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Enhancing Lost Circulation Control: Synergistic Effects of Cedar Fiber, Nutshell, and Sweeps on Filtration of Water-based Drilling Fluids

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Enhancing Lost Circulation Control: Synergistic Effects of Cedar Fiber, Nutshell, and Sweeps on Filtration of Water-based Drilling Fluids

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ABSTRACT

The effective management of lost circulation remains a critical challenge in drilling operations, necessitating the development of advanced strategies to minimize fluid loss and enhance wellbore stability. This study investigates the synergistic effects of various Lost Circulation Materials (LCMs) on fluid loss control and sealing efficiency.

The study further demonstrates the efficacy of specific LCM combinations, such as cedar fiber, nutshell, and sweeps, in reducing filtration volume over time. The baseline for the experiments was drilling mud containing water, bentonite, nutshell, sweeps, and cedar fiber. Experiments were conducted by varying the concentrations of one of LCM components while maintaining the concentration of the other LCMs to assess the individual impact on filtration rates. The filtration tests were conducted using a permeability plugger tester (PPT).

When the concentrations of each LCM have been increased the filtration volume significantly dropped down. Comparatively when cedar fiber concentration increased maximum (50%) reduction in filtration was obtained while the minimum (30%) filtration reduction was observed with sweeps addition. The smaller cedar particles were more effective in plugging the disk slot compared to nutshell and sweeps particles. Additionally, the results showed that cedar fiber reduced the filtration volume more efficiently than the other LCMs at all tested concentration.

CHAPTER ONE

INTRODUCTION

1.1 Overview

Fluid loss into the formation during drilling operations is one of the most significant challenges faced by the drilling industry. The consequences of uncontrolled fluid loss include not only the loss of expensive drilling fluids but also increased non-productive time (NPT), which contributes to higher operational costs, and potential wellbore instability, which can affect the integrity of the well and its future production capabilities. In severe cases, fluid loss can lead to catastrophic events, such as blowouts, which pose greater risks than the fluid losses themselves. It has been estimated to cost the drilling industry over one billion dollars annually in rig time (Chevron Phillips Chemical Company, 2014). Blowouts not only endanger personnel and the environment but can also result in significant damage to the wellbore and surrounding geological formations, compounding the economic impact (Kumar et al., 2010; Salehi and Nygaard, 2012).

Lost circulation commonly occurs due to the presence of natural or induced fractures within the formation. Natural fractures, which are a part of the geological characteristics of the formation, can create pathways for fluid to seep into the rock layers. These fractures are often irregular, making them difficult to assess and manage effectively. Moreover, understanding the size and extent of these fractures is a key challenge, as they can vary significantly in different regions of the well. In contrast, induced fractures are often the result of drilling operations, where excessive drilling pressure or improper wellbore stabilization can cause the formation to crack. These fractures are more predictable, allowing for some level of mitigation through operational strategies such as controlling the equivalent circulating density (ECD), or by employing wellbore strengthening techniques that minimize fracture propagation. Managing these induced fractures is critical to preventing excessive fluid loss, as high fracture conductivity can lead to rapid and uncontrolled fluid loss into the formation.

Conventional Lost Circulation Material (LCM) treatments are widely used to address fluid loss, particularly in cases of seepage and partial losses. LCMs are designed to block the fractures by forming a filter cake or solid barrier, thereby reducing the flow of drilling fluids into the formation. The materials vary in composition, particle size distribution (PSD), and effectiveness, with some being more effective at sealing larger fractures, while others may work better for micro-fractures. Despite their widespread use, there is currently no industry-wide consensus on the best practices for handling extreme fluid losses, particularly in highly fractured or permeable formations. Each formation and wellbore present unique challenges, and LCMs that work well in one scenario may not perform as effectively in another. The effectiveness of LCM treatments is typically evaluated by measuring the volume of fluid lost during drilling operations and monitoring the success of fracture sealing through pressure tests. However, achieving complete sealing remains a difficult and expensive task, especially when dealing with highly permeable formations or large fractures.

This study focuses on evaluating the performance of various LCMs in sealing fractures and preventing fluid loss. By conducting controlled laboratory experiments under different conditions, this research aims to provide insights into the factors that contribute to LCM effectiveness, such as particle size distribution, concentration, and combinations of different LCM materials. The results are intended to aid in developing more effective LCM formulations and strategies for managing fluid loss in a range of drilling scenarios, thereby improving operational efficiency and safety in the drilling process.

1.2 Significance

The findings from this study hold substantial significance for the drilling industry, particularly in the ongoing quest to mitigate fluid loss during drilling operations. The demonstrated efficacy of specific LCM combinations, such as cedar fiber, nutshell, and sweeps, in reducing filtration volume over time offers valuable insights that could lead to more effective drilling practices. One of the key implications of these results is the potential for optimizing LCM formulations to achieve better fluid loss control. The ability to reduce filtration volume over time is critical in preventing the costly and dangerous consequences of lost circulation, such as wellbore instability, NPT, and even blowouts. By showing that certain combinations of LCMs, particularly at specific concentrations, can significantly improve fluid loss control, this study paves the way for the development of more reliable and efficient drilling fluids.

The findings also highlight the importance of understanding the interaction between different LCMs. The observed reduction in filtration volume with various combinations suggests that there is a synergistic effect at play, where the combined materials perform better together than they would individually. This insight is crucial for formulating drilling fluids that can better address the complex challenges posed by natural and induced fractures in the formation. Furthermore, the study's exploration of different concentration ratios such as those involving cedar fiber, nutshell, and sweeps provides a deeper understanding of how to fine-tune LCM formulations for optimal performance. The consistent reduction in filtration volume across different LCM concentrations indicates that there is flexibility in how these materials can be used, allowing for tailored solutions that can be adapted to specific drilling conditions.

These findings contribute to the broader effort of enhancing wellbore stability and reducing operational risks in drilling. By advancing the understanding of how LCM combinations can be optimized for better fluid loss control, this research supports the development of safer, more cost-effective drilling practices, ultimately benefiting the industry.

1.3 Problem Statement

Lost circulation, the uncontrolled flow of drilling fluids into the formation during drilling operations, is a persistent and costly problem in the oil and gas industry. This issue not only results in the direct loss of expensive drilling fluids but also leads to a cascade of operational challenges, including increased Non-Productive Time (NPT), compromised wellbore stability, and, in severe cases, blowouts that can have catastrophic consequences for both safety and the environment (Kumar et al., 2010; Salehi and Nygaard, 2012; Vivas, 2021).

The root causes of lost circulation are complex and multifaceted. Natural fractures within the formation, as well as fractures induced by drilling operations, are the primary pathways through which fluid loss occurs. Managing lost circulation in natural fractures is particularly challenging due to the difficulty in accurately assessing the size and extent of these fractures. On the other hand, induced fractures, often resulting from excessive pressure during drilling, can be mitigated by controlling the ECD or by strengthening the wellbore (Alsaba et al., 2014). However, the industry lacks a standardized approach for effectively handling extreme fluid losses, particularly in highly fractured or permeable formations.

LCMs are widely used to combat fluid loss by sealing fractures and reducing the flow of drilling fluids into the formation. However, conventional LCM treatments often exhibit limited effectiveness, particularly when dealing with a wide range of fracture sizes. The success of LCMs in controlling fluid loss is heavily influenced by factors such as PSD, the concentration of the materials, and the interactions between different types of LCMs. Despite their widespread use, there is still no clear consensus on the optimal combinations and concentrations of LCMs needed to achieve maximum sealing efficiency and fluid loss control.

Furthermore, the variability in formation conditions and fracturing characteristics adds another layer of complexity to the problem. LCMs that perform well in one set of conditions may fail in another, making it difficult to develop a one-size-fits-all solution. This lack of a universally effective strategy leads to inconsistent results and ongoing operational challenges.

Given these challenges, there is a pressing need for a deeper understanding of how different LCMs interact and how their performance can be optimized to address fluid loss more effectively. This thesis seeks to address this critical gap by conducting a series of controlled laboratory experiments to evaluate the performance of various LCM combinations. The study will focus on the impact of different concentrations and particle size distributions on the ability of these materials to reduce fluid loss and seal fractures of varying sizes. By exploring these factors, the research aims to identify the optimal formulations of LCMs that can be tailored to specific drilling conditions, thereby improving the efficiency of lost circulation treatments and reducing the risks and costs associated with fluid loss during drilling operations.

1.4 Objectives and Scope of Study

The literature review also evaluates the performance of various LCMs that have been developed to combat fluid loss. This includes an analysis of the properties of these materials, such as PSD, concentration, and their inherent characteristics, and how these factors influence their ability to seal fractures and control fluid loss. The effectiveness of different LCMs in various drilling conditions is assessed to provide a detailed understanding of their strengths and limitations.

Another critical aspect of the review is identifying the factors that affect LCM performance. This involves examining how formation characteristics, fracture size, and the interaction between different LCM materials contribute to the overall effectiveness of fluid loss control. By understanding these factors, the review aims to highlight how LCMs' performance can be optimized to enhance their sealing efficiency in different drilling environments.

This study's objective is to explore the effectiveness of specific combinations of LCMs in reducing filtration volume during drilling operations using a water-based drilling fluid mixed with bentonite. The research focuses on three key materials: cedar fiber, nutshell, and sweeps, which are recognized for their potential to enhance fluid loss control in drilling scenarios. The study seeks to determine the optimal concentrations of these materials that significantly improve sealing efficiency and reduce fluid loss when used in a bentonite-based drilling fluid.

To achieve these objectives, a series of controlled laboratory experiments were conducted. The performance of different LCM combinations was evaluated under these conditions. One key area of focus in the research was the efficacy of cedar fiber at concentrations of 20 and 30 g, combined with nutshell and sweeps, each at 20 g, in reducing filtration volume over time. This combination was tested to provide insights into the synergistic effects of these materials when mixed with a bentonite-based drilling fluid. Additionally, the study explored the impact of varying concentrations of nutshell (10 and 30 g) and sweeps (10 and 30 g) on fluid loss control, aiming to understand how changes in material concentration influence the effectiveness of the LCMs in reducing fluid loss.

The scope of the study is comprehensive, involving a detailed investigation into the performance of these LCM combinations within the context of a water and bentonite-based drilling fluid. The research is designed to explore the interactions between cedar fiber, nutshell, and sweeps, and how these interactions contribute to fluid loss reduction. By systematically varying the concentrations of these materials, the study seeks to identify the most effective combinations for minimizing fluid loss in the simulated drilling environment.

The materials selected, cedar fiber, nutshell, and sweeps, are evaluated based on their ability to reduce filtration volume and improve sealing efficiency when used in a bentonite-based drilling fluid. The results from these experiments were analyzed to identify trends and correlations between different LCM combinations, material concentrations, and the degree of fluid loss reduction. While the experiments were conducted in a laboratory setting, the findings are intended to apply to real-world drilling operations, offering valuable insights into optimizing LCMs in water-based drilling fluids. By contributing to developing more effective drilling fluid formulations and lost circulation treatments, this research supports the advancement of safer, more efficient drilling practices.

CHAPTER TWO

LITERATURE REVIEW

2.1 Fundamentals

Fluid loss and lost circulation are two of the most critical challenges encountered during drilling operations in the oil and gas industry. While both phenomena involve the escape of drilling fluids into the surrounding formation, they differ in severity, causes, and consequences. Understanding their mechanisms and effective mitigation strategies is essential for maintaining wellbore integrity, optimizing drilling performance, and minimizing operational costs.

Fluid loss refers to the gradual seepage of drilling fluid into the surrounding formation. The pressure differential between the wellbore and the formation drives this process. When the pressure in the wellbore exceeds the formation pressure, drilling fluid is pushed into the formation's pore spaces. Over time, the liquid component of the drilling fluid invades the formation, while solid particles, such as bentonite and other additives, accumulate at the wellbore wall to form a filter cake. This filter cake is crucial because it acts as a barrier, reducing further fluid infiltration and stabilizing the wellbore. However, if the filter cake is poorly formed, thin, or permeable, fluid loss may continue, leading to wellbore instability and other complications (Kumar et al., 2010; Kumar and Savary, 2011).

Several factors influence fluid loss during drilling operations, including the permeability of the formation, the properties of the drilling fluid, and the pressure differential between the wellbore and the surrounding rock. Formations with high permeability, such as sandstone or fractured carbonate rocks, are particularly susceptible to fluid loss because the fluid can easily migrate through the pore spaces (Howard and Scott, 1951). Additionally, the rheological properties of drilling fluid, including viscosity, density, and solid content, affect the extent of fluid loss. Fluids with low viscosity and fewer solids are more likely to seep into the formation, while higher viscosity fluids with greater solid content can form more effective filter cakes, thus reducing fluid loss (Nayberg and Petty, 1986).

Although minor fluid loss is common in drilling operations, excessive fluid loss can have significant operational consequences. For instance, if too much fluid is lost into the formation, it can lead to difficulty maintaining the hydrostatic pressure needed to control the well, increasing the risk of a kick and blowout. Moreover, excessive fluid loss can complicate the cementing process, as the lost fluid may reduce the efficiency of the cement slurry, impairing the ability to form a proper seal around the wellbore (Morita et al., 1990; Van Oort et al., 2009).

To manage fluid loss, operators typically design drilling fluids with optimized properties that enhance the formation of stable filter cakes. Various additives, such as bentonite, polymers, and other fluid loss control agents, are commonly used to reduce fluid loss and improve wellbore stability (Contreras et al., 2014). In addition, continuous monitoring of fluid loss rates and real-time wellbore conditions allows operators to intervene quickly, preventing minor fluid loss from escalating into more severe problems.

Lost circulation is a more severe and abrupt form of fluid loss, characterized by the uncontrolled and rapid loss of large volumes of drilling fluid into fractures, voids, or highly permeable zones in the formation. Unlike fluid loss, which typically involves the gradual seepage of fluid into the formation’s pore spaces, lost circulation occurs when fluid escapes into large fractures or cavernous spaces, often leading to a substantial drop in fluid levels in the wellbore. This sudden loss of fluid can have catastrophic consequences if not addressed promptly.

The causes of lost circulation can be classified into three main categories: natural formation conditions, induced fractures, and depleted reservoirs. Natural formation conditions refer to pre-existing fractures, voids, or highly permeable zones in the rock. These formations, such as fractured carbonates or cavernous limestones, have the capacity to absorb significant volumes of drilling fluid, leading to rapid lost circulation. Induced fractures occur when the pressure in the wellbore exceeds the formation's fracture gradient, causing the formation to crack and create pathways for fluid to escape (Salehi et al.,2012). This is particularly common in weak formations or when drilling with high-pressure mud systems (Canson et al., 1985). Depleted reservoirs, where the formation pressure has been reduced due to prior production activities, can also lead to lost circulation. In such cases, the pressure differential between the wellbore and formation can be so great that it results in severe fluid loss.

The consequences of lost circulation are often more severe than fluid loss. A sudden drop in drilling fluid levels can reduce the hydrostatic pressure in the wellbore, increasing the risk of wellbore instability, formation influxes, or even blowouts (Sanders et al., 2010). Additionally, the loss of large volumes of drilling fluid can result in operational delays, as it may be necessary to stop drilling to address the issue. Lost circulation is also costly, as it requires immediate remedial measures to restore wellbore integrity and prevent further fluid loss (Salehi and Nygaard, 2011).

To mitigate lost circulation, operators typically use Lost Circulation Materials (LCMs), which are designed to seal fractures and voids within the formation. LCMs are available in various forms, including fibrous, granular, or flake-like materials, and are added to the drilling fluid to plug the escape routes and prevent further fluid loss (Ashoori et al., 2022). In more severe cases, remedial actions such as cement plugs, wellbore strengthening techniques, or managed pressure drilling (MPD) may be necessary to control lost circulation and restore wellbore stability (Salehi et al., 2020). LCMs play a crucial role in addressing lost circulation. When properly selected and applied, LCMs can help seal fractures, prevent further fluid loss, and restore wellbore integrity (Kumar et al., 2010).

In extreme cases, cement plugs may seal off large fractures or voids and prevent further lost circulation. This method is particularly effective in high-risk situations where the volume of lost circulation is substantial and needs to be quickly controlled to avoid further damage to the wellbore (Jeennakorn, 2017). Wellbore strengthening techniques, such as adding specific materials to the drilling fluid to reinforce the formation and reduce the risk of induced fractures, may also be used with LCMs to enhance wellbore stability and prevent further fluid loss (Salehi and Nygaard, 2012). The results show that lost circulation pressure is highly dependent on Young's modulus of the formation, wellbore size, and type of drilling fluid. However, the conventional theories have ignored these facts (Morita, N., et al., 1990).

Both fluid loss and lost circulation require a combination of preventive and remedial measures tailored to the specific conditions of the drilling operation. For fluid loss, preventive measures include designing drilling fluids with the appropriate rheological properties to form stable filter cakes and using fluid loss control additives to minimize seepage into the formation. Additionally, real-time monitoring of fluid loss rates allows operators to detect early signs of fluid loss and take corrective action before the problem escalates (Mohamed et al. 2021).

More aggressive and immediate interventions are often required for lost circulation. LCMs are the primary remedial action used to seal fractures and voids within the formation, and their selection and application are critical to ensuring their effectiveness. In extreme cases, cement plugs, wellbore strengthening techniques, or MPD may be required to restore wellbore integrity and control the lost circulation (Kumar et al., 2010). Advanced technologies, such as managed pressure drilling, allow operators to maintain precise control over the wellbore pressure, further reducing the risk of lost circulation in challenging formations (Sanders et al., 2008).

Effective management of fluid loss and lost circulation is essential for maintaining wellbore integrity, optimizing drilling performance, and minimizing operational risks. Understanding the mechanisms behind these phenomena, selecting appropriate mitigation strategies, and employing the right combination of additives, LCMs, and remedial techniques are key to ensuring the success of drilling operations. With the increasing complexity of drilling environments, continuous research and development of new materials and technologies will be necessary to address the evolving challenges of fluid loss and lost circulation (Salehi, 2012). Fluid loss and lost circulation are critical challenges in drilling operations that require a deep understanding of their mechanisms, causes, and effects to manage effectively. While fluid loss is a common and often manageable issue, lost circulation represents a more severe threat to drilling operations, with the potential for significant operational and financial consequences. By understanding the differences between these phenomena and implementing appropriate mitigation strategies, petroleum engineers can enhance wellbore stability, reduce drilling costs, and minimize the environmental impact of drilling operations.

2.2 Mechanism

Fluid loss and lost circulation are two critical challenges encountered during drilling operations. While both phenomena involve the escape of drilling fluid into the formation, they differ significantly in their mechanisms, causes, and severity. Understanding the distinct mechanisms of fluid loss and lost circulation is crucial for implementing effective mitigation strategies to ensure wellbore stability, minimize operational delays, and reduce drilling costs.

Fluid loss refers to the gradual seepage of drilling fluid into permeable formations during drilling operations. The primary driver behind this process is the pressure differential between the wellbore and the surrounding formation. When the pressure in the wellbore exceeds the formation pressure, drilling fluid is forced into the formation, leading to fluid loss. As fluid infiltrates the formation, solid particles from the drilling fluid, such as bentonite and other additives, accumulate on the wellbore walls. This accumulation forms a filter cake, which acts as a barrier to reduce further fluid loss. The effectiveness of the filter cake in controlling fluid loss depends on its quality, permeability, and thickness. A well-formed filter cake with low permeability effectively seals the wellbore and minimizes seepage into the formation (Vivas et al., 2021).

The permeability of the formation influences the rate of fluid loss. High-permeability formations, such as sandstone or fractured carbonates, allow more fluid to infiltrate due to their porous structure. In contrast, low-permeability formations, such as shale, typically experience lower rates of fluid loss. The rheological properties of the drilling fluid, including viscosity, density, and particle size distribution, play a significant role in controlling fluid loss. Fluids with higher viscosity and solid content resist infiltration and form more effective filter cakes, reducing fluid loss. In contrast, low-viscosity fluids may penetrate the formation more easily, leading to increased fluid loss.

The quality of the filter cake is a critical factor in managing fluid loss. A thick, compact filter cake with low permeability reduces fluid loss, while a thin or poorly formed cake can result in continued fluid infiltration. The composition of the filter cake, including the types of solids and additives used in the drilling fluid, determines its effectiveness in sealing the wellbore. In most drilling operations, fluid loss is a manageable issue, and engineers can control it by adjusting the drilling fluid properties and promoting the formation of a stable filter cake. However, excessive fluid loss can lead to operational challenges, including wellbore instability and difficulty maintaining hydrostatic pressure (Howard et al., 1951; Chevron-Phillips, 2014; Nayberg et al., 1986).

Lost circulation is a more severe phenomenon compared to fluid loss. It occurs when large volumes of drilling fluid escape uncontrollably into the formation, leading to a significant and often sudden reduction in wellbore fluid levels. Lost circulation can occur in formations with large void spaces, such as cavernous limestones or highly fractured zones. These formations can allow large quantities of drilling fluid to be lost, leading to an immediate drop in wellbore fluid levels. Cavernous formations are particularly prone to lost circulation due to their ability to accommodate significant fluid volumes.

Lost circulation can also be triggered by induced fractures caused by excessive wellbore pressure. When the ECD exceeds the fracture gradient of the formation, it can cause the formation to crack, creating pathways for the fluid to escape. Induced fractures are more likely to occur in weaker formations or when drilling with high-pressure mud systems. In depleted reservoirs, where formation pressure has been reduced due to previous production activities, the large pressure differential between the wellbore and the formation can lead to severe lost circulation. The reduced formation pressure allows fluid to flow rapidly into the formation, causing significant fluid loss.

Lost circulation is also common in highly permeable zones, such as unconsolidated sands or gravel beds. In these formations, the drilling fluid flows directly into the formation without resistance, resulting in a rapid drop in fluid levels. These zones can absorb substantial volumes of fluid, causing operational delays and increasing drilling costs. Natural fracture networks in the formation can further exacerbate lost circulation. In formations with extensive or interconnected fractures, drilling fluid can flow into multiple fractures simultaneously, resulting in significant fluid loss. These networks can be difficult to detect and manage, making lost circulation a persistent challenge (Canson et al., 1985; Mostafavi et al., 2011; Elahi far et al., 2023).

The consequences of lost circulation are often more severe than those of fluid loss. A sudden and substantial loss of drilling fluid can lead to a rapid reduction in hydrostatic pressure, increasing the risk of wellbore instability or even a blowout if formation fluids enter the wellbore. Lost circulation also causes delays in drilling operations, as engineers may need to stop drilling to address the issue. The costs associated with lost circulation are substantial, including the loss of expensive drilling fluids and the potential need for remedial measures such as LCMs, cement plugs, or wellbore strengthening techniques.

While both fluid loss and lost circulation involve the escape of drilling fluid into the formation, they differ significantly in terms of severity, causes, and management strategies. Fluid loss is a gradual process that occurs as drilling fluid infiltrates the pores of permeable formations. It can typically be managed through adjustments to drilling fluid properties and the promotion of filter cake formation. Although fluid loss can lead to operational challenges, it is generally less severe than lost circulation. Lost circulation is an abrupt and severe event that occurs when large volumes of fluid escape into the formation through voids, fractures, or highly permeable zones. Lost circulation can lead to catastrophic consequences, including wellbore instability, blowouts, and significant operational delays.

Managing fluid loss involves optimizing the properties of the drilling fluid to form an effective filter cake and minimize infiltration into the formation. Common additives include bentonite, polymers, and other fluid-loss control agents. In contrast, managing lost circulation requires more immediate and aggressive interventions, such as using LCMs (fibrous, granular, or flake-like substances) to plug voids or fractures. In severe cases, cement plugs or wellbore strengthening techniques may be necessary to restore wellbore integrity and prevent further fluid loss (Salehi, S., et al., 2011; Soroush et al., 2006)

Fluid loss and lost circulation are critical challenges in drilling operations that require a deep understanding of their mechanisms to manage effectively. By understanding the differences between these phenomena and implementing appropriate mitigation strategies, petroleum engineers can enhance wellbore stability, reduce drilling costs, and minimize the environmental impact of drilling operations.

2.3 Factors Affecting LCM Performance

LCMs play a crucial role in mitigating fluid loss during drilling operations by sealing fractures and preventing the uncontrolled escape of drilling fluids into the formation. The effectiveness of LCMs is influenced by several factors, including the type and properties of the LCMs, the characteristics of the formation, and the conditions of the drilling operation.

The type of LCM used is a primary factor affecting its performance. LCMs come in various forms, including fibrous, granular, and flake-like substances. Each type has distinct properties that influence how it interacts with the formation and the drilling fluid. For example, fibrous LCMs are often used to bridge larger fractures due to their ability to create a physical barrier, while granular LCMs can fill smaller voids and enhance the formation of a filter cake. The choice of LCM type should align with the specific requirements of the drilling operation and the nature of the fractures being targeted (Whitfill et al., 2008; Nayberg et al., 1986).

Identifying the type and location of the loss zone is highly beneficial for optimizing treatment strategies. Analytical techniques that correlate loss rate and type curves to the fracture aperture of the loss zone can play a key role in selecting the appropriate bridging material. Table 2.1 provides a generalized categorization of lost circulation treatments.

Table 2.1: shows the general categories of the LCMs (Scott et al., 2020).

General Categories of Lost Circulation Treatments

Type of Treatment	Method	Examples	Key Feature
Conventional LCM: Granular, fibrous, or flaked particles	Plug or bridge permeability or fracture/faults	Nut Shells, graphite, calcium carbonate, plant or textile fibers, mica or cellophane flakes, and LCM blends	Size & strength matter but BHA tools limit sizes
Fracture Packing: High-fluid loss high-solids squeezes & Stress Cage squeezes	Deposit a large volume of compacted solids into a fracture	Diatomaceous earth high-fluid loss slurries and Stress Cage LCM Blends	Time consuming to mix/spot/squeeze & must be squeezed to work
Reactive High Viscosity Slurries	High viscosity fluid increases pressure in loss zone to limit or stop losses	Gunk & shear activated treatments	Often a treatment of last resort & often temporary
Settable Slurries	Fluid sets to form a rigid plug or semi-solid gel plug	Thixotropic cements, crosslinked polymers & resins	Time consuming for rig, can be difficult to spot, often adversely affected by mud contamination
LPM Wellbore Strengthening	Particles form fracture tip bridge near wellbore preventing fracture propagation	30/60 mesh nut shell LPM at 20-50 lb/bbl	Preventative not remedial and difficult to manage at the rig

The experiments summarized in Table 2.2 involved measuring various material properties. Mechanical properties were assessed using the Particle Material Properties Tester (PMPT), while additional parameters such as specific gravity, bulk density, void fraction, and swelling percentage were also evaluated (Loeppke et al., 1990). One notable experiment tested the softening temperature of thermoset rubber derived from ground automobile battery casings. The results demonstrated that minor fluctuations in applied force during the test had little effect, while changes in the elastic modulus with temperature were highly pronounced. Specifically, the elastic modulus of thermoset rubber decreased gradually within a temperature range of 110 to 192°F (43 to 89°C), identifying the softening temperature range of the material (Table 2.2).

Table 2.2: relative material properties tests results (Loeppke et al., 1990).

Material	Type	SG (advertised/ measured)	Softening T (c)	Resilience Module (lbft/in2)	Bulk Density (lb./ft3)	Void fracture (%)	Swelling (water soak) (%)
Thermoset rubber	Granular	1.1/1.48	43 to 88	333	65.48	31	0
Coal	Granular	1.3/2.3	121 to 165	12	82.17	43	0
Expanded aggregate	Granular	2.2/2.6	>260	60	100.2	39	0
Gill Sonite	Granular	1.06/0.75	173.9 to 190	34	33.23	29	0
Mixed nutshells	Granular	/1.2	193.3 to 249	1443	40.8	45	5
Black walnut shell	Granular	/1.1	182.2 to 260	2271	34	48	11
Pertile	Granular	0.54		20	14.89	56	0

The findings indicated that coal, expanded aggregate, Gilsonite®, and perlite are relatively brittle. Both coal and Gilsonite softened at elevated temperatures, with coal disintegrating and Gilsonite melting due to its asphaltic nature. Expanded aggregate exhibited no adverse effects at temperatures up to 260°C. Mixed-nut and black-walnut shells demonstrated excellent temperature stability and exceptionally high compressive strengths, along with superior elastic and resilient moduli.

For remedial lost circulation treatments, bridging the loss zone permeability is critical, regardless of whether the loss zone is a fracture, vug, or pore. The size of materials that can be effectively used is often constrained by factors such as bit nozzle size, MWD/LWD tool dimensions, their screens or filters, and rotary steerable restrictions. Typically, LCM is limited to granular materials below 0.08 in. MWD/LWD tools are frequently rated for use with 114.2 to 142.6 g./l. of medium nut shells with a D100 slightly under 0.08 in, while many tool manufacturers prohibit fibrous or flake-shaped LCM. To accommodate larger materials, downhole bypass circulation subs are available.

The principles of particle bridging are straightforward. Since the earliest technical studies on lost circulation and bridging, it has been established that creating a stable, high-pressure bridge requires strong granular materials. Fibrous and flake-shaped materials have been found to perform less effectively than granular materials in achieving this stability as shown in Figure 2.1. (Scott et al., 2020).

Blended LCM treatments, combining materials like walnut shells, fibers, and flake cellophane, are effective when granular materials alone fail to establish a bridge. These blends, widely available from various manufacturers, enhance sealing capabilities but typically support lower pressure differentials due to the varied strength and characteristics of their components.

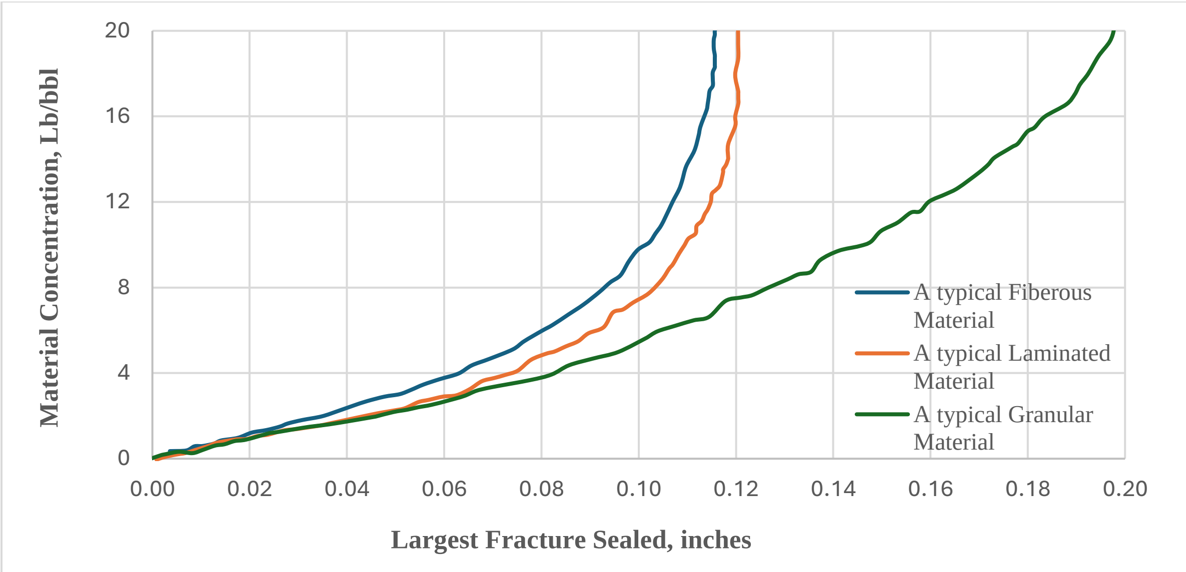


Figure 2.1: Effect of LCM type on sealing (Scott et al., 2020).

One of the most comprehensive studies on bridging mechanics, conducted by Sandia National Labs (Loeppke 1990), highlights that for a stable high-pressure bridge to form, larger particles must be "equal to or slightly larger" than the opening, with concentrations in the range of 28.5–57.1 g./l. The study concluded that "allowable pressure differential increases sharply with particle lengths slightly larger than the fracture width," and granular LCM concentrations up to 57.1 g./l. significantly reduce filtrate loss and enhance the likelihood of forming a high-pressure plug which is shown in Figure 2.2. The modified API tester's plugging performance curve in Figure 2.2 for thermoset rubber particles demonstrates test outcomes across various particle sizes and concentrations. A total of 75 tests were performed, with successful plugs—those sustaining a 6895-kPa differential pressure—marked as Data Point X, while failed plugs were recorded as Data Point O. The plot identifies three key regions: one where plugs consistently held, another where they consistently failed, and a transitional zone where stability varied. The boundary defining the successful plugs serves as a crucial performance benchmark.

This analysis represents a worst-case scenario since not all field applications demand such high-pressure resistance. However, it is a valuable comparison tool, clearly illustrating the effect of concentration. For granular materials, increasing concentration beyond 57.1 g/l yields minimal benefit. If a material proves ineffective at a reasonable concentration, opting for a different size, grade, or type is a more effective approach than simply increasing the quantity used.

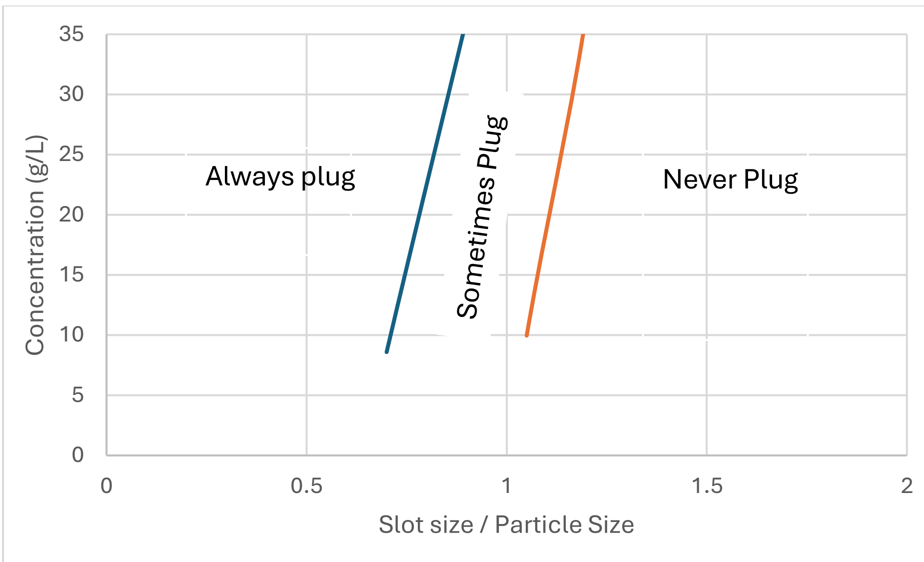


Figure 2.2: Particle size and concentration required for effective bridging (Loeppke 1990).

When the slot size exceeds the maximum particle size (0.07 in), plugging efficiency decreases, as the seal must depend on two- or three-particle bridges. Although multiple-particle plugs can withstand pressure differentials of 6,985 kPa at concentrations as low as 14.3 g/l, their success rate is considerably lower than that of single-particle plugs. Increasing particle concentration primarily improves the likelihood of forming a stable 6,895-kPa plug. Additionally, higher concentrations reduce filtrate volume, with tests at 57 g/l showing about 80% less filtrate than those at 14.3 g/l.

However, practical limitations—such as suspension and settling, rig equipment constraints, nozzle/BHA/tool plugging, attrition, and solids control—often restrict the use of particles above 2 mm, making it challenging to seal fracture apertures larger than 0.08 with conventional LCMs. For such cases, where loss zones with faults, fractures, or vugs exceed 0.08 in size, alternative remedial treatments like high-fluid-loss high-solids squeezes, reactive squeezes, or settled squeezes are typically required.

The size and shape of LCM particles also significantly impact their performance. PSD affects how well LCMs can seal fractures and reduce fluid loss. A well-designed LCM formulation typically includes a range of particle sizes to address different fracture dimensions and formation conditions. Smaller particles can enter and seal narrower fractures, while larger particles are more effective in bridging wider voids. Achieving an optimal PSD helps in forming a stable and effective filter cake that minimizes fluid loss (Wang et al., 2008; Wang et al., 2011). The concentration of LCMs in the drilling fluid is another critical factor. An adequate concentration ensures that there are enough LCM particles to seal fractures and reduce fluid loss effectively. However, excessively high concentrations can lead to issues such as increased fluid viscosity and potential clogging of the equipment. Balancing the concentration of LCMs is essential to maintain fluid properties while optimizing fluid loss control.

The interaction between different LCMs and other additives in the drilling fluid also affects their performance. LCMs can interact with other components, such as polymers and viscosifiers, which can influence the overall effectiveness of the fluid. Understanding these interactions and how they impact the performance of LCMs is crucial for developing effective fluid formulations. Compatibility with other additives can enhance the performance of LCMs and improve fluid loss control.

It is concluded from the study that blends containing NPs and graphite can be successfully implemented in OBM to minimize formation damage in porous media (Contreras et al., 2014).

Establishing a seal within a fracture or at its mouth is influenced by factors such as particle size distribution relative to the fracture aperture, particle morphology, volumetric concentration, fluid rheology, and fluid loss control. Recognizing this distinction is crucial for selecting and applying the most effective treatment for specific field conditions (Kaageson-Loe et al., 2008).

Formation characteristics, such as permeability and fracture density, also play a significant role in LCM performance. In formations with high permeability or extensive fracture networks, LCMs must be able to handle a higher volume of fluid loss and seal larger or more complex fractures. Conversely, LCMs may be required to address less severe fluid loss scenarios in low-permeability formations with fewer fractures. Tailoring LCMs to match the specific formation characteristics ensures better performance and more effective fluid loss control (Schlumberger, 2014).

Operational conditions, including the drilling parameters and wellbore environment, further influence LCM performance. Factors such as temperature, pressure, and flow rates can affect the behavior of LCMs in the drilling fluid. For instance, high temperatures can impact the viscosity and stability of LCMs, while varying flow rates can influence their distribution and effectiveness. Adjusting LCM formulations to account for these operational conditions helps maintain optimal performance throughout the drilling process (Kulkarni et al., 2016).

Experimental studies on the factors influencing the effectiveness and fracture-sealing capability of LCMs have identified several key parameters. These include the fracture dimensions, the friction coefficient of the fracture surfaces, the type and concentration of LCM, the drilling fluid type, slot disc configurations, PSD, LCM stiffness, shape (sphericity and roundness), as well as operational conditions such as pump capacity and wellbore temperature. These factors are critical in designing an effective LCM to efficiently plug and seal fractures present in the wellbore (Mirabbasi et al., 2022). By carefully considering these factors, engineers can develop more effective LCM formulations and strategies to manage fluid loss, enhance wellbore stability, and improve overall drilling efficiency.

2.4 Concentration of the LCM

LCMs are critical components in formulating and applying drilling fluids used in oil and gas operations. They are essential for managing fluid loss during drilling by sealing fractures and voids within the formation. Properly managing the concentration of these materials is crucial to optimizing their performance and ensuring efficient drilling operations. This article provides an in-depth examination of the role of LCM concentration, its impact on drilling fluid performance, and the factors influencing optimal concentrations.

Lost Circulation Materials are additives used in drilling fluids to prevent the uncontrolled fluid loss into the formation. This loss, known as lost circulation, can occur when drilling fluids escape into fractures, voids, or highly permeable zones within the rock formation. LCMs work by bridging these fractures or voids, thereby reducing the fluid's ability to escape and mitigating potential issues such as wellbore instability, increased non-productive time (NPT), and environmental hazards (Nasiri et al., 2018).

LCMs come in various forms, including fibrous materials, granular particles, and flakes. Each type has specific properties that affect its ability to seal fractures and control fluid loss. The effectiveness of these materials is influenced by their concentration in the drilling fluid (Whitfill et al., 2008; Schlumberger, 2024; Baker Hughes 2024; Halliburton, 2024).

The concentration of LCMs in the drilling fluid plays a pivotal role in their ability to seal fractures and effectively reduce fluid loss. At an optimal concentration, LCMs can provide a robust barrier against fluid infiltration, enhancing the stability and efficiency of the drilling process. However, achieving this balance requires a nuanced understanding of several factors.

Higher concentrations of LCMs generally increase the likelihood of successfully bridging and sealing fractures. More particles are available to form a plug or barrier, effectively blocking fluid flow into the formation. This is particularly important in formations with large or numerous fractures. However, simply increasing the concentration does not always yield proportional improvements in sealing efficiency. There is often a threshold beyond which additional LCMs may not significantly enhance performance and may even lead to diminishing returns (Alsaba et al., 2014).

The concentration of LCMs affects the rheological properties of the drilling fluid, including its viscosity, density, and flow characteristics. Optimal concentration ensures the drilling fluid maintains its desired properties, such as manageable viscosity for effective pumping and handling. Excessive LCM concentrations can lead to increased viscosity, which may complicate the pumping process and potentially cause blockages in the drilling equipment. Conversely, insufficient concentrations might not provide adequate sealing, leading to continued fluid loss and potential operational issues (Alsaba et al., 2014; Hemphill et al., 1993).

High concentrations of LCMs can pose operational challenges, such as equipment clogging and increased maintenance needs. The accumulation of LCM particles in the drill string and surface equipment can hinder normal operations and result in additional downtime and costs. Therefore, maintaining appropriate concentration is crucial to avoid these complications while achieving effective fluid loss control (Mansour et al., 2019; Salehi et al., 2020; Kulkarni et al., 2016).

Lost Circulation Material (LCM) is a carefully chosen granular material with specific strength and gravity characteristics. When mixed at an optimal concentration into oil-based or water-based mud, it effectively protects formations from lost circulation during drilling operations (Fuh et al., 1992).

Several factors influence the optimal concentration of LCMs in drilling fluids. The size and extent of fractures or voids in the formation dictate the type and concentration of LCMs required. Larger fractures or more extensive voids generally require higher concentrations of LCMs to ensure effective sealing. The geological and petrophysical properties of the formation must be assessed to determine the appropriate LCM concentration.

The baseline properties of the drilling fluid, such as its viscosity, density, and solid content, must be considered when determining LCM concentration. An optimal concentration must balance effective sealing with maintaining desirable fluid properties. Real-time monitoring of fluid loss rates and wellbore conditions allows for dynamic adjustments to LCM concentrations. This adaptive approach ensures that the concentration remains appropriate for changing conditions, thus maintaining effective control over fluid loss throughout the drilling process.

Different types of LCMs have varying effectiveness based on their particle size, shape, and material properties. For instance, fibrous LCMs might be more effective in certain conditions compared to granular or flake LCMs. The type of LCM used, along with its concentration, must be tailored to the specific drilling conditions and formation characteristics (Van Oort et al., 2009; Sanders et al., 2008).

Several studies provide valuable insights into the impact of LCM concentration on drilling fluid performance. Research highlighted the importance of optimizing LCM concentrations to balance sealing efficiency and fluid properties. Their study emphasized that while higher concentrations generally improve sealing, there is a threshold beyond which additional LCMs do not provide proportional benefits and may cause operational issues (Mirabbasi et al., 2022).

Vivas, C (2021) explored the effects of different LCM concentrations on fluid loss control in various drilling scenarios. Their findings reinforced the need for precise concentration management to achieve effective fluid loss control while avoiding complications such as increased viscosity and equipment clogging.

In their experimental study, Howard and Scott Jr. (1951) investigated the performance of various LCMs under dynamic conditions and at room temperature. They evaluated the sealing capability of different fracture sizes in relation to material type and concentration, measuring the ability to maintain a seal under a differential pressure of 6895 KPa, as shown in Figure 2.3.

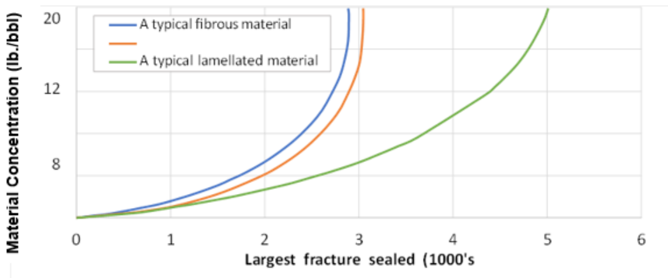


Figure 2.3: Effect of LCM concentration on different fracture sizes experiment (Howard and Scott, 1951).

Smith, Williams, and Jones (2021) demonstrated the significance of adapting LCM concentrations based on real-time monitoring of drilling conditions. Their research showed that dynamic adjustments to LCM concentrations based on observed fluid loss rates and formation characteristics could lead to more efficient and cost-effective drilling operations.

The concentration of Lost Circulation Materials is critical in managing fluid loss during drilling operations. An optimal concentration balances the need for effective sealing with the maintenance of desirable fluid properties and operational considerations. Understanding the role of LCM concentration and the factors influencing it is essential for optimizing drilling fluid formulations and ensuring successful drilling operations. Through careful management and real-time adjustments, petroleum engineers can enhance wellbore stability, reduce drilling costs, and minimize the environmental impact of drilling activities.

2.5 Particle Size Distribution

Fluid circulation is a common problem encountered during drilling operations, where the drilling fluid is lost into the formation due to the presence of fractures, vugs, or highly permeable zones. LCMs are introduced into the drilling fluid to mitigate this problem by sealing fractures and reducing fluid loss. The selection of appropriate LCMs, particularly their PSD, plays a crucial role in achieving an effective seal in fractures of varying sizes. This chapter presents an analysis of how PSD and fracture width affect the sealing pressure and integrity of LCMs, along with recommendations for optimizing LCM formulations for enhanced performance (Xu et al. 2017).

Several studies have demonstrated the significant impact of PSD on the sealing performance of LCMs. When the concentration of fine particles decreases and the concentration of coarse particles increases, a noticeable decrease in maximum sealing pressure is observed (van Oort, 1994). To enhance sealing efficiency, using a blend of materials with varied particle sizes and shapes in the LCM formulation is crucial. This minimizes the dependence on fracture size for effective sealing (Jeennakorn et al., 2017; Alsaba et al., 2016). Using a wide PSD allows for forming a more robust seal, particularly when the fracture width increases from 1,000 to 3,000 microns. Despite the increase in fracture width, no significant reduction in maximum sealing pressure was noted, indicating that with an optimized PSD, fracture size has a limited effect on the functionality of the LCM blend (Alsaba et al., 2016).

Among the various LCM formulations tested, those containing oak shell demonstrated superior performance compared to the others, followed by formulations with mica and cane blends, respectively. The findings indicate that combining these materials yields better results than using them individually. As detailed later, a wide diversity in particle size (broad PSD) leads to more effective fluid loss control. Additionally, to minimize the dependence of an LCM formulation's sealing ability on fracture size, it is recommended to mix materials with varying particle sizes and shapes (Ashoori et al., 2022).

The size of granular LCM is crucial for both addressing lost circulation and preventing drill string plugging. However, the absence of industry-standard naming conventions creates confusion, as product names often vary widely within and across suppliers (Scott et al., 2020). For example, "fine" walnut shells from one supplier may have a D50 six times larger than those labeled "fine" by another, and over 300 LCM products from 50+ companies use inconsistent naming criteria.

The size of the larger solids in most field muds is in the 75–150-micron range, depending on the shaker screen size openings (Table 2.3), not the additives used in the mud formulation.

Table 2.3: Mesh opening diameters in microns (Scott 2020).

US Sieve number	Opening Microns
50	300
60	250
70	212
80	180
100	150
120	125
140	106
170	90
200	75
230	63
270	53
325	45
400	38
450	32
500	25

Naming conventions differ further with materials like calcium carbonate, which may be labeled using D50 or D90, while others use different labeling methods or screen sizes. Some products specify size ranges (e.g., 40-200), but terms like “fine,” “medium,” and “coarse” often lack consistency. Adopting a standardized naming system for LCMs, particularly granular materials, would greatly enhance clarity and product selection.

LCM formulations consisting of particles ranging from small to coarse sizes prove advantageous in sealing fractures. The experimental data support the conclusion that a wide PSD can enhance the overall effectiveness of sealing. In this context, the D90 parameter, which represents the size at which 90% of particles are smaller, plays a crucial role in determining the LCM's effectiveness. Ensuring that the D90 value is large enough to allow for adequate bridging is essential for successful sealing (Alsaba et al., 2016). For instance, fine nutshell particles have been found to fill the voids between larger particles, facilitating the sealing of fractures as wide as 2,000 microns with minimal fluid loss, a result attributed to the wide PSD of the LCM system (Alsaba et al., 2016).

Statistical analysis suggests that the sealing pressure is influenced by several factors, including fracture width, fluid density, and PSD. Among these factors, PSD stands out as the most influential in determining the sealing ability of a particular LCM formulation. Weighting materials in the drilling fluid also play a critical role in the sealing process by interacting with LCM particles to enhance sealing integrity (Nayberg et al., 1986). These solid particles in both water-based fluids (WBF) and oil-based fluids (OBF) contribute to the sealing process before reaching the fracture zone.

To better understand the relationship between PSD and seal integrity, experiments were conducted using dry sieve analysis. Seal integrities for different fracture widths were graphed against the PSD on a y-axis, demonstrating that the D90 value has the most substantial influence on overall seal performance. Larger particles improve seal integrity, and matching the D90 value with the fracture width ensures effective sealing, corroborating findings from earlier studies.

The results from this study strongly suggest that any granular LCM formulation targeting a specific fracture width should have a D90 equal to or slightly larger than the expected fracture Sealing performance is influenced by fracture size, orientation, and LCM concentration (Fuh et al., 1992). When the concentration of LCM is reduced below the optimal level, the sealing efficiency drops as fewer LCM particles reach the loss zone. Coarse particles create a bridging structure, which is then filled with finer particles, closing gaps in the bridge. In high-temperature geothermal operations, the use of LCMs with a broad PSD has proven effective in sealing fractures, with minimal fluid loss, even under challenging conditions.

For Mica blends, increasing concentration from 71.33 to 142.65 g/L led to a corresponding increase in maximum sealing pressure. However, an excessive increase in coarse particle concentration hindered particle penetration into the fracture, resulting in incomplete sealing. The PSD of the weighting materials significantly influences sealing pressure, with finer PSDs correlating to improved sealing.

The performance of LCMs was assessed using a series of experiments involving different concentrations and particle sizes across a set of fracture-simulating cells. These tests confirmed that both the concentration and PSD selection significantly impact on LCM performance. For example, increasing the nutshell concentration from 42.8 to 142.65 g/L improved seal integrity by approximately 500%. In LCM blends, such as a mixture of graphite and nutshell, the seal integrity improved by 22% and 113% when tested under different sealing pressures.

The performance of LCMs under dynamic conditions has also been explored. Howard and Scott Jr. (1951) evaluated the performance of LCMs under room temperature, assessing their ability to seal fractures of varying sizes at differential pressures of up to 6895 Kpa. Their findings support the idea that LCM concentration and particle size distribution are critical factors in determining sealing effectiveness.

The effectiveness of LCM formulations depends significantly on the PSD, with the D90 parameter being crucial for optimizing fracture sealing. By selecting a D90 value that matches or slightly exceeds the expected fracture width, effective sealing can be achieved. Furthermore, the concentration of LCM, the interaction between weighting materials, and the influence of PSD on sealing pressure must all be considered when designing LCM formulations for specific fracture conditions. These findings offer valuable insights for enhancing the performance of LCMs in preventing lost circulation during drilling operations (Alsaba et al., 2016).

2.6 Shape of LCM

Lost circulation is a critical problem in the oil and gas industry, often leading to significant delays, increased costs, and compromised well integrity. To mitigate these challenges, CMS are deployed to prevent or reduce the loss of drilling fluid into fractured or highly permeable formations. The effectiveness of an LCM in sealing these fractures is influenced by a variety of factors, including PSD, material composition, and concentration. Among these, the shape of the LCM particles is often overlooked but plays a pivotal role in optimizing the performance and achieving an effective seal. This article explores how the shape of LCM particles impacts their performance in the sealing process.

The shape of LCM particles directly influences their ability to bridge and seal fractures within the formation. In most formulations, LCM particles come in varied shapes such as angular, fibrous, flat, or spherical. Each of these shapes behaves differently under pressure and in the presence of fluid flow, which determines how well the particles can fill fractures or voids (Magzoub et al., 2020). Angular particles may interlock better, providing structural support, while fibrous particles are more effective in forming a mesh that can block fluid movement. Flat and spherical particles, on the other hand, may behave differently by either stacking or rolling, impacting their effectiveness in fracture sealing (Scott et al., 2020).

Angular Particles: Angular particles, such as ground nutshells or calcium carbonate, are often effective for initiating the bridging process. Their sharp edges allow them to catch onto the rough surfaces of fractures, helping to create an initial barrier. However, angular particles may not always fully seal a fracture as their sharp corners can leave voids between particles (Canson, 1985). This is why angular materials are often combined with other shapes in LCM blends to ensure a more comprehensive seal.

Fibrous Particles: Fibrous materials, such as cedar fibers, mica, or cellulose, offer unique advantages in the sealing process. Their elongated, string-like structure allows them to intertwine, providing a flexible and adaptable seal that conforms well to fracture surfaces. Fibrous LCMs are particularly effective in narrow or irregularly shaped fractures where other particle shapes may struggle to bridge the gaps. Fibers can also be packed tightly, which increases their ability to resist fluid loss even under high differential pressures (Mansour et al., 2019).

Flat or Plate-Like Particles: Flat or plate-like particles, such as mica or graphite, are particularly efficient at sealing wide fractures. Due to their large surface area, these particles lay flat across the fracture opening and can quickly form a dense, impermeable layer. Their ability to stack each other creates a strong seal, especially when combined with smaller, finer particles that can fill in the gaps between the flat plates (Salehi et al., 2020).

Spherical Particles: Spherical materials, like beads or certain synthetic materials, are often used in conjunction with other particle shapes. Their primary advantage is their ability to flow easily into fractures, especially under dynamic conditions. However, due to their shape, they may not always provide the best bridging capability alone. Spherical LCMs are often used to complement angular or fibrous particles, filling the spaces left between larger particles to create a more complete seal.

Ground nutshells were incorporated into the formulated water-based drilling fluid systems to enhance sealing capabilities. The results showed that a combination of 142 g/L nutshells and barite nano-micro particles achieved significantly higher sealing compared to other LCM-treated drilling fluids. The addition of nano-micro particles alongside nutshells improved the sealing pressure by over 205% when utilizing mechanically produced nanoparticles, compared to the baseline scenario (Scott et al. (2020)) The shape of LCM particles influences two primary aspects of their performance: bridging and packing

Bridging: This refers to the ability of LCM particles to lodge themselves into a fracture or void, creating an initial barrier that prevents the drilling fluid from escaping. Angular and fibrous particles tend to excel at bridging due to their irregular shapes, which provide more contact points for catching onto fracture surfaces (Rahmat et al., 2021).

Packing: Once the bridge is established, the LCM particles must pack together tightly to form a low-permeability seal. This process is where the combination of different shapes becomes crucial. For example, angular particles may form the bridge, but spherical or flat particles can fill the voids between them, resulting in a more robust seal (Rahmat et al., 2021).

Several studies have been conducted to evaluate the effect of LCM particle shape on sealing performance. A notable finding is that a combination of particle shapes typically yields the best results. For instance, blends that include angular, fibrous, and flat particles are shown to create better seals than single-shape LCMs. These mixed-shape blends offer the dual benefit of effective bridging (from angular particles) and improved packing (from fibrous and flat particles) (Salehi et al., 2012).

A shape memory polymer (SMP) that can effectively seal large fractures in geothermal formations while minimizing the risk of obstructing downhole drilling and logging tools (Mohamed et al., 2022).

A study (Mostafavi et al., 2011) reported that using fibrous LCMs in combination with flat mica particles significantly reduced fluid loss in fractures with widths of 2,000 microns. The fibrous particles created an initial bridge, while the flat particles layered over the bridge to form a dense, impermeable barrier. This combination also exhibited better resistance to high pressures compared to using fibrous or flat particles alone. Based on the analysis of particle shapes and their role in LCM performance, the following recommendations can help optimize LCM formulations:

Use a Combination of Shapes: To maximize sealing efficiency, LCM formulations should include a mixture of angular, fibrous, flat, and spherical particles. This blend ensures that the LCM can both bridge the fracture and pack tightly enough to form a strong seal (Mostafavi et al., 2011).

Tailor LCM Shape to Fracture Type: Different fractures require different shapes for optimal sealing. For example, narrow, irregular fractures may benefit more from fibrous particles, while wide fractures can be more effectively sealed using flat or plate-like particles.

Consider Fluid Dynamics: In dynamic conditions, such as those encountered in drilling, spherical and fibrous particles perform better as they can more easily flow into and seal fractures. Angular particles, while effective in static conditions, may not be as efficient under these conditions.

The shape of LCM particles plays a vital role in determining the success of the sealing process during drilling operations. Angular, fibrous, flat, and spherical particles each bring unique advantages, and combining them in an LCM formulation can lead to better sealing efficiency. By understanding the role of particle shape and how it affects bridging and packing mechanisms, engineers can optimize LCM formulations to tackle lost circulation more effectively. Future research and field trials will continue to show how different shapes interact in various drilling environments, allowing for even more precise LCM designs.

Figure 2.4 from Alsaba et al. (2016) presents optical microscopy images illustrating the physical characteristics of three lost circulation materials (LCMs): graphite, sized calcium carbonate, and nutshells at two magnification levels: ×60 and ×200. At 60 times magnification, graphite appears as flat, flaky particles with irregular shapes, indicating its potential to form thin sealing layers. Sized calcium carbonate particles are more angular and uniform, which helps them bridge across pore spaces in the formation. Nutshells show a rough, irregular surface with varying shapes and sizes, suggesting they could provide a mechanical plugging effect.

At a higher magnification (×200), the graphite flakes become more clearly visible with sharp edges and thin layering. The angular structure and consistent sizing of the calcium carbonate particles are even more pronounced. Nutshell particles at this magnification reveal a porous surface texture, which could enhance their fluid absorption and plugging efficiency. These images provide detailed visual evidence of the structural differences among the LCMs, offering insight into how their physical characteristics may affect their sealing performance in drilling applications.

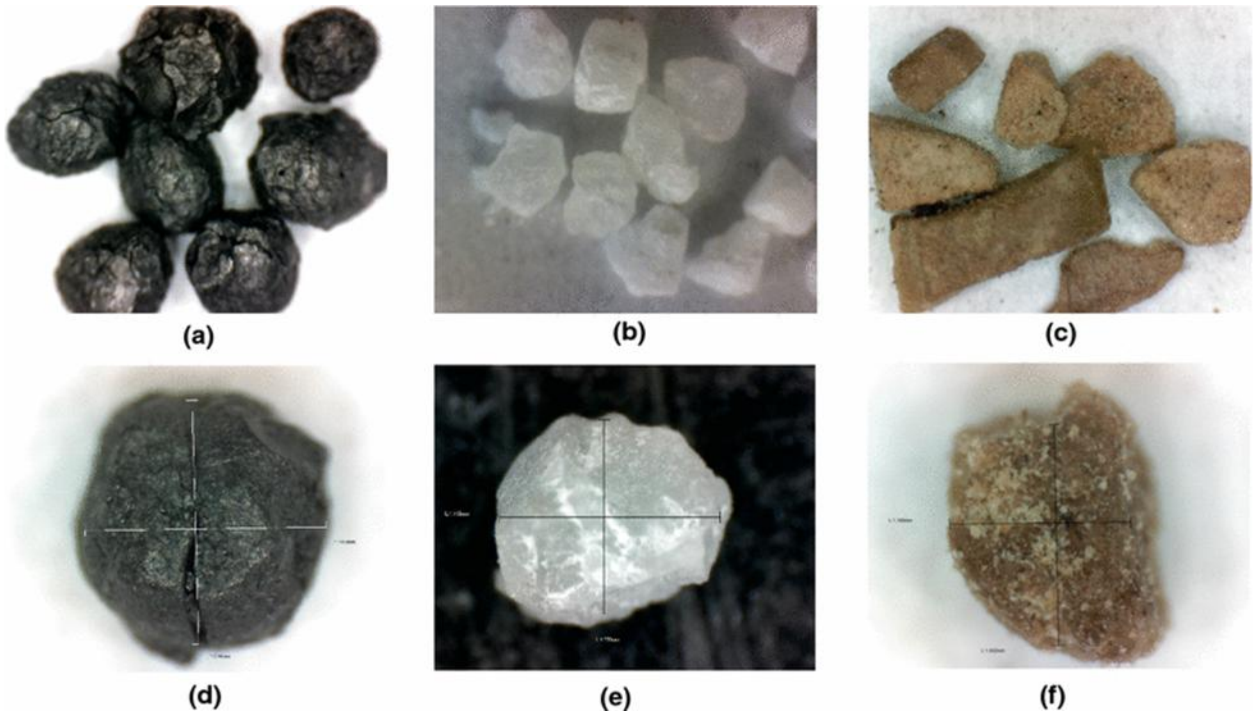


Figure 2.4: optical microscopy images of the three lcms. (a) graphite (×60 magnification), (b) sized calcium carbonate (×60 magnification), (c) nutshells (×60 magnification), (d) graphite (×200 magnification), (e) sized calcium Carbonate (× 200 magnification), (f) nutshells (×200 magnification), (Alsaba et al., 2016).

Figure 2.5 shows SEM images that capture the microscopic structure of seals formed by Lost Circulation Materials (LCMs). These images provide detailed visual evidence of how different LCM particles interact and pack together to form a seal that plugs fractures or pores in the formation. The different shapes of nutshells, combined with the presence of finer graphite particles significantly enhanced the seal integrity of the graphite and nutshells blend. Compared to other blends, this improvement can be attributed to the diverse particle shapes and sizes, allowing for more efficient fracture bridging and packing. The course, irregular shapes of the nutshells initiate the bridging process, while the finer graphite particles fill the voids, creating a tighter and more effective seal (Mansour et al. 2019). The synergy between these particles helps reduce fluid loss and improves overall sealing performance in fractures of varying sizes.

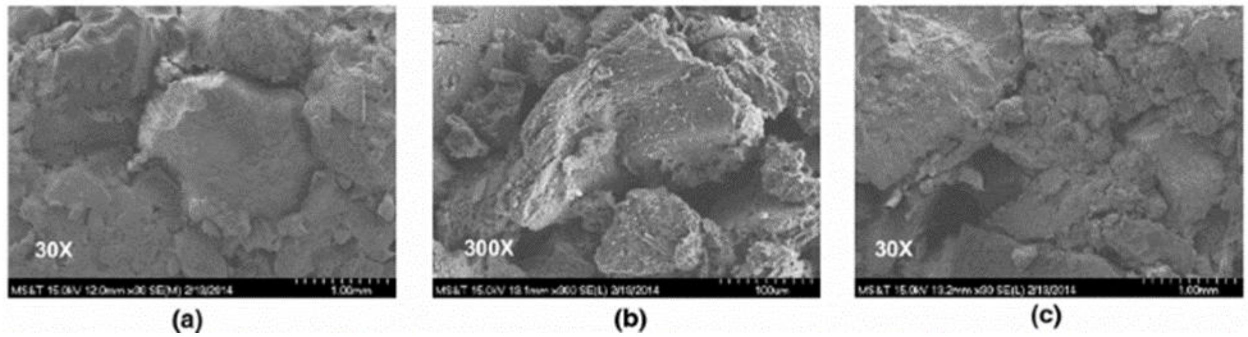


Figure 2.5: Scanning electron microscopy (SEM) images of the formed seals, (Alsaba et al., 2016).

2.7 Size of Fracture

The size of the fracture in the formation is one of the most significant factors that affect the performance of LCMs. Fractures in the subsurface vary in width, orientation, and complexity, all of which influence how effectively an LCM can bridge and seal the opening to prevent fluid loss. The ability of LCMs to perform efficiently in various fracture sizes is critical in mitigating lost circulation problems. Let's break down how the size of the fracture impacts LCM performance:

Fracture width, which can range from a few microns to several millimeters, plays a key role in determining the type and size of LCM particles that will be most effective in sealing it. The bridging theory suggests that for an LCM to successfully seal a fracture, the particle sizes in the LCM mixture must be carefully chosen based on the width of the fracture (Xu et al. (2017).

Small Fractures: For small fractures, fine particles or fibrous materials are more effective. Smaller LCM particles (such as fibers or powdered materials) can penetrate and tightly pack these narrow gaps. For example, cedar fibers and fine nutshell particles are often used in narrow fractures as they can flexibly conform to the fracture opening (Fuh et al., 1992).

Large Fractures: In the case of larger fractures, coarse and angular particles are typically needed. These larger particles (e.g., ground nutshells, mica flakes, or calcium carbonate) act as bridging agents, catching on the rough fracture surfaces to form an initial barrier. Without this, smaller particles may simply flow through the fracture without creating an effective seal (Luzardo et al., 2015).

The size of the fracture affects how LCMs perform both in terms of bridging and packing:

Bridging: In larger fractures, angular and coarse particles are crucial because they can create a mechanical bridge across the fracture. The bridging particles prevent the drilling fluid from flowing into the loss zone by creating physical obstruction. As fracture width increases, the particle size required to bridge the fracture also increases. However, if the fracture is too large and the particles are too small, they may not effectively bridge the gap, leading to continued fluid loss (Mansour et al. (2019)).

Packing: Once the fracture is bridged by larger particles, smaller particles can fill the voids between the larger particles to complete the seal. For smaller fractures, fine particles such as graphite or mica are often used, as they can pack tightly and reduce permeability, minimizing fluid loss. Packing efficiency is essential for larger fractures, where a combination of course and fine particles ensures that the gaps between the larger bridging particles are effectively sealed

To effectively seal fractures of varying sizes, the Particle Size Distribution (PSD) of the LCM blend is critical. The PSD refers to the range of particle sizes in the LCM formulation, from fine to coarse. A wide PSD increases the likelihood that the LCM particles will match the fracture size, improving bridging and packing efficiency.

For example, fractures between 1,000 to 3,000 microns in width typically require a blend of both fine and coarse particles. In this case, D90, a parameter in PSD, becomes significant. D90 represents the particle size where 90% of the LCM particles are smaller. To seal larger fractures effectively, the D 90 value should be equal to or slightly larger than the fracture width to ensure proper bridging and sealing (Alsaba et al., 2016). Hence:

Small Fractures: A smaller D 90 value is necessary for finer fractures. This ensures that the LCM blend contains enough small particles to bridge and pack small fracture gaps. If the D 90 value is too high, the particles may be too large and simply pass through the fracture without forming a seal.

Large Fractures: For wider fractures, the D 90 value should be higher to ensure that larger particles are available to bridge the fracture. At the same time, a broad PSD should include enough fine particles to fill the voids left by the bridging particles, creating a complete seal (Bao, D., et al., 2019).

Figure 2.6 from Alsaba et al. (2015) displays optical microscopy images of a seal formed using a combination of graphite and nutshells at a concentration of 114 g/L, retrieved from a fracture width of 2000 microns.

The images provide a close-up view of the internal structure of the seal after it was removed from the simulated fracture. The graphite particles appear as flat, thin flakes that are layered within the seal, contributing to its ability to form a dense and continuous barrier. Their platy shape allows them to overlap and create a low-permeability structure, which helps reduce fluid loss.

The nutshell particles are visible as larger, more irregular components embedded within the seal. Their rough texture and rigid structure provide mechanical support, enabling them to bridge the wide 2000-micron fracture and help maintain seal integrity under pressure.

Together, the mixture of graphite and nutshells forms a composite structure where the graphite fills the voids and enhances sealing efficiency, while the nutshells offer structural stability. The microscopy images demonstrate how the combination of these two materials creates an effective physical barrier across a relatively large fracture, highlighting their complementary roles in lost circulation control.

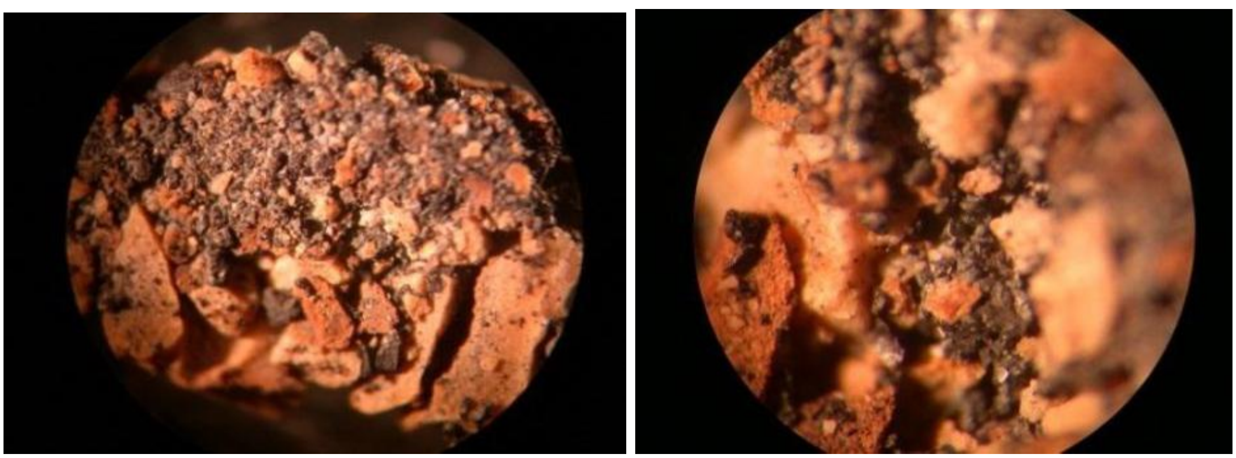


Figure 2.6: Optical microscopy images of graphite and nutshells (114 g/L) seal retrieved from 2000 microns fracture width, (Alsaba et al., 2015)

Studies have shown that as fracture width increases, the ability of an LCM to maintain sealing pressure becomes more challenging. For example, (Alsaba et al., 2016) demonstrated that LCM blends with larger particles can seal fractures up to 3,000 microns without significant fluid loss, provided that the particles' size distribution is wide enough to bridge and pack the fracture effectively.

The laboratory evaluation focused on testing the effectiveness of various LCMs for sealing wide fractures, a common challenge in drilling operations. To simulate wide fractures, the researchers used tapered slots with widths up to 2000 microns. They tested four different types of conventional LCMs, including 13 particle sizes (D 50), alongside a new type of LCM based on foam wedges. This variety allowed them to compare traditional methods with innovative approaches. A total of 200 tests were conducted to assess the impact of different parameters on LCM performance, including LCM type, concentration, tapered slot PSD, temperature, and injection rate (Alsaba et al., 2016).

Among the materials tested, ground walnut shell proved particularly effective at sealing wide fractures, achieving sealing pressures of up to 15168 Kpa. Microscopic examination revealed that ground walnut shell worked well because its particles could deform under pressure, allowing them to fill fractures more effectively and form a tight seal.

The findings suggest that LCMs that can adapt and compress to fit the shape of fractures are more successful at sealing, which is crucial for preventing fluid loss during drilling. The study highlights the importance of selecting LCMs based on their ability to conform to fractures rather than just their size. Materials like ground walnut shell, which can adjust to the fracture shape, offer significant advantages in managing lost circulation (Alsaba et al., 2016). This insight could improve the selection and formulation of LCMs in future drilling operations.

Figure 2.7 from Alsaba et al. (2015) presents optical microscopy images of the seals formed using different combinations of Lost Circulation Materials (LCMs) under varying fracture widths. These images illustrate how the material composition and fracture size influence the structure and effectiveness of the resulting seals.

Image (a) shows the seal formed by a combination of graphite and sized calcium carbonate (G&SCC) when tested in a 1000-micron fracture. The seal appears dense and compact, indicating that this LCM blend effectively bridges and plugs medium-sized fractures. The sized calcium carbonate particles, with their relatively uniform size and rigid structure, fill the gaps between the layered graphite flakes, contributing to a low-permeability seal.

Images (b) and (c) both show seals formed by a blend of graphite and nutshells (G&NS) tested in a 2000-micron fracture. The seals display a more porous and heterogeneous structure compared to image (a), reflecting the challenge of bridging wider fractures. The nutshell particles, being larger and more irregular in shape, act as bridging agents, while the graphite fills the smaller voids between them. Although some gaps remain, the combination still demonstrates an ability to partially seal the large fracture, aided by the layered nature of the graphite.

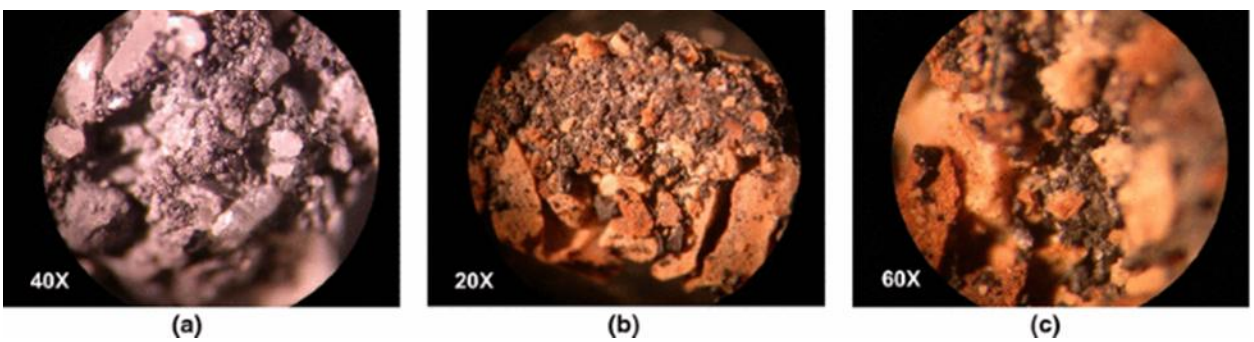


Figure 2.7: Optical microscopy images of the formed seals. a G&SCC seal when tested at 1000 microns fracture, b G&NS seal when tested at 2000 microns fracture, c G&NS seal when tested at 2000 microns fracture (Alsaba et al., 2015).

Extremely large fractures or fractures with irregular geometries pose additional challenges for LCM performance. In these cases, conventional LCMs may struggle to create an effective seal due to the wide variation in fracture width along the length of the fracture. In such scenarios, more specialized LCMs, such as expandable or deformable materials, may be required to bridge and seal irregular gaps.

Fracture size is a critical factor in determining the performance of LCMs in mitigating lost circulation. The width of the fracture dictates the size and type of LCM particles required to form an effective seal. Larger fractures need coarse bridging particles combined with fine packing particles, while smaller fractures benefit from fine materials that can pack tightly to reduce permeability. The optimal LCM formulation depends on a thorough understanding of the fracture's dimensions, along with the proper particle size distribution to match these conditions. By tailoring LCM formulations to the specific fracture sizes encountered in drilling operations, engineers can enhance the efficiency of lost circulation treatments and improve wellbore stability.

CHAPTER THREE

METHODOLOGY

The research is focused on using a filter press to measure the filtration properties of drilling fluid. The setup was assembled from various equipment, including the filter press, which was central to the experimental process. The experiments were conducted under identical environmental conditions to ensure accuracy and facilitate valid comparisons. This section provides a detailed description of the experimental setup, the equipment used, materials involved, the methodology for conducting the filtration tests, the scope of the investigation, and an in-depth analysis of the results obtained from the filtration measurements.

In this study, the filter press served as the primary instrument to simulate downhole filtration conditions and evaluate the sealing efficiency of different Lost Circulation Materials (LCM). Each test was run at a constant pressure for a fixed duration (usually 30 minutes), and the volume of filtrate collected was recorded. These measurements enabled the determination of filtration rate, filter cake thickness, and the effectiveness of each LCM blend.

3.1 Experimental Setup

The schematic shown in Figure 3.1 illustrates the experimental setup used to evaluate fluid loss behavior. The process begins with preparing tap water, which is placed in a container. The weight required of each Lost Circulation Material (LCM) for the tests is measured using a weighing scale. Subsequently, the water, bentonite, and LCMs are added to a beaker and mixed thoroughly using a multiple-speed blender, as shown in Figure 3.2.

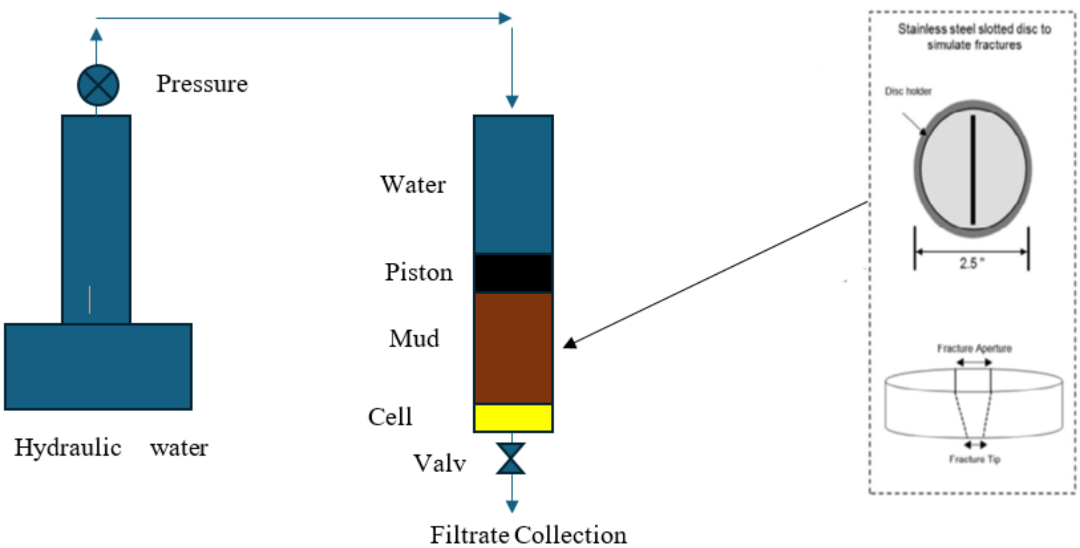


Figure 3.1: Schematic of the experimental setup used to evaluate the performance of drilling fluids with Lost Circulation Materials (LCMs).

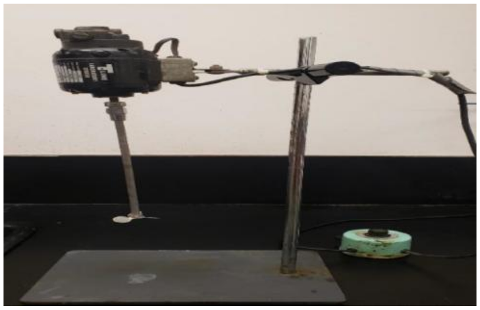


Figure 3.2: Multiple-speed laboratory blender with regulator.

The experiments are conducted using a high-pressure hydraulic pump, depicted in Figure 3.3. This pump maintains the necessary water pressure during testing, ensuring that the test fluid is subjected to controlled conditions that simulate the static downhole environment. The pump is connected to a filter press (Figure 3.3), which houses the tested fluid within a test cell, as shown in Figure 3.4. The fluid then passes through a slotted disc located at the bottom of the test cell, as illustrated in Figure 3.5.

After pressurization, the filtrate is collected in a graduated cylinder, allowing for precise measurement of filtration behavior. This experimental setup enables engineers to predict the performance of drilling fluids under actual downhole conditions. By analyzing the results, necessary adjustments can be made to fluid formulations to minimize fluid loss and optimize drilling performance.

Figure 3.3: Hydraulic water pump and press (Elahi far et al., 2023)

Figure 3.4: Test cell of the filter press (OFI Testing Equipment, Inc. 2019).

Figure 3.5: 2.5 mm slot cell disc of the test cell (Elahi far et al., 2023)

3.2 Test Materials

The fluid used in this research is Water-Based Mud (WBM), a commonly used drilling fluid due to its affordability, availability, and adaptability in different drilling environments. WBM plays a critical role in stabilizing the wellbore, controlling downhole pressures, and ensuring the smooth transport of cuttings to the surface during drilling operations. In this study, several materials were included in the WBM formulation, each serving a distinct function in optimizing the fluid's properties, particularly in managing lost circulation and rheology.

Materials and Their Functions:

3.2.1 Bentonite

Bentonite, a type of absorbent clay, is well-known for its ability to increase the viscosity of drilling fluids. In the Water-Based Mud formulation, bentonite acts as a rheology control agent, improving the mud's ability to suspend and transport solid particles, such as rock cuttings, to the surface. Higher viscosity also helps prevent the settling of solids within the wellbore, thus maintaining fluid consistency and ensuring smooth drilling operations. The 57 g/L concentration of bentonite was chosen to maintain the LCM in the suspension and to control viscosity to avoid any difficulty in the pumping.

3.2.2 Cedar Fiber

Cedar fiber in Figure 3.6 was used in varying concentrations to prevent the loss of drilling fluid into porous or fractured formations during the drilling process. Due to its fibrous structure, it forms a mat-like barrier when introduced into zones where fluid loss occurs. This barrier helps plug the porous formations, minimizing fluid escape and maintaining circulation within the wellbore. The particle size distribution of the cedar fiber is shown in Table 3.1, with an appearance characterized as a flake blend and a specific gravity of 1.43, and the sack of 40lb. These properties enhance its effectiveness by optimizing its ability to bridge and seal formation fractures effectively.

Table 3.1: Particle size distribution of cedar fiber (Typical percent retained, microns).

Sieve size (Micron meter)	Amount retained	Slot size/Particle size	Concentration in the baseline (lb./bbl.)	Average of the size (Micron Meter))	Average of the slot size/particle size	Average Sieve size * Amount retained	Size range name
38 - 150	25%	16.7 - 65.8	5	94	41.25	23.5	A
150 - 1000	24%	2.5 – 16.7	4.8	575	9.6	138	B
1000 - 2000	19%	1.25 - 2.5	3.8	1500	1.875	285	C
2000 - 3350	8.4%	0.7 – 1.25	1.68	2690	0.975	225.96	D
3350 - 7800	3%	0.32 - 0.7	0.6	5575	0.01	167.25	E
					2.95	**848.71**	

Figure 3.6: Image of cedar fiber

The concentration of cedar fiber was varied (28.5, 57.1, and 85.7 g/L) to observe its effectiveness in reducing filtration loss and enhancing the sealing efficiency of the drilling fluid. Higher concentrations of cedar fiber are expected to provide better plugging of loss zones, but the trade-off with fluid mobility and flow properties must also be considered.

3.2.3 Nutshell

The common name of nutshell is GLO NUT, which is derived from specialized walnut shells, is a biodegradable, chemical inert, and nontoxic LCM widely used in drilling applications. It's hard, fibrous nature makes it effective for controlling lost circulation in both water- and oil-based drilling fluids. It can be used independently in recirculated fluids or in pill form alongside fibrous and flaky materials, ensuring compatibility with various fluid systems. Additionally, it enhances lubricity, reducing torque and drag while minimizing risks like bit balling.

The material offers several advantages, including its environmental friendliness, stability, and adaptability. It is non-fermenting, chemically stable, and synergizes well with other LCMs to improve performance. Nutshell ability to control seepage, combined with its excellent lubricating properties, makes it an essential and sustainable choice for mitigating lost circulation challenges in modern drilling operations. Physical properties of nutshell are presented in Figure 3.7 and Table 3.2.

Figure 3.7: Image of medium size nutshell

Table 3.2: Physical parameters of the nutshell.

Properties	Value
Physical State	Brownish-Tan Granules
Specific	1.25-1.30
pH	4-6
Moisture	<10%

Table 3.3: Particle size distribution of nutshell fiber (Typical percent retained, microns).

Sieve size (Micron meter)	Amount retained	Slot size/Particle size	Concentration in the baseline (lb./bbl.)	Average slot size/Particle size	Average size (microns meter)	Average size * amount retained	Size range name
2000	5%	Less than 1.25	1.045	1.25	1000	50	A
841	15%	1.25 - 2.97	3.135	2.11	1420.5	213	B
250	80%	2.97 - 10	16.72	6.485	545.5	436.4	C
				3.5		**699**	

3.2.4 Sweeps

Sweeps (MAGMA FIBER) is a specially designed, extrusion-spun mineral fiber that effectively enhances circulation by bridging and selling voids, fractures, and permeable formations. This course, long, and flexible fiber is compatible with both oil- and water-based muds, as well as emulsions. Its interlocking structure forms a durable, low-permeability mud cake, reducing fluid loss and preventing hole caving. The low-alkaline, flexible, and inorganic composition of sweeps makes it inert to drill fluids and non-corrosive to equipment while being highly soluble in diluted hydrochloric acid, making it particularly suited for rework operations.

Coated with a specialized surfactant that facilitates fiber separation, it forms nodules that disassemble into individual fibers when agitated in drilling fluids. This acid-soluble fiber is non-combustible, non-toxic, non-fermenting, environmentally friendly, and temperature-stable. It is also free of asbestos and non-polluting and ensures reliable performance without harming equipment or the environment.

Sweeps in Figure 3.8 are another type of LCM added to the drilling fluid to control lost circulation and improve the overall cleaning efficiency of the mud system. Sweeps are often used to sweep the wellbore and clean cuttings while simultaneously forming a barrier in fractured or highly permeable formations. This study introduced sweeps at three concentrations to examine their role in reducing fluid loss and improving wellbore stability. The tests focused on how the concentration of sweeps influences filtration control and fluid performance.

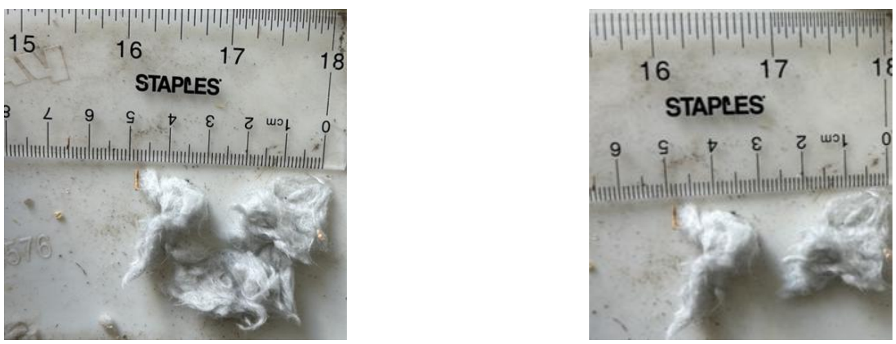


Figure 3.8: Image of fiber sweeps

3.2. Water

Throughout the experiments, the water volume in the WBM was maintained at 350 ml to ensure consistent test conditions and allow for accurate comparison of the materials' effects on fluid performance. By keeping the water volume constant, it was possible to isolate the impact of the varying concentrations of bentonite, cedar fiber, nutshell, and sweeps on key properties like filtration rate, viscosity, and wall cake formation. This approach ensured that the differences in the experimental outcomes were directly attributable to the changes in material concentrations, rather than variations in fluid volume. Tap water was used during the preparation of the fluids.

3.3 Experimental Procedure

Experimental procedure was developed for the steps of conducting the tests, and the steps of the experiments are as follows:

Step 1. The test fluid was prepared by first adding water to a beaker and starting the mixer. Bentonite was then gradually added to the water, followed by the specified concentration of LCMs. The mixture was stirred thoroughly for 20 minutes using a high-speed mixer to ensure proper dispersion and homogeneity.

Step 2. All the components of the filter press including the O-rings and testing cell were ensured to be in good working condition, confirming they were pliable with no nicks, cuts, or damage during assembly. An O-ring (170-13-3) was carefully installed in the O-ring groove in the cell body, and another identical O-ring was placed in the cell cap. A thin film of grease was applied to all O-rings.

Step 3. The cap locked screws, and their seats were inspected. Using an Allen wrench, the six locking set screws were tightened to secure the cell cap in place. The valve was then tightened into the cell cap with a wrench, and the manifold block from the pump was connected to the inlet valve stem and locked in place. It was verified that the filtrate bleeder needle valve was closed by ensuring the knob was turned clockwise.

Step 4. The inlet valve was opened ½ turn to pressurize the sample, and pressure was maintained on the fluid. The filtrate valve was carefully opened to allow the fluid to pour into the graduated cylinder, and the valve was closed immediately after the filtrate was collected. The pressure gauge was carefully monitored throughout the process. Filtrate was collected at various intervals: 7, 15, 30 seconds and 1.5, 2.5, 3.5, 4, 7.5, 15, and 30 minutes.

Step 5. The total amount of filtrate collected in the graduated cylinder was recorded. The pressure from the inlet pressuring unit was released by opening the valve (turning it counterclockwise). The six cap locking screws were loosened but not removed, and the cap was separated from the cell with a slight motion. The OFITE Cell Cap removal tool was used to remove tight cell caps as needed.

Step 6. The fluid inside the cell was discarded, and the apparatus was thoroughly cleaned and dried after each test.

3.4 Scope of Experimental Study

In this study, the filtration behavior of drilling fluids was analyzed by plotting the volume of filtrate collected over time, focusing on the effect of Lost Circulation Materials (LCMs) like cedar fiber, nutshell, and sweeps on the filtration rate. The total duration of each experiment was 30 minutes, as per the API standard, with measurements taken at regular intervals. The time was plotted on the x-axis and the filtrate volume on the y-axis. A steeper slope indicated a higher filtration rate, while a flatter slope signaled improved fluid retention.

The baseline mud, containing 57.1 g/L each of cedar fiber, nutshell, and sweeps, exhibited a moderate filtration rate. When the concentration of LCMs was reduced to 28.5 g/L, the filtrate volume collected over time increased, indicating a higher filtration rate. Conversely, increasing the concentration to 85.7 g/L led to a slower filtration rate, showing that higher LCM concentrations were more effective in preventing fluid loss, the values of the concentrations were taken from the previous studies (Alsaba et.al, 2015; Vivas et.al. 2021). Table 3.4 presents test materials and parameters, including the use of water-based mud with LCMs, tested under ambient temperature and a pressure of 6894 Kpa.

Table 3.4: Test materials and parameters.

Mud Type	Water-based Mud with LCMs
Liquid Phase	water
LCMs Type	Cedar Fiber, Nutshell, Sweeps
Viscosifier	Bentonite
Filtration Tests	Permeability Plugging Apparatus Tests
Temperature	Ambient
Pressure	6894 Kpa

Table 3.5 provides a detailed summary of the test metrics used to evaluate the impact of LCMs on water-based mud. Seven different tests were conducted, each with varying concentrations of Cedar Fiber, Nutshell, and Cotton Sweeps, measured in grams per 350 ml of the liquid phase.

For Test 1, the mud formulation included 28.5 g/L of Cedar Fiber, 57.1 g/L of Nutshell, and 20 g of Cotton Sweeps, representing the lowest concentration of Cedar Fiber in the study. In Test 2, the concentration of Cedar Fiber increased to 57.1 g/L, while the Nutshell and Cotton Sweeps remained constant at 57.1 g/L each. Test 3 further raised the Cedar Fiber concentration to 85.7 g/L, maintaining the same levels of Nutshell and Cotton Sweeps as in the previous tests.

Tests 4 and 5 explored variations in the concentration of Cotton Sweeps, using 28.5 g/L and 85.7 g/L, respectively, while holding the Cedar Fiber and Nutshell concentrations constant at 57.1 g/L each. Tests 6 and 7 adjusted the concentration of Nutshell to 28.5 g/L and 85.7 g/L, respectively, while keeping Cedar Fiber and Cotton Sweeps at 57.1 g/L each.

This systematic variation of LCM concentrations across the tests allows for an in-depth analysis of their individual and combined effects on filtration performance.

Table 3.5: Test matrix

Test No	Cedar Fiber Concentration (g / L)	Nutshell Concentration (g / L)	Cotton Sweeps Concentration (g / L)
Test 1	28.5	57.1	57.1
Test 2	57.1	57.1	57.1
Test 3	85.7	57.1	57.1
Test 4	57.1	57.1	28.5
Test 5	57.1	57.1	85.7
Test 6	57.1	28.5	57.1
Test 7	57.1	85.7	57.1

This setup provided a comprehensive view of the relationship between LCM concentration and filtration rate, showing a clear trend of decreasing fluid loss as LCM concentrations increased. These findings were crucial for optimizing the formulation of drilling fluids to enhance the wellbore stability and reduce fluid loss.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Effect of Cedar Fiber

The experiments examined the effect of varying cedar fiber concentrations on the filtration rate. The baseline mud, containing 57.1 g/L of cedar fiber along with 57.1 g/L of nutshell and 57.1 g/L of sweeps, was tested against samples with cedar fiber concentrations of 28.5 and 85.7 g/L. A plot of the fluid filtered over time (30 minutes) was generated to further analyze each concentration's performance.

The 28.5 g/L cedar fiber sample's filtration rate increased compared to the baseline fluid. The plot showed a steeper slope, indicating more fluid loss over time. This suggests that a lower concentration of cedar fiber provides insufficient material to form an effective filter cake, resulting in higher fluid loss.

Conversely, the 85.7 g/L cedar fiber sample exhibited a significant reduction in the filtration rate, as reflected by a much gentler slope in the plot. This indicates that the higher concentration of cedar fiber improved the fluid’s ability to reduce filtration volume over time by creating a denser, more effective barrier in the mud.

The plot in Figure 4.1 highlights those higher concentrations of cedar fiber consistently led to better filtration control, with the 85.7 g/L sample demonstrating the most significant reduction in fluid loss. Cedar fiber, acting as an LCM, forms a fibrous network within the mud, which helps in the development of a stronger filter cake on the wellbore. Therefore, optimizing cedar fiber concentration is essential for enhancing fluid performance and minimizing filtration during drilling operations.

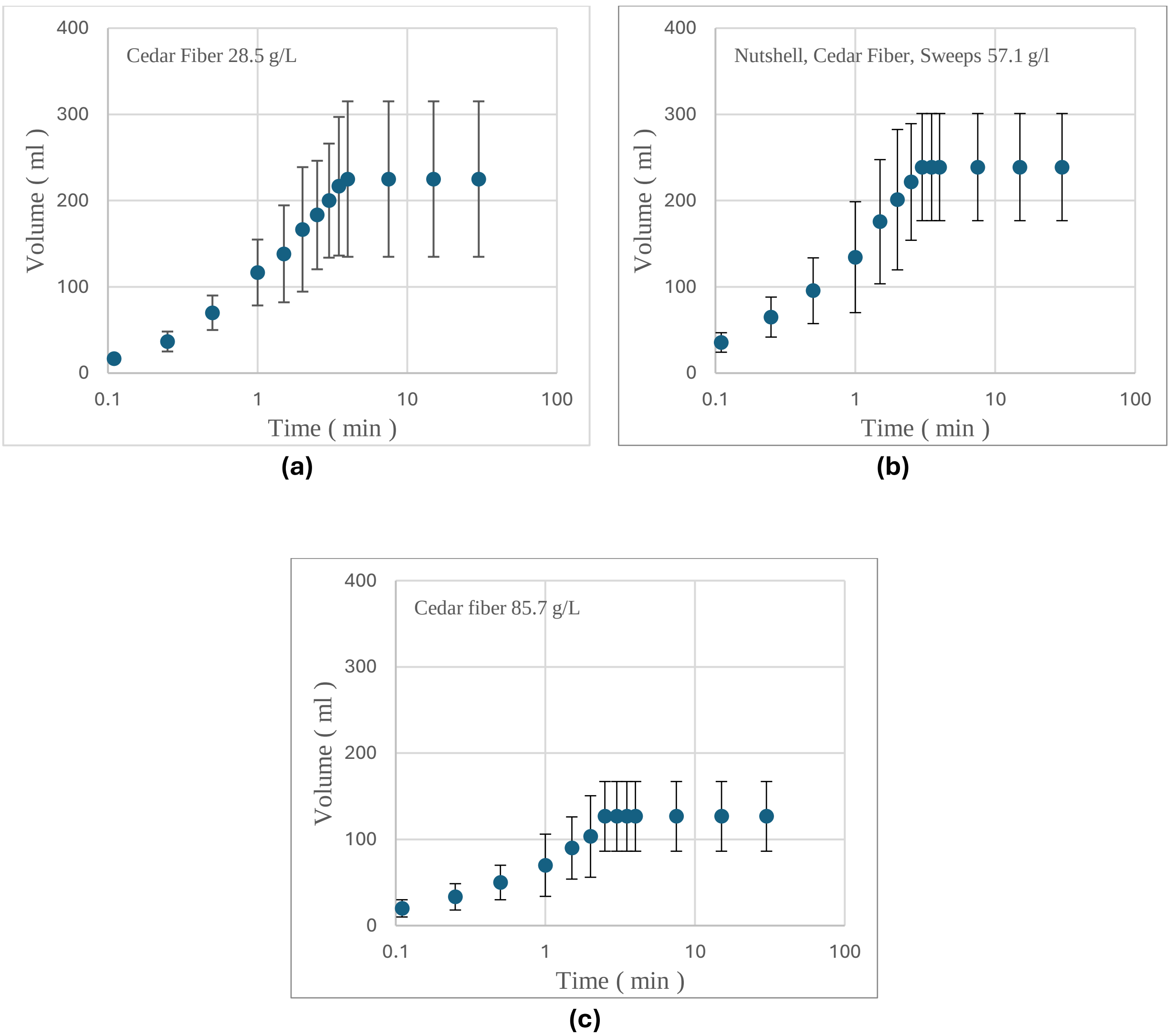


Figure 4.1:Graph illustrating the effect of cedar fiber concentration on filtration performance in the presence of other LCMs.

At lower concentrations (28.5 to 57.1 g/L), the increase in cedar fiber content results in a gradual improvement in sealing efficiency, leading to only a slight reduction in filtrate volume. This suggests that at lower concentrations, the particles are insufficient to form a strong bridge, and the additional 28.5 g/L only provides a minor improvement. When the concentration increases from 57.5 to 85.7 g/L, a more noticeable reduction in filtrate volume is observed. This indicates that at 85.7 g/L, the bridging mechanism becomes much more effective, significantly decreasing fluid loss. A higher concentration of particles likely promotes the formation of a denser, more impermeable plug, causing a sharper decrease in filtrate volume compared to the previous concentration increase.

The plugging efficiency of cedar fiber as an LCM is significantly influenced by its particle size distribution, slot size-to-particle size ratio, and concentration. Previous experimental study (Leoppke et al., 1990) developed a chart that categorizes the efficiency of LCMs into three distinct plugging behaviors: always plugging, sometimes plugging, and never plugging, depending on the ratio of the slot size to the particle size of the material and its concentration. Using the concentration and size distribution provided by the manufacturer, cedar fiber particles are presented in the Leopold chart (Figure 4.2) to examine their bridging and sealing capabilities.

The largest size fraction (Size E, 3350 - 7800 µm) demonstrated a consistent plugging ability, as it fell within the "Always Plug" region of the plugging efficiency chart. The effectiveness of this size fraction can be attributed to its low slot size-to-particle size ratio (0.32 - 0.7), meaning that these particles are significantly larger than most slot openings. As a result, they form an immediate and stable bridge across fractures, preventing major fluid loss, despite the low concentration (0.6 lb./bbl.) of these large particles in the tested mud system, their plugging efficiency is expected to be high. This suggests that even a small amount of well-sized large particles can effectively bridge slots to allow other medium particles to be trapped. The results highlight the importance of incorporating large bridging materials in lost circulation treatments, particularly in formations with wide fractures.

The medium sized particles (Size D, 2000 - 3350 μm) exhibited inconsistent plugging behavior, placing it within the "Sometimes Plug" category. These particles had a slot size-to-particle size ratio of 0.7 – 1.25, suggesting that their effectiveness depended on the slot size. When the slot was slightly smaller than or close to the particle size, partial plugging occurred, but when the slot was larger, the particles passed through or formed weak bridges that were unable to sustain effective sealing, the moderate concentration (1.68 lb./bbl.) of Size D particles in the mud system may have also contributed to its variable performance. The findings indicate that while medium-sized particles can assist in bridging, their effectiveness is expected to improve when combined with larger particles (Size E) to create a proper particle distribution that enhances overall sealing efficiency.

The smallest particle size fractions, Size B (150 - 1000 μm) and Size C (1000 - 2000 μm), are expected not to plug slots. This was primarily due to their high slot size-to-particle size ratio (2.5 – 16.5), and (1.25 – 2.5), which rendered them too small to bridge even the tested slot. These particles provide sealing capability instead of bridging, and they are required at a high concentration.

Although these smaller particles were present in relatively high concentrations 5 lb./bbl. for Size A and 4.8 lb./bbl. for Size B, their inability to create effective bridges suggests that their role in lost circulation mitigation is in sealing not the bridging. However, these finer particles may still serve an indirect function by filling voids within larger bridging structures, thereby increasing the density and cohesion of the plug. Nonetheless, their effectiveness as primary plugging (bridging) agents remains negligible.

Large particles (Size E) should be prioritized as they demonstrate the highest plugging efficiency and require minimal concentration to be effective. Additionally, the ratio calculated by the average particle size doesn't show the plugging capability. As a result, it is not appropriate for such analysis.

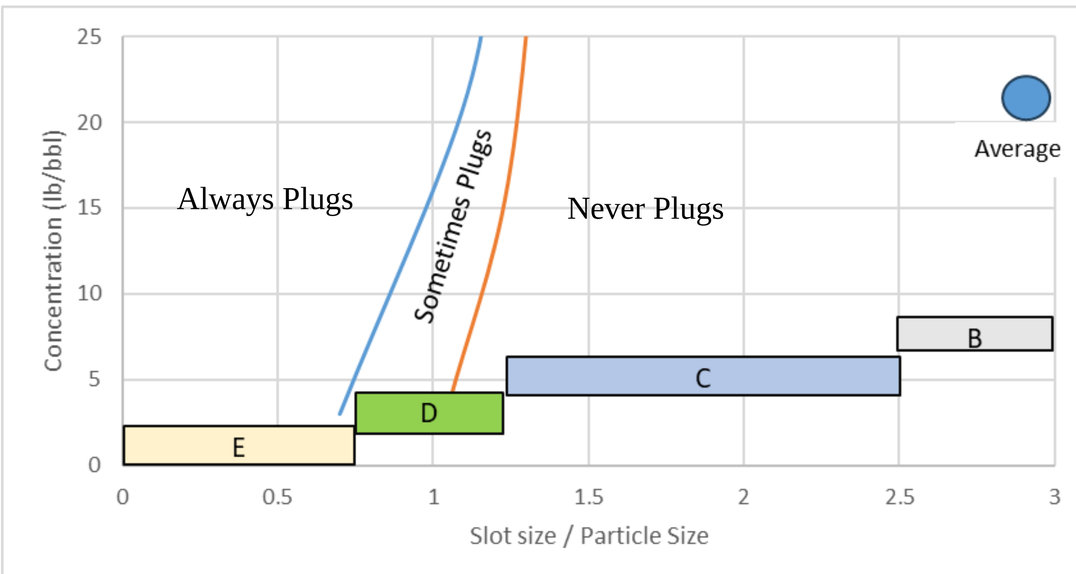


Figure 4.2: Plugging behavior of cedar fiber based on concentration and slot size-to-particle size ratio (Adopted from Leoppke et al., 1990).

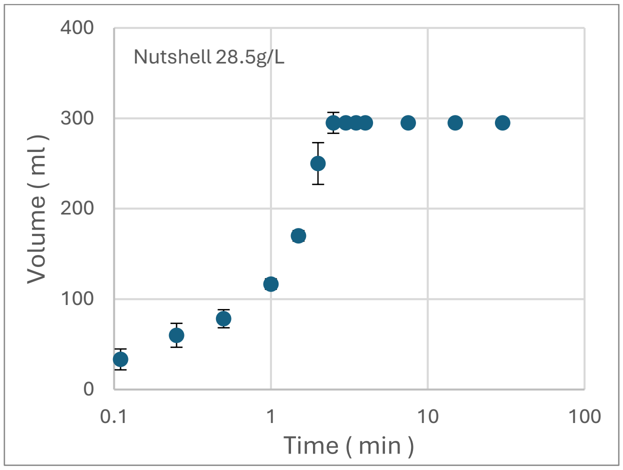
4.2 Effect of Nutshell

The experiments examined the effect of varying nutshell concentrations on the filtration rate. The baseline mud, containing 57.1 g/L of nutshell along with 57.1 g of cedar fiber and 57.1 g of sweeps, was tested against samples with nutshell concentrations of 28.5 and 85.7 g/L. A plot of fluid filtered over time (30 minutes) was generated to further analyze the performance of each concentration.

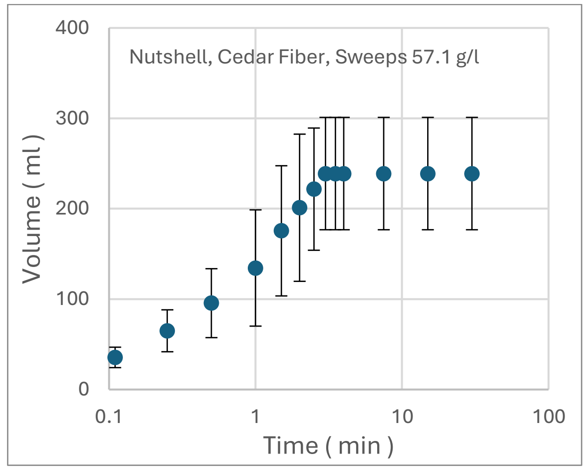
The 28.5 g/L nutshell sample's filtration rate increased compared to the baseline fluid. The plot showed a steeper slope, indicating more fluid loss over time. This suggests that a lower concentration of nutshell provides insufficient material to form an effective filter cake, resulting in higher fluid loss.

Conversely, the 85.7 g/L nutshell sample exhibited a significant reduction in the filtration rate, as reflected by a gentler plot slope. This indicates that the higher concentration of nutshells improved the fluid’s ability to reduce filtration volume over time by creating a denser, more effective barrier in the mud.

The plot in Figure 4.3 highlights that higher concentrations of nutshell consistently led to better filtration control, with the 85.7 g/L sample demonstrating the most significant reduction in fluid loss. Nutshell, acting as an LCM, forms a granular network within the mud, which helps develop a stronger filter cake on the wellbore. Therefore, optimizing nutshell concentration is essential for enhancing fluid performance and minimizing filtration during drilling operations.



(a)



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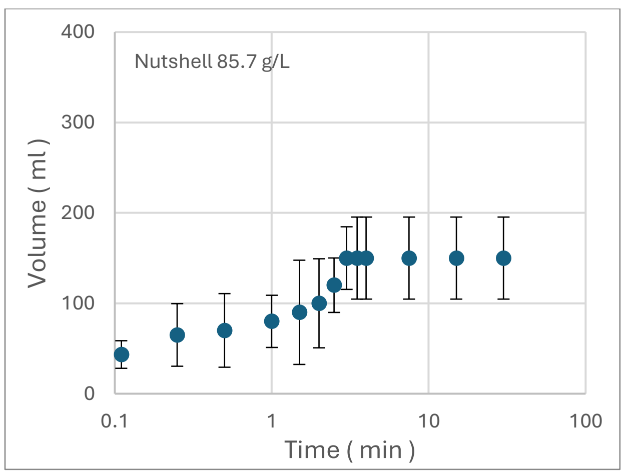


(c)

Figure 4. 3: Graph illustrating the effect of nutshell concentration on filtration performance in the presence of other Lost Circulation Materials (LCMs).

At lower concentrations (28.5 to 57.1 g/L), the increase in nutshell content leads to gradual improvement in sealing efficiency, causing only a slight reduction in filtrate volume.

This suggests that at lower concentrations, the particles are not yet sufficient to form an effective bridge, and the additional 28.5 g/L provides only marginal improvement.

When increasing the concentration from 57.1 to 85.7 g/L, a more significant reduction in filtrate volume occurs. This indicates that 85.7 g/L reaches a threshold where the bridging mechanism becomes much more effective, significantly reducing fluid loss. Higher particle concentration likely enhances the formation of a denser, more impermeable plug, leading to a sharper decline in filtrate volume compared to the previous concentration increase.

the efficiency of LCMs into three distinct plugging behaviors: always plugging, sometimes plugging, and never plugging, depending on the ratio of the slot size to the particle size of the material and its concentration. Using the concentration and size distribution provided by the manufacturer, nutshell particles are presented in the Leoppke chart (Figure 4.4) to examine their bridging and sealing capabilities.

The largest size fraction (Size A, 2000 - 3000 µm) demonstrated a consistent plugging ability, as it fell within the "Always Plug" region of the plugging efficiency chart. The effectiveness of this size fraction can be attributed to its low slot size-to-particle size ratio (1.25 – 0.833), meaning that these particles are significantly larger than most slot openings. As a result, they form an immediate and stable bridge across fractures, preventing major fluid loss. Despite the low concentration (1.045 lb./bbl.) of these large particles in the tested mud system, their plugging efficiency is expected to be high. This suggests that even a small amount of well-sized large particles can effectively bridge slots to allow other medium particles to be trapped. The results highlight the importance of incorporating large bridging materials in lost circulation treatments, particularly in formations with wide fractures. As the slot size increases relative to the particle size, plugging effectiveness becomes inconsistent. This Sometimes Plug region is indicated by the space between the blue and orange curves. In this range, plugging success depends on increasing the concentration of LCM.

The smallest particle size fraction, Size B (841 - 2000 µm), falls within the Never Plug region due to its high slot size-to-particle size ratio, ranging from 1.25 to 16.5. This means that these particles are too small to effectively bridge the tested slots, preventing them from forming a stable plug. Instead of bridging, these particles contribute to sealing by reducing permeability within the loss zone. However, their effectiveness relies on being present at high concentrations, as individual particles cannot independently form a structural barrier. This highlights the limitations of smaller granular materials in plugging larger fractures and underscores the need for alternative lost circulation strategies when dealing with wide slot openings. Additionally, the ratio calculated by the average particle size doesn't show the plugging capability. As a result, it is not appropriate for such analysis.

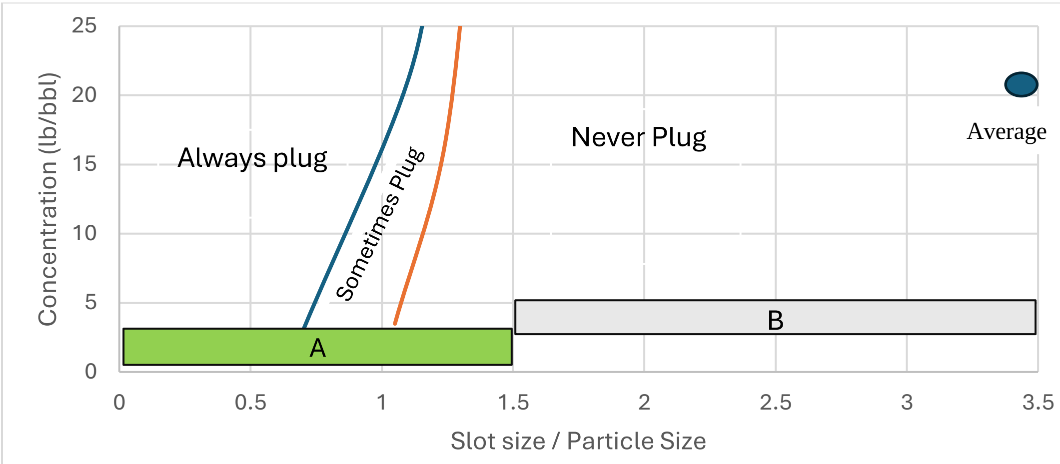


Figure 4.4: Plugging behavior of nutshell based on concentration and slot size-to-particle size ratio, (Adopted from Leoppke et al., 1990).

4.3 Effect of Sweeps

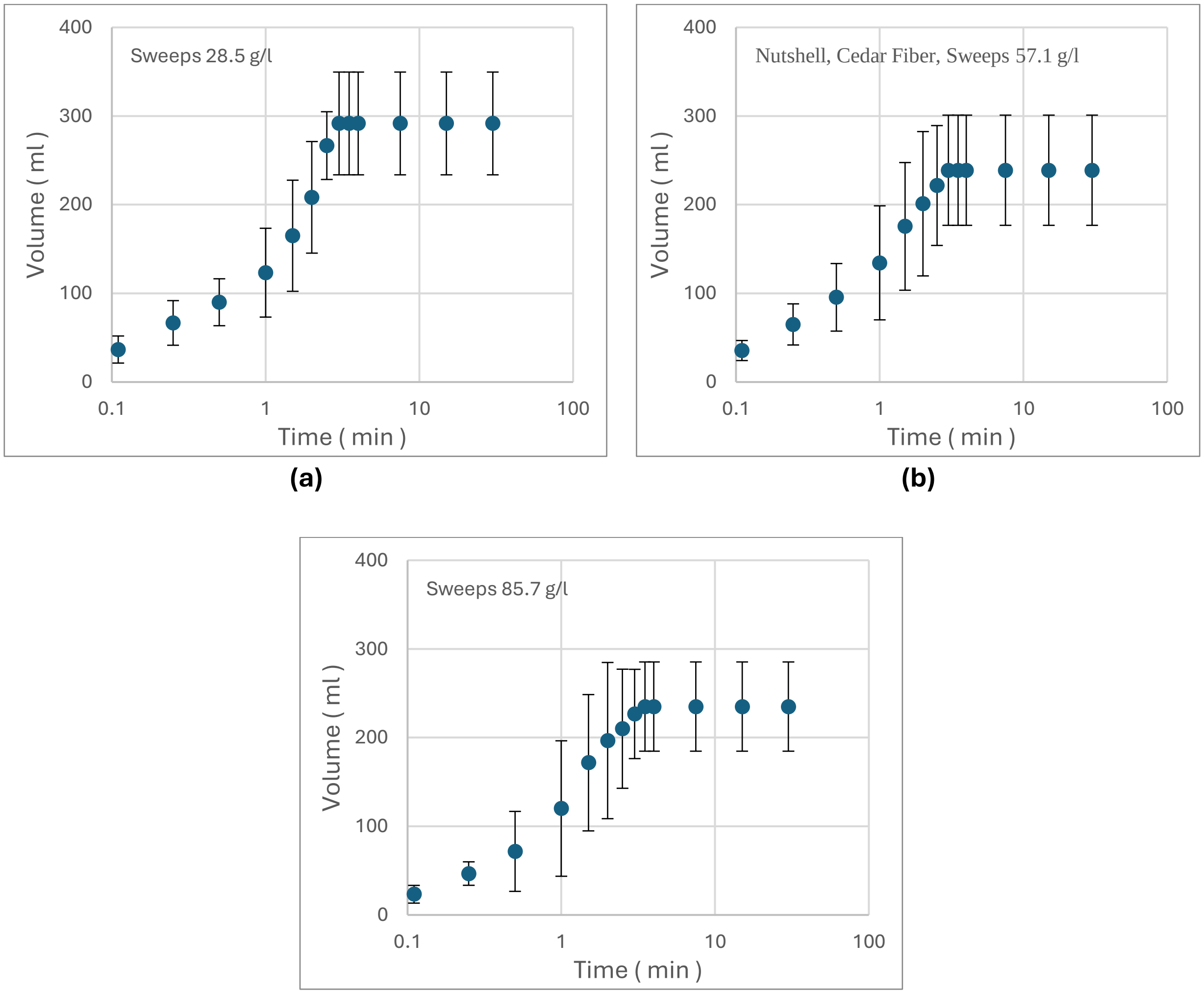
The experiments on the effect of sweeps on filtration rates were conducted over a 30-minute period, with three repetitions for each concentration to ensure accuracy. The average filtration rate was calculated based on these repeated trials.

At a lower concentration of 28.5 g/L, the filtration rate was higher compared to the baseline. The plot over the 30-minute period showed a steeper slope, indicating increased fluid loss as time progressed. This suggests that a lower concentration of sweeps provided less material to effectively control fluid loss, resulting in inadequate filter cake formation.

For the baseline mud containing 57.1 g/L of sweeps, the filtration rate was moderately lower. The slope of the plot was less steep compared to the 28.5 g/L concentration, indicating that 57.1 g/L of sweeps offered improved filtration control, forming a more effective filter cake.

The 85.7 g/L g sweeps sample showed the greatest reduction in fluid loss over the 30-minute period. The plot displayed a much flatter slope, suggesting that the higher concentration of sweeps significantly improved the mud’s ability to reduce fluid loss. This was likely due to the increased material available to form a denser, more cohesive filter cake, enhancing the drilling fluid's sealing properties.

Overall, the results of the experiments in Figure 4.5 demonstrated that increasing the concentration of sweeps led to improved filtration control over time. As an additive, sweeps help reinforce the filter cake, plugging pores and fractures in the wellbore to reduce fluid loss. The 30-minute data emphasize that optimizing sweeps concentration is critical for enhancing drilling fluid performance, particularly in minimizing filtration during operations.



(c)

Figure 4.5: Graph illustrating the effect of sweeps concentration on filtration performance in the presence of other Lost Circulation Materials (LCMs).

4.4 Comparison between Types of LCMs

A comparative analysis of filtrate volume over time in Figure 4.6 reveals that Cedar Fiber consistently produces the lowest filtrate volume, while sweeps result in the highest fluid loss. The nutshell shows intermediate performance, reducing filtration but not as effectively as Cedar Fiber.

The ability of Cedar Fiber to significantly limit fluid loss suggests that its fibrous nature enhances filter cake formation, leading to better sealing of the permeable medium.

Interestingly, Cedar Fiber has a larger average particle size than Nutshell, yet it performs better in reducing filtrate volume. This finding indicates that particle size alone does not determine filtration efficiency; rather, the shape and structure of the particles play a crucial role. The fibrous structure of Cedar Fiber likely allows for better interlocking and bridging, enhancing its ability to form an effective barrier against fluid invasion. In contrast, while Nutshell has a smaller particle size, its relatively rigid and non-fibrous structure may limit its capacity to form a highly impermeable filter cake.

On the other hand, Sweeps allow the highest filtrate volume, indicating lower efficiency in sealing formations. This suggests that its particle characteristics do not provide sufficient bridging or sealing capabilities, leading to higher fluid loss than the other materials tested.

The trend in Figure 4.6 suggests that at a lower concentration of 28.5 g/L, Cedar Fiber remains the most effective at reducing filtrate volume due to its ability to form a well-structured, interlocking filter cake. Nutshell provides moderate filtration control, while Sweeps show minimal effectiveness in reducing fluid loss at the concentration of 28.5 g/L. When the concentration of each additive increased to 85.7 g/L of Cedar Fiber, 85.7 g/L of Nutshell, and 85.7 g/L of Sweeps, the trends remained consistent. Cedar Fiber continues to yield the lowest filtrate volume, reinforcing its superior performance in reducing fluid loss. The Nutshell shows moderate improvement, further decreasing fluid loss as concentration increases. However, Sweeps still result in the highest filtrate volume, indicating that it remains the least effective in minimizing fluid loss even at higher concentrations.

These results confirm that increasing the concentration of LCMs enhances their ability to reduce filtration, but the effectiveness still depends on the material's physical properties. Despite its larger particle size, Cedar Fiber benefits from its fibrous structure, which contributes to improved filter cake formation and enhanced sealing capabilities. Nutshell, while effective, does not match the filtration control of Cedar Fiber, likely due to its particle rigidity. Sweeps, in contrast, continues to exhibit the highest fluid loss, suggesting that its particle characteristics are not as well suited for filtration control.

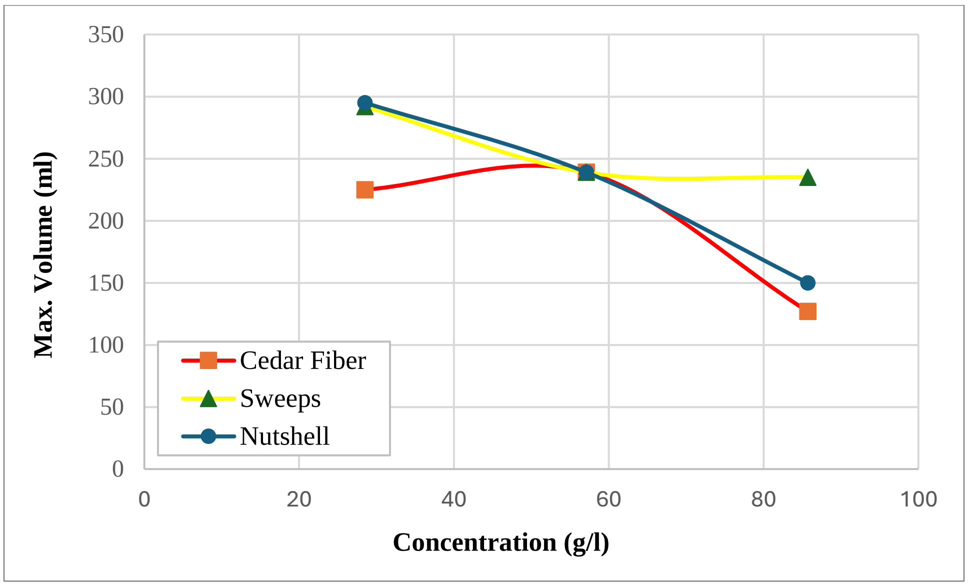


Figure 4.6: Maximum filtration vs. concentration of different LCMs

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Management of lost circulation is a critical challenge in drilling operations, and refining strategies to minimize fluid loss while enhancing wellbore stability is essential. Recent studies investigating the efficacy of various LCMs have revealed several key recommendations for optimizing lost circulation management practices in the drilling industry. This study tested three different LCMs by varying their concentration. Each experiment was repeated three times to obtain a consistent trend. The LCM size distribution was obtained from the manufacturer's documentation. The size distribution was used to analyze LCM's bridging and sealing performance based on an experimental chart developed from a previous study. Based on these measurements and analyses, the following conclusions can be drawn:

- Smaller amounts of coarse particles present in LCM are sufficient to bridge fracture slots and create favorable conditions for sealing. As a result, the average particle size of the LCMs cannot be used to assess their plugging capability and performance.
- The slot size-to-particle size ratio governs the plugging efficiency of LCMs. To effectively seal slots, LCMs should have particles with a size significantly larger than the slot size that can form bridges, which smaller LCM particles can later seal.

- The particle size distribution of an LCM is critical in determining its performance. In addition to coarse particles, medium and fine-sized particles are required for effective sealing.
- LCM concentration can have a significant impact on filtration control. Increasing the cedar fiber concentration from 57.1 to 85.7 g/L resulted in a 50% reduction in filtration, indicating the highest efficiency. In contrast, increasing the sweeps concentration over the same range led to only a 30% reduction in filtration, representing the lowest performance among the tested additives.

5.2 Recommendations

By implementing these recommendations, drilling operations can significantly enhance their approach to managing lost circulation. Continued research into the interactions and effectiveness of various LCMs is essential for optimizing formulations and adapting to the specific challenges posed by different geological formations. Practical field applications will provide critical insights into the real-world performance of LCMs, allowing for iterative improvements based on direct feedback from drilling operations.

Rigorous personnel training programs are crucial for fostering a culture of innovation and responsiveness within drilling teams. By equipping them with the skills to assess and adapt to the dynamics of lost circulation, companies can enhance their ability to mitigate risks and improve operational outcomes. Additionally, forming strategic partnerships with LCM suppliers will not only facilitate access to cutting-edge materials but also drive collaborative research initiatives that push the boundaries of current technology.

Focusing on cost-effective and environmentally responsible practices will position drilling companies as leaders in sustainable resource extraction. By prioritizing using biodegradable and low-impact materials, industry can address regulatory pressures and societal expectations regarding environmental stewardship.

Furthermore, robust data collection and monitoring systems will empower companies to make informed decisions based on empirical evidence, ensuring that strategies remain effective and adaptive in the face of evolving challenges. By investing in these areas, drilling operations will not only enhance their immediate efficiency and profitability but also build a reputation for sustainability and innovation in a competitive market.

Ultimately, these measures will contribute to the overall success and sustainability of drilling operations in an ever-evolving industry landscape. As the demand for energy continues to grow, the ability to manage lost circulation effectively will be paramount in ensuring that drilling operations are both economically viable and environmentally sound, paving the way for a more resilient and responsible industry in the future.

Nomenclature and Acronym

Symbol	Description
LCM	Lost Circulation Materials
PSD	Particle Sized Distribution
ECD	Equivalent Circulating Density
WBM	Water Based Mud
PPT	Permeability Plugger Tester
SEM	Scanning Electron Microscope
Ppb	Pound per barrel
SMP	Shape Memory Polymer
NPT	Non-Productive Time
MWD	Measurement While Drilling
LWD	Logging While Drilling
MPD	Managed Pressure Drilling
BHA	Bottom Hole Assembly
OBM	Oil Based Mud

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