy forces are often larger than capillary and viscous forces, which can allow CO₂ to flow upward. This upward motion is brought on by differences in density between the introduced carbon dioxide and the aquifer brine, which causes water to be displaced in a manner comparable to imbibition.

The upward movement of CO₂ causes gravity separation, but the ultra-low permeability cap at the top of the formation stops any further upward movement to the surface. Vertical movement of CO₂ stops when it approaches the top of the formation, but horizontal migration may go on until it finds a sealing fault or formation border. When the buoyant CO₂ reaches the seal, a thorough geomechanical evaluation is necessary to guard against CO₂ leakage. When the CO₂ pressure is higher than the seal's entry pressure, leaking is one possibility (Hesse et al., 2006). Others might come from caprock cracks, thermal strains brought on by temperature differences between the carbon dioxide that was injected and the aquifer, the existence of open faults, fractures, and abandoned wells, as well as other factors (Chiquet et al., 2007; Goodarzi et al., 2013). One of the elements that affect the

sequestering ability of the overlaying seal is the geomechanical assessment of cap rock stability.

Hysteresis, or the modification of capillary pressure and relative permeability curves, can result from drainage and imbibition-like activities that take place during the injection and post-injection stages of CO₂ storage. Therefore, when simulating CO₂ entrapment methods, hysteresis is an essential phenomenon that must be taken into consideration in order to guarantee their success (Ghomian et al., 2008; Goodarzi et al., 2013; Spiteri et al., 2005). The water that is shifting the CO₂ at the trailing edge causes the CO₂ that was introduced during the period of storage to move upward, leaving behind residual or capillary entrapment mechanisms in the form of unconnected blobs. Since CO₂ becomes trapped in these blobs over time and dissolves in the formation brine as a result, this process is essential to the precise simulation of CO₂ entrapment methods.

The aquifer's wettability and heterogeneity must be taken into account while designing the residual or capillary entrapment method. There are two scales that separate heterogeneity: small and large (Gershenzon et al., 2014; Lasseeter et al., 1986; Li & Benson, 2014). The role of viscous and capillary forces is crucial in CO₂ flow during the storage process, particularly when small-scale heterogeneities are considered. Gravity forces are generally not significant in this case. However, when large-scale heterogeneities exist in the formation, pore throat sizes vary, creating different capillary tube sizes that require variable amounts of entry capillary pressure to displace the formation fluid. As there is more pressure generated than entry pressure, it means better and more effective carbon dioxide entrapment (Bennion & Bachu, 2006; Chiquet et al., 2007; Jung & Wan, 2012; Yang et al., 2005).

Three main mechanisms have been identified for the dissolution of CO₂ into brine during its residence time in the blobs and ganglia, namely molecular diffusion, convective mixing, and chemical reaction (Ennis-King & Paterson, 2005). The key process for the long-term dissolution of CO₂ in the formation brine, according to Ennis-King and Paterson, is convective mixing. They claimed that compared to diffusion and chemical reactivity with the host material, this mechanism is considerably quicker.

Gravitational instability is caused by the excessive dissolving of CO₂ in brine, and this instability may help with solubility entrapment. Therefore, numerous scientists have sought to identify the convective mixing's beginning timing and its influencing factors. The time needed for convective instability to start was estimated by Ennis-King and Paterson (Ennis-King & Paterson, 2005) using the linear stability evaluation technique. They anticipated the period to last up to 10 years on average, and this approach has been employed by numerous additional researchers. Applying the principle of linear stability technique, Riaz (Riaz et al., 2006) identified the key period and wavelength, or the beginning of convective mixing. For a permeability range ranging from 1-3000 mD, the crucial period was demonstrated to range between 2000 years and 10 days, while the critical wavelength ranges between 200 and 0.3 m. Last but not least, as long as carbon dioxide continues to be dispersed in brine, it creates an acidic fluid that is weak and interacts with the host materials to create sludge (Gunter et al., 2000; Kumar et al., 2005; Xu et al., 2001).

1.3 Problem statement and Research Objectives

The knowledge we have from studying different types of acid is broad. It is clear that the formation rock will react with the carbonic acid produced by the CO₂ and aquifer saline water reaction to alter its mechanical and petrophysical properties. Therefore, the risk of causing a fault to fail or an intact rock to fail, which could reduce rock strength or even cause a CO₂ leak, can be avoided by being aware of the doubts surrounding the effect of carbonic acid on the rock. Over the years, numerous studies have been conducted to investigate the effects of CO₂ injection into carbonate rock and how it alters its properties. Despite these efforts, only a handful of researchers have been able to achieve continuous wormhole formation during their CO₂ injection studies. Surprisingly, there has not been a single study that specifically focuses on understanding the mechanism of wormhole formation and how various injection parameters influence this process. This lack of knowledge and understanding of the complex relationship between injection parameters, wormhole generation, and rock properties is a significant challenge that needs to be addressed to mitigate the potential risks and uncertainties associated with CO₂ sequestration and enhanced oil recovery (EOR) by CO₂. It is imperative to conduct further research in this area to minimize the risk of worst-case scenarios such as CO₂ leakage and ensure the effectiveness and sustainability of CO₂ injection as a viable EOR and sequestration method. By filling the existing gaps in the literature, this study can contribute to developing more accurate models and effective strategies that optimize CO₂ injection for various geological formations and reservoir conditions.

Therefore, the specific objectives of this research will be as follows.

- 1) Ascertain the effects of injection parameters on wormhole generation

- Understand the effect of the injection rate
 - Understand the effect of the pore pressure
 - Understand the effect of the rock permeability
- 2) Determination of the effects of a generated wormhole on the mechanical and petrophysical characteristics of rocks

CHAPTER 2

A Study of The Optimum Injection Rate of CO₂-Saturated Brine in Limestone Aquifers

Abstract

Deep saline aquifers are promising locations for carbon sequestration, but the impact of CO₂ injection on rock properties requires careful investigation. This study will examine the effects of CO₂-saturated brine injection on limestone, specifically analyzing how injection rate influences wormhole formation and subsequent changes in petrophysical and geomechanical properties. Six Indiana limestone samples, each with dimensions of 1.5 inches in diameter and 3 inches in length, were utilized. These samples have an average porosity of 16.5% and an average permeability of 3 mD. During the experiments, the samples were subjected to a pore pressure of 2,000 psi and a temperature of 60°C, with a brine concentration of 120,000 ppm mixed with CO₂ at a ratio of 70:30, maintained at 1200 psi initially. Various injection rates were employed to investigate the impact of injection rate, ranging from 0.25 to 10 cm³/min, for the coreflooding experiments. Before and after coreflooding, Young's modulus (YM) and Poisson's ratio of the samples were measured at various confining pressures. Additionally, the porosity, permeability, and surface hardness of the treated samples were assessed. To visualize the generated wormholes and quantify their volumes for calculating the Damkohler number, micro-CT scan was employed. Our study revealed that among the six tested injection rates, 1 cm³/min resulted in the lowest PVBT. We employed the Buijse and Glasbergen model, curve-fitting our data to determine the optimum velocity for CO₂-saturated brine, which was found to be 0.4 cm/min

(equivalent to an injection rate of $0.75 \text{ cm}^3/\text{min}$). A strong correlation was observed for velocities exceeding the optimum, while a weaker correlation existed at lower values. This suggests the need to modify the Buijse and Glasbergen model to accurately predict behavior in the context of CO_2 -saturated brine. Furthermore, the Damkohler numbers calculated for our experiments deviated from the generalized Damkohler curve. This discrepancy is likely attributed to the distinct reaction mechanisms of carbonic acid compared to stronger acids typically used in such models.

Keywords; Optimum Injection rate; Live brine; CO_2 Storage; Wormhole

2.1 Introduction

Carbon sequestration involves the process of injecting and securely storing carbon dioxide (CO_2) in either natural or artificial storage repositories. This method has been in use since the 1990s, marking the inception of the first significant carbon capture, utilization, and storage (CCUS) initiative in Norway. Carbon sequestration can be broadly categorized into three main groups: terrestrial, oceanic, and geological (J. G. Kaldi et al., 2009; Lal, 2008b; Metz et al., 2005b; B. A. Seibel & Walsh, 2001; Thomson, Izaurrealde, et al., 2008). Terrestrial sequestration involves storing carbon dioxide within soil and vegetation. Conversely, oceanic sequestration focuses on intentionally introducing CO_2 into the ocean, where it can be dissolved or utilized by marine organisms. Lastly, geological sequestration centers on storing CO_2 within deep underground formations, such as saline aquifers, depleted oil and gas reservoirs, or coal seams. (Ajayi et al., 2019a). Geological storage of CO_2 stands as a promising and efficient strategy to combat the escalating challenges of global climate change. This approach directly addresses the rise in atmospheric CO_2 concentration, mitigating its impacts on the environment.

Saline aquifers are the primary reservoirs targeted for CO₂ sequestration due to their vast capacity and favorable geological properties. However, other storage methods, such as depleted oil and gas reservoirs and coal seams, present limitations (Luo et al., 2022). With atmospheric CO₂ concentration currently at 421 ppm and projected to rise further, carbon sequestration presents a promising avenue for mitigating climate change. Deep limestone aquifers offer a potential solution for carbon capture and storage (CCS), a technology aimed at reducing greenhouse gas emissions. These formations boast advantages like large storage potential, the ability of limestone to react with CO₂ for permanent trapping, the potential to utilize existing oil and gas infrastructure, and their widespread availability. However, there are also significant drawbacks. Risks include potential CO₂ leakage, contamination of groundwater due to acidification, the possibility of induced earthquakes, and high costs associated with site assessment, infrastructure, and monitoring. It's important to recognize that carbon sequestration is most effective when combined with other mitigation strategies, forming a comprehensive approach to combatting climate change (Al-Dhafeeri et al., 2024; Bachu, 2000; Metz et al., 2005b; Rasool et al., 2023).

The sequestration of CO₂ in saline water formations has the potential to induce the creation of wormholes within limestone formations. This phenomenon is largely attributed to the existence of a mild carbonic acid formed during the dissolution of CO₂ in the water phase. (Aldhafeeri et al., 2023; Espinoza et al., 2018; Major et al., 2018; Selvadurai et al., 2017). The formation of wormholes resulting from the injection of CO₂ leads to notable alterations in the petrophysical and mechanical properties of the formation rock, including porosity and permeability. Numerous researchers have undertaken experimental and modeling studies to comprehend the influence of various parameters on wormhole

generation induced by acids. However, there is a scarcity of studies focused on comprehending this phenomenon in the context of CO₂ injection rate.

Fredd & Fogler (1999) studied the optimal conditions for generating wormholes in carbonate porous media through an exploration of the influences of transport and reaction. A diverse range of fluid systems, encompassing strong acids, weak acids, and chelating agents, were employed in the conducted experiments. They found that there is an optimum Damkohler (a dimensionless number comparing reaction rate to transport rate) number, 0.29, for all the fluid systems used in their research. This single description is obtained by normalizing the pore volumes to breakthrough (PVBT) by the average minimum PVBT for the respective fluids. Plotting the normalized PVBT against the inverse Damkohler number yields a master curve. This curve allows for estimation of the entire PVBT curve and corresponding wormhole structures from a single coreflood experiment conducted near the optimum Damkohler number. Additionally, they discovered optimum that dimensionless parameter called kinetic parameter to be 130.

Cheng et al. (2017) conducted research to understand how the generated CO₂ during carbonate acidizing with HCl would affect wormhole propagation. They conducted coreflooding experiments with varying pressures, temperatures, and injection rates (500 to 3000 psi; 70 and 150 °F; 1.2, 1.5, 3, 5, 8, and 12 cm³/min). Experiments indicated that at low injection rates, the presence of CO₂ in a gaseous phase significantly hampers the efficiency of wormhole propagation, leading to an observable increase in the diameter of the formed wormholes. When injection rates surpass the optimal level, the impact of CO₂ becomes less noticeable, especially at elevated temperatures. Zakaria et al. (2015) offer a valuable investigation into the link between carbonate pore structure and the success of

acid stimulation. Their work across six different formations employed comprehensive analysis (thin-sections, mercury injection, NMR (Nuclear magnetic resonance), XRD to characterize pore heterogeneity and mineralogy. Importantly, they introduce the parameter f' , representing the fraction of the pore structure that actively contributes to flow. This parameter, as demonstrated by over 30 acid-coreflood experiments, is crucial in understanding and predicting acid behavior in carbonate rocks. Their results highlight the impact of pore classes on acid response, underscoring the potential for improved hydrocarbon recovery through tailored acidization strategies based on detailed pore structure analysis.

Dos Santos Lucas et al. (2023) did a review to find out how different parameters affect the generation of wormholes in carbonate rock samples during acidizing with HCl. The main parameters they discussed were concentration of acid, reaction rate, flow rate, temperature, dimension of core samples, and heterogeneity. The primary parameters under discussion included the concentration of acid, reaction rate, flow rate, temperature, dimensions of core samples, and heterogeneity. The findings suggest that increasing acid concentration leads to a downward shift in the PVBT (pore volume to breakthrough) plot, reducing the breakthrough volume and altering the optimal flow rate. Moreover, the flow rate is closely linked to the type of wormhole generated, with various dissolution patterns observed. The reaction rate is highlighted as a crucial factor influencing wormhole formation, with Damkohler and Peclet numbers providing valuable insights into its dimensionless approach encompassing advection, diffusion, and reactivity. Furthermore, the geometry of the reactive flow significantly impacts dissolution patterns. Core properties, such as diameter and saturation, also affect PVBT, albeit core length seems to have minimal impact,

especially in experiments over 6 inches. Lastly, temperature exhibits varied effects on limestone and dolomite formations, further emphasizing the nuanced considerations in matrix acidizing operations. Zareei et al. (2022) investigate the impact of carbon dioxide injection on carbonate rocks' petrophysical properties, crucial for optimizing CO₂ storage strategies in saline aquifers. Their research identifies how CO₂ sequestration affects rock-fluid geochemical interactions, particularly focusing on the dissolution/precipitation of minerals and its influence on formation properties like flow and injectivity. Employing core flooding experiments across a spectrum of rock mineralogies and distances from the injection point, they applied both qualitative and quantitative assessments, including X-ray Diffraction (XRD), CT scanning, porosity, and permeability measurements. Their findings reveal a significant permeability increase in rocks with minerals soluble in acidic environments, attributed to the formation of wormholes. Conversely, rocks composed of acid-insoluble minerals exhibited a permeability decrease. The study highlights the differential impact of CO₂ injection based on the rock's mineral composition and proposes that managing these geochemical interactions is essential for the success of CO₂ sequestration efforts.

Al-Dhafeeri et al. (2024) conducted a study to understand the brine salinity impact of a carbonated brine on the generation of wormholes. Furthermore, they analyzed the effects of the generated wormholes on the properties of a rock. They found out that the fastest and the thickest wormhole formed with the lowest salinity brine as the solubility of CO₂ increased with decreasing salinity, resulting in a more acidic solution. They also suggested that acid stimulation can be carried out using fresh carbonated water or water with low salinity. In another study, Al-Dhafeeri et al. (2023) conducted experiments on the impact

of carbonated brine temperature on the generation of wormholes. Similar to the other study, they analyzed the effects of created wormholes on the properties of a rock. They found that two parameters acted against each other: reaction kinetics and CO₂ solubility. The reaction kinetics increases at high temperature while the solubility of CO₂ decreases. They mentioned that the pH played a greater role as the fastest breakthrough of a wormhole happened at the lowest temperature (35 °C).

While previous studies have examined the influence of parameters such as salinity and temperature of a carbonated brine on the creation of wormholes in carbonate reservoirs, there is a noticeable gap in the literature regarding the impact of velocity on wormhole generation resulting from the interaction of carbonated brine with limestone. There are also no studies researching optimum injection rate for CO₂-saturated brine. This study aims to address this gap and enhance our understanding of the optimum velocity of carbonic acid injection into carbonate reservoirs. Also, the study highlights the impact of injection rate on the alteration of rock geomechanical and petrophysical properties. Through an examination of these factors, the study seeks to offer valuable insights into the mechanisms governing the generation of wormholes in carbonate formations induced by CO₂ injection.

2.2 Methodology

To better understand the impact of injection rate on wormhole generation in deep saline carbonate formations during storage of CO₂, six coreflooding experiments with varying flow rates were done. The experimental process is visually outlined in **Figure 1**. Firstly, six core samples were collected within the permeability range of 2.5-5 mD. These samples were subjected to extensive characterization involving the assessment of petrophysical and geomechanical properties. Furthermore, a coreflooding setup was used to inject carbonated

brine and wet CO₂ into the core samples. **Table 1** illustrates the initial characterization results for the core samples as well as the experimental conditions of each experiment. After the creation of partial or continuous wormholes, treated samples underwent micro-CT scanning to visualize the generated wormhole and calculate the wormhole volume for additional analysis. Notice that the same volume of CO₂-saturated brine was injected in all experiments (i.e., 700 ml brine). Through this experimental methodology, the study sought to explore the influence of different injection velocities on wormhole development during the storage of CO₂ process in saline aquifers.

To explain the flowrate impact and find the optimum injection rate for carbonated brine, six different injection rates were used: 10, 5, 2, 1, 0.5, and 0.25 cm³/min. The salinity level of the selected brine was 120,000 ppm, while the temperature for the experiments was 60 °C. A pore pressure of 2000 psi was utilized for the experiments. These conditions replicate the characteristics of the actual saline aquifer intended for CO₂ sequestration.

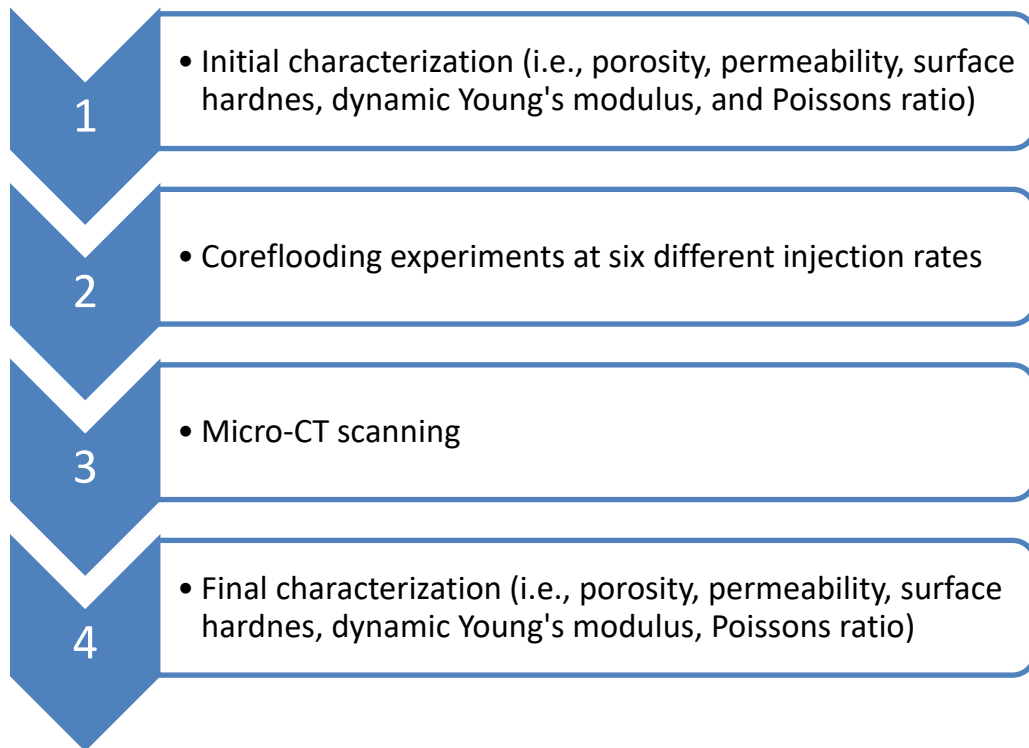


Figure 2.1. The steps for assessing changes in the mechanical and petrophysical characteristics of rocks due to CO₂-saturated brine injection.

Table 2.1. Design of experiments outlining the parameters for coreflooding conditions.

Sample (ID)	Temperature (°C)	Salinity (ppm)	Permeability (mD)	Porosity (%)	Pore Pressure (psi)	Injection Rate (cm³/min)
ME-1	60 °C	120,000	5	16.74	2,000	10
ME-2			2.55	15.72		5
ME-3			3.6	17.16		2
ME-4			3.16	16.91		1
ME-5			2.8	15.92		0.5
ME-6			3.11	16.57		0.25

2.2.1 Core Samples

The research concentrated on using typical outcrop samples of Indiana limestone (IL) for experimental inquiries. Six homogeneous cores, each with a diameter of 1.5 inches and a length of 3 inches, were collected for analysis. The average porosity of the samples was determined to be 16.5%, while the permeability was in the range of 2.5-5 mD. XRD analysis revealed that the sample composition was nearly 100% calcite.

2.2.2 Brine composition

The CO₂-saturated brine solution was prepared by mixing 70% brine with 30% pure-grade CO₂. **Table 2** outlines the composition of the brine, mirroring the typical composition

found in deep saline aquifers. In examining the influence of velocity, a consistent salinity level of 120,000 ppm was maintained throughout all the experiments.

Table 2.2. Brine composition with salinity levels comparable to those found in deep saline limestone aquifers.

Salt	Weight (g/L)
NaHCO ₃	0.27
Na ₂ SO ₄	0.29
NaCl	84.46
MgCl ₂	5.36
CaCl ₂	29.62

2.2.3 Experiments

Table 3 outlines the experiments and their corresponding data. To measure the porosity of the samples, a helium porosimeter was used, which works according to Boyle's law. Importantly, this device is limited to measuring effective porosity and only functions accurately under ambient conditions.

Mechanical properties were also assessed like the dynamic Young's modulus and Poisson ratio. We used the Autolab 500 to measure these through acoustic analysis, as the device generates shear and propagation waves within the samples. Measurements were taken at overburden pressures of 1000, 2000, 3000 and 4000 Psi (7, 14, 21, and 28 MPa

approximately). We then used the samples' density and the measured wave velocities to calculate Young's modulus and Poisson's ratio. This process was done both before and after CO₂-saturated brine injection, allowing to evaluate the changes rock mechanical properties. Moreover, a micro-CT scan was utilized to obtain a detailed wormhole structure after coreflooding. The micro-CT scan had a resolution of 49 μm , allowing us to see fine details. We then analyzed the CT image to calculate the volume of the wormhole within the samples.

Figure 2 illustrates the coreflooding setup from which the rock permeability was measured, and the CO₂-saturated brine was injected. In this system, CO₂ and brine are blended within the accumulator at a pressure of 1,200 psi until the mixture achieves a stable pressure, indicating equilibrium conditions. The 1 L accumulator, which contained 70% brine (having a salinity of 120,000 ppm) and 30% scCO₂, was subsequently placed in the oven. Following this, the chamber is heated to attain the target temperature of 60°C, causing an elevation in pressure stabilized at 1,500 psi before the syringe pump pressurizes the mixture in the accumulator to 2,000 psi. The injection at 2,000 psi occurred in all experiments after 1 hour of waiting to ensure CO₂/brine equilibrium. A pump then injects the mixture into a coreholder where the rock samples were placed, operating at six distinct injection rates. This coreholder is subjected to a confining pressure of 3,500 psi and is encased in a Viton sleeve to reduce any interaction between the live brine and the sleeve material. To further prevent external flow around the core sample, it is encased in a shrinkable tube. The outlet part of the coreholder is linked to a back-pressure regulator, which allows the flow when the pressure exceeds 2,000 psi, with the differential pressure monitored by a data logging system. Injection proceeds until the entire volume of the accumulator (1 liter) is dispensed.

Additionally, the coreholder is connected to an alternate conduit for injecting dead brine to evaluate rock permeability both prior to and following the coreflooding process.

Table 2.3. Experiments for characterization of core samples and their corresponding equipments

Porosity	Permeability	Dynamic Young's Modulus	Wormhole Visualization
Helium Porosimeter	Core-Flood	Autolab 500	Micro-CT – ZEISS VERSA XRM - 500

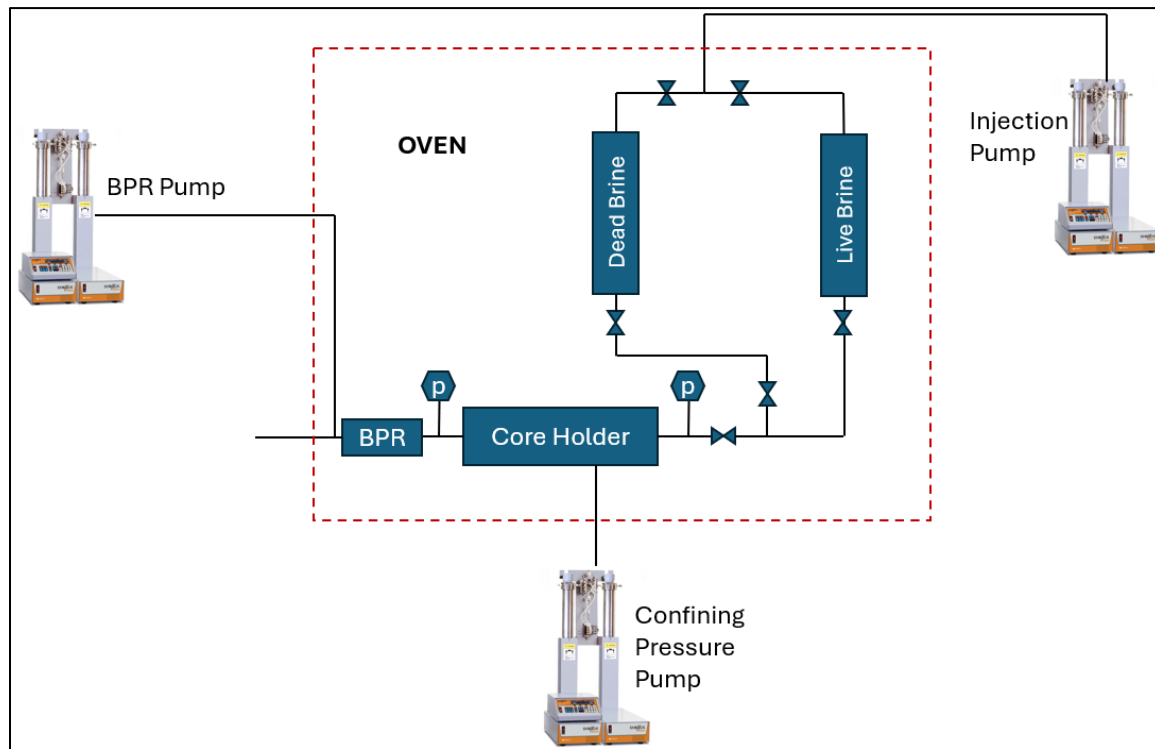


Figure 2.2. Coreflooding setup to inject live brine into the limestone samples

2.3 Results

2.3.1 Coreflooding

Six different injection rates were used in our experiments, with each rate applied to a separate sample. Samples were flooded at 60°C with a pore pressure of 2000 psi. The injection rates were: 10, 5, 2, 1, 0.5, and 0.25 cm³/min. The accumulator contained a 70% brine / 30% CO₂ mixture, ensuring full saturation of the liquid phase with CO₂ and resulting in a wet CO₂ gas phase. In all experiments, the injection sequence consisted of liquid-phase CO₂-saturated brine followed by wet CO₂. **Figures 3 and 4** illustrate the pressure variation during the injection of carbonated brine and wet CO₂. An initial differential pressure increase followed by a subsequent decline was observed. The differential pressure increase is attributed to the reaction between carbonic acid and the limestone samples (Mustafa et al., 2021). The decline indicates the formation of a non-resistant flow pathway (i.e., wormhole). Notably, wormhole breakthrough (i.e., full penetration of the sample) occurred when the pressure drop approached zero. Notice that the 10 and 5 cm³/min experiments did not breakthrough with the injection of 700 mL of carbonated brine. To estimate the PVBT, a linear line is extended. This method overestimates the actual PVBT by 10 to 15% when we apply it to other experiments with actual breakthrough. The reason for that is when the sample is near the breakthrough point, there is a rapid decrease in pressure difference (see **Figure 4**).

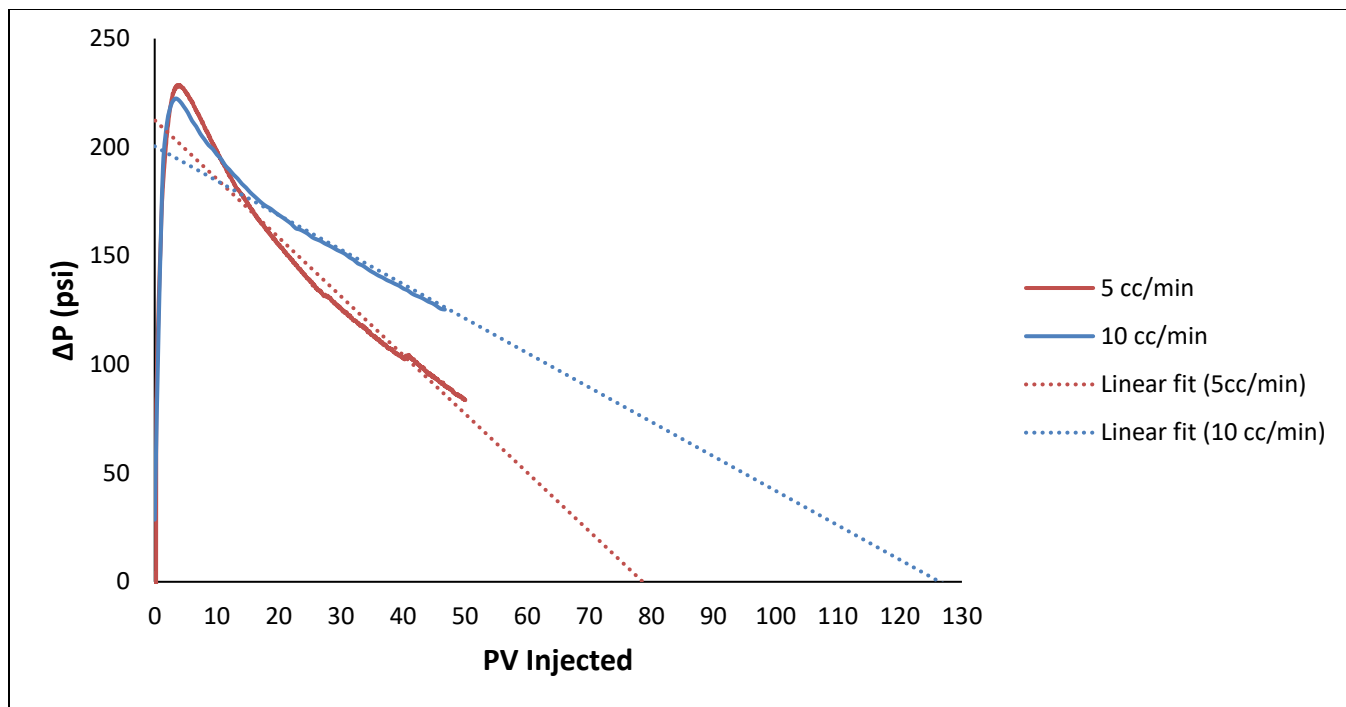


Figure 2.3. Coreflooding outcomes in terms of pressure drop resulted from treating two Indiana limestone samples at 5 and 10 cm^3/min

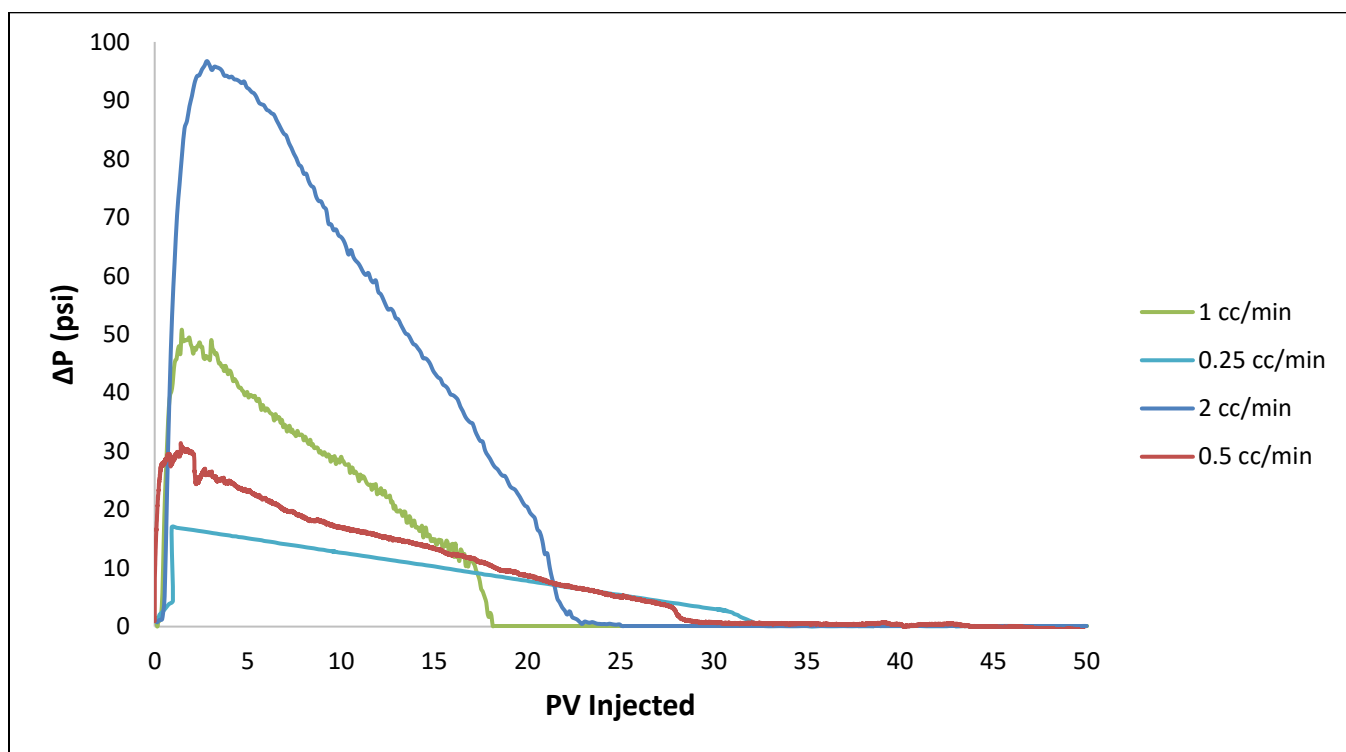


Figure 2.4. Coreflooding outcomes in terms of pressure drop resulted from treating four Indiana limestone samples at 2, 1, 0.5 and 0.25 cm^3/min

Figure 5 illustrates the pore volume to breakthrough (PVBT) for each experiment. PVBT represents the volume of fluid required for complete wormhole penetration of the sample, normalized by the sample's pore volume. This value is determined from **Figures 3 and 4**, where it corresponds to the injected pore volume at the point of zero pressure drop. It is noticeable that around $1 \text{ cm}^3/\text{min}$, the wormhole penetrates the sample more rapidly. As an example, it required only 18 pore volumes (PVs) at a flow rate of $1 \text{ cm}^3/\text{min}$, 25 PVs at $2 \text{ cm}^3/\text{min}$, 28 PVs at $0.5 \text{ cm}^3/\text{min}$, and 126 PVs at $10 \text{ cm}^3/\text{min}$.

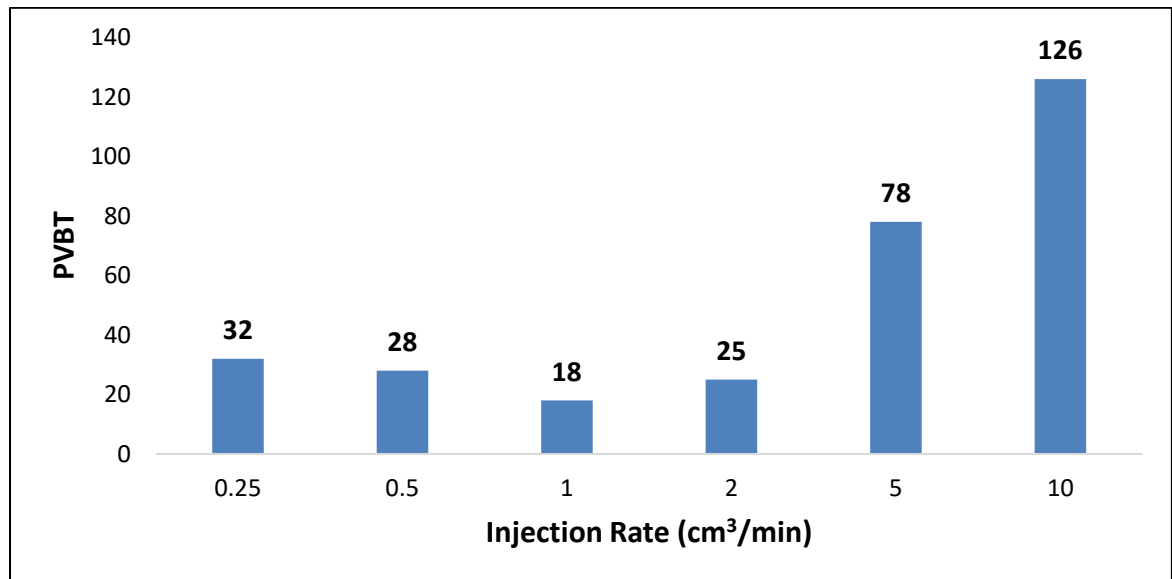


Figure 2.5. The pore volume required to achieve breakthrough (PVBT) at different treatment velocities.

2.3.2 Petrophysical Properties

Injection of CO_2 -saturated brine caused changes in petrophysical properties, specifically porosity and permeability, due to the ensuing chemical reaction and wormhole formation.

Figure 6a demonstrates porosity changes for each sample. No clear trend exists between the porosity change and the live brine injection rate. The deviation from the expected trend in the $10 \text{ cm}^3/\text{min}$ experiment may be attributed to the core sample's higher permeability (twice that of other samples), potentially resulting in reduced reactivity. If we consider the

10 cm³/min data as an outlier, a general trend emerges: porosity increase correlates positively with increasing injection rate. **Figure 6b** reveals a linear relationship between wormhole size and porosity change. The largest wormhole volume was observed at the injection rate of 5 cm³/min, while the smallest occurred at 0.25 cm³/min. However, when considering only continuous wormholes, the 1 cm³/min case exhibited the thickest wormhole with the highest volume. In cases where continuous wormholes were formed, the pressure drop approaches zero, suggesting near-infinite permeability. In the 10 cm³/min and 5 cm³/min experiments, while wormholes did not achieve a breakthrough, they still significantly increased permeability. The permeability doubled in the 10 cm³/min experiment and nearly quadrupled in the 5 cm³/min experiment, rising from 2.5 mD to 8.5 mD (**Figure 7**).

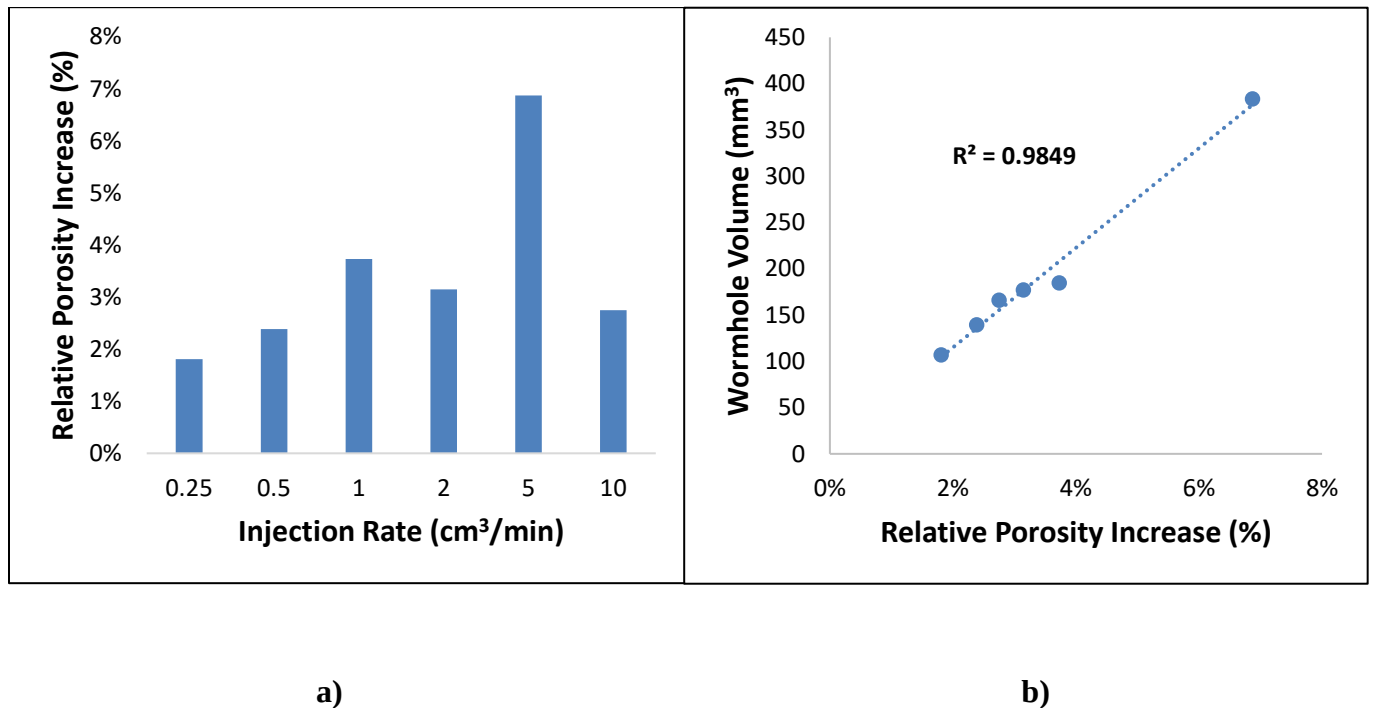


Figure 2.6. (a) The variations in the porosity with respect to treatment injection rate and (b) the cross plot illustrating the correlation between wormhole volume and porosity change

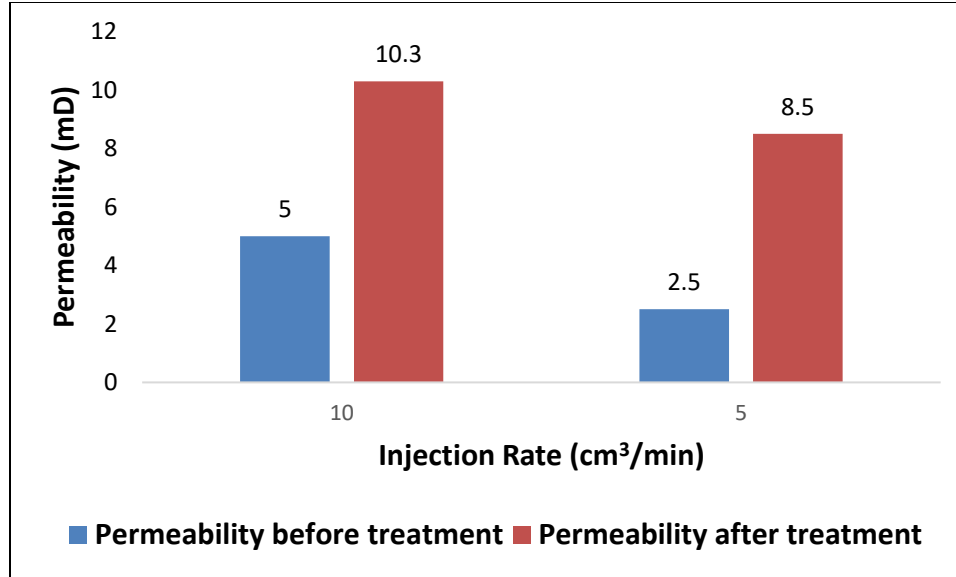
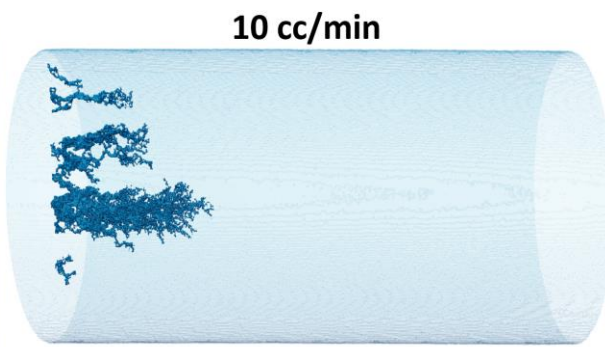


Figure 2.7. Permeability changes in samples with half wormholes

Figure 8 presents images of the samples at the inlet and outlet faces. The presence of wormholes within the samples is highlighted by red circles. Moreover, Micro-CT scan images revealed distinct differences in wormhole shape based on flow rate. Higher flow rates produced ramified/branched wormhole structures, while lower flow rates resulted in dominant, single-channel wormholes. The thickest continuous wormhole was observed in the 1 cm³/min experiment, with the thinnest occurring in the 0.25 cm³/min experiment. When comparing total wormhole volumes across all samples, the 5 cm³/min experiment exhibited the highest value at 383 mm³, while volumes for other samples ranged from 106 to 184 mm³. **Table 4** presents the measured wormhole volume of each experiment along with the corresponding diameter, calculated assuming a cylindrical wormhole geometry.



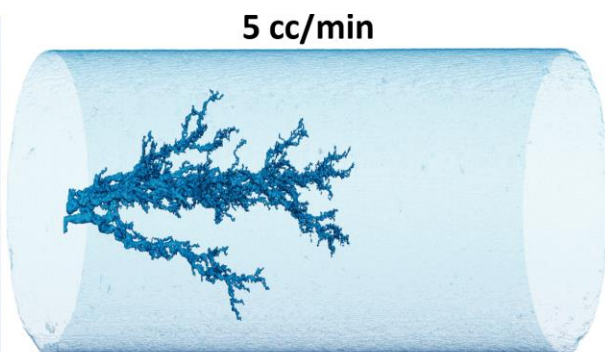
Inlet



Outlet



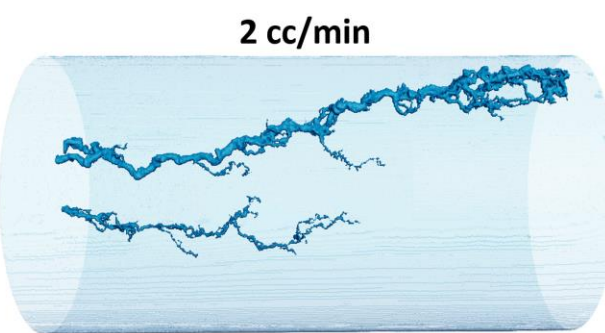
Inlet



Outlet



Inlet



Outlet

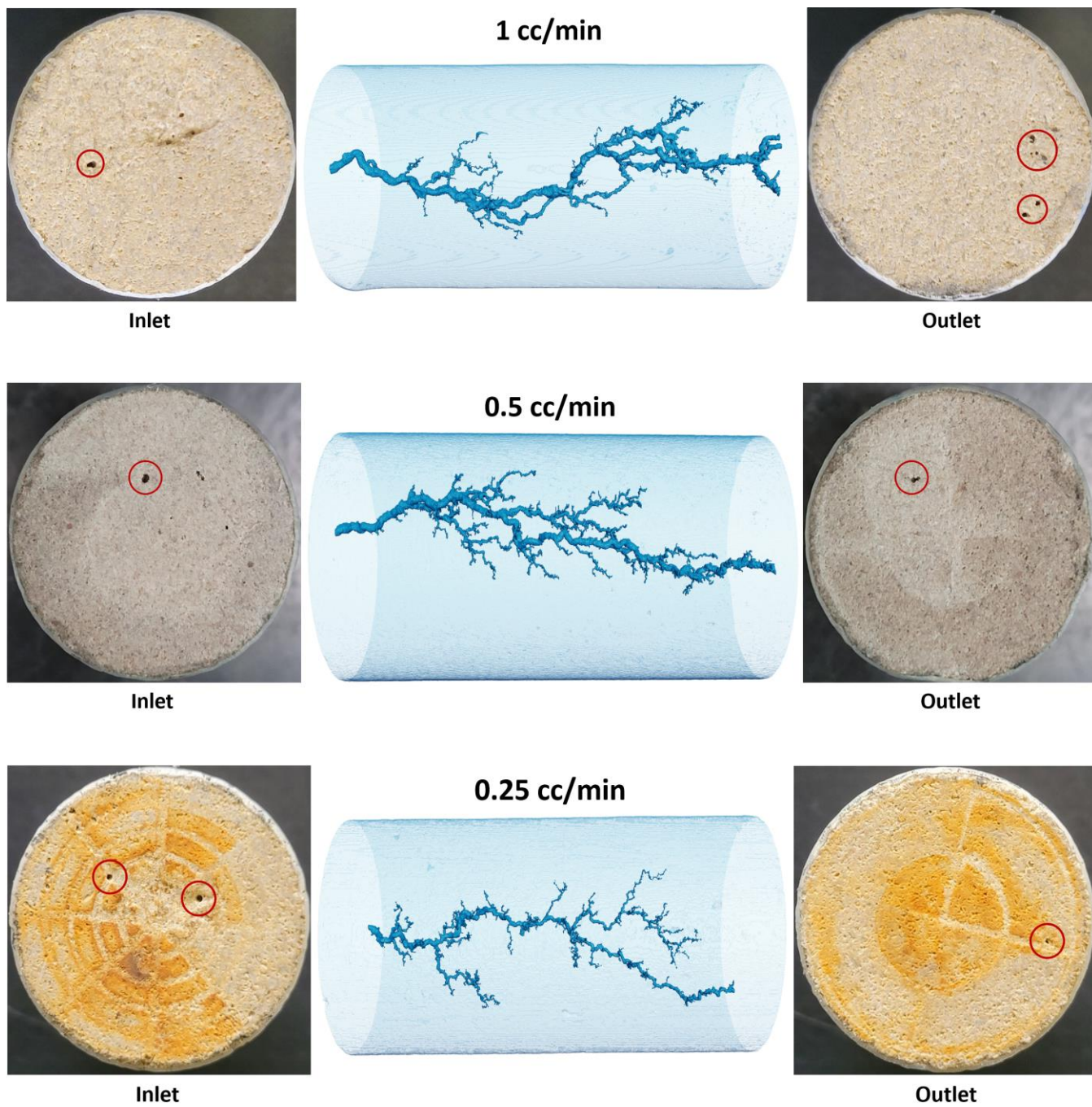


Figure 2.8. Images of the treated samples at the inlet and outlet and micro-CT scan images showing the wormhole structure

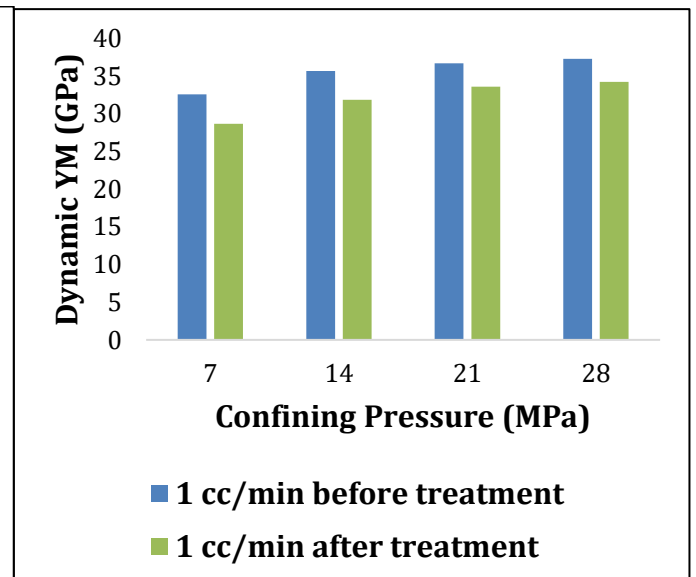
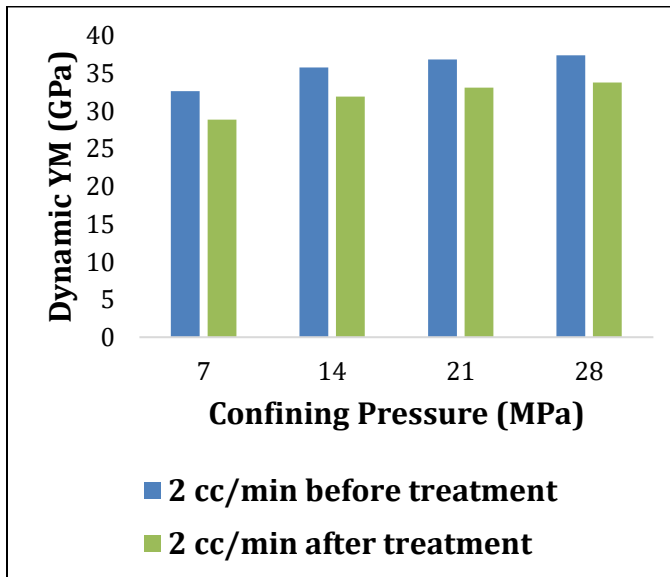
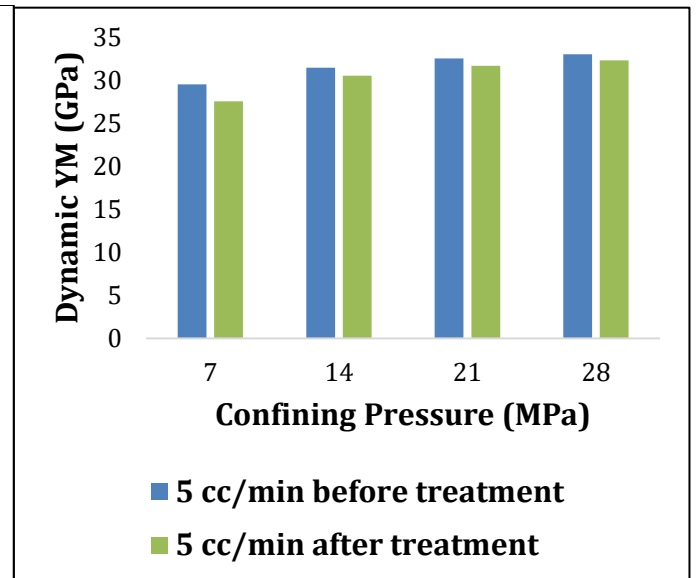
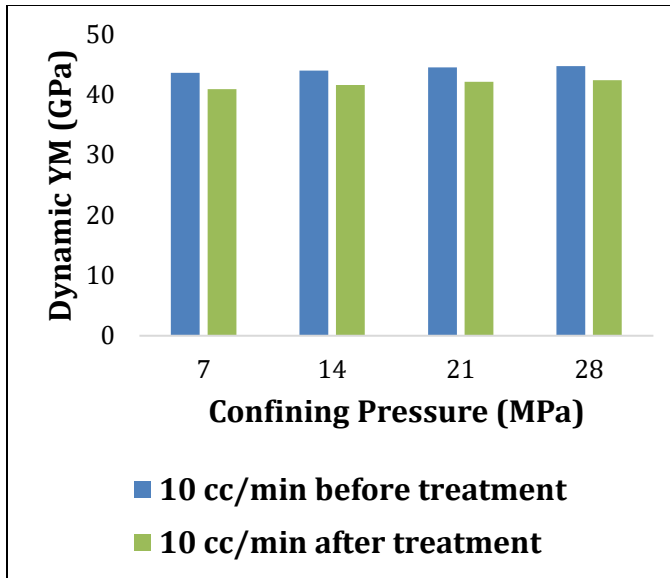
Table 2.4. Wormhole volume and diameter assuming cylindrical wormhole shape

Injection Rate (cm³/min)	Wormhole Volume (mm³)	Wormhole Diameter (mm)
10	166.09	2.87
5	383.36	3.35
2	177.14	1.71
1	184.72	1.78
0.5	139.45	1.55
0.25	106.68	1.33

2.3.3 Mechanical Properties

Figure 9 demonstrates the relationship between dynamic Young's Modulus (YM) and confining pressure for the four samples, both before and after CO₂-saturated brine injection. As expected, increasing confining pressure resulted in higher YM values, likely due to the compression of pore spaces and subsequent reduction in porosity. Moreover, all samples exhibited a significant YM decrease following their interaction with CO₂-saturated brine.

Figure 10 compares Young's Modulus (YM) reduction in samples with continuous wormholes (**Fig. 10a**) versus those with partial wormholes (10 and 5 cm³/min experiments, **Fig. 10b**). At a low confining pressure of 7 MPa, samples with continuous wormholes exhibit a greater reduction in YM than those with partial wormholes. The CT image for the 10 cm³/min sample reveals a wormhole extending through only 20% of the sample, explaining the minimal difference in YM reduction between low and high confining pressures. The 5 cm³/min sample demonstrated a higher YM decrease than the 10 cm³/min sample at 7 MPa, but this reduction decreased significantly with increased confining pressure. Unexpectedly, despite its longer exposure to live brine, the 0.25 cm³/min experiment exhibited the smallest YM reduction among samples with continuous wormholes. This counterintuitive finding may be explained by the significantly thinner wormhole generated in this experiment. Meanwhile, the 0.5 cm³/min sample exhibited the highest reduction at 7 MPa, which then decreased to less than that of the 2 cm³/min sample at 28 MPa. The 1 cm³/min and 2 cm³/min samples yielded similar results. The 2, 1, and 0.5 cm³/min experiments exhibited similar reductions in YM at 28 MPa. This similarity could be attributed to their comparable wormhole shapes, volumes, and diameters.



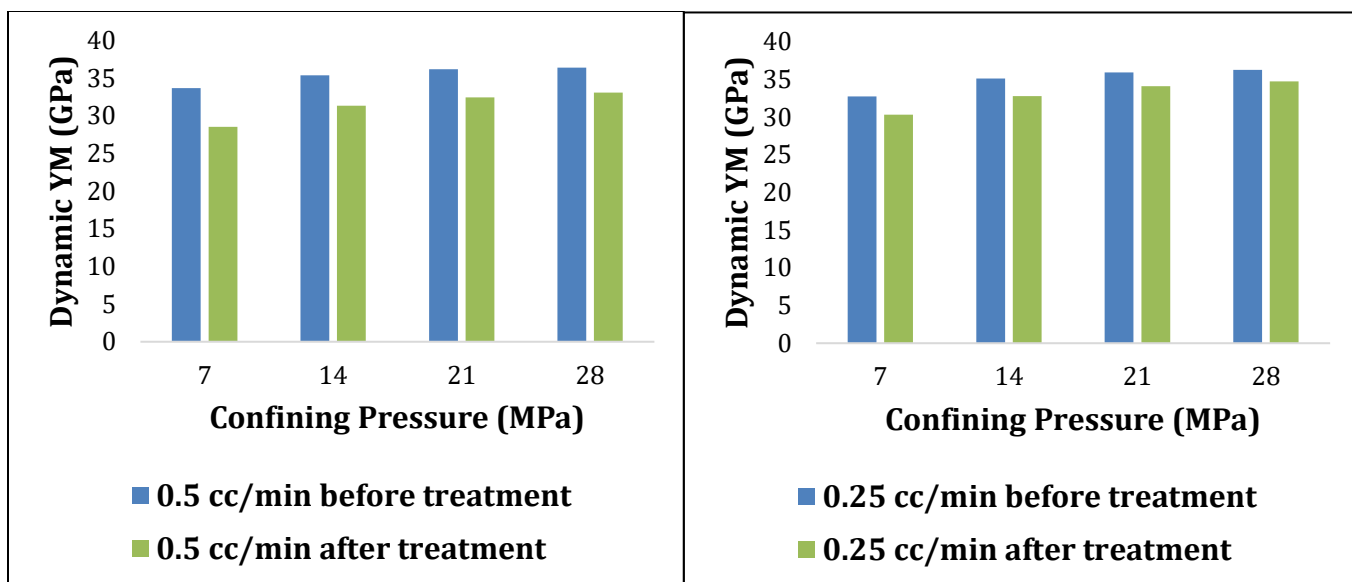
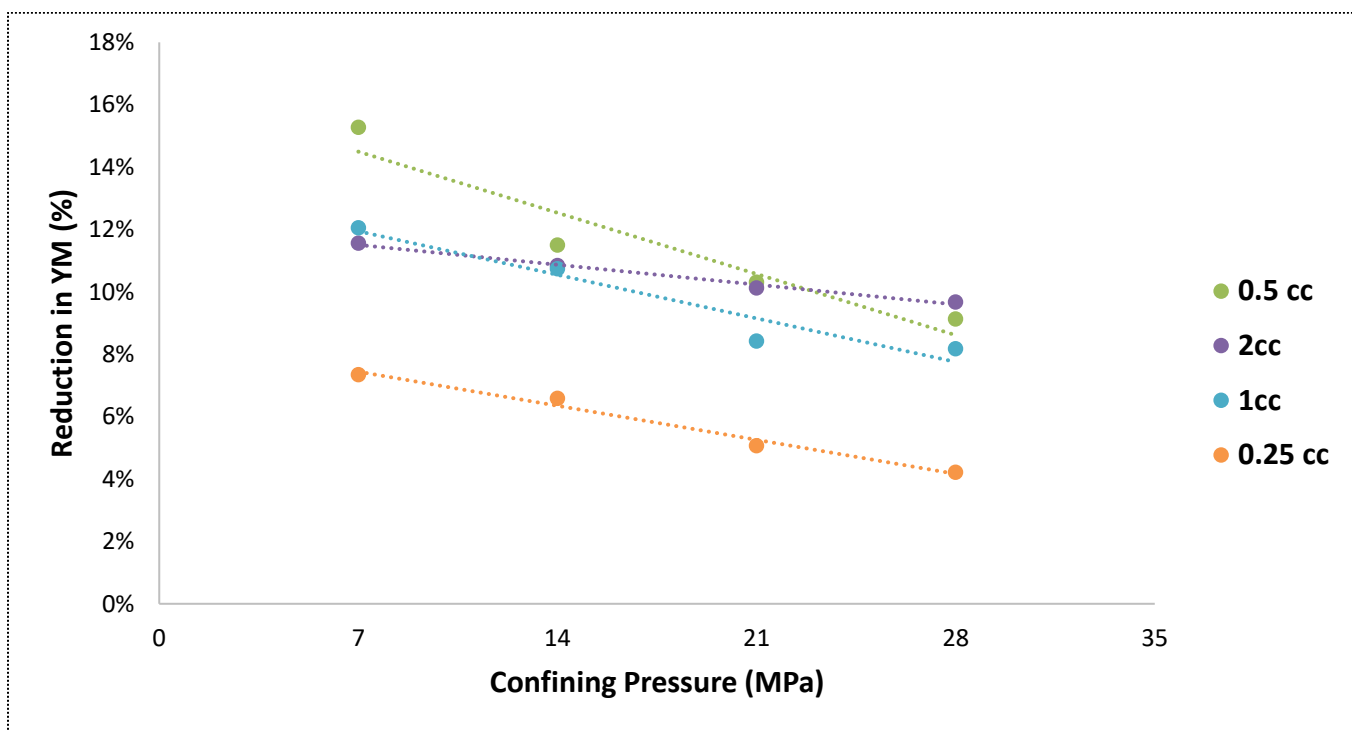
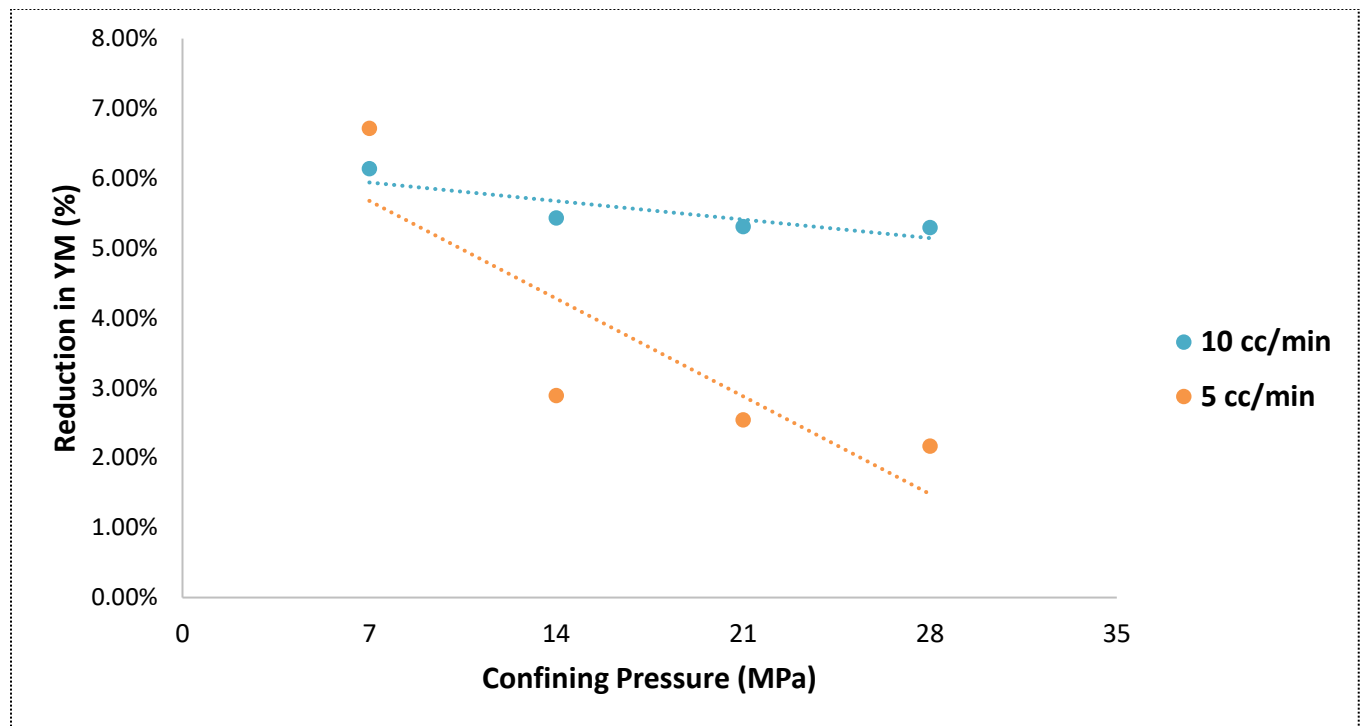


Figure 2.9. Change in Young's Modulus of samples following live brine injection



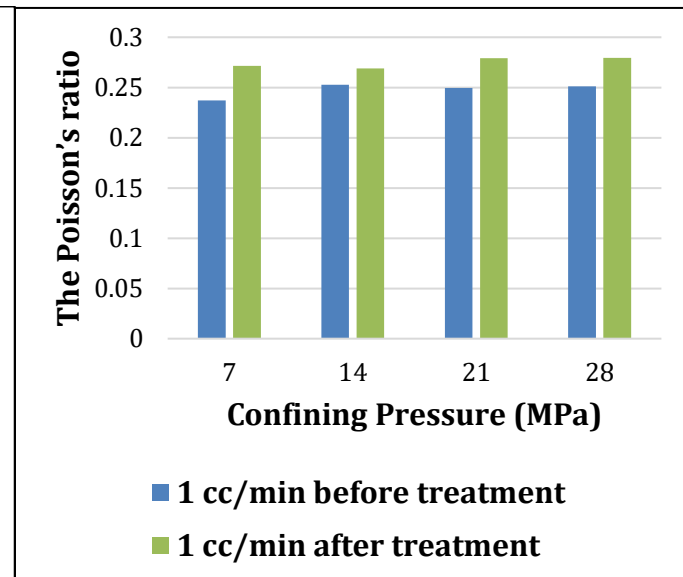
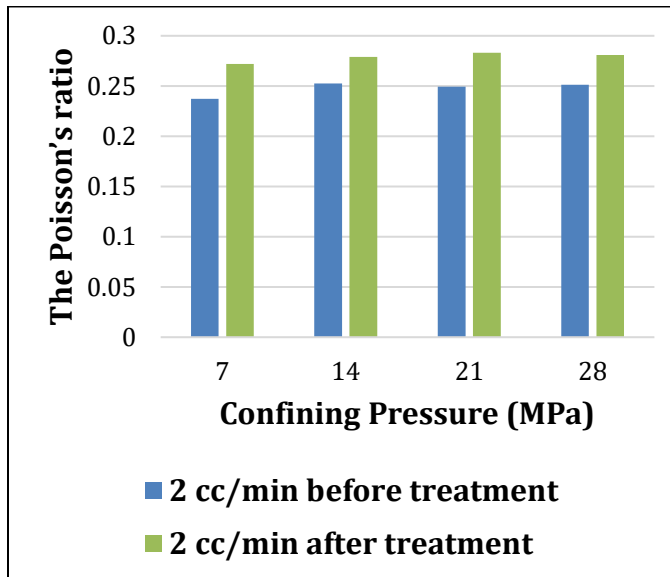
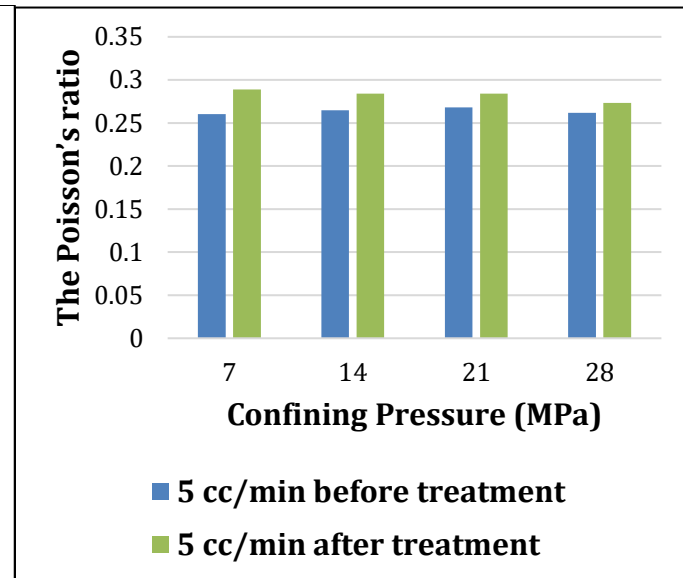
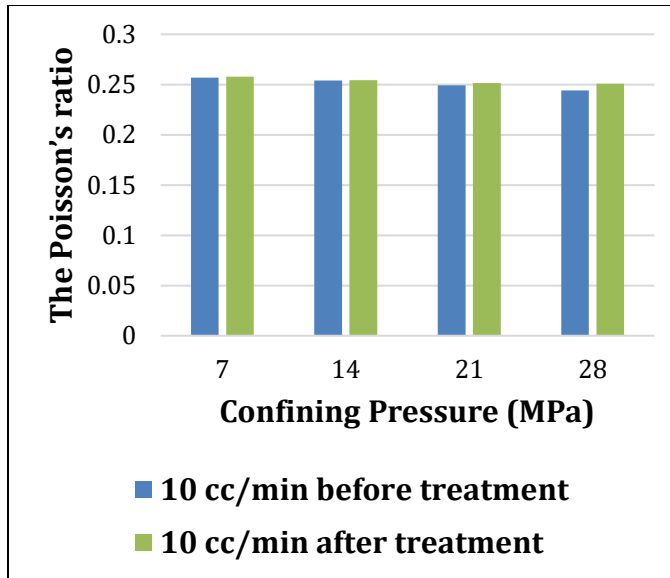
(a)



(b)

Figure 2.10. Young's Modulus reduction (%) at different confining pressures and injection rates

Figure 11 illustrates the Poisson's ratio before and after exposure to CO₂-saturated brine and wet CO₂. Notably, the trend observed in Poisson's ratio contrasts with that of Young's Modulus (YM), exhibiting an increase after treatment. Poisson's ratio, typically ranging between 0 and 0.5, quantifies a material's tendency to deform perpendicular to an applied load. The observed increase in Poisson's ratio for the intact samples suggests that the rock became softer following the reaction with carbonic acid.



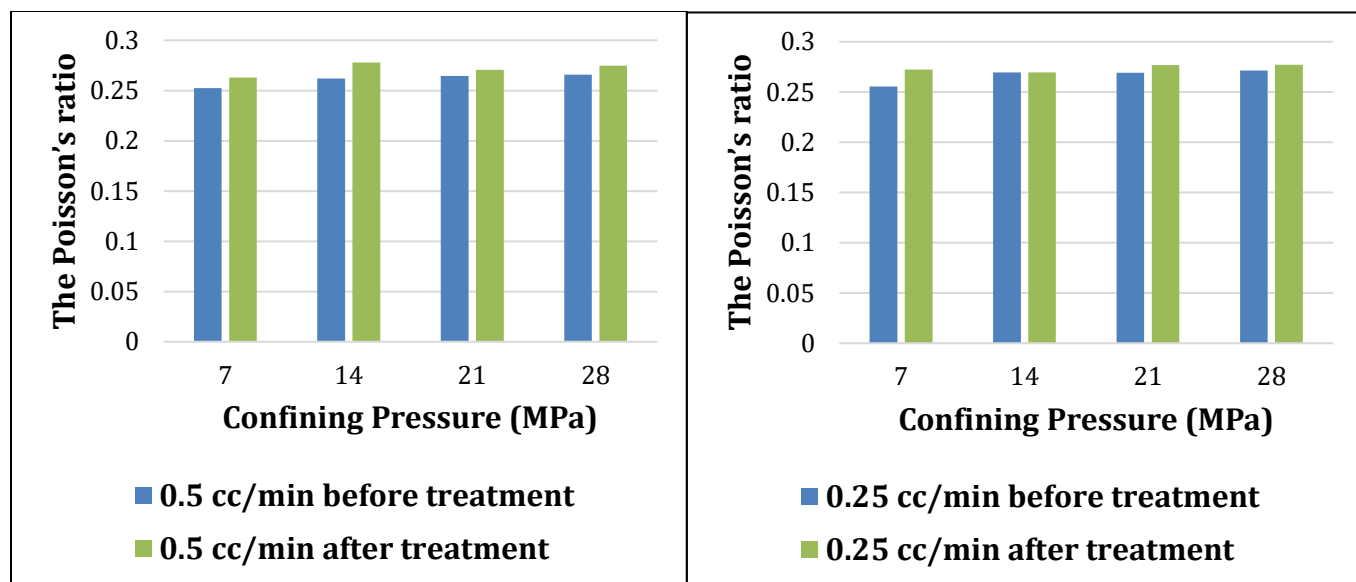


Figure 2.11. Comparison of samples' Poisson's ratio before and after live-brine injection

2.4 Discussion

This article demonstrates the significant influence of CO₂-saturated brine injection rate on its reactivity with carbonates. Consistent with expectations, higher flow rates (10 and 5 cm³/min) resulted in ramified wormhole structures, while lower rates yielded dominant, single-channel wormholes. **Figure 12** demonstrates the curve fit of our experimental data to the Buijse & Glasbergen model, facilitating the determination of the actual optimum velocity. A strong correlation is observed for velocities exceeding the optimum, while a weaker correlation exists for values below the optimum. The graph indicates an optimum velocity of 0.4 cm/min, corresponding to a calculated optimum injection rate of 0.75 cm³/min. Curve-fitting experimental data to the Buijse and Glasbergen model revealed a strong correlation for injection rates exceeding the optimum velocity but a poor relationship for velocities below the optimum. This discrepancy is likely attributed to the model's original development for strong acids, such as HCl. To the best of our knowledge, existing literature lacks investigations on optimum injection rates for weak acids using the

Buijse and Glasbergen model. Moreover, there is a dearth of experimental research on matrix acidizing using carbonic acid. While studies have been conducted on acetic acid, EDTA (ethylenediaminetetraacetic acid), CDTA (cyclohexanediaminetetraacetic acid), and GLDA (glutamic acid diacetate), none have attempted to fit experimental data from CO₂-saturated brine to this model (Dong et al., 2017; Fredd & Fogler, 1998; Huang et al., 2000; M. Mahmoud et al., 2017; M. A. Mahmoud et al., 2010). To address this gap, a reevaluation of the model for weak acids is necessary. Experimental data from weak acids should be curve-fitted to the model to determine if the observed differences are unique to carbonated brine or common to other weak acids. If necessary, modifications should be incorporated to extend the model's applicability to CO₂-saturated brine.

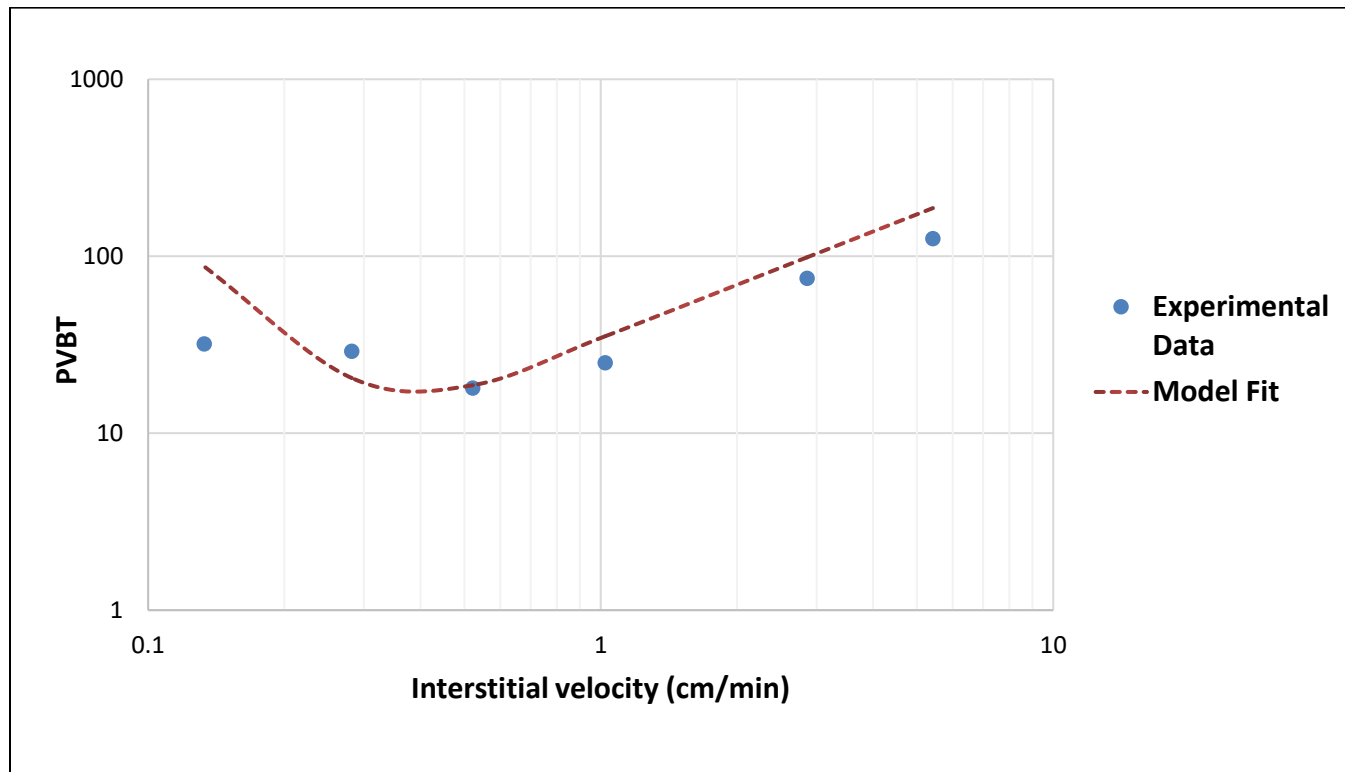


Figure 2.12. Curve fit of our experimental data to Buijse & Glasbergen model

As noted in the introduction, Fredd & Fogler (1998) established an optimal Damkohler number of 0.29 for various acidic fluids. Mathematically, the Damkohler number (N_{Da}), under the assumption of reaction-kinetics limited conditions, can be expressed as:

$$N_{Da} = \frac{\pi v k_r L D}{q}$$

In this equation, v represents the stoichiometric coefficient (a dimensionless quantity), k_r denotes the reaction rate constant (expressed in cm/s), L refers to the core characteristic length, typically the core's half-length (in cm), D is the wormhole diameter (in cm), and q symbolizes the injection rate (measured in cm³/s).

For our calculations the reaction rate constant considered to be 8.3×10^{-5} cm/s at 60° C and 2000 psi according to Peng et al. (2015). For accurate normalization, the PVBT should be divided by the specific optimum PVBT determined for the given rock type and fluid system. Consequently, optimum PVBT for our experiments was 18. When plotted against the generalized curve, carbonic acid exhibits a markedly different behavior compared to other acids (**Figure 13**). Our study found a significantly lower optimal Damkohler number of 0.01 for carbonic acid. This could be attributed to the low reactivity/reaction kinetics.

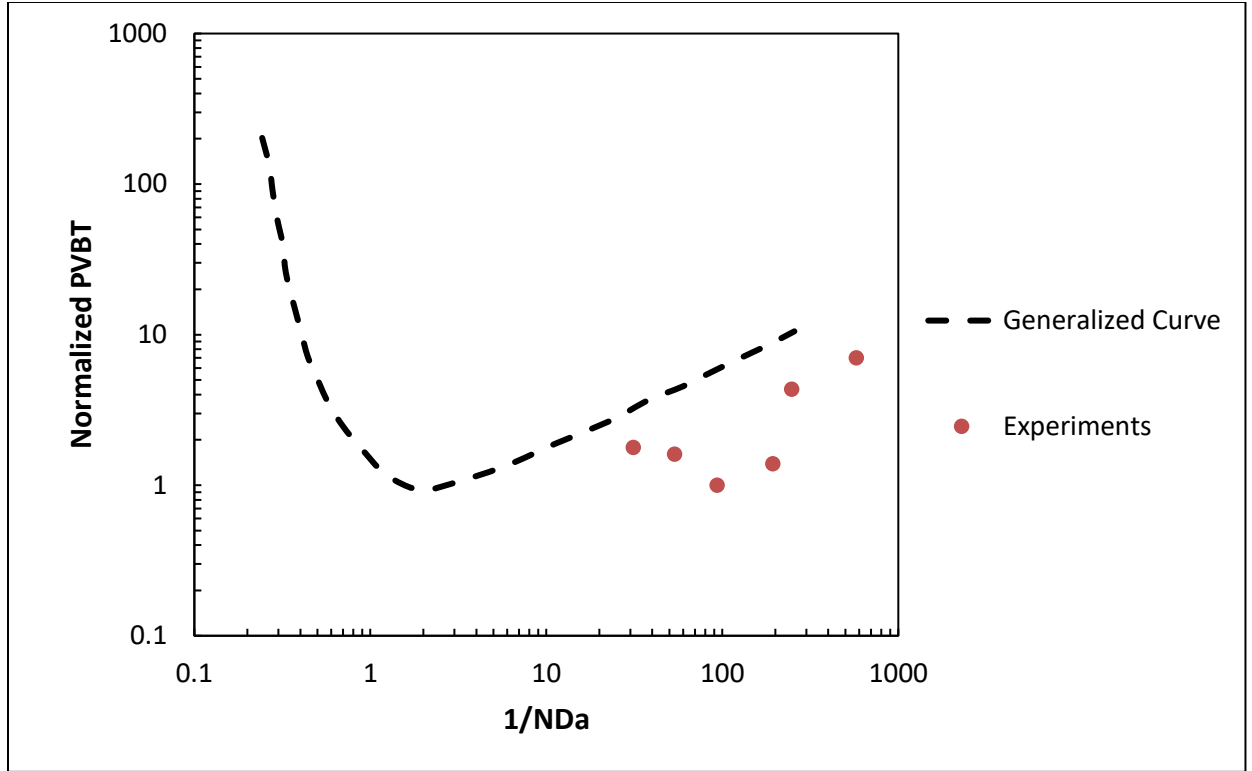


Figure 2.13. Plotting the normalized pore volume to breakthrough (PVBT) against the inverse of the Damköhler number for both the generalized curve and the experimental data from this study

Based on our results, we can suggest the following guidelines. In reservoir zones with low flow rates (around $0.5 \text{ cm}^3/\text{min}$ or less) and CO_2 injection volumes less than one pore volume (PV), we expect minimal impact on rock integrity. Near the wellbore, high flow rates ($>5 \text{ cm}^3/\text{min}$) are preferable to minimize CO_2 -rock interaction and reduce potential rock failure. This recommendation is supported by the observation that Young's Modulus (YM) changed minimally, indicating that the rock remained stable after CO_2 injection. Lastly, for tight reservoirs, lower flow rates may be advantageous to improve CO_2 injectivity. Moreover, while increasing porosity and permeability can enhance CO_2 storage capacity, it's important to note potential trade-offs. Increased permeability may accelerate CO_2 plume migration, potentially impacting structural trapping mechanisms. Conversely,

increased porosity can lower capillary pressure and residual trapping, which can enhance structural trapping effectiveness.

Conclusions

The investigation disclosed the influence of the injection rate of CO₂-saturated brine on the rate of wormhole formation and the changes in petrophysical and mechanical properties. The research was performed using Indiana limestone samples to simulate the process of CO₂ injection in deep saline limestone aquifers. The coreflooding experiments were conducted at 60°C with a brine salinity of 120,000 ppm to emulate conditions typical of a saline aquifer reservoir. Six injection rates (10, 5, 2, 1, 0.5 and 0.25 cm³/min) were utilized to find the optimum injection rate for the carbonated brine. These are the main conclusions that can be drawn from this study:

1. Our experiments established an optimal injection rate of 1 cm³/min for efficient wormhole formation. Additionally, we performed curve fitting of the experimental data to the Buijse & Glasbergen model, which yielded an optimum injection rate of 0.75 cm³/min through back-calculation. However, a poor correlation exists for velocities below the optimum, suggesting potential modifications to the model may be necessary to accurately predict behavior in the context of carbonated brine.
2. Experiments revealed that injecting CO₂-saturated brine at various velocities induced changes in the petrophysical properties of limestone samples, particularly porosity and permeability. Increased injection rate generally resulted in higher porosity, with a linear relationship observed between porosity change and wormhole volume. The injected volume (700 mL) was insufficient for wormhole breakthrough in the 10 cm³/min and 5 cm³/min experiments, although permeability

still increased. In samples with continuous wormholes, permeability is considered to approach infinity.

3. The highest reduction in rock YM was observed at 2, 1 and 0.5 cm³/min experiments overall. Unexpectedly, the experiment conducted at a flow rate of 0.25 cm³/min, despite its longer exposure to live brine, exhibited the smallest reduction in Young's Modulus (YM) among samples featuring continuous wormholes.
4. Our results suggest that low flow rates (around 0.5 cm³/min) and limited CO₂ volumes (<1 PV) in the reservoir interior minimize impact on rock integrity. Near the wellbore, high flow rates (>5 cm³/min) reduce CO₂-rock interaction, maintaining rock stability as indicated by minimal changes in Young's Modulus. For tight reservoirs, lower flow rates may improve injectivity.
5. Increasing porosity and permeability can enhance storage capacity, consider potential trade-offs: increased permeability may accelerate plume migration, while increased porosity could enhance structural trapping through lower capillary pressure.

CHAPTER 3

Impact of Pore Pressure on Wormhole Generation Due to CO₂-Saturated Brine Injection

Abstract

Deep saline aquifers are promising locations for carbon sequestration, but the impact of CO₂ injection on rock properties requires careful investigation. This study will examine the effects of CO₂-saturated brine injection on limestone, specifically analyzing how pore pressure influences wormhole formation and subsequent changes in petrophysical and geomechanical properties. Four Indiana limestone samples, each with dimensions of 1.5 inches in diameter and 3 inches in length, were utilized. These samples exhibited an average porosity of 15.7% and an average permeability of 2.6 mD. During the experiments, the samples were subjected to one of selected pore pressure values (4,000, 3,000, 2,000, and 1,500 psi) and a temperature of 60°C, with a brine concentration of 120,000 ppm mixed with CO₂ at a ratio of 70:30. Notice that the pressure was kept in the accumulator at 1,200 psi initially before compressing it to the desired pressure to maintain the same mass of CO₂ in all experiments. An injection rate of 1 cm³/min was employed for the coreflooding experiments. Before and after coreflooding, Young's modulus (YM) and Poisson's ratio of the samples were measured at various confining pressures. Additionally, the porosity, permeability, and surface hardness of the treated samples were assessed. A micro-CT scan was employed to visualize the generated wormholes and quantify their volumes. Our study demonstrated that among the four tested injection pressures, 2,000 psi yielded the lowest PVBT. No clear trend was observed between PVBT and pore pressure. However, a strong

correlation emerged between the mechanical properties of treated samples and pore pressure values. The investigation established that increasing injection pressure results in greater damage to the core, as evidenced by reductions in both surface hardness and dynamic Young's modulus.

Keywords; Pore Pressure; Live brine; CO₂ Storage; Wormhole

3.1 Introduction

Carbon sequestration aims to capture and securely store carbon dioxide (CO₂) to prevent its atmospheric release and help mitigate climate change. This method has been implemented since the 1990s, with Norway launching the first major carbon capture, utilization, and storage (CCUS) project. There are three primary methods for carbon sequestration. (J. G. Kaldi et al., 2009; Lal, 2008b; Metz et al., 2005b; B. A. Seibel & Walsh, 2001; Thomson, Izaurralde, et al., 2008). The first method, terrestrial sequestration, enhances the natural ability of plants and soils to absorb and store CO₂ through activities like reforestation, improved agricultural practices, and soil management. The second method, oceanic sequestration, involves depositing CO₂ in the ocean, where it can dissolve in seawater or be utilized by marine life. The third method, geological sequestration, is particularly promising and involves injecting CO₂ deep underground into geological formations such as depleted oil and gas reservoirs, saline aquifers, or unmineable coal seams. (Ajayi et al., 2019a). This approach is considered highly effective in combating global climate change as it directly reduces atmospheric CO₂ concentrations, thereby mitigating environmental impacts.

Saline aquifers are the primary reservoirs targeted for CO₂ sequestration due to their vast capacity and favorable geological properties. However, other storage methods, such as depleted oil and gas reservoirs and coal seams, present limitations (Luo et al., 2022). As atmospheric CO₂ concentrations continue to rise, carbon sequestration in deep limestone aquifers has emerged as a potential solution for carbon capture and storage (CCS). These geological formations offer several advantages, including vast storage capacity, the ability of limestone to react with CO₂ for permanent trapping, the potential to repurpose existing oil and gas infrastructure, and their global prevalence. However, the utilization of deep limestone aquifers for CCS also presents challenges, such as the risk of CO₂ leakage, potential groundwater contamination due to acidification, the possibility of induced seismicity, and high costs associated with site assessment, infrastructure development, and monitoring. It is crucial to acknowledge that carbon sequestration should be implemented as part of a broader climate change mitigation strategy, incorporating various approaches to effectively address this global challenge (Al-Dhafeeri et al., 2024; Bachu, 2000; Metz et al., 2005b; Rasool et al., 2023).

The sequestration of CO₂ in saline water formations has the potential to trigger the formation of wormholes within limestone structures. This process is primarily driven by the presence of mild carbonic acid, which forms as a result of CO₂ dissolving in the water phase. The acidic environment created by this dissolution promotes the dissolution of limestone, leading to the development of wormhole networks. (Aldhafeeri et al., 2023; Al-Yaseri et al., 2022; Espinoza et al., 2018; Major et al., 2018; Selvadurai et al., 2017). The formation of wormholes resulting from the injection of CO₂ leads to notable alterations in the petrophysical and mechanical properties of the formation rock, including porosity and

permeability. Numerous researchers have undertaken experimental and modeling studies to comprehend the influence of various parameters on wormhole generation induced by acids. However, there is a scarcity of studies focused on comprehending this phenomenon in the context of pore pressure impact during CO₂ sequestration.

Cheng et al. (2017) conducted research to understand how the generated CO₂ during carbonate acidizing with HCl would affect wormhole propagation. They conducted coreflooding experiments with varying pressures, temperatures, and injection rates (500 to 3000 psi; 70 and 150 °F; 1.2, 1.5, 3, 5, 8, and 12 cm³/min). Experiments indicated that at low injection rates, the presence of CO₂ in a gaseous phase significantly hampers the efficiency of wormhole propagation, leading to an observable increase in the diameter of the formed wormholes. When injection rates surpass the optimal level, the impact of CO₂ becomes less noticeable, especially at elevated temperatures. Zakaria et al. (2015) offer a valuable investigation into the link between carbonate pore structure and the success of acid stimulation. Their work across six different formations employed comprehensive analysis (thin-sections, mercury injection, NMR (Nuclear magnetic resonance), XRD to characterize pore heterogeneity and mineralogy. Importantly, they introduce the parameter f' , representing the fraction of the pore structure that actively contributes to flow. This parameter, as demonstrated by over 30 acid-coreflood experiments, is crucial in understanding and predicting acid behavior in carbonate rocks. Their results highlight the impact of pore classes on acid response, underscoring the potential for improved hydrocarbon recovery through tailored acidization strategies based on detailed pore structure analysis.

Dos Santos Lucas et al. (2023) did a review to find out how different parameters affect the generation of wormholes in carbonate rock samples during acidizing with HCl. The main parameters they discussed were concentration of acid, reaction rate, flow rate, temperature, dimension of core samples, and heterogeneity. The primary parameters under discussion included the concentration of acid, reaction rate, flow rate, temperature, dimensions of core samples, and heterogeneity. The findings suggest that increasing acid concentration leads to a downward shift in the PVBT (pore volume to breakthrough) plot, reducing the breakthrough volume and altering the optimal flow rate. Moreover, the flow rate is closely linked to the type of wormhole generated, with various dissolution patterns observed. The reaction rate is highlighted as a crucial factor influencing wormhole formation, with Damkohler and Peclet numbers providing valuable insights into its dimensionless approach encompassing advection, diffusion, and reactivity. Furthermore, the geometry of the reactive flow significantly impacts dissolution patterns. Core properties, such as diameter and saturation, also affect PVBT, albeit core length seems to have minimal impact, especially in experiments over 6 inches. Lastly, temperature exhibits varied effects on limestone and dolomite formations, further emphasizing the nuanced considerations in matrix acidizing operations.

Zareei et al. (2022) investigate the impact of carbon dioxide injection on carbonate rocks' petrophysical properties, crucial for optimizing CO₂ storage strategies in saline aquifers. Their research identifies how CO₂ sequestration affects rock-fluid geochemical interactions, particularly focusing on the dissolution/precipitation of minerals and its influence on formation properties like flow and injectivity. Employing core flooding experiments across a spectrum of rock mineralogies and distances from the injection point,

they applied both qualitative and quantitative assessments, including X-ray Diffraction (XRD), CT scanning, porosity, and permeability measurements. Their findings reveal a significant permeability increase in rocks with minerals soluble in acidic environments, attributed to the formation of wormholes. Conversely, rocks composed of acid-insoluble minerals exhibited a permeability decrease. The study highlights the differential impact of CO₂ injection based on the rock's mineral composition and proposes that managing these geochemical interactions is essential for the success of CO₂ sequestration efforts. Khather et al. (2022) investigated how carbon dioxide (CO₂) injection impacts oil recovery from carbonate rocks. Three different rock samples with varying permeabilities were used. CO₂ and brine were injected alternately after initial water flooding. X-ray scans showed changes in the rock structure, porosity, and permeability due to CO₂ interactions. CO₂ injection led to over 30% more oil recovery compared to water flooding alone. The lowest permeability sample had the smallest overall oil recovery but the largest increase in permeability, indicating significant rock dissolution and formation of preferential flow paths (wormholes). The study suggests that low oil recovery in tight rocks is mainly due to wormhole formation, as they allow CO₂-saturated brine to bypass trapped oil.

Al-Dhafeeri et al. (2024) conducted a study to understand the brine salinity impact of a carbonated brine on the generation of wormholes. Furthermore, they analyzed the effects of the generated wormholes on the properties of a rock. They found out that the fastest and the thickest wormhole formed with the lowest salinity brine as the solubility of CO₂ increased with decreasing salinity, resulting in a more acidic solution. They also suggested that acid stimulation can be carried out using fresh carbonated water or water with low salinity. In another study, Al-Dhafeeri et al. (2023) conducted experiments on the impact

of carbonated brine temperature on the generation of wormholes. Similar to the other study, they analyzed the effects of created wormholes on the properties of a rock. They found that two parameters acted against each other: reaction kinetics and CO₂ solubility. The reaction kinetics increases at high temperature while the solubility of CO₂ decreases. They mentioned that the pH played a greater role as the fastest breakthrough of a wormhole happened at the lowest temperature (35 °C).

Khalil et al. (2021) experimentally investigated the effects of injection pressure during matrix acidizing of carbonate-rich Marcellus shale core samples. Nine samples were treated with 15 wt.% HCl (determined to be optimal in preliminary tests) under reservoir conditions (confining pressure of 10.34 MPa, temperature of 66°C). Samples were categorized by carbonate layer continuity, and injection pressures were varied (1.72, 3.45, and 5.17 MPa) to assess the impact on solubility, porosity, and permeability. The study concluded that matrix acidizing significantly enhances permeability in Marcellus shale with continuous carbonate layers by forming wormholes. Importantly, increasing acid injection pressure up to 3.45 MPa led to improvements in acid penetration, reaction rate, solubility, porosity, and permeability. However, further increases beyond 3.45 MPa offered minimal additional benefits.

While earlier studies have investigated the effects of variables such as salinity and temperature of carbonated brine on wormhole formation in carbonate reservoirs, there remains a notable gap in the literature regarding the influence of pore pressure on the creation of wormholes caused by the interaction of CO₂-saturated brine with limestone. This research aims to fill this gap and advance our understanding of how injection pressure or pore pressure affects wormhole development during CO₂ storage. By analyzing these

aspects, the study aims to provide valuable insights into the mechanisms driving wormhole formation in carbonate formations as a result of CO₂ injection.

3.2 Experimental Methodology

Four coreflooding experiments with differing pore pressure values were conducted to investigate the relationship between pore pressure and wormhole formation in deep saline carbonate formations during carbon dioxide storage. The experimental process is visually outlined in **Figure 1**. Firstly, four core samples were collected within the permeability range of 2-3 mD. These samples were subjected to extensive characterization involving the assessment of petrophysical and geomechanical properties. Furthermore, coreflooding setup was used to inject carbonated brine and wet CO₂ into core samples. **Table 1** illustrates the initial characterization results for the core samples as well as the experimental conditions of each experiment. After the creation of continuous wormholes, treated samples underwent micro-CT scanning to visualize the generated wormhole and calculate the wormhole volume for additional analysis. Through this experimental approach, the study aimed to examine how various pore pressure levels affect the formation of wormholes during the process of CO₂ storage in saline aquifers.

To explain the pore pressure impact, four different pore pressure values were tested: 1500, 2000, 3000 and 4000 psi. The salinity level of the selected brine was 120,000 ppm while the temperature for the experiments were 60 °C. Experiments were conducted at 1 cm³/min. These conditions replicate the characteristics of the actual saline aquifer intended for CO₂ sequestration.

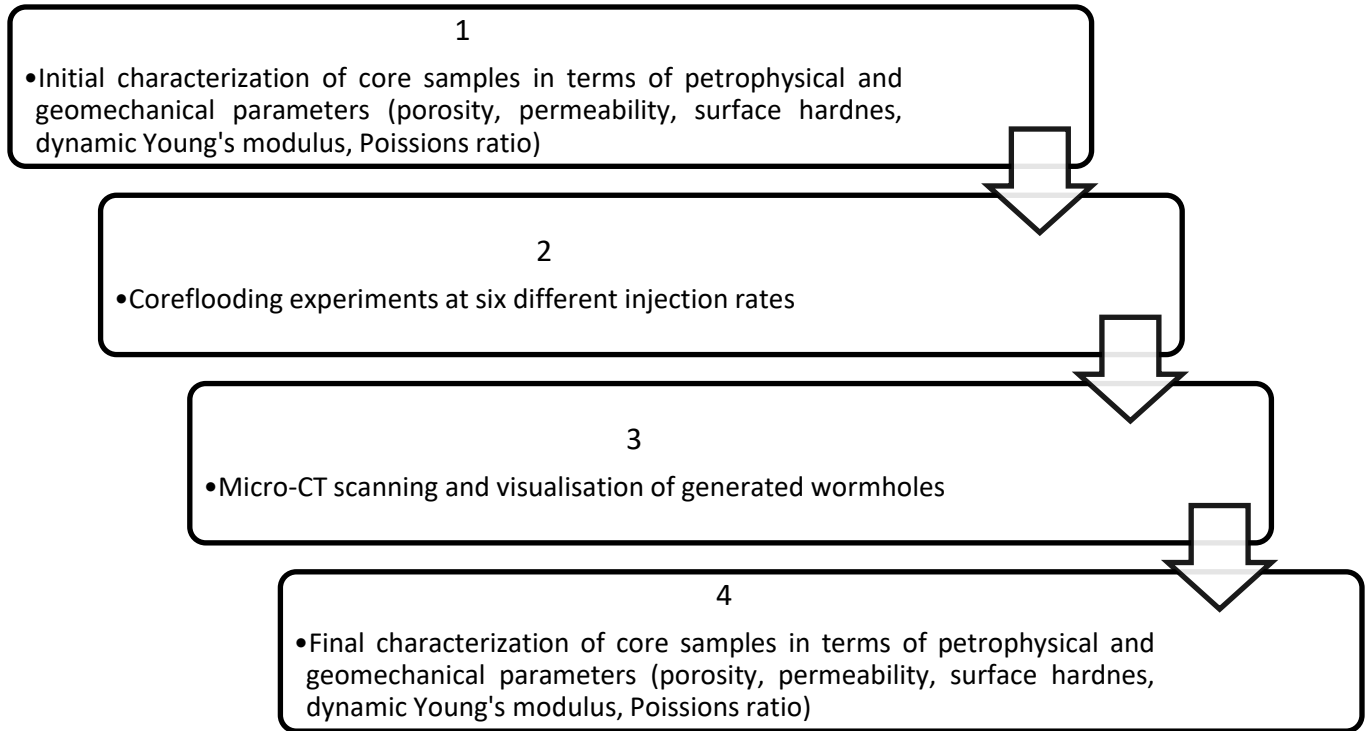


Figure 3.1. The process steps for assessing changes in the mechanical and petrophysical characteristics of rocks due to carbon dioxide storage.

Table 3.1. Design of experiments outlining the parameters for coreflooding conditions

Sample (ID)	Temperature (°C)	Salinity (ppm)	Permeability (mD)	Porosity (%)	Pore Pressure (psi)	Injection Rate (cm ³ /min)
EM-1	60 °C	120,000	2.4	15.31	1500	1
EM-2			3.16	17.16	2000	
EM-3			2.1	15.18	3000	
EM-4			2.7	15.34	4000	

3.2.1 Core Samples

The research concentrated on using typical outcrop samples of Indiana limestone (IL) for experimental inquiries. Four homogeneous cores, each with a diameter of 1.5 inches and a length of 3 inches, were collected for analysis. The average porosity of the samples was determined to be 15.7%, while the permeability was in the range of 2.4-3.16 mD. XRD analysis revealed that the sample composition was nearly 100% calcite.

3.2.2 Live brine composition

The active brine solution was prepared by combining 70% brine with 30% pure-grade CO₂. **Table 2** outlines the composition of the brine, mirroring the typical composition found in deep saline aquifers. In examining the influence of velocity, a consistent salinity level of 120,000 ppm was maintained throughout all the experiments.

Table 3.2. Brine composition with salinity levels comparable to those found in deep saline limestone aquifers

Salt	Weight (g/L)
NaHCO ₃	0.27
Na ₂ SO ₄	0.29
NaCl	84.46
MgCl ₂	5.36
CaCl ₂	29.62

3.2.3 Conducted Experiments

The experimental methodology and resulting data are detailed in **Table 3**. A helium porosimeter, operating on the principles of Boyle's law, was employed to determine sample

porosity. It is crucial to note that this instrument measures solely effective porosity and is accurate only under ambient conditions.

Hardness, a material's resistance to permanent deformation under applied force, was evaluated using the Autoscan (New England Research). This instrument employs a probe that applies a predefined force at specific points on the rock sample. Reduced Young's modulus served as the quantification metric for surface hardness, with measurements taken at twelve locations on the inlet face before and after each sample's exposure to CO₂-saturated brine.

We evaluated supplementary mechanical characteristics, including the dynamic bulk Young's modulus and Poisson ratio. These properties were measured using acoustic analysis conducted with the Autolab 500. Measurements were taken at overburden pressures of 1000, 2000, 3000 and 4000 Psi (7, 14, 21, and 28 MPa approximately). We then used the samples' density and the measured wave velocities to calculate Young's modulus and Poisson's ratio. This process was done both before and after creating wormholes, allowing us to compare changes in these properties.

We used a micro-CT scan to get a detailed picture of the wormhole's shape after coreflooding. The micro-CT scan had a resolution of 49 μm , allowing us to see fine details. We then analyzed the CT image to calculate the volume of the wormhole within the samples.

Figure 2 depicts the experimental setup designed to assess rock permeability and inject live brine. CO₂ and brine are mixed at a 70/30 ratio within an accumulator at 1200 psi. The mixture is allowed to equilibrate until a stable pressure is achieved. This mixture is then

heated to 60°C in an oven, resulting in a pressure increase to 1500 psi. Subsequently, a syringe pump pressurizes the mixture to the desired injection pressure, followed by a one-hour equilibration period before injection. To ensure consistency, the CO₂ mass remained a controlled variable throughout the experiments, with only the pump being utilized to manipulate accumulator pressure. The CO₂-brine mixture is injected via a pump and conduits into a coreholder containing the rock sample. Four different pore pressure values (1500, 2000, 3000, and 4000 psi) are used throughout the experiment while a constant flowrate of 1 cm³/min is maintained. A confining pressure of 1500 psi higher than the pore pressure is applied. The coreholder is encased in a Viton sleeve to prevent interaction with the fluid, and a shrinkable tube further prevents external flow around the core sample. The rear of the coreholder connects to a back-pressure regulator, facilitating flow when pressure exceeds the set pore pressure. A data logging system monitors the differential pressure. The entire 1-liter volume of the accumulator is injected. A separate conduit allows for injecting dead brine to evaluate rock permeability before and after the live brine coreflooding process.

Table 3.3. Experiments for characterization of core samples and their corresponding equipments

Porosity	Permeability	Surface Hardness	Dynamic Young's Modulus	Wormhole Visualization
Helium Porosimeter	Coreflood	Auto-Scan	Autolab 500	Micro-CT – ZEISS VERSA XRM - 500

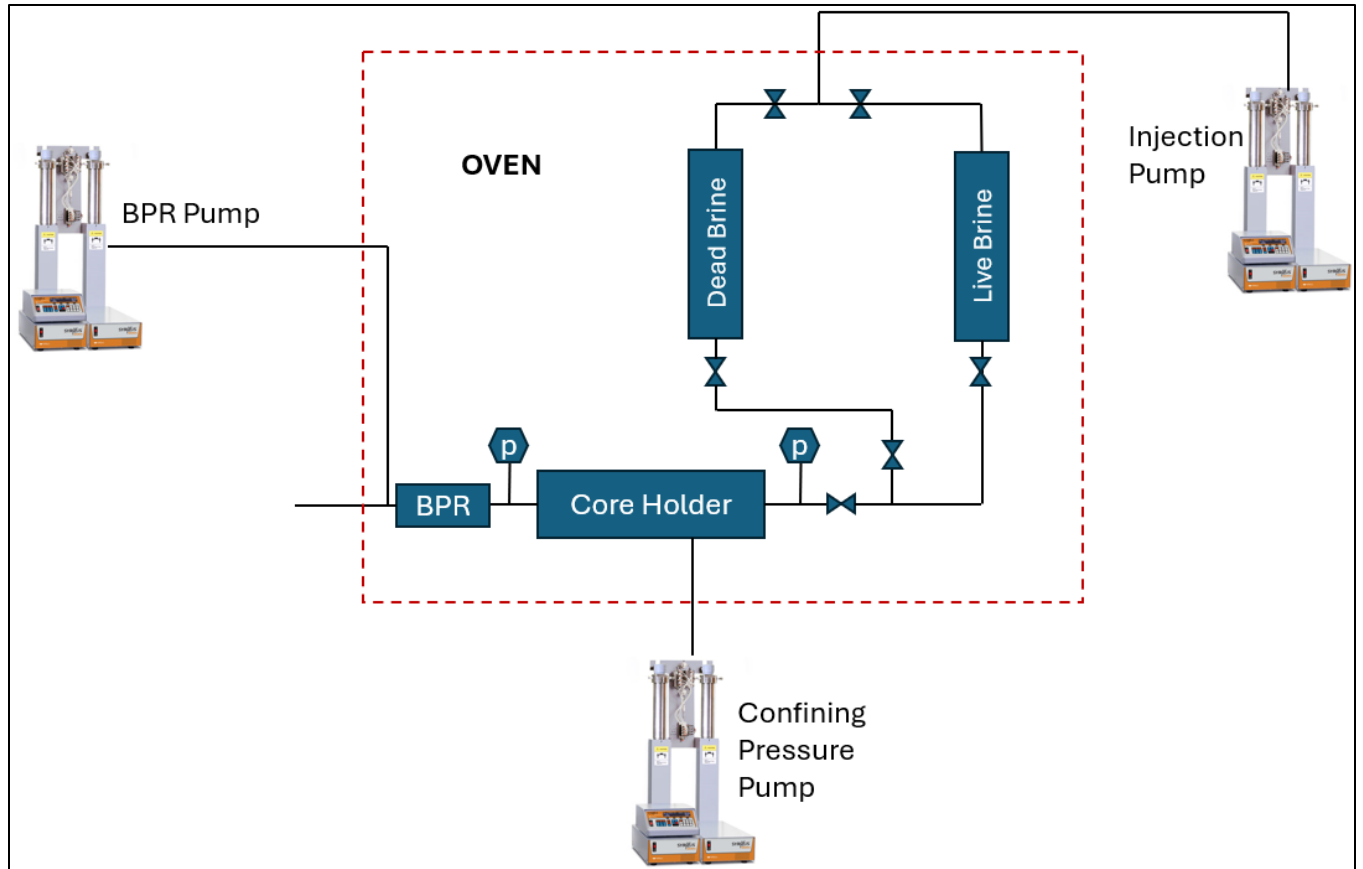


Figure 3.2. Coreflooding setup to inject live brine into the limestone samples

3.3 Results

3.3.1 Coreflooding

Four distinct experiments were conducted, each employing a different pore pressure (1500, 2000, 3000, or 4000 psi) on individual samples. All experiments maintained a constant temperature of 60°C and a flow rate of 1 cm³/min. The injected fluid consisted of a 70% brine / 30% CO₂ mixture, ensuring CO₂ saturation in the liquid phase, and resulting in a wet CO₂ gas phase. The injection sequence consistently began with CO₂-saturated brine, followed by wet CO₂. **Figure 3** illustrates the evolution of pressure differential during the injection of the CO₂-saturated brine. Initially, a sharp increase in pressure differential is

observed. However, as the CO₂-saturated brine reacts with the carbonate rock and forms a wormhole, the pressure differential gradually diminishes, ultimately reaching zero upon complete wormhole penetration of the sample.

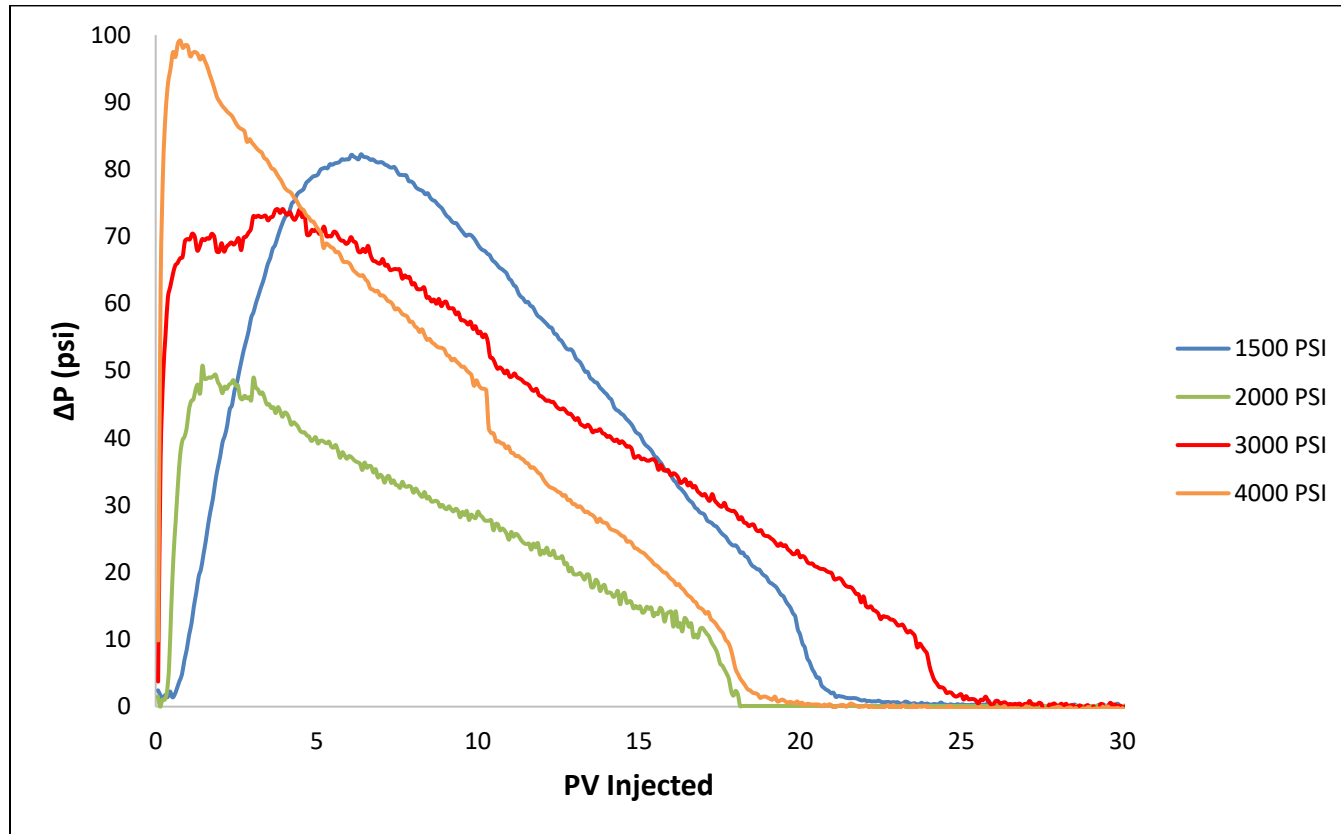


Figure 3.3. Coreflooding outcomes in terms of pressure drop resulted from treating four Indiana limestone samples at 1500, 2000, 3000 and 4000 psi pore pressure

Figure 4 depicts the pore volume to breakthrough (PVBT) for each experiment, indicating the volume of CO₂-saturated brine needed to achieve complete penetration of the carbonate sample by the wormhole. PVBT is computed by dividing the total injected volume until breakthrough by the sample's pore volume. This calculation is derived from **Figure 3**, where it aligns with the injected pore volume at the moment of zero pressure drop.

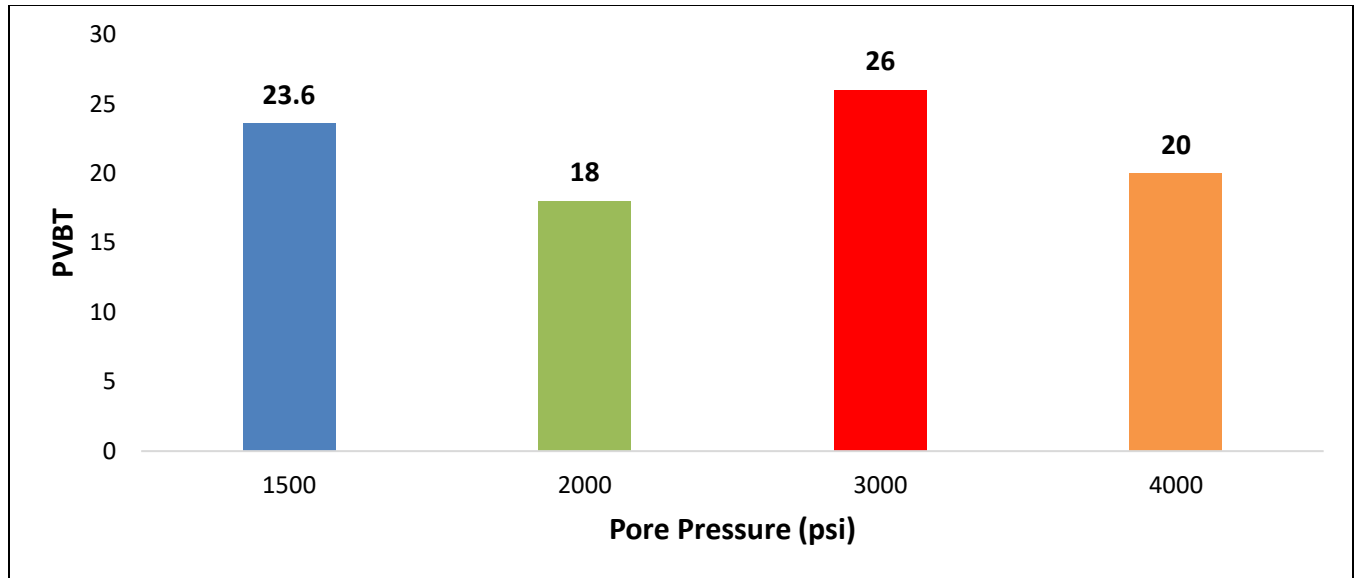


Figure 3.4. The pore volume required to achieve breakthrough (PVBT) at different treatment pressures.

3.3.2 Petrophysical Properties

The experiments demonstrated that injecting CO₂-saturated brine alters key petrophysical properties of carbonate rock - namely, porosity and permeability. These changes stem from the chemical reaction between the live brine and the rock, and the subsequent formation of wormholes. **Figure 5a** shows the porosity changes for each sample. Surprisingly, we found no clear relationship between the degree of porosity change and the injection pressure of the CO₂-saturated brine. This suggests that wormhole structure and branching, which directly determine wormhole size, are the primary factors influencing porosity change. This is supported by **Figure 5b**, which reveals a linear relationship between wormhole size and porosity change. The largest wormhole volume was observed at the pore pressure of 2000 psi, while the smallest occurred at 3,000 psi. Because of continuous wormholes formed, the pressure drop approaches zero, suggesting near-infinite permeability.

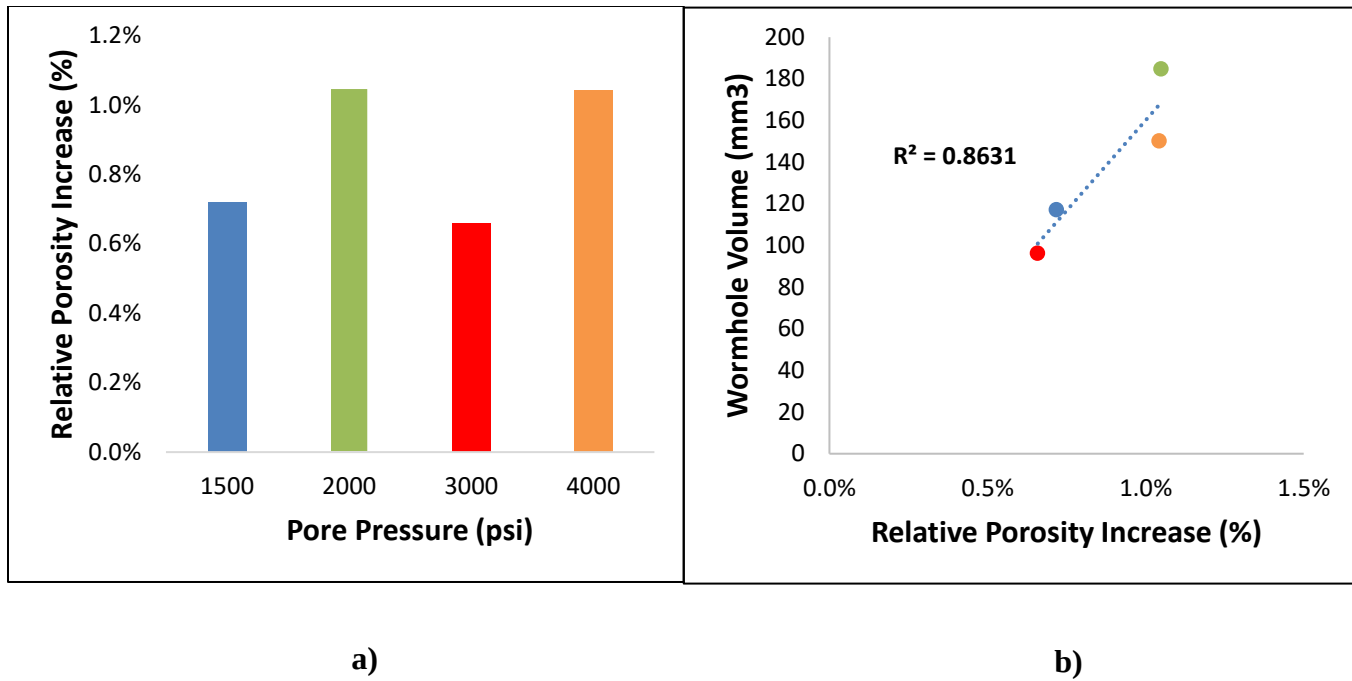


Figure 3.5. (a) The variations in the porosity with respect to pore pressure and (b) the cross plot illustrating the correlation between wormhole volume and porosity change

Figure 6 presents images of the inlet and outlet faces of the samples, with red circles highlighting the presence of wormholes. Micro-CT scans were employed to further reveal the internal structures of these wormholes. The CT images show that the wormholes created in the 1500 psi, 3000 psi, and 4000 psi experiments exhibited a relatively simple, single-channel structure with minimal branching. In contrast, the wormhole generated at 2000 psi displayed a more complex morphology. Furthermore, the 2000 psi experiment yielded the thickest wormhole, while the thinnest one was observed in the 3000 psi experiment. **Table 4** quantifies the volume of wormholes measured in each experiment.

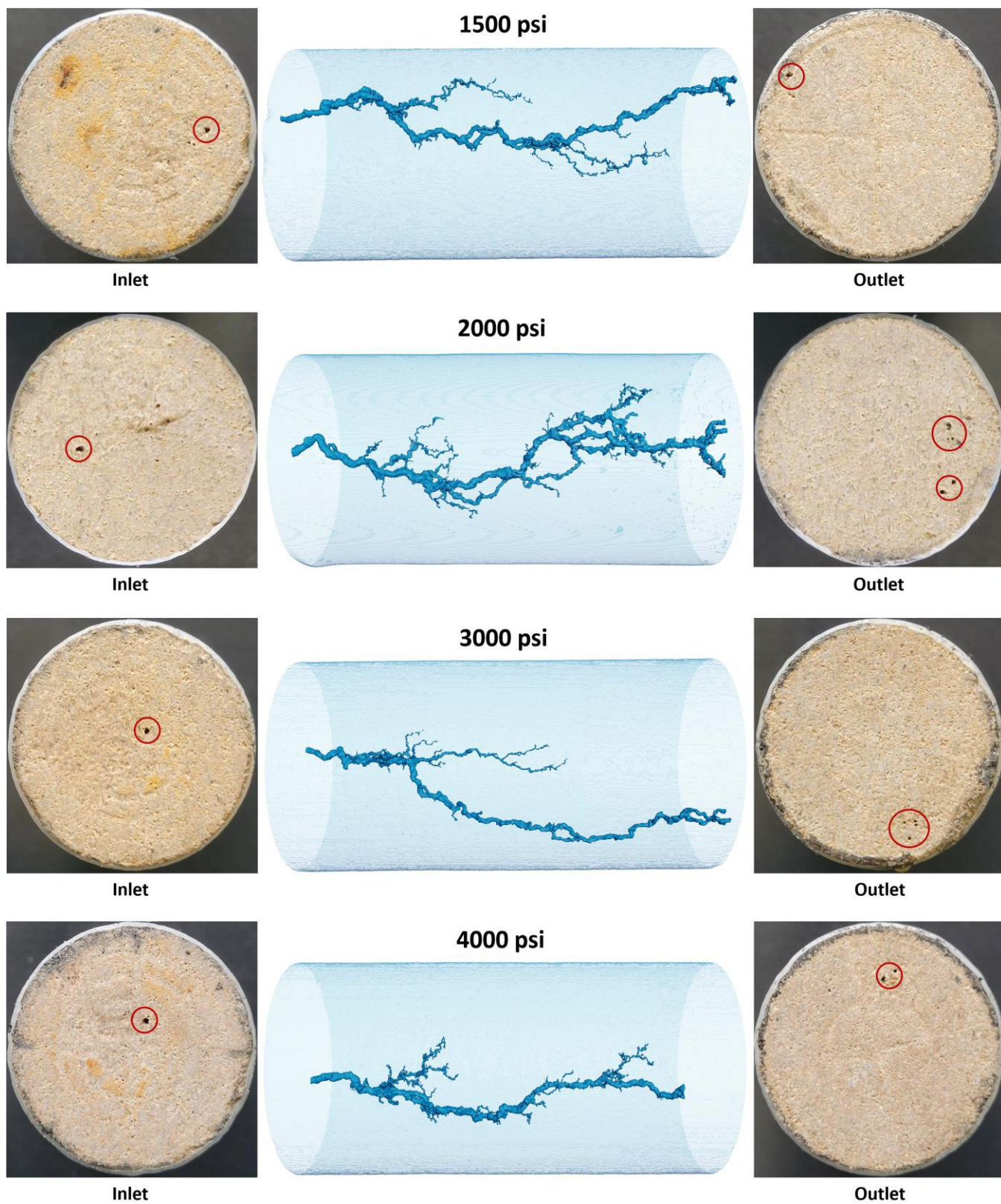


Figure 3.6. Images of the treated samples at the inlet and outlet and micro-CT scan images showing the wormhole structure

Table 3.4. Wormhole volumes for each experiment

<i>Pore Pressure (psi)</i>	<i>Wormhole Volume (mm³)</i>
1500	117.04
2000	184.72
3000	96.2
4000	150.18

3.3.3 Mechanical Properties

Figure 7 illustrates the impact of confining pressure on the dynamic Young's Modulus (YM) of the four samples, measured before and after exposure to CO₂-saturated brine. As anticipated, a direct relationship exists between confining pressure and YM: higher confining pressure leads to increased YM values. This trend is likely attributable to pore space compression and the resulting decrease in porosity. Moreover, all samples exhibited a significant YM decrease following their interaction with CO₂-saturated brine.

Figure 8 demonstrates the extent of dynamic Young's Modulus (YM) reduction across all experimental cases. The treatment at 4,000 psi induced the most significant reduction in YM, whereas the 1,500 psi experiment exhibited the least reduction. A clear trend emerges, demonstrating that increased pore pressure leads to greater deterioration in rock strength as measured by dynamic Young's Modulus. Additionally, a lower reduction in rock strength is observed at higher confining pressures, likely attributed to the compression of pore spaces and wormholes.

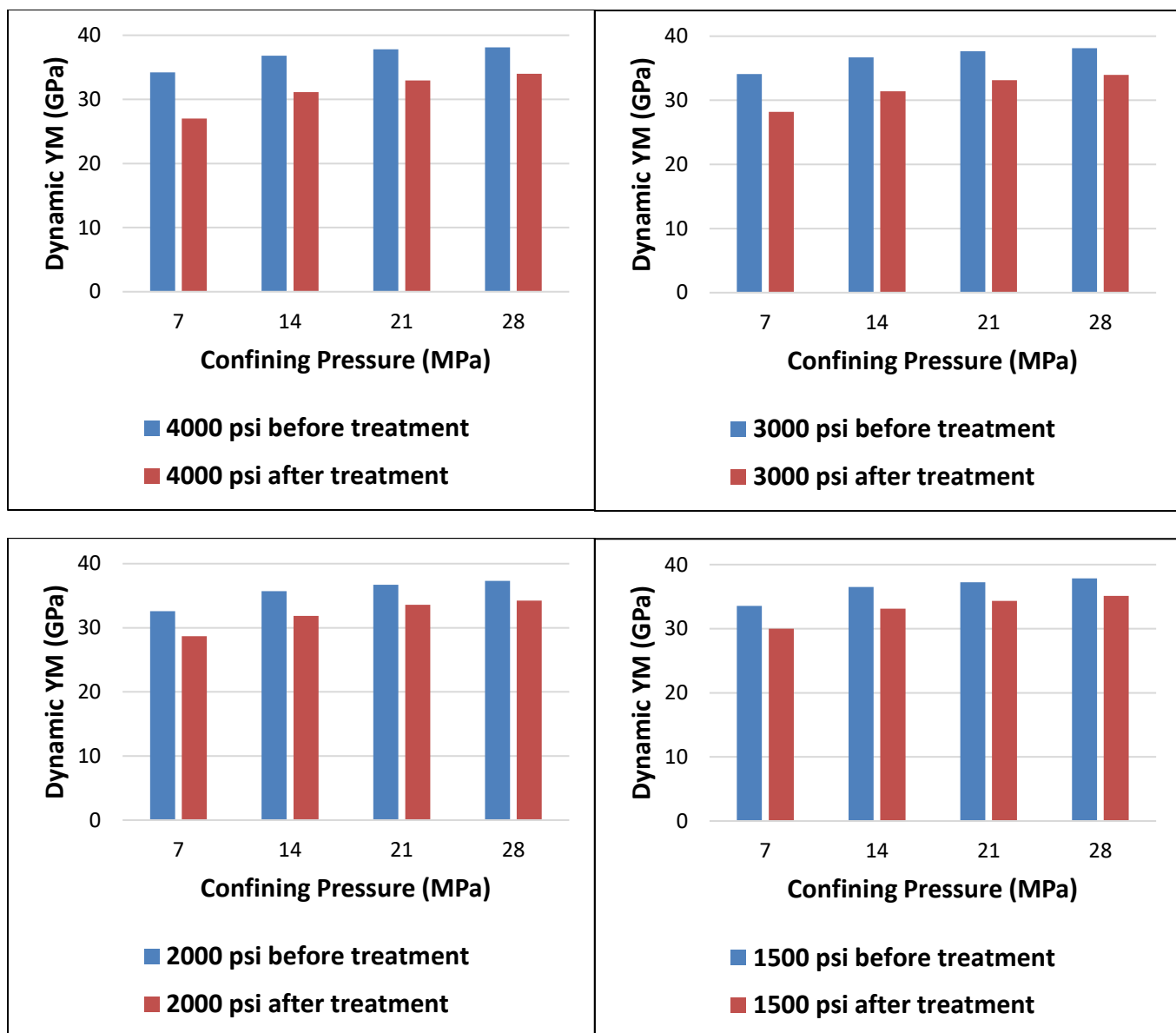


Figure 3.7. Change in Young's Modulus of samples following live brine injection

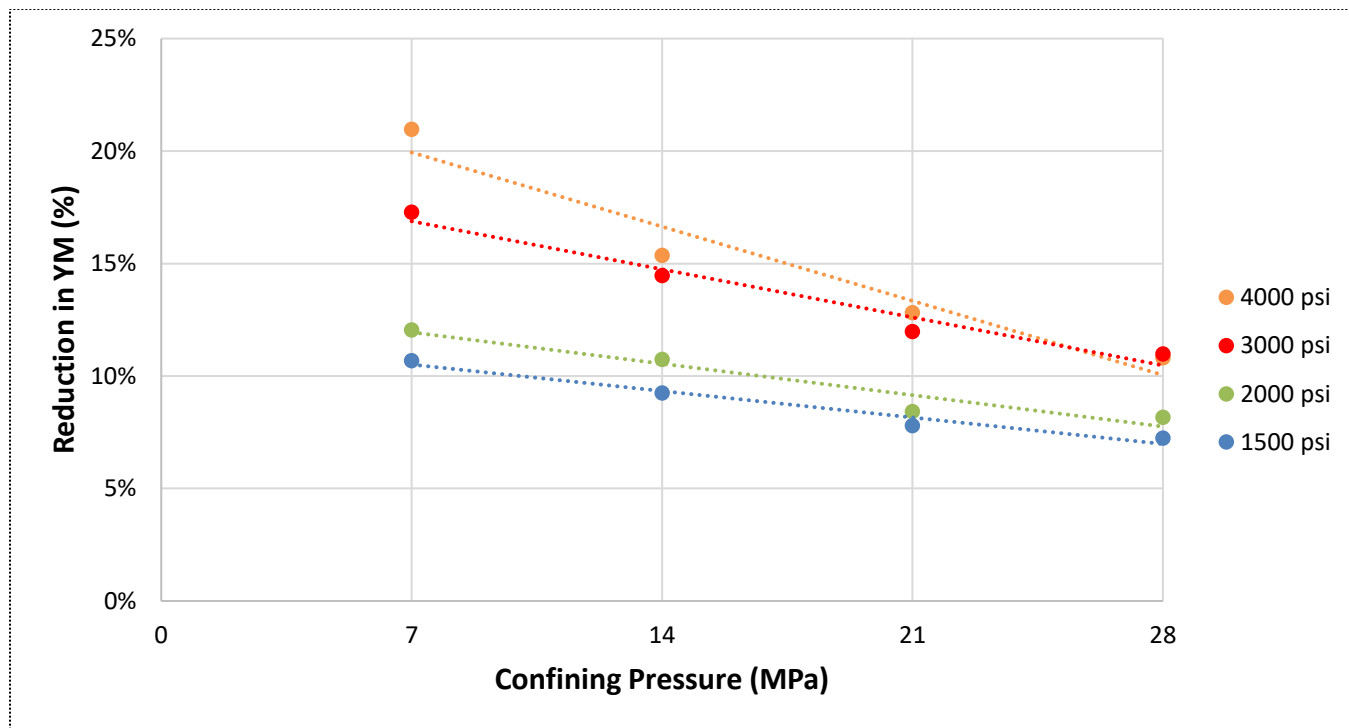


Figure 3.8. Young's Modulus reduction (%) at different confining pressures and injection rates

Figure 9 reveals an expected contrast in the behavior of Poisson's ratio compared to Young's Modulus (YM) following exposure to CO₂-saturated brine and wet CO₂. Unlike YM, Poisson's ratio increases post-treatment. This ratio, which generally falls between 0 and 0.5, measures the propensity of a material to deform perpendicularly to an applied load. The observed increase in Poisson's ratio for intact samples indicates that the carbonic acid reaction resulted in a softening of the rock.

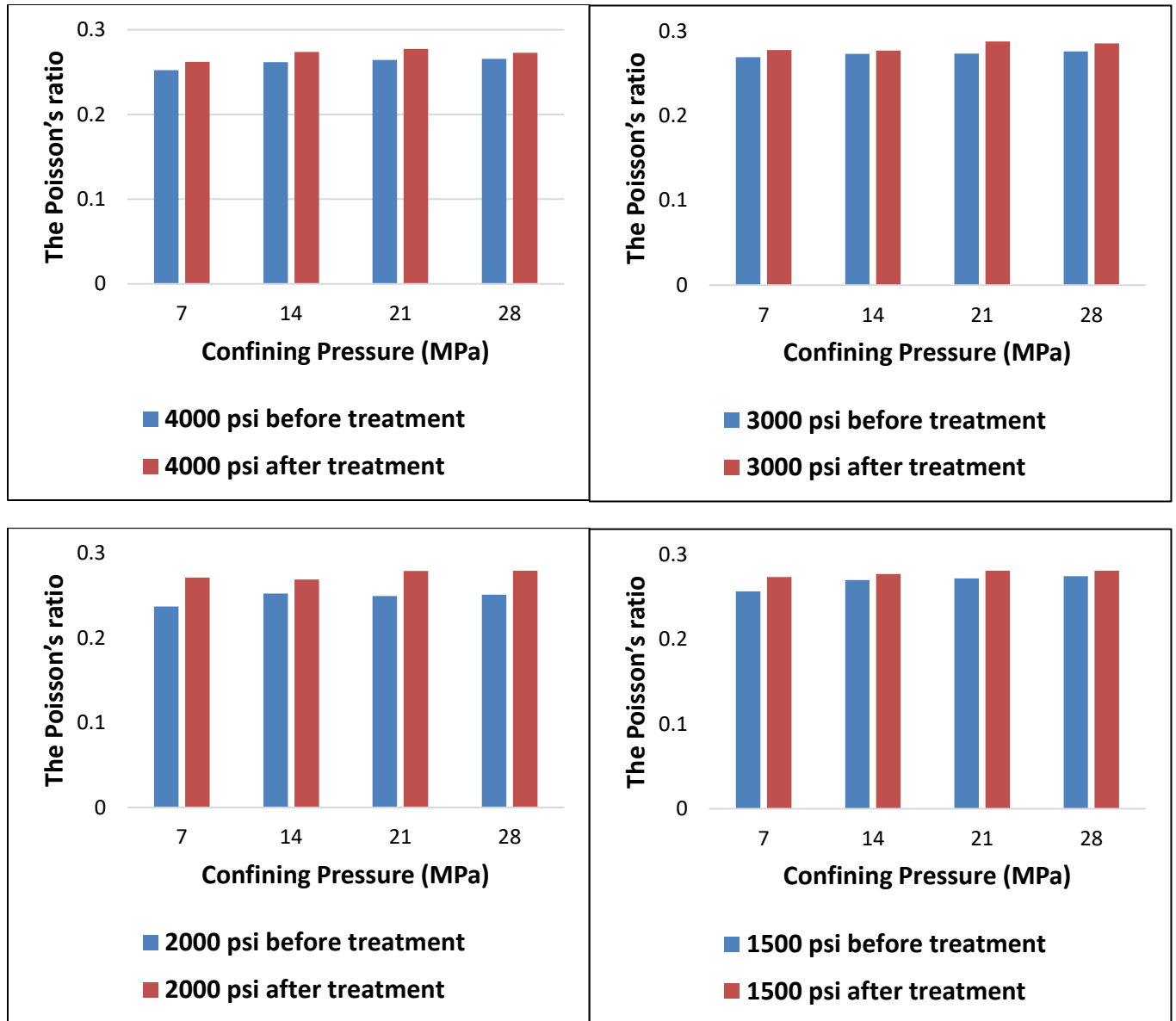


Figure 3.9. Comparison of samples' Poisson's ratio before and after live-brine injection

Rock hardness, a surface property measured at the sample inlet (**Figure 10**), indicates the sample's heterogeneity. Intact samples demonstrated average rock hardness values between 16 GPa and 18 GPa. Dissolution resulted in a reduction in rock hardness across all tested pore pressures, with the most pronounced reduction occurring at 4,000 psi and the least at 1,500 psi. The 3,000 psi and 2,000 psi experiments exhibited similar reductions, with the 3,000 psi case displaying a slightly greater decrease in inlet hardness (**Figure 11**). In

general, a trend of increasing rock hardness reduction with increasing pore (injection) pressure was observed. Due to wormhole formation, the bulk of the sample experienced differential exposure to live brine and wet CO₂, with most fluid channeling through the wormhole. Consequently, at the reservoir scale, Young's Modulus (YM), a bulk property, provides a more accurate representation of overall formation strength compared to rock hardness.

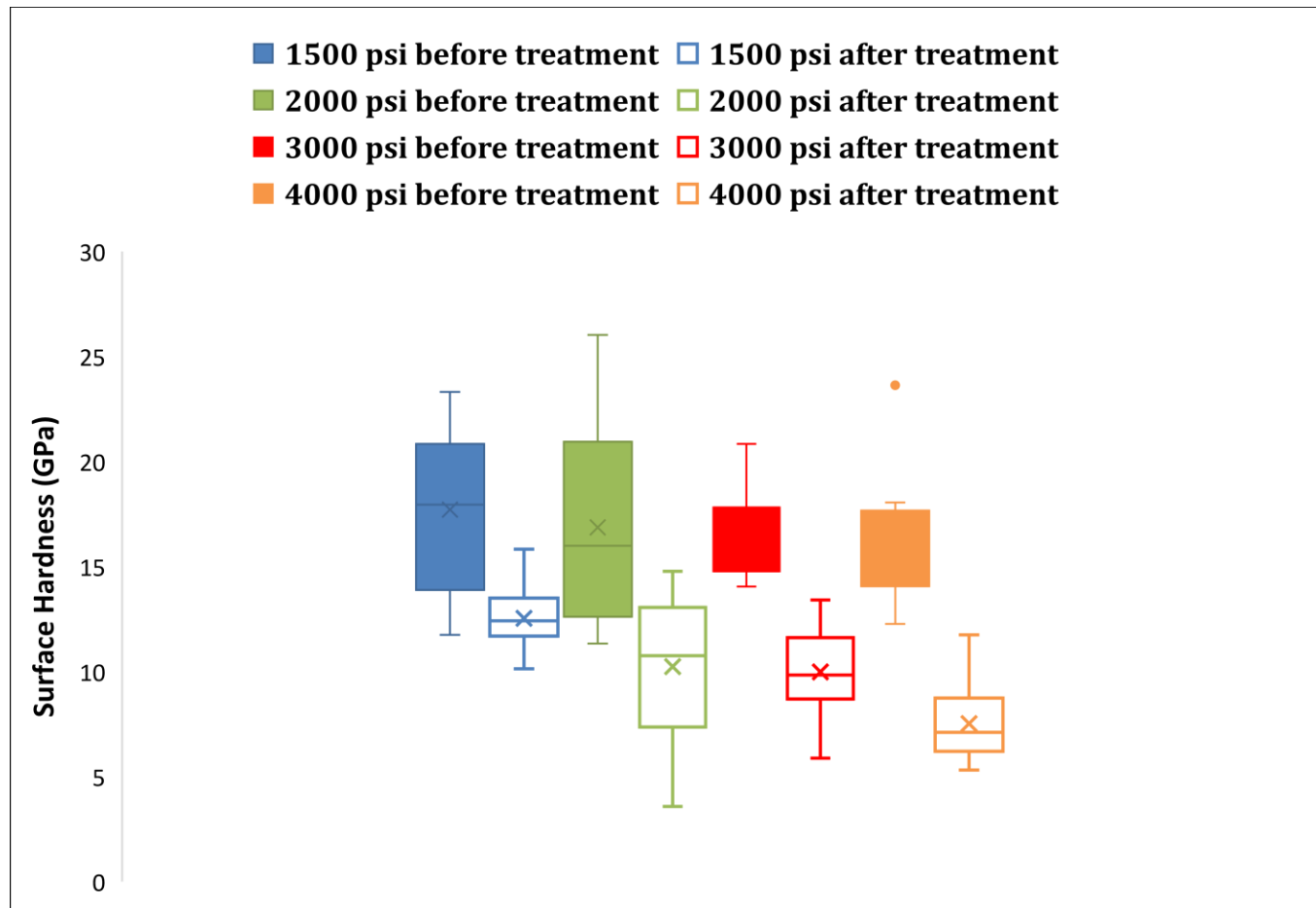


Figure 3.10. Comparison of sample inlet hardness before and after exposure to live brine

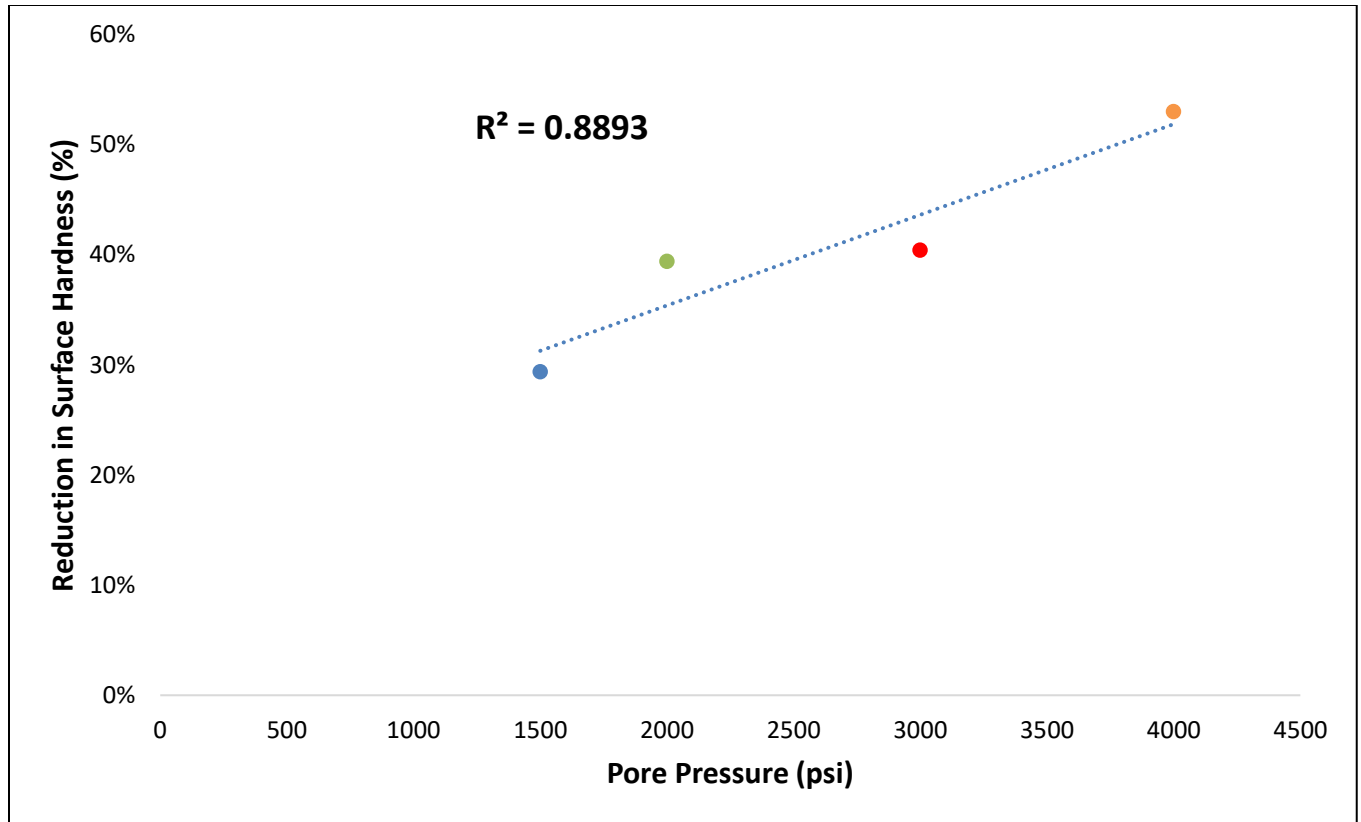


Figure 3.11. Percentage reduction in rock hardness at the sample inlet for different injection rates

3.4 Discussion

Our investigation into the effects of CO₂-saturated brine injection pressure on carbonate reactivity provides novel insights into the complexities of wormhole generation during CO₂ sequestration. In contrast, Khalil et al. (2021) stated that an increase in pressure from 250 to 500 psi had improvements in acid penetration. This study was done with HCl while for CO₂ storage purposes CO₂ is injected in supercritical phase which means the pressure of 1070 psi or higher which we applied in our experiments. Deng et al. (2018) investigated the solubility of CO₂ in brine, revealing a distinct pressure-dependent behavior. At pressures below the critical point of CO₂, the solubility demonstrates a linear increase, aligning with Henry's Law. However, as the pressure approaches and surpasses the critical

point, the rate of solubility increase undergoes a marked deceleration, signifying a deviation from the linear relationship and reflecting the transition of CO₂ from a gaseous to a supercritical fluid state. **Figure 12** demonstrates this phenomenon (Steel et al., 2016).

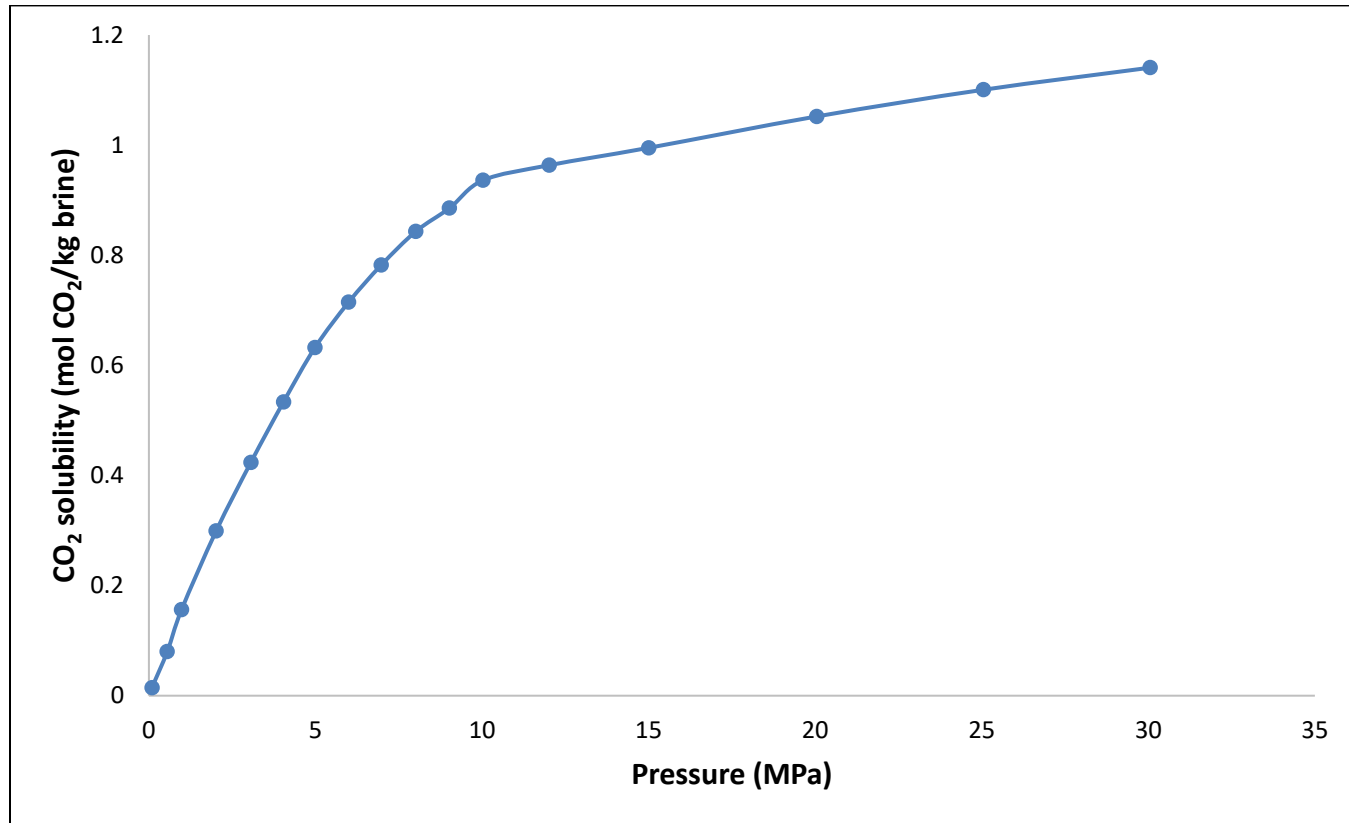


Figure 3.12. CO₂ solubility as a function of pressure at 323 K and 1 mol NaCl/kg brine

Based on our experiments operating within and above the supercritical range, we conclude that further pressure increases do not substantially enhance CO₂ solubility. Consequently, the acidity of the CO₂-saturated brine remains relatively stable within this pressure range. This stability, coupled with the established importance of carbonic acid acidity in driving wormhole formation (Aldhafeeri et al., 2023; Al-Dhafeeri et al., 2023, 2024), indicates that pressure-induced changes in solubility are insufficient to significantly affect wormhole development rates under these conditions (Al-Dhafeeri et al., 2023, 2024). Furthermore,

our study builds upon the work of Al-Dhafeeri et al. by analyzing the interplay between pressure, temperature, and salinity. These factors are crucial for a comprehensive understanding of CO₂ solubility and carbonic acid acidity.

Our study demonstrates that while increasing injection pressure leads to a greater degree of rock deterioration, as evidenced by reductions in surface hardness and dynamic Young's Modulus, it does not meaningfully enhance CO₂ storage capacity. This observation has significant implications for CO₂ sequestration strategies, as it suggests that prioritizing higher injection pressures may not be the most effective approach for maximizing storage potential. Notably, the observed deterioration is primarily attributed to the mechanical effects of higher pressure, which induce increased stresses and strains within the rock matrix. This mechanical stress can lead to the formation of microfractures, weakening the overall rock structure and compromising its integrity. Such damage may ultimately hinder long-term storage security, potentially increasing the risk of CO₂ leakage. This highlights the importance of strategic reservoir selection to mitigate potential stability issues and leakage risks during CO₂ sequestration. In conclusion, while existing research has illuminated factors influencing wormhole behavior, our investigation offers a nuanced understanding of the response of carbonate reservoirs to CO₂-saturated brine under varying pressures. The minimal impact of injection pressure on wormhole formation rates, alongside the associated risks of increased rock damage, underscores the need for a strategic approach to CO₂ sequestration. Careful reservoir selection based on pressure conditions promises to maximize efficiency and minimize environmental risks.

Conclusions

This study examined how different pore pressure values during CO₂-saturated brine injection affect the formation of wormholes and its impact on the properties of Indiana limestone samples. The aim was to simulate CO₂ sequestration within deep limestone saline aquifers. Conditions replicating a typical saline aquifer reservoir were used during coreflooding experiments: 1 cm³/min injection rate, 60°C temperature, 120,000 ppm brine salinity, and four different pore pressure values (4000, 3000, 2000, and 1500 psi). The following key conclusions were drawn from this investigation:

1. Our experiments demonstrated that pore pressure above 1500 psi (at constant CO₂ mass) does not significantly influence wormhole generation, as evidenced by the lack of a clear trend between PVBT values and pore pressure. Variations in PVBT between experiments are likely attributed to differences in pore geometry rather than pore pressure.
2. Experiments demonstrated that injecting CO₂-saturated brine at varying pore pressures caused alterations in the petrophysical properties of limestone samples, specifically porosity and permeability. The formation of continuous wormholes resulted in increased porosity, with a linear relationship observed between porosity change and wormhole volume. Due to continuous wormholes, the pressure drop between inlet and outlet approaches zero, suggesting near-infinite permeability.
3. The most significant reduction in Young's Modulus (YM) occurred at the 4000 psi pore pressure, with the 1500 psi experiment exhibiting the least reduction.

A general trend was observed: increased pore pressure resulted in greater deterioration of the core samples in terms of dynamic Young's modulus.

4. Similar to the trend observed in dynamic Young's modulus, the most significant decrease in surface hardness occurred at 4000 psi pore pressure. The 3000 psi and 2000 psi experiments exhibited comparable reductions, with the 3000 psi case displaying a slightly greater decrease. Overall, a direct relationship was observed between increasing pore pressure and increased reduction in surface hardness.

Overall, this work contributes to the broader goal of developing sustainable energy solutions by providing crucial information for optimizing CO₂ sequestration processes in deep saline aquifers. It underscores the importance of considering geomechanical and petrophysical properties when designing and implementing carbon sequestration projects, ultimately aiding in the transition to a low-carbon future.

CHAPTER 4

Impact of Rock's Permeability on Wormhole Generation Due to CO₂-Saturated Brine Injection

Abstract

Deep saline aquifers are promising locations for carbon sequestration, but the impact of CO₂ injection on rock properties requires careful investigation. This study will examine the effects of CO₂-saturated brine injection on limestone, specifically analyzing how rock permeability influences wormhole formation and subsequent changes in petrophysical and geomechanical properties. Four Indiana limestone samples, each with dimensions of 1.5 inches in diameter and 3 inches in length, were utilized. Four different permeability values were tested: 3, 10, 15, and 22 mD. During the experiments, the samples were subjected to a pore pressure of 2,000 psi and a temperature of 60°C, with a brine concentration of 120,000 ppm mixed with CO₂ at a ratio of 70:30, maintained at 1200 psi initially. An injection rate of 1 cm³/min was employed for the coreflooding experiments. Before and after coreflooding, Young's modulus (YM) and Poisson's ratio of the samples were measured at various confining pressures. Additionally, the treated samples' porosity, permeability, and surface hardness were assessed. To visualize the generated wormholes and quantify their volumes, a micro-CT scan was employed. Our study demonstrated that among the four tested permeability values, the experiment with a 3 mD core yielded the lowest PVBT. A clear trend was observed between PVBT and the permeability of carbonate samples as PVBT increased significantly with increasing rock permeability. Additionally, a general correlation was observed between the mechanical properties of

treated samples and rock permeability: increased permeability resulted in less significant deterioration of the core samples due to the lower dissolution. The investigation established that low permeability samples result in greater damage to the core, as evidenced by reductions in both surface hardness and dynamic Young's modulus.

Keywords; Permeability impact; Live brine; CO₂ Storage; Wormhole

4.1 Introduction

Carbon sequestration involves the process of capturing and securely storing carbon dioxide (CO₂) to prevent its release into the atmosphere and mitigate climate change. This strategy has been employed since the 1990s, when the first major carbon capture, utilization, and storage (CCUS) project was launched in Norway. There are three primary approaches to carbon sequestration (J. G. Kaldi et al., 2009; Lal, 2008b; Metz et al., 2005b; B. A. Seibel & Walsh, 2001; Thomson, Izaurrealde, et al., 2008). Terrestrial sequestration focuses on enhancing the natural capacity of plants and soil to absorb and store CO₂ through reforestation, improved agricultural practices, and soil management techniques. Oceanic sequestration involves storing CO₂ in the ocean, where it can dissolve in seawater or be used by marine organisms. Geological sequestration, a particularly promising technique, injects CO₂ deep underground into suitable geological formations such as depleted oil and gas reservoirs, saline aquifers, or unmineable coal seams (Ajayi et al., 2019a). Geological storage of CO₂ stands as a promising and efficient strategy to combat the escalating challenges of global climate change. This approach directly addresses the rise in atmospheric CO₂ concentration, mitigating its impacts on the environment.

Saline aquifers are the primary reservoirs targeted for CO₂ sequestration due to their vast capacity and favorable geological properties. However, other storage methods, such as depleted oil and gas reservoirs and coal seams, present limitations (Luo et al., 2022). With atmospheric CO₂ concentration currently at 421 ppm and projected to rise further, carbon sequestration presents a promising avenue for mitigating climate change. Deep limestone aquifers offer a potential solution for carbon capture and storage (CCS), a technology aimed at reducing greenhouse gas emissions. These formations boast advantages like large storage potential, the ability of limestone to react with CO₂ for permanent trapping, the potential to utilize existing oil and gas infrastructure, and their widespread availability. However, there are also significant drawbacks. Risks include potential CO₂ leakage, contamination of groundwater due to acidification, the possibility of induced earthquakes, and high costs associated with site assessment, infrastructure, and monitoring. It's important to recognize that carbon sequestration is most effective when combined with other mitigation strategies, forming a comprehensive approach to combatting climate change (Al-Dhafeeri et al., 2024; Bachu, 2000; Metz et al., 2005b; Rasool et al., 2023).

The sequestration of CO₂ in saline water formations has the potential to induce the creation of wormholes within limestone formations. This phenomenon is largely attributed to the existence of a mild carbonic acid formed during the dissolution of CO₂ in the water phase. (Aldhafeeri et al., 2023; Al-Yaseri et al., 2022; Espinoza et al., 2018; Major et al., 2018; Selvadurai et al., 2017). The formation of wormholes resulting from the injection of CO₂ leads to notable alterations in the petrophysical and mechanical properties of the formation rock, including porosity and permeability. Numerous researchers have undertaken experimental and modeling studies to comprehend the influence of various parameters on

wormhole generation induced by acids. However, there is a scarcity of studies focused on comprehending this phenomenon in the context of the CO₂ injection rate.

Cheng et al. (2017) conducted research to understand how the generated CO₂ during carbonate acidizing with HCl would affect wormhole propagation. They conducted coreflooding experiments with varying pressures, temperatures, and injection rates (500 to 3000 psi; 70 and 150 °F; 1.2, 1.5, 3, 5, 8, and 12 cm³/min). Experiments indicated that at low injection rates, the presence of CO₂ in a gaseous phase significantly hampers the efficiency of wormhole propagation, leading to an observable increase in the diameter of the formed wormholes. When injection rates surpass the optimal level, the impact of CO₂ becomes less noticeable, especially at elevated temperatures. Zakaria et al. (2015) offer a valuable investigation into the link between carbonate pore structure and the success of acid stimulation. Their work across six different formations employed comprehensive analysis (thin-sections, mercury injection, NMR (Nuclear magnetic resonance), and XRD to characterize pore heterogeneity and mineralogy. Importantly, they introduce the parameter ' f' ', representing the fraction of the pore structure that actively contributes to flow. This parameter, as demonstrated by over 30 acid-coreflood experiments, is crucial in understanding and predicting acid behavior in carbonate rocks. Their results highlight the impact of pore classes on acid response, underscoring the potential for improved hydrocarbon recovery through tailored acidization strategies based on detailed pore structure analysis.

Dos Santos Lucas et al. (2023) did a review to find out how different parameters affect the generation of wormholes in carbonate rock samples during acidizing with HCl. The main parameters they discussed were concentration of acid, reaction rate, flow rate, temperature,

dimension of core samples, and heterogeneity. The primary parameters under discussion included the concentration of acid, reaction rate, flow rate, temperature, dimensions of core samples, and heterogeneity. The findings suggest that increasing acid concentration leads to a downward shift in the PVBT (pore volume to breakthrough) plot, reducing the breakthrough volume and altering the optimal flow rate. Moreover, the flow rate is closely linked to the type of wormhole generated, with various dissolution patterns observed. The reaction rate is highlighted as a crucial factor influencing wormhole formation, with Damkohler and Peclet numbers providing valuable insights into its dimensionless approach encompassing advection, diffusion, and reactivity. Furthermore, the geometry of the reactive flow significantly impacts dissolution patterns. Core properties, such as diameter and saturation, also affect PVBT, albeit core length seems to have minimal impact, especially in experiments over 6 inches. Lastly, temperature exhibits varied effects on limestone and dolomite formations, further emphasizing the nuanced considerations in matrix acidizing operations.

Zareei et al. (2022) investigate the impact of carbon dioxide injection on carbonate rocks' petrophysical properties, crucial for optimizing CO₂ storage strategies in saline aquifers. Their research identifies how CO₂ sequestration affects rock-fluid geochemical interactions, particularly focusing on the dissolution/precipitation of minerals and its influence on formation properties like flow and injectivity. Employing core flooding experiments across a spectrum of rock mineralogies and distances from the injection point, they applied both qualitative and quantitative assessments, including X-ray Diffraction (XRD), CT scanning, porosity, and permeability measurements. Their findings reveal a significant permeability increase in rocks with minerals soluble in acidic environments,

attributed to the formation of wormholes. Conversely, rocks composed of acid-insoluble minerals exhibited a permeability decrease. The study highlights the differential impact of CO₂ injection based on the rock's mineral composition and proposes that managing these geochemical interactions is essential for the success of CO₂ sequestration efforts. Khather et al. (2022) investigated how carbon dioxide (CO₂) injection impacts oil recovery from carbonate rocks. Three different rock samples with varying permeabilities were used. CO₂ and brine were injected alternately after initial water flooding. X-ray scans showed changes in the rock structure, porosity, and permeability due to CO₂ interactions. CO₂ injection led to over 30% more oil recovery compared to water flooding alone. The lowest permeability sample had the smallest overall oil recovery but the largest increase in permeability, indicating significant rock dissolution and formation of preferential flow paths (wormholes). The study suggests that low oil recovery in tight rocks is mainly due to wormhole formation, as they allow CO₂-saturated brine to bypass trapped oil.

Khalil et al. (2021) experimentally investigated the effects of injection pressure during matrix acidizing of carbonate-rich Marcellus shale core samples. Nine samples were treated with 15 wt.% HCl (determined to be optimal in preliminary tests) under reservoir conditions (confining pressure of 10.34 MPa, temperature of 66°C). Samples were categorized by carbonate layer continuity, and injection pressures were varied (1.72, 3.45, and 5.17 MPa) to assess the impact on solubility, porosity, and permeability. The study concluded that matrix acidizing significantly enhances permeability in Marcellus shale with continuous carbonate layers by forming wormholes. Importantly, increasing acid injection pressure up to 3.45 MPa led to improvements in acid penetration, reaction rate,

solubility, porosity, and permeability. However, further increases beyond 3.45 MPa offered minimal additional benefits.

Al-Dhafeeri et al. (2024) conducted a study to understand the brine salinity impact of a carbonated brine on the generation of wormholes. Furthermore, they analyzed the effects of the generated wormholes on the properties of a rock. They found out that the fastest and the thickest wormhole formed with the lowest salinity brine as the solubility of CO₂ increased with decreasing salinity, resulting in a more acidic solution. They also suggested that acid stimulation can be carried out using fresh carbonated water or water with low salinity. In another study, Al-Dhafeeri et al. (2023) conducted experiments on the impact of carbonated brine temperature on the generation of wormholes. Similar to the other study, they analyzed the effects of created wormholes on the properties of a rock. They found that two parameters acted against each other: reaction kinetics and CO₂ solubility. The reaction kinetics increases at high temperature while the solubility of CO₂ decreases. They mentioned that the pH played a greater role as the fastest breakthrough of a wormhole happened at the lowest temperature (35 °C).

Etten et al. (2015) investigated how permeability and pore structure affects carbonate matrix acidizing. Their findings demonstrate a direct relationship between rock permeability and the optimal volume required for wormhole breakthrough, highlighting the significant influence of permeability on acidizing efficiency. Importantly, this study reveals that permeability's impact on optimal conditions is most pronounced at lower permeability values, with its influence tending to diminish as permeability increases. Furthermore, their analysis highlights that pore structure, particularly the size of the largest

pore, plays a crucial role alongside permeability in determining wormhole propagation and subsequently, the success of acidizing.

Previous research has explored the impact of carbonated brine properties, such as salinity and temperature, on wormhole development in carbonate reservoirs. However, there remains a significant knowledge gap concerning the influence of rock permeability on wormhole formation during CO₂ storage in limestone. This study aims to address this gap by investigating the role of carbonate sample permeability in the generation of wormholes induced by CO₂ injection. By examining this factor, the study seeks to enhance our understanding of the mechanisms driving wormhole formation in carbonate formations during CO₂ storage.

4.2 Methodology

Four coreflooding experiments with differing core permeability values were conducted to investigate the relationship between permeability and wormhole formation in deep saline carbonate formations during carbon dioxide storage. The experimental process is visually outlined in **Figure 1**. Firstly, four core samples were collected within the permeability range of 3-22 mD. These samples were subjected to extensive characterization involving the assessment of petrophysical and geomechanical properties. Furthermore, coreflooding setup was used to inject carbonated brine and wet CO₂ into core samples. **Table 1** illustrates the initial characterization results for the core samples as well as the experimental conditions of each experiment. After the creation of continuous or partial wormholes, treated samples underwent micro-CT scanning to visualize the generated wormhole and calculate the wormhole volume for additional analysis. Through this experimental

approach, the study aimed to examine how various permeability levels affect the formation of wormholes during the process of CO₂ storage in saline aquifers.

To explain the permeability impact, four different core samples with varying permeability values were tested: 3, 10, 15, and 22 mD. The salinity level of the selected brine was 120,000 ppm while temperature for the experiments was 60 °C. A pore pressure of 2,000 psi was utilized for the experiments. Experiments were conducted at 1 cm³/min. These conditions replicate the characteristics of the actual saline aquifer intended for CO₂ sequestration.

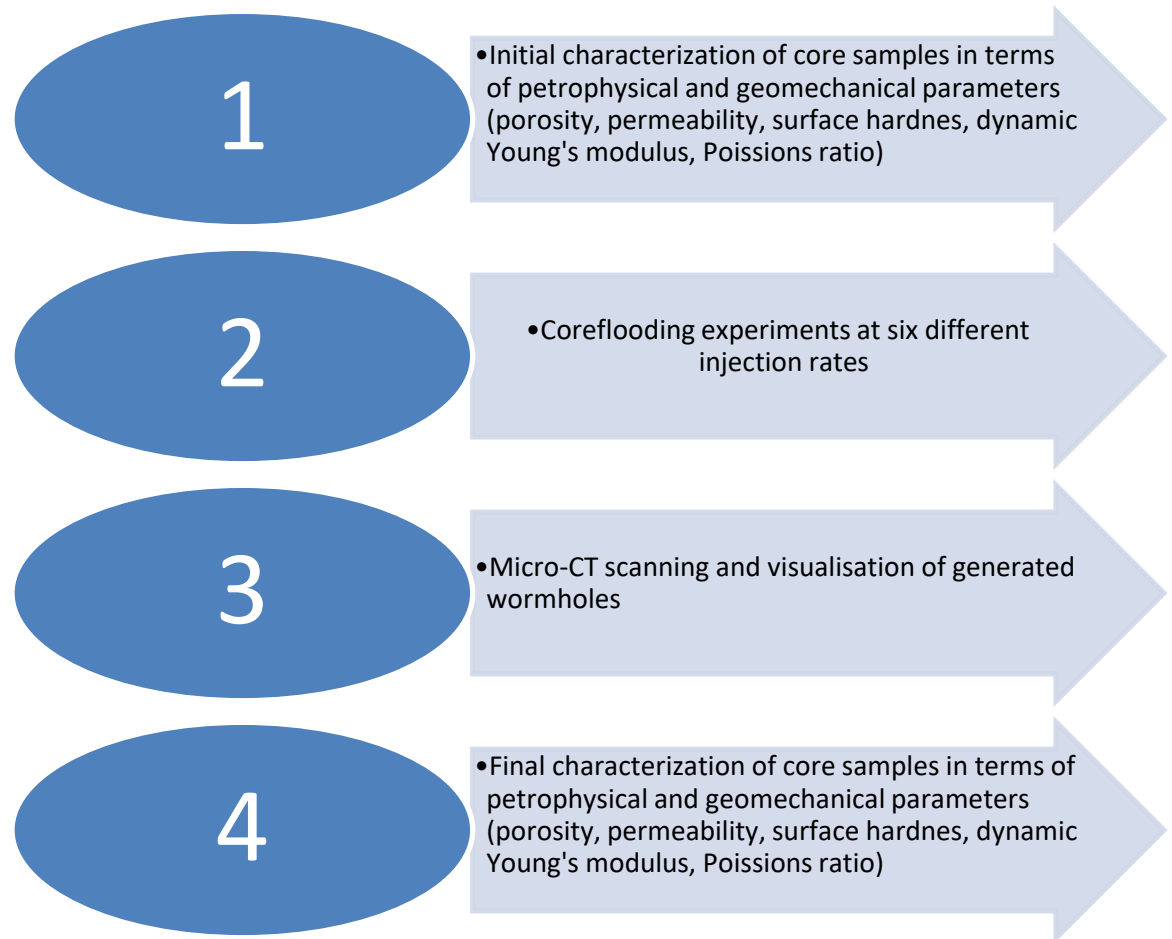


Figure 4.1. The process steps for assessing changes in rocks' mechanical and petrophysical characteristics due to carbon dioxide storage

Table 4.1. Design of experiments outlining the parameters for coreflooding conditions.

Sample (ID)	Temperature (°C)	Salinity (ppm)	Permeability (mD)	Porosity (%)	Pore Pressure (psi)	Injection Rate (cm³/min)
EM-1	60	120,000	3	17.16	2000	1
EM-2			10	17.09		
EM-3			15	18.41		
EM-4			22	16.77		

4.2.1 Core Samples

Indiana limestone (IL) outcrop samples were utilized for experimental inquiries. Four homogeneous cores, each with a diameter of 1.5 inches and a length of 3 inches, were collected for analysis. The average porosity of the samples was determined to be 15.7%. XRD analysis revealed that the sample composition was nearly 100% calcite. The cores were selected to have different permeability to investigate the effect of permeability on the wormhole generation during CO₂ injection.

4.2.2 Live brine composition

The active brine solution was prepared by combining 70% brine with 30% pure-grade CO₂. **Table 2** outlines the composition of the brine, mirroring the typical composition found in deep saline aquifers. In examining the influence of velocity, a consistent salinity level of 120,000 ppm was maintained throughout all the experiments.

Table 4.2. Brine composition with salinity levels comparable to those found in deep saline limestone aquifers

Salt	Weight (g/L)
NaHCO ₃	0.27
Na ₂ SO ₄	0.29
NaCl	84.46
MgCl ₂	5.36
CaCl ₂	29.62

4.2.3 Conducted Experiments

Table 3 outlines the experiments and their corresponding data. To measure the porosity of the samples, a helium porosimeter was used, which works according to Boyle's law. Importantly, this device is limited to measuring effective porosity and only functions accurately under ambient conditions.

Hardness is a mechanical property that determines how easily a material is permanently deformed under applied force. Autoscan (from New England Research) was used to figure out the hardness of our samples. The autoscan utilizes a probe that exerts a predetermined force at designated locations on the rock sample. Reduced Young's modulus was used to quantify hardness at twelve points on the inlet face, with measurements taken prior to and following the introduction of CO₂-saturated brine to each sample.

Other mechanical characteristics, including the dynamic bulk Young's modulus and Poisson ratio were evaluated. These properties were measured using acoustic analysis conducted with the Autolab 500. Measurements were taken at overburden pressures of 1000, 2000, 3000, and 4000 Psi (7, 14, 21, and 28 MPa approximately). The samples'

density and the measured wave velocities were used to calculate Young's modulus and Poisson's ratio. This process was done both before and after creating wormholes, allowing us to compare changes in these properties.

A micro-CT scan was used to get a detailed picture of the wormhole's shape after coreflooding. The micro-CT scan had a resolution of 49 μm , allowing us to see fine details. The CT image was analyzed to calculate the volume of the wormhole within the samples.

Figure 2 illustrates the setup used to assess rock permeability and inject the live brine. In this system, CO_2 and brine are blended within the accumulator at a pressure of 1200 psi until the mixture achieves a stable pressure, indicating thorough mixing. This accumulator with a mixture composition of 70% brine (having a salinity of 120,000 ppm) and 30% CO_2 is subsequently placed into the oven. Following this, the chamber is heated to attain the target temperature of 60°C, causing an elevation in pressure, which stabilizes at 1,500 psi before the syringe pump pressurizes the mixture in the accumulator to 2,000 psi. A waiting period of one hour is observed to ensure equilibrium before commencing the injection at 2,000 psi. The mixture is then injected by a pump through conduits into a coreholder where the rock sample placed, operating at six distinct injection rates throughout the experiment. This coreholder is subjected to a confining pressure of 3500 psi and is encased in a Viton sleeve to reduce any interaction between the live brine and the sleeve material. To further prevent external flow around the core sample, it is encased in a shrinkable tube. The rear part of the coreholder is linked to a back-pressure regulator, which allows the flow when the pressure exceeds 2000 psi, with the differential pressure monitored by a data logging system. Injection proceeds until the entire volume of the accumulator (1 liter) is dispensed.

Additionally, the coreholder is connected to an alternate conduit for injecting dead brine to evaluate rock permeability both prior to and following the coreflooding process.

Table 4.3. Experiments for characterization of core samples and their corresponding equipment

Porosity	Permeability	Surface Hardness	Dynamic Young's Modulus	Wormhole Visualization
Helium Porosimeter	Coreflood	Auto-Scan	Autolab 500	Micro-CT – ZEISS VERSA XRM - 500

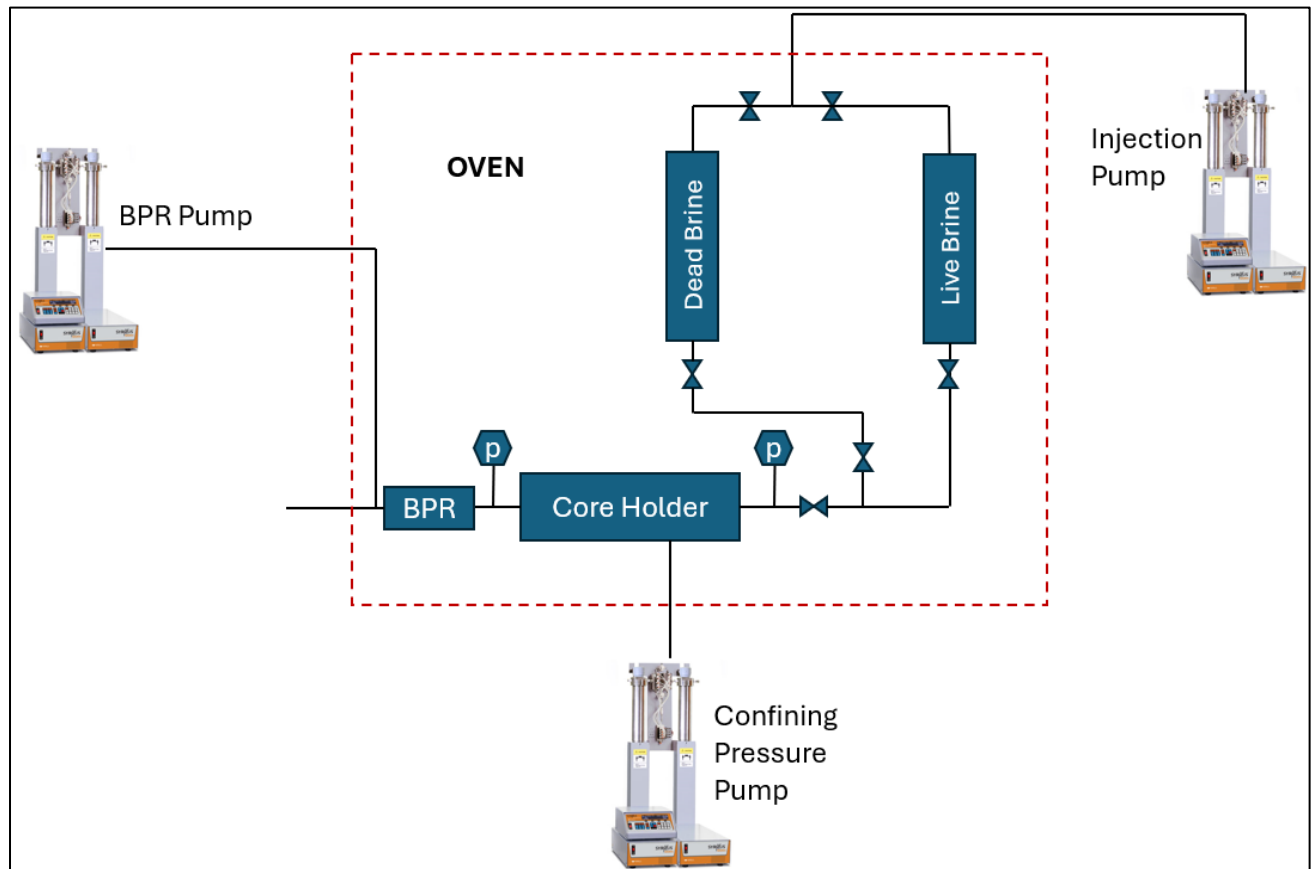


Figure 4.2. Coreflooding setup to inject live brine into the limestone samples

4.3 Results

4.3.1 Coreflooding

Four different permeability values were used in our experiments. Experiments were conducted at 60°C and flooded with an injection rate of 1 cm³/min. The pore pressure was 2000 psi. The accumulator contained a 70% brine / 30% CO₂ mixture, ensuring full saturation of the liquid phase with CO₂ and resulting in a wet CO₂ gas phase. In all experiments, the injection sequence consisted of liquid-phase CO₂-saturated brine followed by wet CO₂. **Figure 3** illustrates the change of pressure difference during the injection of the liquid phase, which is CO₂-saturated brine. The experiment began with a sharp pressure differential increase. As the CO₂-saturated brine reacted with the carbonate rock, a non-resistant flow path (wormhole) began to form (Mustafa et al., 2021). This caused the initial pressure differential to decrease, eventually reaching zero as the wormhole fully penetrated the sample. Notice that the 22mD experiment did not breakthrough with the injection of 700 mL of carbonated brine. To estimate the PVBT, a linear line was extended. This method overestimates the actual PVBT by 10 to 15% when it was applied to other experiments with actual breakthrough.

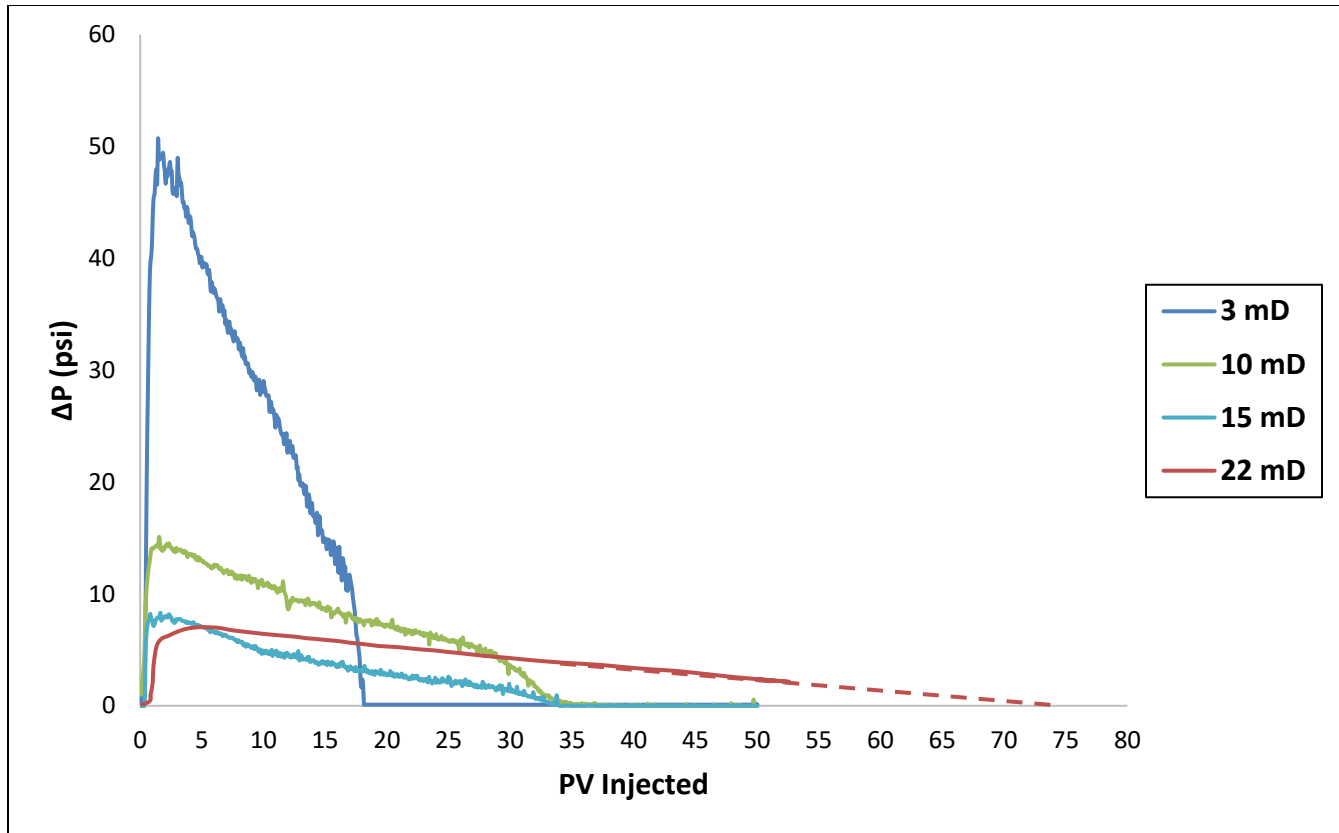


Figure 4.3. Coreflooding outcomes in terms of pressure drop resulted from treating four Indiana limestone samples with different permeability values.

Figure 4 illustrates the pore volume to breakthrough (PVBT) for each experiment, which represents the volume of CO₂-saturated brine required to achieve full wormhole penetration of the carbonate sample. PVBT is calculated by dividing the total volume injected until breakthrough by the sample's pore volume. This value is determined from **Figure 3**, where it corresponds to the injected pore volume at the point of zero pressure drop.

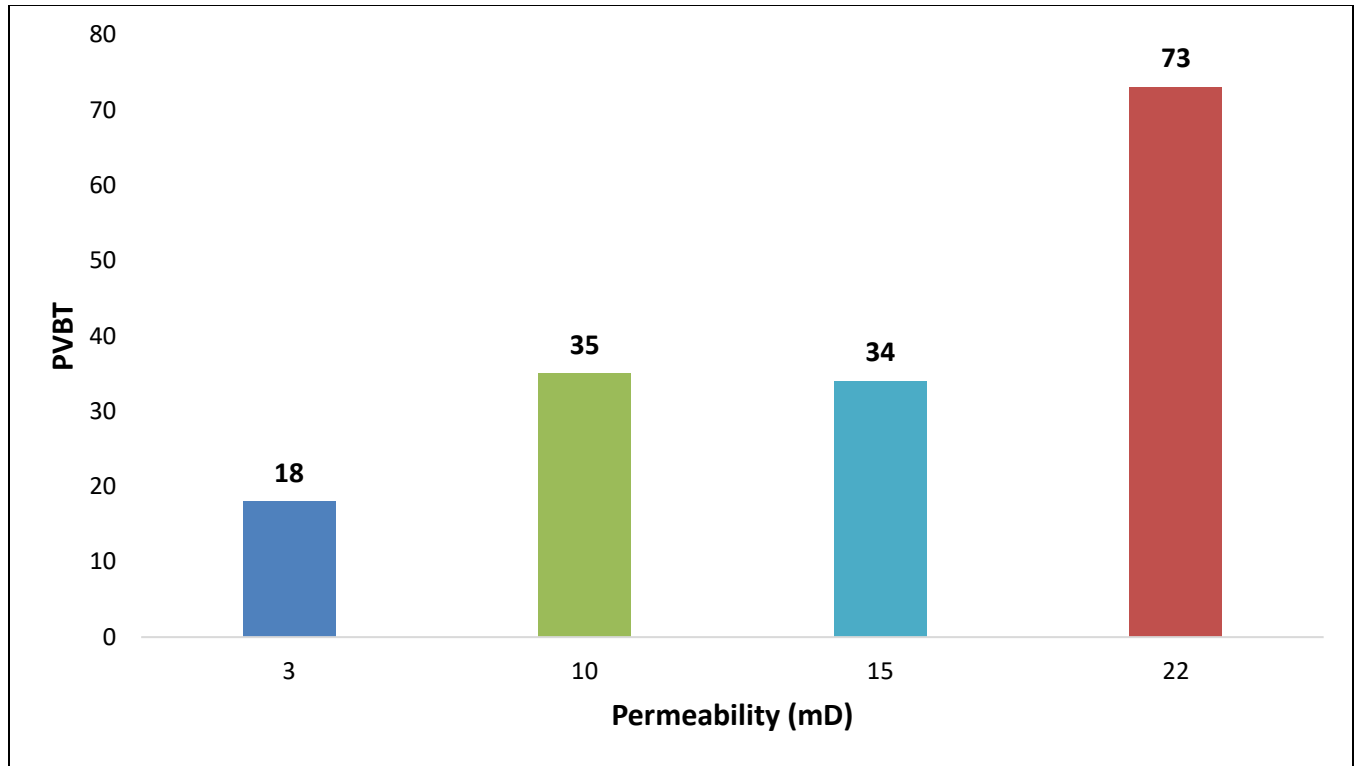


Figure 4.4. The pore volume required to achieve breakthrough (PVBT) at different treatment pressures.

4.3.2 Petrophysical Properties

Our experiments demonstrated that injecting CO₂-saturated brine alters key petrophysical properties of carbonate rock - namely, porosity and permeability. These changes stem from the chemical reaction between the live brine and the rock, and the subsequent formation of wormholes. **Figure 5a** shows the porosity changes for each sample. No clear relationship was found between the degree of porosity change and the permeability values. This suggests that wormhole structure and branching, which directly determine wormhole size, are the primary factors influencing porosity change. This is supported by **Figure 5b**, which reveals a linear relationship between wormhole size and porosity change. The largest wormhole volume was observed at the experiment of 3 mD, while the smallest occurred at

10 mD. Additionally, in the case of a partial wormhole (22 mD experiment), the permeability increased to 36.75 mD.

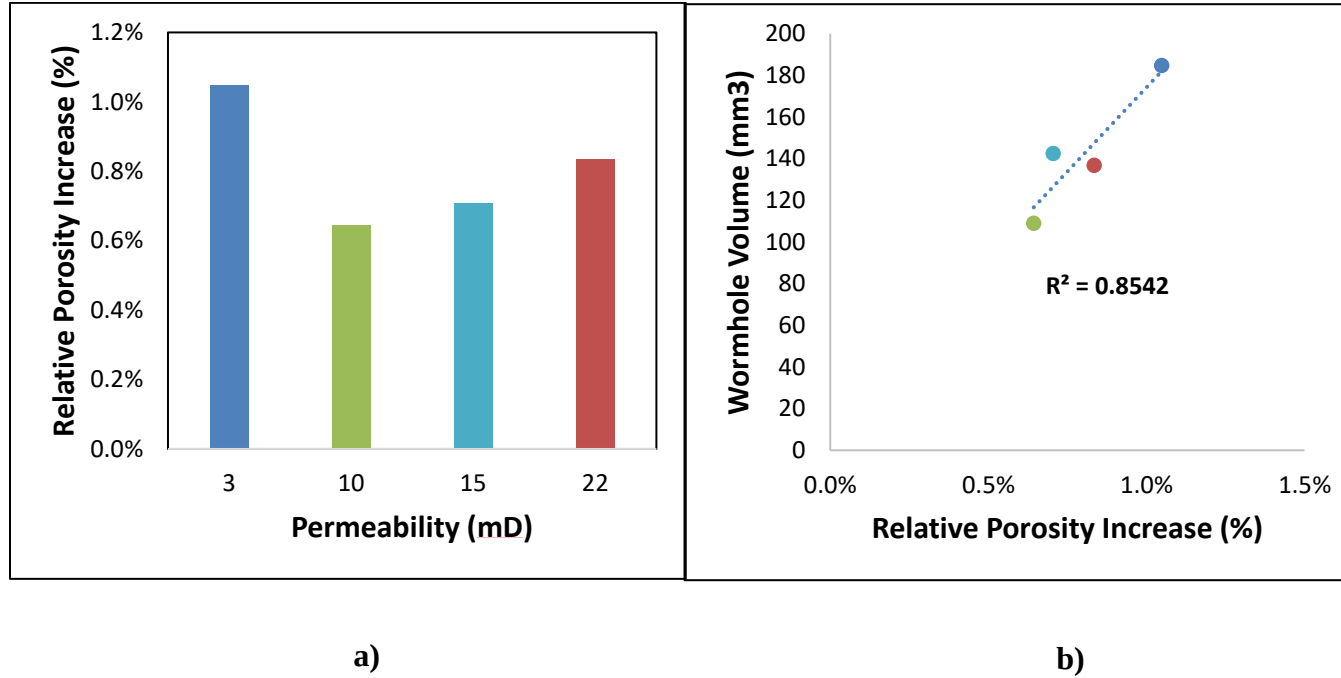


Figure 4.5. (a) The variations in the porosity with respect to pore pressure and (b) the cross plot illustrating the correlation between wormhole volume and porosity change

Figure 6 presents images of the inlet and outlet faces of the samples, with red circles highlighting the presence of wormholes. Micro-CT scans were employed to further reveal the internal structures of these wormholes. The CT images show that the wormhole created in the 10 mD experiment exhibited a relatively simple, single-channel structure with minimal branching. In contrast, the wormholes generated in the 3 and 15 mD experiments displayed a more complex morphology. In the 22 mD experiment, a partial wormhole was formed, exhibiting extensive branching. Furthermore, the 3 mD experiment yielded the thickest wormhole, while the thinnest one was observed in the 10 mD experiment. **Table 4** quantifies the volume of wormholes measured in each experiment.

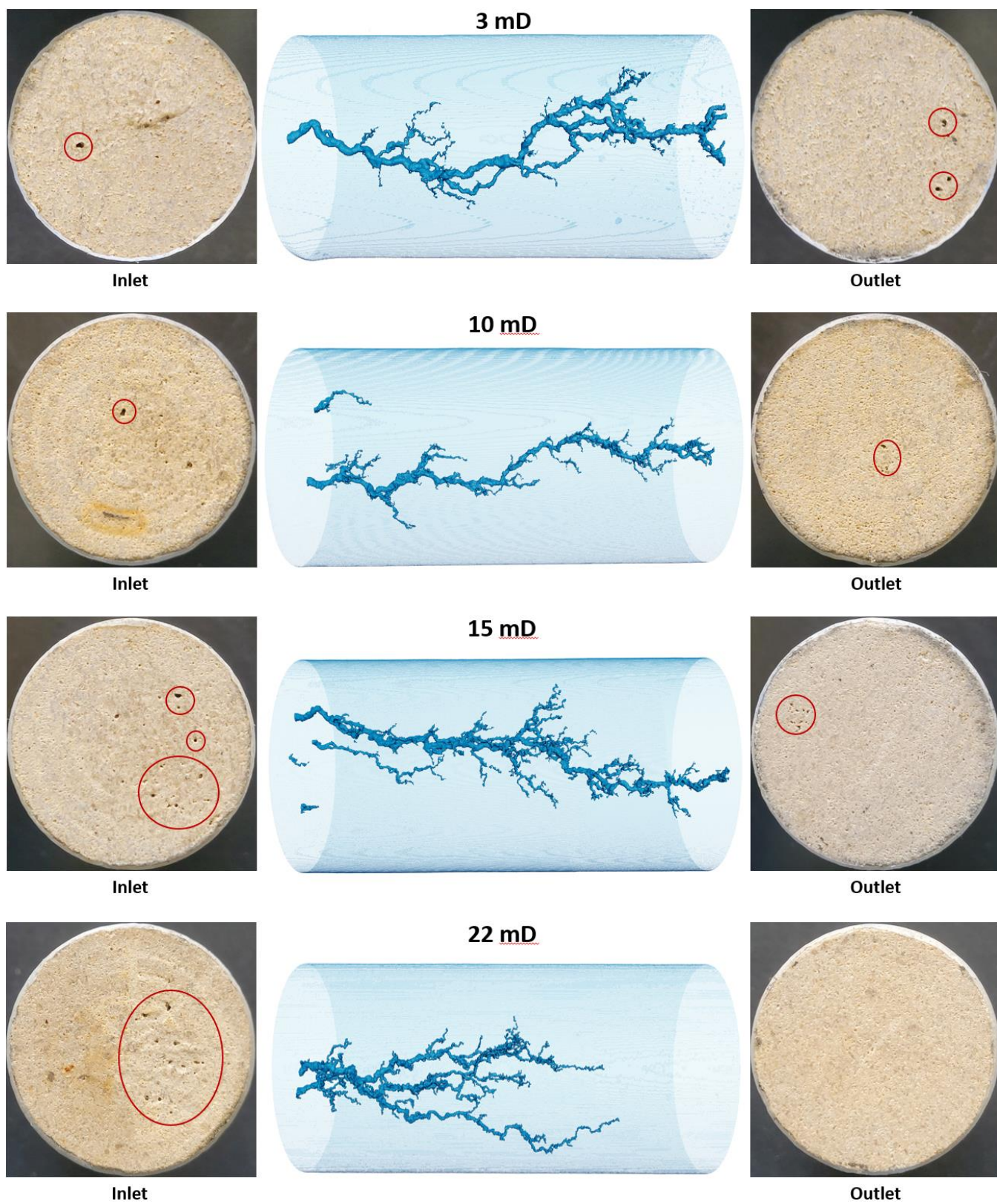


Figure 4.6. Images of the treated samples at the inlet and outlet and micro-CT scan images showing the wormhole structure

Table 4.4. Wormhole volumes for each experiment

<i>Rock Permeability (mD)</i>	<i>Wormhole Volume (mm³)</i>
3	184.72
10	108.98
15	142.5
22	136.83

4.3.3 Mechanical Properties

Figure 7 illustrates the impact of confining pressure on the dynamic Young's Modulus (YM) of the four samples, measured before and after exposure to CO₂-saturated brine. As anticipated, a direct relationship exists between confining pressure and YM: higher confining pressure leads to increased YM values. This trend is likely attributable to pore space compression and the resulting decrease in porosity. Moreover, all samples exhibited a significant YM decrease following their interaction with CO₂-saturated brine.

Figure 8 demonstrates the extent of dynamic Young's Modulus (YM) reduction across all experimental cases. The treatment at 3 mD induced the most significant reduction in YM, whereas the 22 mD experiment exhibited the least reduction. The 22 mD experiment exhibited the least reduction in Dynamic Young's Modulus because the wormhole did not fully penetrate the sample, unlike the continuous wormholes observed in other experiments. Additionally, the 10 mD and 15 mD experiments displayed similar results, not only in terms of PVBT values but also in their Dynamic Young's Modulus behavior. Additionally, a lower reduction in rock strength is observed at higher confining pressures, likely attributed to the compression of pore spaces and wormholes.

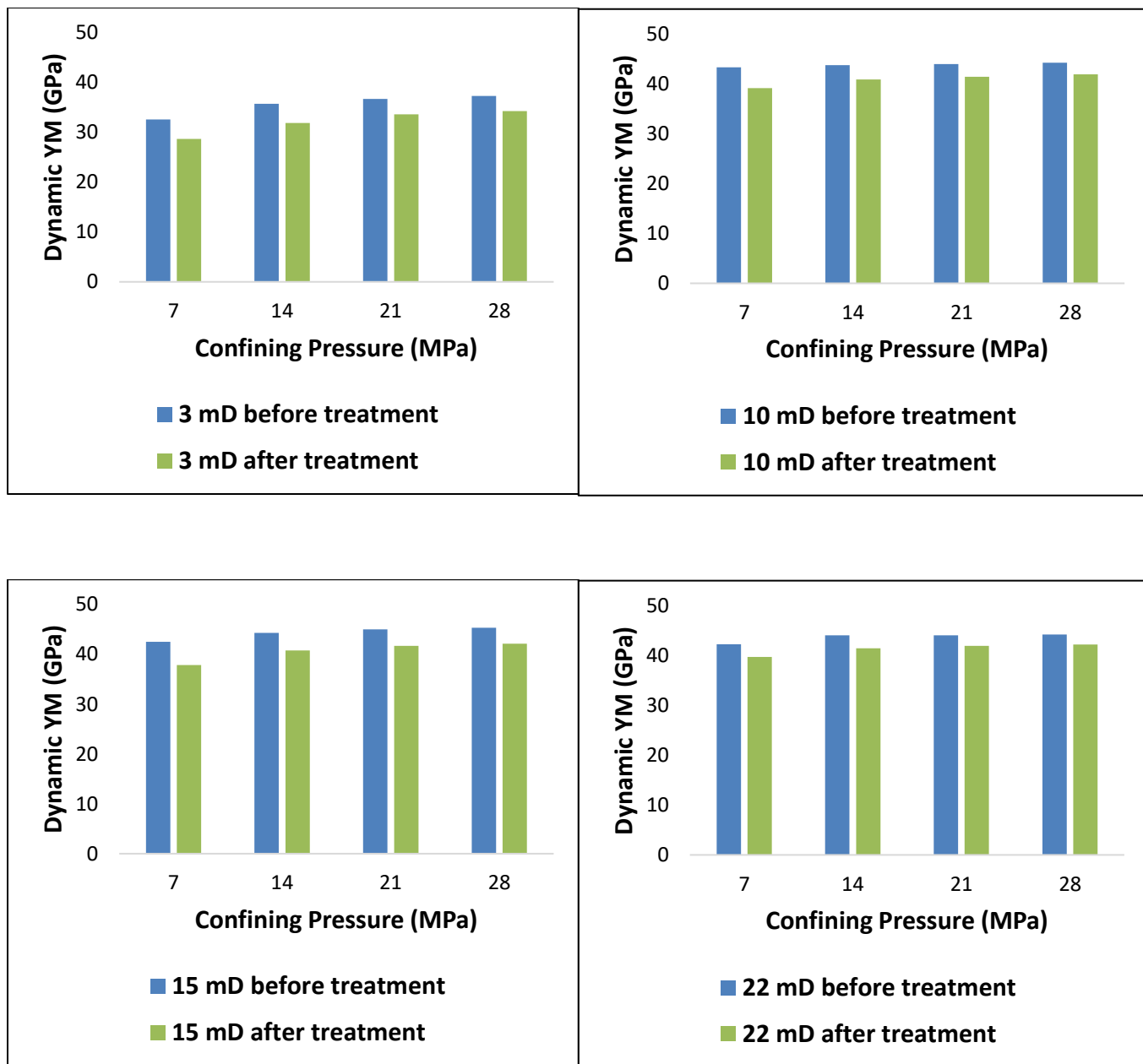


Figure 4.7. Change in Young's Modulus of samples following live brine injection

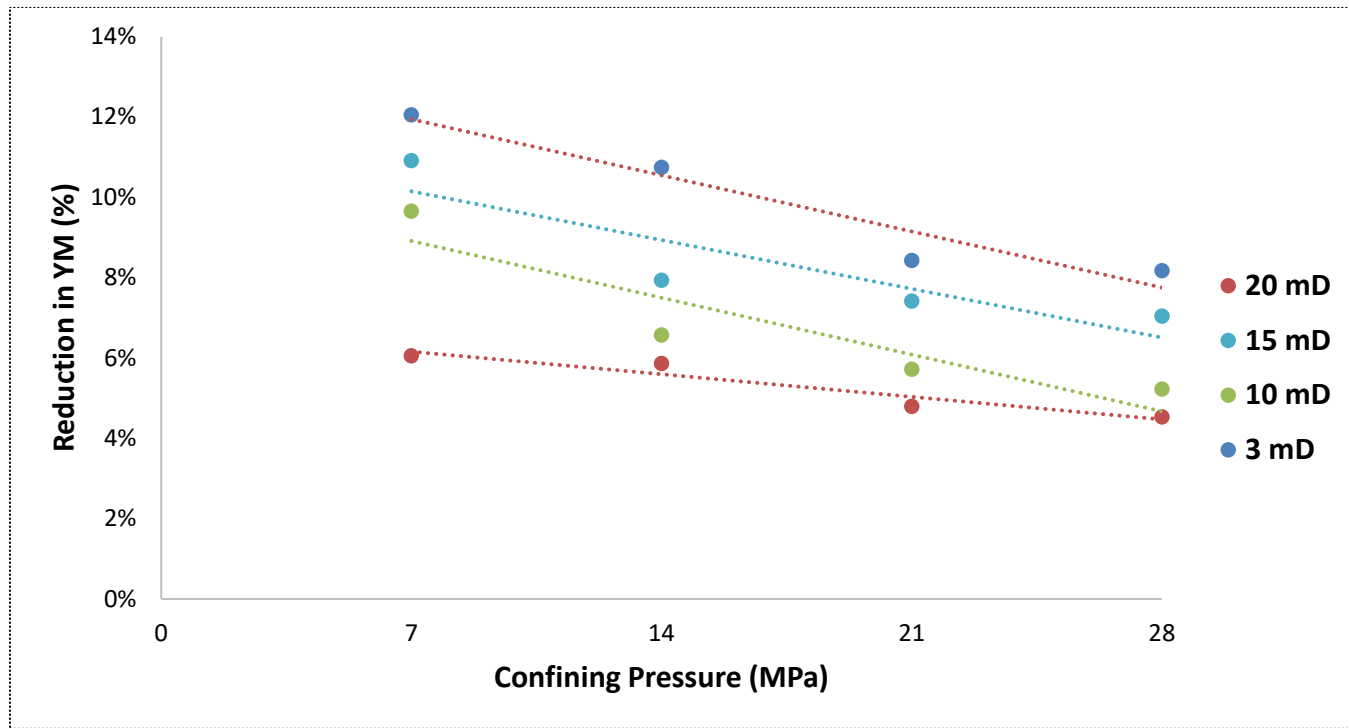


Figure 4.8. Young's Modulus reduction (%) at different confining pressures and injection rates

Figure 9 reveals an expected contrast in the behavior of Poisson's ratio compared to Young's Modulus (YM) following exposure to CO₂-saturated brine and wet CO₂. Unlike YM, Poisson's ratio increases post-treatment. This ratio, which generally falls between 0 and 0.5, measures the propensity of a material to deform perpendicularly to an applied load. The observed increase in Poisson's ratio for intact samples indicates that the carbonic acid reaction resulted in a softening of the rock.

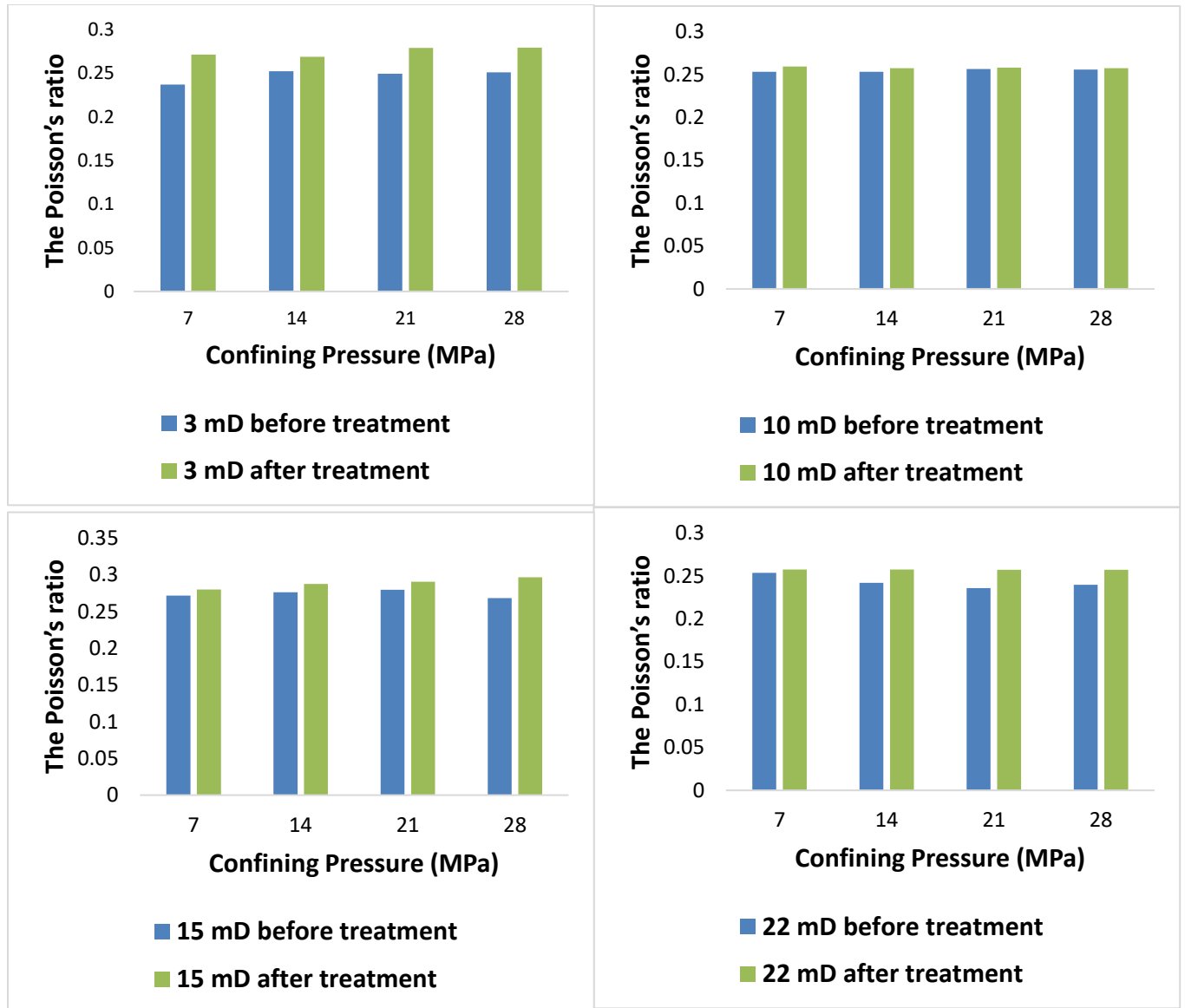


Figure 4.9. Comparison of samples' Poisson's ratio before and after live-brine injection

Rock hardness, a surface property measured at the sample inlet (**Figure 10**), indicates the sample's heterogeneity. Intact samples demonstrated average rock hardness values between 17 GPa and 24 GPa. Dissolution resulted in a reduction in rock hardness across all tested permeability values, with the most pronounced reduction occurring at 3 mD and the least at 22 mD. In general, a trend of increasing rock hardness reduction with decreasing permeability was observed (**Figure 11**). Due to wormhole formation, the bulk of the sample

experienced differential exposure to live brine and wet CO₂, with most fluid channeling through the wormhole. Consequently, at the reservoir scale, Young's Modulus (YM), a bulk property, provides a more accurate representation of overall formation strength compared to rock hardness.

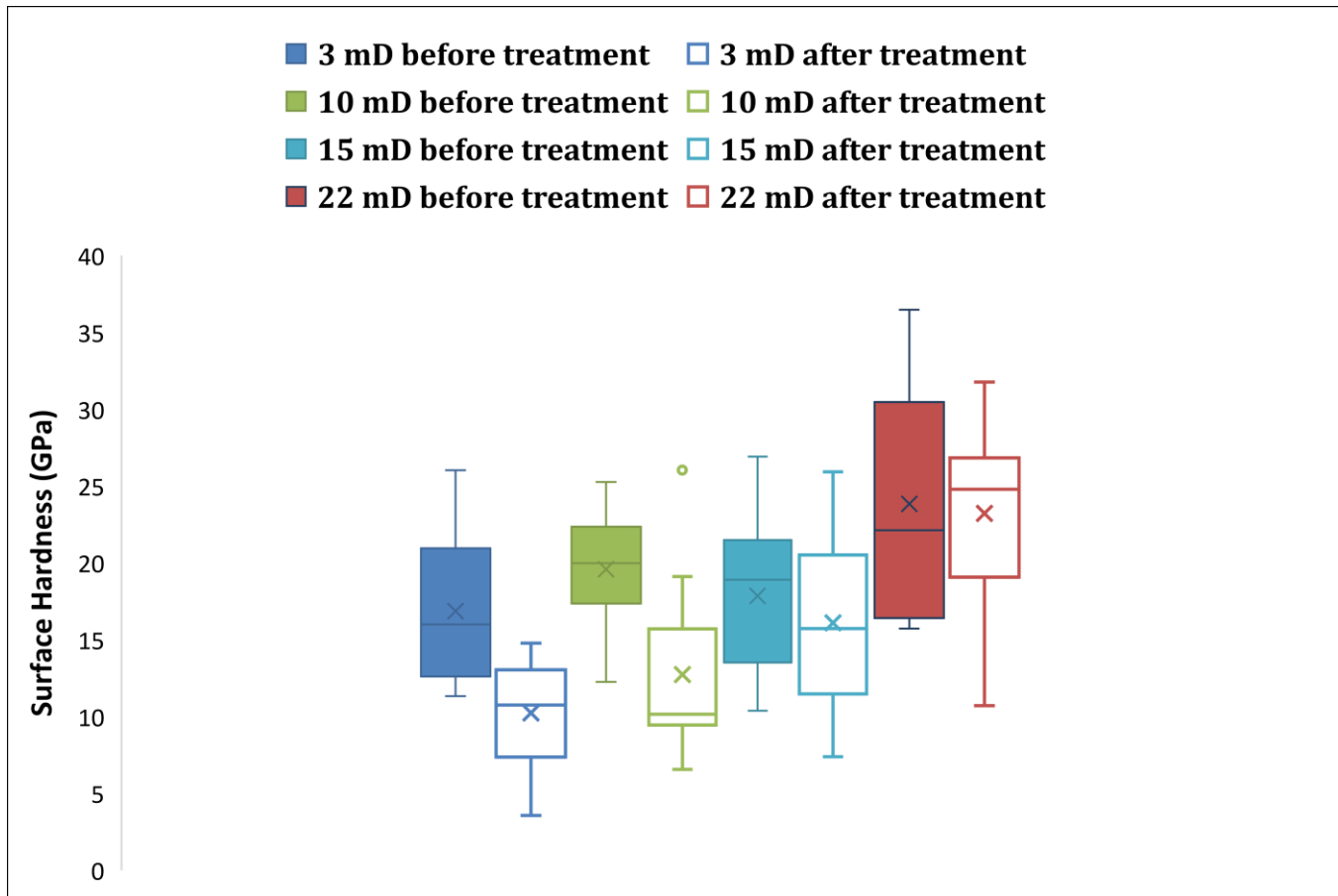


Figure 4.10. Comparison of sample inlet hardness before and after exposure to live brine

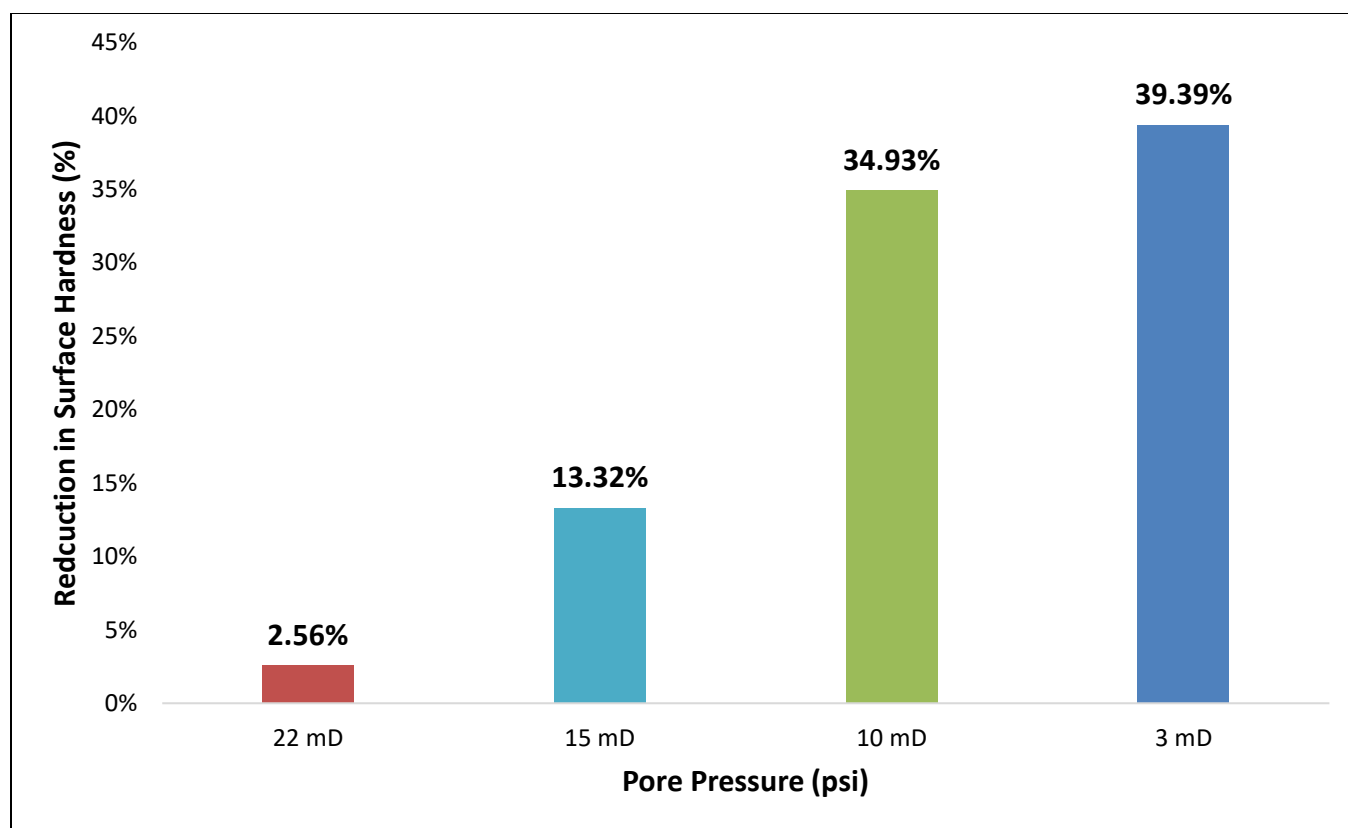


Figure 4.11. Percentage reduction in rock hardness at the sample inlet for different injection rates

4.4 Discussion

Our investigation into the impact of core sample permeability on carbonate reactivity during CO₂-saturated brine injection offers new insights into the complex dynamics of wormhole generation in CO₂ sequestration. Our findings support the observations of Etten et al. (2015), who emphasize the crucial role of permeability in matrix acidizing. As anticipated, our experiments revealed an increasing trend in PVBT with increasing permeability values. However, we did not observe the plateau effect described by Etten et al. (2015). This is likely because our experiments focused on a lower permeability range, where the influence of permeability on optimal flow rate is most pronounced. The difference in PVBT values can be explained through the varying permeability of the formations being treated. In high-permeability formations, the acid faces less resistance

from the rock matrix. This lower resistance allows the acid to leak off more easily into the surrounding rock, diluting its concentration within the primary wormhole. As a result, the rate of rock dissolution slows down, which in turn hampers the forward propagation of the wormhole. Furthermore, the increased leak off contributes to the development of a wider and more branched wormhole structure. This branching consumes more acid, as the acid must be distributed across a larger area to maintain wormhole growth. The non-uniform dissolution due to this leak off further complicates the wormhole formation, making it less efficient and reducing its penetration depth. Conversely, in low-permeability formations, the situation is quite different. The acid encounters significantly greater resistance from the rock matrix, which minimizes leak off. This resistance ensures that a higher concentration of acid remains within the wormhole. The focused acid concentration results in a more efficient dissolution process, as the acid's reactive power is concentrated in a smaller area. Consequently, the wormhole that forms in low-permeability formations tends to be narrower but more effective in penetrating the formation. This efficient penetration means that the wormhole can reach greater depths with less acid, as the acid is not wasted on creating a wide, branched structure but is instead used to extend the wormhole deeper into the rock formation.

Moreover, higher permeability reservoirs offer greater promise for CO₂ sequestration for several reasons. Firstly, the injection process becomes economically more feasible due to the reduced energy demands for achieving the necessary injection pressures. Secondly, our research suggests that higher permeability reservoirs are likely to maintain greater structural integrity during CO₂ injection, as carbonic acid tends to generate slower-penetrating wormhole structures within them. However, it's important to note that reservoir

selection for CO₂ sequestration is a complex process involving a multitude of factors beyond just permeability. Geomechanical stability, the presence of adequate caprock to prevent leakage, and proximity to existing infrastructure must also be carefully evaluated to ensure the long-term safety and viability of the storage project.

Conclusions

This study examined how different rock permeability values during CO₂-saturated brine injection affect the formation of wormholes and its impact on the properties of Indiana limestone samples. The aim was to simulate CO₂ sequestration within deep saline aquifers. Conditions replicating a typical saline aquifer reservoir were used during coreflooding experiments: 1 cm³/min injection rate, 60°C temperature, 120,000 ppm brine salinity, and pore pressure 2000 psi. Tested permeability values were 3, 10, 15 and 22 mD. The following key conclusions were drawn from this investigation:

1. Our experiments demonstrated that the permeability of a core sample significantly influences wormhole generation, as evidenced by the clear trend between increasing PVBT and permeability. As permeability increases, the reaction rate between CO₂-saturated brine and the pore surfaces decreases, resulting in higher PVBT values.
2. Experiments demonstrated that injecting CO₂-saturated brine at varying pore pressures caused alterations in the petrophysical properties of limestone samples, specifically porosity and permeability. The formation of continuous wormholes resulted in increased porosity, with a linear relationship observed between porosity change and wormhole volume. Due to continuous wormholes,

the pressure drop between the inlet and outlet approaches zero, suggesting near-infinite permeability. In case of the partial wormhole, the permeability increased from 22 mD to 36.75 mD.

3. The most significant reduction in Young's Modulus (YM) occurred at the 3 mD experiment, with the 22 mD experiment exhibiting the least reduction. A general trend was observed: lower permeability resulted in greater deterioration of the core samples in terms of dynamic Young's modulus.
4. Similar to the trend observed in dynamic Young's modulus, the most significant decrease in surface hardness occurred in the 3 mD experiment. Overall, a direct relationship was observed between increasing permeability and decreased reduction in surface hardness.

CHAPTER 5

CONCLUSION, FUTURE WORK AND RECOMMENDATION

5.1 Conclusion

The study indicates that CO₂-saturated brine can result in wormhole generation and deteriorate rock integrity. Furthermore, the rate of wormhole formation depends on different injection parameters. The key findings of the study are as follows:

1. Experiments established an optimal injection rate of 1 cm³/min for efficient wormhole formation. Additionally, we performed curve fitting of the experimental data to the Buijse & Glasbergen model, which yielded an optimum injection rate of 0.75 cm³/min through back-calculation. However, a poor correlation exists for velocities below the optimum, suggesting potential modifications to the model may be necessary to accurately predict behavior in the context of carbonated brine.
2. Experiments revealed that injecting CO₂-saturated brine at various velocities induced changes in the petrophysical properties of limestone samples, particularly porosity and permeability. Increased injection rate generally resulted in higher porosity, with a linear relationship observed between porosity change and wormhole volume. The injected volume (700 mL) was insufficient for wormhole breakthrough in the 10 cm³/min and 5 cm³/min experiments, although permeability still increased. In samples with continuous wormholes, permeability is considered to approach infinity.

3. The highest reduction in rock YM was observed at 2, 1 and 0.5 cm³/min experiments overall. Unexpectedly, the experiment conducted at a flow rate of 0.25 cm³/min, despite its longer exposure to live brine, exhibited the smallest reduction in Young's Modulus (YM) among samples featuring continuous wormholes.
4. Results suggest that low flow rates (around 0.5 cm³/min) and limited CO₂ volumes (<1 PV) in the reservoir interior minimize impact on rock integrity. Near the wellbore, high flow rates (>5 cm³/min) reduce CO₂-rock interaction, maintaining rock stability as indicated by minimal changes in Young's Modulus. For tight reservoirs, lower flow rates may improve injectivity.
5. Increasing porosity and permeability can enhance storage capacity, consider potential trade-offs: increased permeability may accelerate plume migration, while increased porosity could enhance structural trapping through lower capillary pressure.
6. Experiments demonstrated that pore pressure above 1500 psi (at constant CO₂ mass) does not significantly influence wormhole generation, as evidenced by the lack of a clear trend between PVBT values and pore pressure. Variations in PVBT between experiments are likely attributed to differences in pore geometry rather than pore pressure.
7. Experiments demonstrated that injecting CO₂-saturated brine at varying pore pressures caused alterations in the petrophysical properties of limestone samples, specifically porosity and permeability. The formation of continuous wormholes resulted in increased porosity, with a linear relationship observed between porosity

change and wormhole volume. Due to continuous wormholes, the pressure drop between inlet and outlet approaches zero, suggesting near-infinite permeability.

8. The most significant reduction in Young's Modulus (YM) occurred at the 4000 psi pore pressure, with the 1500 psi experiment exhibiting the least reduction. A general trend was observed: increased pore pressure resulted in greater deterioration of the core samples in terms of dynamic Young's modulus.
9. Similar to the trend observed in dynamic Young's modulus, the most significant decrease in surface hardness occurred at 4000 psi pore pressure. The 3000 psi and 2000 psi experiments exhibited comparable reductions, with the 3000 psi case displaying a slightly greater decrease. Overall, a direct relationship was observed between increasing pore pressure and increased reduction in surface hardness.
10. Experiments demonstrated that the permeability of a core sample significantly influences wormhole generation, as evidenced by the clear trend between increasing PVBT and permeability. As permeability increases, the reaction rate between CO₂-saturated brine and the pore surfaces decreases, resulting in higher PVBT values.
11. Experiments demonstrated that injecting CO₂-saturated brine at varying pore pressures caused alterations in the petrophysical properties of limestone samples, specifically porosity and permeability. The formation of continuous wormholes resulted in increased porosity, with a linear relationship observed between porosity change and wormhole volume. Due to continuous wormholes, the pressure drop between the inlet and outlet approaches zero, suggesting near-infinite permeability.

In case of the partial wormhole, the permeability increased from 22 mD to 36.75 mD.

12. The most significant reduction in Young's Modulus (YM) occurred at the 3 mD experiment, with the 22 mD experiment exhibiting the least reduction. A general trend was observed: lower permeability resulted in greater deterioration of the core samples in terms of dynamic Young's modulus.
13. Similar to the trend observed in dynamic Young's modulus, the most significant decrease in surface hardness occurred in the 3 mD experiment. Overall, a direct relationship was observed between increasing permeability and decreased reduction in surface hardness

5.2 Future Work and Recommendations

The following work could be done based on our experiments:

1. Changing standard conditions of experiments (i.e. CO₂ volume, permeability of cores for pressure and injection rate studies)
2. Developing a new model alternative to Buijse and Glasbergen (2005) for CO₂-saturated brine
3. Trying to integrate the available data into a fine-grid simulation of an actual reservoir to be close to the reality

REFERENCES

- Ajayi, T., Gomes, J. S., & Bera, A. (2019a). A review of CO₂ storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches. *Petroleum Science*, 16, 1028–1063.
- Ajayi, T., Gomes, J. S., & Bera, A. (2019b). A review of CO₂ storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches. In *Petroleum Science* (Vol. 16, Issue 5, pp. 1028–1063). China University of Petroleum Beijing. <https://doi.org/10.1007/s12182-019-0340-8>
- Al-Dhafeeri, A., Aljawad, M. S., Al Ramadan, M., Ibrahim, A. F., Al Majid, M. M., Al-Yousef, Z., & Al-Yaseri, A. (2023). The impact of CO₂ saturated brine temperature on wormhole generation and rock geomechanical and petrophysical properties. *Gas Science and Engineering*, 119, 205120.
- Al-Dhafeeri, A., Aljawad, M. S., Al-Ramadan, M., Ibrahim, A. F., Al Majid, M. M., Al-Yousif, Z., & Al-Yaseri, A. (2024). The impact of CO₂ saturated brine salinity on wormhole generation and rock geomechanical and petrophysical properties. *Geoenergy Science and Engineering*, 233, 212490.
- Aldhafeeri, A., Mirzayev, E., Aljawad, M. S., Al-Ramadan, M., Ibrahim, A. F., Al-Yousef, Z., Almajid, M. M., Al-Ramadhan, A. M., & Al-Yaseri, A. (2023). Impact of Salinity and Temperature on Wormhole Generation Due to CO₂ Sequestration. *SPE Annual Technical Conference and Exhibition?*, D022S012R002.
- Al-Yaseri, A., Yekeen, N., Al-Mukainah, H. S., Kakati, A., Alfarge, D., & Myers, M. (2022). Rock-Wettability Impact on CO₂-Carbonate Rock Interaction and the

- Attendant Effects on CO₂ Storage in Carbonate Reservoirs. *Journal of Natural Gas Science and Engineering*, 104, 104664.
- Aydin, G., Karakurt, I., & Aydiner, K. (2010). Evaluation of geologic storage options of CO₂: Applicability, cost, storage capacity and safety. *Energy Policy*, 38(9), 5072–5080. <https://doi.org/10.1016/j.enpol.2010.04.035>
- Bachu, S. (2000). Sequestration of CO₂ in geological media: criteria and approach for site selection in response to climate change. *Energy Conversion and Management*, 41(9), 953–970.
- Bachu, S., & Adams, J. J. (2003). Sequestration of CO₂ in geological media in response to climate change: Capacity of deep saline aquifers to sequester CO₂ in solution. *Energy Conversion and Management*, 44(20), 3151–3175. [https://doi.org/10.1016/S0196-8904\(03\)00101-8](https://doi.org/10.1016/S0196-8904(03)00101-8)
- Bennion, B., & Bachu, S. (2006). The impact of interfacial tension and pore-size distribution/capillary pressure character on CO₂ relative permeability at reservoir conditions in CO₂-brine systems. *SPE/DOE Symposium on Improved Oil Recovery*.
- Benson, S. M., & Cole, D. R. (2008). CO₂ sequestration in deep sedimentary formations. *Elements*, 4(5), 325–331.
- Buijse, M., & Glasbergen, G. (2005). A semiempirical model to calculate wormhole growth in carbonate acidizing. *SPE Annual Technical Conference and Exhibition?*, SPE-96892.

- Burnside, N. M., & Naylor, M. (2014). Review and implications of relative permeability of CO₂/brine systems and residual trapping of CO₂. *International Journal of Greenhouse Gas Control*, 23, 1–11.
- Busch, A., & Gensterblum, Y. (2011). CBM and CO₂-ECBM related sorption processes in coal: A review. In *International Journal of Coal Geology* (Vol. 87, Issue 2, pp. 49–71). <https://doi.org/10.1016/j.coal.2011.04.011>
- Cheng, H., Zhu, D., & Hill, A. D. (2017). The effect of evolved CO₂ on wormhole propagation in carbonate acidizing. *SPE Production & Operations*, 32(03), 325–332.
- Chiquet, P., Broseta, D., & Thibeau, S. (2007). Wettability alteration of caprock minerals by carbon dioxide. *Geofluids*, 7(2), 112–122.
- Deng, K., Lin, Y., Ning, H., Liu, W., Singh, A., & Zhang, G. (2018). Influences of temperature and pressure on CO₂ solubility in saline solutions in simulated oil and gas well environments. *Applied Geochemistry*, 99, 22–30.
- Dong, K., Zhu, D., & Hill, A. D. (2017). Theoretical and experimental study on optimal injection rates in carbonate acidizing. *SPE Journal*, 22(03), 892–901.
- dos Santos Lucas, C. R., Neyra, J. R., Araújo, E. A., da Silva, D. N. N., Lima, M. A., Ribeiro, D. A. M., & Aum, P. T. P. (2023). Carbonate acidizing—A review on influencing parameters of wormholes formation. *Journal of Petroleum Science and Engineering*, 220, 111168.

- Ennis-King, J., & Paterson, L. (2005). Role of convective mixing in the long-term storage of carbon dioxide in deep saline formations. *Spe Journal*, 10(03), 349–356.
- Espinoza, D. N., Jung, H., Major, J. R., Sun, Z., Ramos, M. J., Eichhubl, P., Balhoff, M. T., Choens, R. C., & Dewers, T. A. (2018). CO₂ charged brines changed rock strength and stiffness at Crystal Geyser, Utah: Implications for leaking subsurface CO₂ storage reservoirs. *International Journal of Greenhouse Gas Control*, 73, 16–28.
- Etten, J., Zhu, D., & Hill, A. D. (2015). The combined effect of permeability and pore structure on carbonate matrix acidizing. *SPE Europec Featured at EAGE Conference and Exhibition?*, SPE-174314.
- Fredd, C. N., & Fogler, H. S. (1998). Alternative stimulation fluids and their impact on carbonate acidizing. *SPE Journal*, 3(01), 34–41.
- Fredd, C. N., & Fogler, H. S. (1999). Optimum conditions for wormhole formation in carbonate porous media: Influence of transport and reaction. *Spe Journal*, 4(03), 196–205.
- Gershenzon, N. I., Soltanian, M., Ritzi Jr, R. W., & Dominic, D. F. (2014). Influence of small scale heterogeneity on CO₂ trapping processes in deep saline aquifers. *Energy Procedia*, 59, 166–173.
- Ghomian, Y., Pope, G. A., & Sepehrnoori, K. (2008). Hysteresis and field-scale optimization of WAG injection for coupled CO₂-EOR and sequestration. *SPE Symposium on Improved Oil Recovery*.

- Goodarzi, S., Settari, A., Zoback, M., & Keith, D. W. (2013). Thermal effects on shear fracturing and injectivity during CO₂ storage. *ISRM International Conference for Effective and Sustainable Hydraulic Fracturing*.
- Grobe, M., Pashin, J. C., & Dodge, R. L. (2010). Carbon dioxide sequestration in geological media. *State of the Science*.
- Gunter, W. D., Perkins, E. H., & Hutcheon, I. (2000). Aquifer disposal of acid gases: modelling of water–rock reactions for trapping of acid wastes. *Applied Geochemistry*, 15(8), 1085–1095.
- Han, W. S. (2008). *Evaluation of CO₂ trapping mechanisms at the SACROC northern platform: Site of 35 years of CO₂ injection*. Citeseer.
- Hesse, M. A., Tchelepi, H. A., & Orr, F. M. (2006). Scaling analysis of the migration of CO₂ in saline aquifers. *SPE Annual Technical Conference and Exhibition*.
- Huang, T., Ostensen, L., & Hill, A. D. (2000). Carbonate matrix acidizing with acetic acid. *SPE International Conference and Exhibition on Formation Damage Control*, SPE-58715.
- Jalil, M., Masoudi, R., Darman, N. B., & Othman, M. (2012). Study of the CO₂ injection, storage, and sequestration in depleted M4 carbonate gas condensate reservoir, Malaysia. *Carbon Management Technology Conference*.
- Juanes, R., Spiteri, E. J., Orr Jr, F. M., & Blunt, M. J. (2006). Impact of relative permeability hysteresis on geological CO₂ storage. *Water Resources Research*, 42(12).

- Jung, J.-W., & Wan, J. (2012). Supercritical CO₂ and ionic strength effects on wettability of silica surfaces: Equilibrium contact angle measurements. *Energy & Fuels*, 26(9), 6053–6059.
- Kaldi, J. G., Gibson-Poole, C. M., & Payenberg, T. H. D. (2009). *Geological input to selection and evaluation of CO₂ geosequestration sites*.
- Kaldi, J., Kaldi, J. G., Gibson-Poole, C. M., & Payenberg, T. H. D. (2009). *Geological Input to Selection and Evaluation of CO₂ Geosequestration Sites*.
<https://doi.org/10.1306/13171230St59227>
- Kampman, N., Bickle, M., Wigley, M., & Dubacq, B. (2014). Fluid flow and CO₂–fluid–mineral interactions during CO₂-storage in sedimentary basins. *Chemical Geology*, 369, 22–50.
- Kane, R. L., & Klein, D. E. (2002). Carbon sequestration: an option for mitigating global climate change. *Environmental Challenges and Greenhouse Gas Control for Fossil Fuel Utilization in the 21st Century*, 75–88.
- Khalil, R., Emadi, H., & Altawati, F. (2021). Investigating the effect of matrix acidizing injection pressure on carbonate-rich Marcellus shale core samples: an experimental study. *Journal of Petroleum Exploration and Production*, 11, 725–734.
- Khather, M., Yekeen, N., Al-Yaseri, A., Al-Mukainah, H., Giwelli, A., & Saeedi, A. (2022). The impact of wormhole generation in carbonate reservoirs on CO₂-WAG oil recovery. *Journal of Petroleum Science and Engineering*, 212.
<https://doi.org/10.1016/j.petrol.2022.110354>

- Koide, H., Tazaki, Y., Noguchi, Y., Nakayama, S., Iijima, M., Ito, K., & Shindo, Y. (1992). Subterranean containment and long-term storage of carbon dioxide in unused aquifers and in depleted natural gas reservoirs. *Energy Conversion and Management*, 33(5–8), 619–626.
- Kong, X., Delshad, M., & Wheeler, M. F. (2013). An Integrated Capillary, Buoyancy, and Viscous-Driven Model for Brine/CO₂ Relative Permeability in a Compositional and Parallel Reservoir Simulator. *Modelling and Simulation in Fluid Dynamics in Porous Media*, 125–142.
- Kumar, A., Ozah, R., Noh, M., Pope, G. A., Bryant, S., Sepehrnoori, K., & Lake, L. W. (2005). Reservoir simulation of CO₂ storage in deep saline aquifers. *Spe Journal*, 10(03), 336–348.
- Lal, R. (2008a). Carbon sequestration. In *Philosophical Transactions of the Royal Society B: Biological Sciences* (Vol. 363, Issue 1492, pp. 815–830). Royal Society.
<https://doi.org/10.1098/rstb.2007.2185>
- Lal, R. (2008b). Carbon sequestration. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1492), 815–830.
- Lamy, C., Iglaauer, S., Pentland, C. H., Blunt, M. J., & Maitland, G. (2010). Capillary trapping in carbonate rocks. *SPE EUROPEC/EAGE Annual Conference and Exhibition*.

- Lasseter, T. J., Waggoner, J. R., & Lake, L. W. (1986). Reservoir heterogeneities and their influence on ultimate recovery. In *Reservoir characterization* (pp. 545–559). Elsevier.
- Li, B., & Benson, S. M. (2014). Small-scale heterogeneities and buoyancy-driven CO₂ migration in geological storage. *Energy Procedia*, 63, 3608–3615.
- Luo, A., Li, Y., Chen, X., Zhu, Z., & Peng, Y. (2022). Review of CO₂ sequestration mechanism in saline aquifers. *Natural Gas Industry B*, 9(4), 383–393.
- Mahmoud, M. A., Nasr-El-Din, H. A., De Wolf, C. A., & LePage, J. N. (2010). Optimum injection rate of a new chelate that can be used to stimulate carbonate reservoirs. *SPE Annual Technical Conference and Exhibition?*, SPE-133497.
- Mahmoud, M., Barri, A., & Elkatatny, S. (2017). Mixing chelating agents with seawater for acid stimulation treatments in carbonate reservoirs. *Journal of Petroleum Science and Engineering*, 152, 9–20.
- Major, J. R., Eichhubl, P., Dewers, T. A., & Olson, J. E. (2018). Effect of CO₂–brine–rock interaction on fracture mechanical properties of CO₂ reservoirs and seals. *Earth and Planetary Science Letters*, 499, 37–47.
- Metz, B. (2005). *CARBON DIOXIDE CAPTURE AND STORAGE*.
- Metz, B., Davidson, O., De Coninck, H. C., Loos, M., & Meyer, L. (2005a). *IPCC special report on carbon dioxide capture and storage*. Cambridge: Cambridge University Press.

- Metz, B., Davidson, O., De Coninck, H., Loos, M., & Meyer, L. (2005b). *Carbon dioxide capture and storage. Summary for policymakers.*
- Mukherjee, M., & Misra, S. (2018). A review of experimental research on Enhanced Coal Bed Methane (ECBM) recovery via CO₂ sequestration. In *Earth-Science Reviews* (Vol. 179, pp. 392–410). Elsevier B.V.
<https://doi.org/10.1016/j.earscirev.2018.02.018>
- Mustafa, A., Aly, M., Aljawad, M. S., Dvorkin, J., Solling, T., & Sultan, A. (2021). A green and efficient acid system for carbonate reservoir stimulation. *Journal of Petroleum Science and Engineering*, 205, 108974.
- Pan, Z., Ye, J., Zhou, F., Tan, Y., Connell, L. D., & Fan, J. (2018). CO₂ storage in coal to enhance coalbed methane recovery: a review of field experiments in China. *International Geology Review*, 60(5–6), 754–776.
<https://doi.org/10.1080/00206814.2017.1373607>
- Peng, C., Crawshaw, J. P., Maitland, G. C., & Trusler, J. P. M. (2015). Kinetics of calcite dissolution in CO₂-saturated water at temperatures between (323 and 373) K and pressures up to 13.8 MPa. *Chemical Geology*, 403, 74–85.
- Perkins, E., Czernichowski-Lauriol, I., Azaroual, M., & Durst, P. (2005). Long term predictions of CO₂ storage by mineral and solubility trapping in the Weyburn Midale Reservoir. In *Greenhouse Gas Control Technologies 7* (pp. 2093–2096). Elsevier.

- Rasool, M. H., Ahmad, M., & Ayoub, M. (2023). Selecting geological formations for CO₂ storage: A comparative rating system. *Sustainability*, 15(8), 6599.
- Riaz, A., Hesse, M., Tchelepi, H. A., & Orr, F. M. (2006). Onset of convection in a gravitationally unstable diffusive boundary layer in porous media. *Journal of Fluid Mechanics*, 548, 87–111.
- Saadatpoor, E., Bryant, S. L., & Sepehrnoori, K. (2010). New trapping mechanism in carbon sequestration. *Transport in Porous Media*, 82, 3–17.
- Seibel, B. A. , & W. P. J. (2001). (2001). *Potential Impacts of CO₂ Injection on Deep-Sea Biota*. VOL 294. <https://doi.org/https://doi.org/10.1126/science.1065301>
- Seibel, B. A., & Walsh, P. J. (2001). Potential impacts of CO₂ injection on deep-sea biota. *Science*, 294(5541), 319–320.
- Selvadurai, A. P. S., Couture, C.-B., & Rezaei Niya, S. M. (2017). Permeability of wormholes created by CO₂-acidized water flow through stressed carbonate rocks. *Physics of Fluids*, 29(9).
- Spiteri, E. J., Juanes, R., Blunt, M. J., & Orr, F. M. (2005). Relative permeability hysteresis: Trapping models and application to geological CO₂ sequestration. *SPE Annual Technical Conference and Exhibition*.
- Steel, L., Liu, Q., Mackay, E., & Maroto-Valer, M. M. (2016). CO₂ solubility measurements in brine under reservoir conditions: A comparison of experimental and geochemical modeling methods. *Greenhouse Gases: Science and Technology*, 6(2), 197–217.

- Thomson, A. M., César Izaurralde, R., Smith, S. J., & Clarke, L. E. (2008). Integrated estimates of global terrestrial carbon sequestration. *Global Environmental Change*, 18(1), 192–203. <https://doi.org/10.1016/j.gloenvcha.2007.10.002>
- Thomson, A. M., Izaurralde, R. C., Smith, S. J., & Clarke, L. E. (2008). Integrated estimates of global terrestrial carbon sequestration. *Global Environmental Change*, 18(1), 192–203.
- Torp, T. A., & Gale, J. (2004). Demonstrating storage of CO₂ in geological reservoirs: The Sleipner and SACS projects. *Energy*, 29(9–10), 1361–1369. <https://doi.org/10.1016/j.energy.2004.03.104>
- Xu, T., Apps, J. A., & Pruess, K. (2001). *Analysis of mineral trapping for CO₂ disposal in deep aquifers*.
- Xu, T., Apps, J. A., & Pruess, K. (2003). Reactive geochemical transport simulation to study mineral trapping for CO₂ disposal in deep arenaceous formations. *Journal of Geophysical Research: Solid Earth*, 108(B2).
- Xu, T., Apps, J. A., & Pruess, K. (2004). Numerical simulation of CO₂ disposal by mineral trapping in deep aquifers. *Applied Geochemistry*, 19(6), 917–936.
- Yang, D., Tontiwachwuthikul, P., & Gu, Y. (2005). Interfacial interactions between reservoir brine and CO₂ at high pressures and elevated temperatures. *Energy & Fuels*, 19(1), 216–223.

Zakaria, A. S. S., Nasr-El-Din, H. A. A., & Ziauddin, M. (2015). Predicting the performance of the acid-stimulation treatments in carbonate reservoirs with nondestructive tracer tests. *SPE Journal*, 20(06), 1238–1253.

Zareei, D., Rostami, B., & Kostarelos, K. (2022). Petrophysical changes of carbonate rock related to CO₂ injection and sequestration. *International Journal of Greenhouse Gas Control*, 117, 103648.

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Aldhafeeri, A., Mirzayev, E., Aljawad, M. S., Al-Ramadan, M., Ibrahim, A. F., Al-Yousef, Z., ... & Al-Yaseri, A. (2023, October). Impact of Salinity and Temperature on Wormhole Generation Due to CO₂ Sequestration. In SPE Annual Technical Conference and Exhibition? (p. D022S012R002). SPE. <https://doi.org/10.2118/214779-MS>