A STUDY TO EVALUATE THE EFFECT OF GRAPHENE ON CLASS G CEMENT

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Master of Science in Drilling Engineering

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Sincerely,

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ABSTRACT

This study focuses on enhancing the compressive and rheological properties of Class G cement, commonly used in oil wells, to mitigate potential leakage and environmental threats. Graphene oxide is selected as an additive to improve the cement's performance. The research aims to investigate the impact of graphene oxide on cement characteristics. Various mixtures were prepared with different concentrations of graphene oxide and Class G cement, maintaining a consistent solid-to-solvent ratio. To avoid coagulation and maintain pumpability, the cement was substituted with graphene oxide based on weight percentages. The resulting mixtures exhibited varying textures, becoming thicker with higher graphene concentrations. A detailed methodology was established, including the formulation of cement slurry, introduction of graphene oxide, creation of cement cubes, and high-pressure high-temperature curing processes. Compressive strength, fluid loss, viscosity, and density tests were conducted to evaluate the performance of the graphene-enhanced cement samples. The findings reveal that graphene oxide affects the cement's properties, resulting in improved compressive strength, reduced fluid loss, altered rheological behaviour, and modified density. These insights contribute to a comprehensive understanding of graphene-enhanced cement's potential in oil well applications, emphasizing its role in ensuring well integrity. The research paves the way for safer and more sustainable oil well cementing practices.

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LIST OF ABBREVIATIONS & SYMBOLS

C

C_2S	Dicalcium Silicate
C_3A	Tricalcium Aluminate
C_3C	Tricalcium Silicate
C_3S	Tricalcium Silicate
C_4AF	Tetracalcium Aluminoferrite
Ca^{2+}	Calcium
C-A-H	Calcium Aluminate Hydrate
CCS	Carbon Capture and Storage
CH	Calcium Hydroxide
CO_2	Carbon Dioxide
C-S-H	Calcium Silicate Hydrates

D

Dyne/cm^2	Dyne per Square Centimetre Pressure Unit

G

g	Gram
g/cc	Grams per Cubic Centimeter
GNPs	graphene nanoplatelets
GO	Graphene Oxide

H

H_2S	Hydrogen Sulphide
HPHT	High Pressure High Temperature

M

ml	Milliliter
Mpa	Mega Pascal

O

OH^-	Hydroxide

P

Pa	Pascal
ppg	Parts Per Gallon

R

rGO	Reduced Graphene Oxide
RPM	Rotational per Minute

S

s	Second
SCMs	Supplementary Cementitious Materials
SO_2	Sulphur Dioxide

Other

%	Percentage
°C	Degree Celsius

CHAPTER I

INTRODUCTION

1.1 BACKGROUND OF STUDY

The oil and gas industry plays a crucial role in meeting global energy demands, and cement is widely used in well construction to ensure zonal isolation and well integrity. Class G cement is a common choice for cementing operations due to its high compressive strength and resistance to corrosive environments. However, basic Class G cement has been associated with issues such as leakage and potential threats to the surrounding ecosystem as shown by Smith et al. [127].

To address these concerns and enhance the performance of Class G cement, researchers have been exploring various additives to improve its properties. One promising additive is graphene oxide, a two-dimensional material with exceptional mechanical, thermal, and electrical properties as shown by Geim & Novoselov [41]. Graphene oxide has shown great potential in reinforcing cement matrices and enhancing their mechanical properties as mentioned by Qian et al. [102].

The combination of graphene oxide with Class G cement could lead to improved cementing materials with enhanced compressive and rheological properties. However, to achieve optimal results, it is essential to carefully determine the right concentration of graphene oxide to be incorporated into the cement slurry.

In previous studies, researchers have investigated the effects of different graphene concentrations on cement performance. For example, Liu et al. [78] conducted experiments on graphene oxide-enhanced cement composites and observed improvements in compressive strength and durability. Similarly, Zhang et al. [160] explored the influence of graphene oxide on cement's rheological properties, reporting enhanced fluidity and stability.

Despite these promising results, the interaction between graphene oxide and cement is still a relatively unexplored area. Therefore, further research is needed to gain a comprehensive understanding of how different concentrations of graphene oxide affect the properties of Class G cement.

This study aims to fill this research gap by evaluating the effect of graphene oxide on Class G cement's compressive and rheological properties. The investigation will involve formulating different mixtures of graphene oxide and Class G cement and subjecting them to laboratory experiments. The obtained experimental data will contribute to the development of more accurate models for well integrity, helping to address environmental concerns related to cement leakage in oil wells.

1.2 PROBLEM STATEMENT

The oil and gas industry heavily relies on cement to ensure well integrity and prevent leakage of fluids from the reservoir into the surrounding ecosystem. Class G cement is commonly used in oil wells due to its high compressive strength and rheological properties. However, basic Class G cement has been associated with certain limitations, including the risk of leakage and potential harm to the environment. The primary concern lies in the formation of channels and micro-fractures within the cement, which may compromise the sealing integrity and allow fluid migration in and out of the wellbore as shown by Almond et al. [7]. These issues pose significant challenges for long-term well performance and environmental safety.

To address these challenges and improve the performance of Class G cement, researchers have turned their attention to the use of nanomaterial additives. Graphene, a two-dimensional carbon nanomaterial, has garnered attention in various industries due to its exceptional mechanical, thermal, and electrical properties as shown by Chen et al. [31]. As a potential additive, graphene holds promise in enhancing the properties of Class G cement, leading to improved well integrity and reduced environmental risks.

However, the incorporation of graphene into cement brings its own set of challenges. The high surface area and reactivity of graphene may lead to issues in maintaining a homogeneous cement slurry and could result in coagulation of solid particles as mentioned by Qin et al. [104]. This, in turn, affects the pumpability and handling of the cement slurry during well cementing operations.

The scientific problem addressed in this study is the leakage and potential threat to the surrounding ecosystem caused by the basic Class G cement used in oil wells. To mitigate these issues, the research focuses on selecting graphene oxide as an additive to strengthen the compressive and rheological properties of Class G cement.

The research aims to evaluate the effect of graphene oxide on Class G cement and investigate the performance of different concentrations of graphene-enhanced cement. The study will conduct various laboratory experiments, including compressive strength testing, viscosity testing, and high-pressure high-temperature filter press testing, to comprehensively assess the behaviours of graphene-enhanced cement under simulated downhole conditions. By obtaining systematic experimental data, the research intends to contribute to a better understanding of the potential of graphene as an additive for well cementing applications.

1.3 MAIN OBJECTIVE

The main objective of this study is to evaluate the effect of graphene on Class G cement and its potential as an additive to enhance the compressive and rheological properties of cement used in oil wells. The research aims to address the issue of cement leakage and potential threats to the surrounding ecosystem caused by the conventional Class G cement. By incorporating graphene oxide into the cement, the study seeks to strengthen the cement slurry, making it more suitable for use in oil well cementing operations.

The addition of graphene to cement has gained attention due to its unique properties, such as high surface area, mechanical strength, and thermal conductivity. By studying the effect of different concentrations of graphene oxide on Class G cement, the researchers aim to understand how this additive interacts with the cement matrix and how it affects the overall performance of the cement slurry.

The research tasks include formulating cement samples with varying concentrations of graphene oxide, creating cement cubes for testing purposes, and conducting various laboratory experiments. Compressive strength testing will be conducted to evaluate the strength properties of the formulated cement samples, while viscosity testing will help determine the rheological properties of the cement at different graphene concentrations and temperatures. Additionally, high-pressure high-temperature filter press testing will assess the fluid loss properties of the cement under elevated conditions.

The ultimate goal of this study is to identify the optimal concentration of graphene oxide that can be incorporated into Class G cement to improve its performance in oil well cementing operations. By achieving this objective, the research aims to contribute to the development of more reliable and effective cementing solutions that can help mitigate cement leakage and enhance well integrity.

1.3.1 SPECIFIC OBJECTIVES

To achieve the main objective, this study is designed to accomplish the following specific objectives:

1. Evaluate the Effect of Graphene Concentration: This objective involves the preparation of different mixtures of graphene-enhanced Class G cement with varying concentrations of graphene oxide. The compressive strength and rheological properties of each mixture will be measured to identify the optimum concentration that enhances cement performance.

2. Assess the Influence of Graphene on Cement Pumpability: This objective focuses on understanding the impact of graphene on cement pumpability during downhole injection. The study will investigate the changes in cement slurry texture and consistency at different graphene concentrations to ensure that the mixture remains pumpable without coagulation.

3. Evaluate Cement Performance under High-Pressure and High-Temperature Conditions: This objective involves conducting high-pressure high-temperature (HPHT) curing chamber experiments to simulate downhole conditions. The compressive strength, fluid loss properties, and rheological behaviour of graphene-enhanced cement samples will be assessed under these extreme conditions.

4. Investigate the Fluid Loss Properties of Graphene-Enhanced Cement: This objective aims to evaluate the fluid loss characteristics of graphene-enhanced cement samples using the high-pressure high-temperature filter press testing. By analysing the fluid loss rate, the potential for wellbore leakage can be assessed, contributing to the selection of suitable cementing materials.

5. Characterize the Rheological Properties of Graphene-Enhanced Cement: This objective involves measuring the viscosity of the graphene-enhanced cement samples at different

concentrations and temperatures. The plastic viscosity and yield point will be determined to assess the changes in cement behaviour due to graphene addition.

6. Assess the Density of Graphene-Enhanced Cement Slurry: This objective aims to determine the density of the formulated graphene-enhanced cement slurry in grams per cubic centimeter (g/cc). The density measurement is crucial for designing cementing jobs in oil wells to ensure wellbore stability and proper zonal isolation.

1.4 SCOPE OF STUDY

The scope of this study encompasses a comprehensive investigation into the effect of incorporating graphene oxide into Class G cement for the purpose of enhancing its compressive and rheological properties. The research will focus on evaluating the performance of graphene-enhanced G type cement under various conditions, particularly under high-pressure and high-temperature environments. The following paragraphs outline the specific aspects covered within this scope.

One crucial aspect of the study involves the formulation of cement samples with varying concentrations of graphene oxide. These samples will be prepared using a specific procedure to ensure consistent solid-to-solvent ratios. The concentration levels chosen for graphene oxide, namely 0.2%, 0.5%, and 1.0%, will allow for a comprehensive assessment of how different amounts of the additive influence cement properties. This experimentation aligns with the goals of addressing the scientific problem of cement leakage and environmental threats associated with traditional Class G cement used in oil wells.

The formulated cement samples will undergo various testing processes to analyse their performance characteristics. The testing protocols include the creation of cement cubes for compressive strength analysis. This involves the use of iron molds and a curing process to solidify the samples. The cubes will then be subjected to compressive strength testing to quantify their resistance to deformation and evaluate the effect of graphene oxide on enhancing the cement's mechanical properties. The results of this testing will contribute to the overall understanding of how graphene oxide influences cement performance.

Furthermore, the research scope encompasses the assessment of fluid loss properties using a high-pressure high-temperature (HPHT) filter press. This evaluation will provide insights into the ability of graphene-enhanced cement to withstand elevated pressure and temperature conditions. Fluid loss is a critical factor in cement integrity, and understanding how graphene oxide influences this property is essential for assessing the viability of the additive for real-world applications. The test results will be crucial in determining the potential of graphene oxide to enhance well cementing operations.

Rheological properties of the graphene-enhanced cement samples will also be thoroughly investigated through viscosity testing using a Fann viscometer. Rheological properties, including plastic viscosity and yield point, play a significant role in the fluid behaviours of well cement slurries. Evaluating how graphene oxide affects these properties will provide valuable insights into the material's flow behaviours, aiding in the development of optimized cement formulations for well integrity. This analysis will enhance the understanding of the practical implications of graphene oxide on cement slurry behaviours.

Additionally, the study will encompass density testing to determine the density of the graphene-enhanced cement slurries. The density measurements will be converted from parts per gallon (ppg) to grams per cubic centimeter (g/cc), providing a comprehensive understanding of the material's mass per unit volume. This aspect of the study is vital for characterizing the fundamental properties of the cement slurries and will contribute to a holistic assessment of graphene's impact on cement performance.

Overall, this study's scope includes a rigorous evaluation of the effects of graphene oxide on Class G cement properties. By systematically investigating various performance indicators, from compressive strength and fluid loss properties to rheological behaviours and density, the research aims to provide valuable insights into the potential of graphene-enhanced cement for oil well applications. The results obtained from this study will not only contribute to enhancing well cementing operations but also advance the understanding of nanomaterial additives in cement technology.

CHAPTER II

LITERATURE REVIEW

2.1 INTRODUCTION

The use of Class G cement in oil wells has been a common practice for cementing well casings to ensure zonal isolation and prevent leakage of oil and gas from the reservoir. However, conventional Class G cement has been associated with potential threats to the surrounding ecosystem due to its limited compressive and rheological properties, which may lead to well integrity issues and leakage as mentioned by Brown et al [25] and Li et al. [70]. To address these challenges, researchers have explored the use of additives to enhance the performance of Class G cement.

Graphene oxide, a two-dimensional material with exceptional mechanical and thermal properties, has emerged as a promising additive to strengthen cement properties as shown by Novoselov et al. [96] and Khan et al. [56]. Its high surface area and unique structure offer the potential to improve the mechanical strength and fluid loss control of cement slurries, making it an interesting candidate for enhancing Class G cement properties.

Previous studies have shown that incorporating graphene oxide into cement formulations can enhance the compressive strength and reduce fluid loss as shown by Bai et al. [16] and Zhou et al. [165]. However, the interactions between graphene oxide and the cement slurry, especially at higher concentrations, can lead to challenges during the mixing process; Zhang et al. 161. These factors necessitate a comprehensive investigation to understand the impact of graphene on Class G cement properties and optimize the mixture for practical applications.

This chapter reviews the existing literature related to the effect of graphene oxide on Class G cement and its potential benefits and challenges. It also explores the methodologies and tools used in previous studies to evaluate the performance of graphene-enhanced cement, focusing on compressive strength testing, rheological analysis, and fluid loss measurements.

In conclusion, understanding the potential of graphene oxide as an additive to improve the properties of Class G cement can offer valuable insights into designing environmentally friendly and effective cement slurries for oil well applications. This study aims to build upon existing research and generate comprehensive experimental data to enhance our knowledge and optimize the performance of graphene-enhanced G type cement for well integrity.

2.2 CLASS G CEMENT

2.2.1 INTRODUCTION TO CLASS G CEMENT

Class G cement is a commonly used material in the oil and gas industry for cementing wellbores. It is a type of oil well cement specially designed to withstand high temperatures and pressures encountered during drilling and completion operations (ASTM C150). Class G cement is commonly used in oil wells where temperatures and pressures exceed those typical of shallow wells as mentioned by El-Korchi et al. [37].

Class G cement typically consists of a mixture of clinker, gypsum, and other additives. The clinker is a nodular material produced by heating limestone and other materials to high temperatures. Gypsum is added to control the setting time and prevent flash setting, while other additives may be included to enhance specific properties as shown by Schemm et al. [112].

One of the main challenges associated with Class G cement is its potential for microannulus formation and gas migration, leading to the leakage of oil, gas, or other fluids into the surrounding formation as mentioned by El-Korchi et al. [37]. These microannuli can result from incomplete cement bonding with the wellbore, allowing pathways for fluid migration and compromising well integrity. Such issues can lead to potential environmental hazards and economic losses in the long run as shown by Sarshar et al. [110].

To address these challenges and enhance the performance of Class G cement, researchers have explored various additives and modifications. Graphene oxide (GO) is a promising nanomaterial that has garnered significant interest due to its exceptional mechanical, thermal, and electrical properties as shown by Geim and Novoselov [41]. Graphene oxide is a derivative of graphene, a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice. Graphene oxide possesses numerous oxygen functional groups, making it highly compatible with different materials as shown by Chen et al. [31].

The incorporation of graphene oxide into Class G cement aims to improve its compressive and rheological properties, as well as reduce fluid loss and enhance wellbore integrity during oil and gas operations. Several studies have demonstrated that graphene oxide can significantly improve the mechanical strength and durability of cementitious materials as mentioned by Zhang et al. [156] and Zhang et al. [150].

In summary, Class G cement is widely used in the oil and gas industry for cementing wellbores, but its potential for microannuli and fluid migration poses challenges to well integrity. The introduction of graphene oxide as an additive holds promise to enhance the mechanical properties and reduce fluid loss, thus improving the performance of Class G cement in high-pressure and high-temperature environments.

2.2.2 COMPOSITION AND PROPERTIES OF CLASS G CEMENT

Class G cement, also known as API Class G cement, is a type of oil well cement widely used in the oil and gas industry for cementing operations in wellbore casings. It is formulated to meet the American Petroleum Institute (API) specification 10A, which outlines the requirements for various types of oil well cements. Class G cement is primarily composed of Portland cement clinker, gypsum, and various additives to achieve specific properties suitable for downhole applications.

The basic composition of Class G cement typically consists of around 95% to 100% Portland cement clinker, which is a hydraulic cement made by grinding clinker, a mixture of calcium silicates, and calcium aluminates. The clinker provides the cementitious properties necessary for bonding and strength development in the cement slurry. Gypsum, a common mineral consisting of calcium sulphate dihydrate, is added to control the cement's setting time and prevent rapid setting upon mixing with water.

To enhance certain properties and performance characteristics of Class G cement, additional additives may be incorporated into the formulation. These additives can include pozzolanic materials such as fly ash or silica fume, which improve the cement's resistance to chemical attack and reduce permeability. Furthermore, retarders and dispersants might be added to modify the cement's setting time and rheological behaviour, allowing it to be pumped effectively downhole.

The properties of Class G cement are carefully controlled during manufacturing to meet specific API requirements. One crucial property is the thickening time, which refers to the time it takes for the cement slurry to reach a certain consistency suitable for placement. A precise thickening time is essential to ensure proper cement placement and zonal isolation in the wellbore. The thickening time is influenced by the type and amount of retarder used in the cement formulation.

Another important property of Class G cement is its compressive strength, which is the ability of the hardened cement to withstand axial loads without failure. API specifications dictate the minimum compressive strength requirements at various curing temperatures and time intervals. This property ensures the long-term integrity of the cement sheath in the wellbore, preventing gas or fluid migration between different formations.

In addition to thickening time and compressive strength, Class G cement is also characterized by its density, which is typically measured in pounds per gallon (ppg) or grams per cubic centimeter (g/cc). The density is critical for designing the cement slurry with the appropriate weight to counteract the pressure exerted by the formations in the well.

The rheological properties, such as plastic viscosity and yield point, also play a significant role in the cementing process. Plastic viscosity refers to the internal resistance of the cement slurry to flow, while the yield point represents the minimum stress required for the cement to start flowing. These properties are essential for optimizing cement displacement and ensuring effective mud removal during placement.

The accurate composition and precise control of these properties make Class G cement a reliable and widely used material for cementing operations in the oil and gas industry. Its ability to provide zonal isolation and wellbore integrity contributes significantly to the success and safety of oil well operations.

2.2.3 APPLICATIONS OF CLASS G CEMENT

Class G cement, also known as API Class G cement, is a widely used type of cement in the oil and gas industry due to its excellent properties and performance under high-pressure and high-temperature conditions. It finds various applications in well construction and completion operations. Some of the key applications of Class G cement are discussed below:

1. PRIMARY CEMENTING OF OIL AND GAS WELLS:

Class G cement is primarily used for the primary cementing of oil and gas wells. During the drilling and completion process, a cement slurry is pumped into the annulus between the wellbore and the casing. This slurry fills the space between the casing and the formation, providing zonal isolation and supporting the casing in place. The excellent compressive strength and setting properties of Class G cement make it suitable for achieving a durable and secure bond between the casing and the wellbore walls, ensuring well integrity and preventing fluid migration between different zones as shown by Ahmed, S., & Islam, M. R. [4].

2. CEMENTING IN HIGH-PRESSURE HIGH-TEMPERATURE (HPHT) ENVIRONMENTS:

In high temperature high pressure wells, where the temperature and pressure conditions are significantly elevated, Class G cement is favoured for its ability to withstand extreme downhole conditions. The cement slurry is exposed to higher temperatures and pressures during the cementing process, and Class G cement exhibits good rheological properties and resistance to degradation under such harsh environments. It ensures effective zonal isolation and maintains structural integrity despite the challenging downhole conditions as mentioned by Zhang, C., & Li, S. [149].

3. CEMENTING IN DEEPWATER WELLS:

Class G cement is commonly used in cementing operations for deepwater wells, where the depths are substantial, and downhole pressures can be very high. Deepwater wells pose specific challenges due to the long column of cement and the potential for gas influx. Class G cement, with its high compressive strength and resistance to gas migration, is ideal for maintaining well integrity and preventing gas channels in these deepwater environments as shown by Kanjo, Y., Nasr-El-Din, H. A., & Al-Muntasheri, G. A. [54].

4. ABANDONMENT AND PLUGGING OF WELLS:

When a well reaches the end of its productive life or becomes uneconomical, it needs to be properly abandoned and plugged to prevent any environmental and safety hazards. Class G cement is widely used for well abandonment and plugging operations due to its long-term durability and ability to seal the wellbore effectively. It ensures that no fluid migration occurs between the abandoned well and adjacent formations, reducing the risk of groundwater contamination as shown by Thiercelin, M., Islam, M. R., & Cuss, R. J. [129].

5. REPAIR AND REMEDIAL CEMENTING:

In well workover and remedial operations, Class G cement is utilized for cement squeeze treatments to repair casing leaks or improve wellbore integrity. The cement slurry is squeezed into the problematic zones to seal off any perforations or fractures in the casing, thus preventing fluid communication between different reservoir layers or between the wellbore and surrounding formations as shown by Rathore, S. S., Al-Sulaimani, G., Islam, M. R., & Chandran, K. [105].

These applications demonstrate the versatility and reliability of Class G cement in the oil and gas industry. Its properties and performance characteristics make it a preferred choice for ensuring well integrity and operational success in a wide range of well construction and completion scenarios.

2.2.4 CHALLENGES AND ENHANCEMENTS IN CLASS G CEMENT

Class G cement is commonly used in oil wells as a primary cementing material due to its high compressive strength and durability as shown by Bhargava et al. [19]. However, there are challenges associated with its use, particularly in terms of its susceptibility to gas migration and potential leakage, which can lead to compromised well integrity and environmental concerns as shown by Chen et al. [30]. These challenges stem from the cement's inherent characteristics, including its porosity and permeability, which can result in the migration of fluids and gases through the cement sheath as shown by Cao et al. [26].

To address these challenges and enhance the performance of Class G cement, researchers have been exploring various additives and technologies. One promising avenue is the incorporation of nanomaterials, such as graphene oxide, to improve the mechanical and rheological properties of the cement and reduce its permeability as shown by Li et al. [67]. Graphene oxide, with its high surface area and unique structural properties, has shown potential in improving cement's resistance to gas migration and fluid flow, thereby enhancing wellbore integrity as shown by Zhang et al. [162].

Furthermore, the interaction between graphene oxide and cementitious materials can result in the formation of strong interfacial bonds, leading to improved adhesion and mechanical properties as shown by Shi et al. [118]. This enhancement in bond strength can potentially reduce micro-annuli and pathways for fluid migration along the cement sheath. Additionally, graphene oxide's ability to act as a filler material can contribute to denser cement microstructures, thereby reducing permeability and enhancing the cement's overall sealing capability as shown by Ma et al. [80].

However, the introduction of graphene oxide also presents challenges, particularly in terms of the mixing process and its compatibility with other cement additives as shown by Sarvaramini et al. [111]. The high surface area and hydrophilic nature of graphene oxide can affect the rheological behaviour of cement slurries, potentially leading to difficulties in achieving homogenous mixtures and proper placement within the wellbore. Furthermore, the stability of graphene oxide dispersions in cement slurries can be influenced by factors such as pH and temperature, which can impact the effectiveness of the additive as shown by Boury et al. [22].

In summary, while Class G cement offers strong mechanical properties, its susceptibility to gas migration and fluid flow poses challenges to wellbore integrity. The incorporation of graphene oxide presents a promising solution to enhance the sealing and mechanical properties of the cement. However, the challenges related to mixing, compatibility, and stability need to be addressed for effective utilization of graphene oxide as a cement additive.

2.3 HYDRATION/CURING

Hydration is a critical process in cement-based materials, including Class G cement, where water reacts with cement particles to form calcium silicate hydrates (CSH) and other cementitious compounds. The curing of cement samples is essential to control the hydration process and ensure the development of desirable properties in the cement matrix.

During the hydration process, water penetrates the cement particles and initiates a series of chemical reactions that result in the formation of calcium silicate hydrates. The calcium silicate hydrates gel is responsible for binding the cement particles together and providing the cement matrix with its strength and durability as shown by Mehta and Monteiro [82]. Proper curing is crucial to maintain sufficient water content in the cement paste, allowing for continuous hydration and the formation of a dense and strong microstructure as shown by Siddique [119].

The curing process is typically carried out at specific temperatures and durations to promote effective hydration and the development of desired cement properties. High-pressure high-temperature (HPHT) curing is employed in the oil and gas industry to simulate downhole conditions where Class G cement is subjected to elevated pressure and temperature during oil well cementing operations as mentioned by Hossain et al. [44]. High pressure high temperature curing involves placing the cement samples in a curing chamber, applying pressure, and controlling the temperature to simulate well conditions.

Studies have shown that the curing conditions, including pressure and temperature, significantly influence the hydration kinetics and microstructure development of cementitious materials as mentioned by Narayanan and Ramamurthy [86]. The use of high pressure high temperature curing allows researchers to assess the performance of graphene-enhanced Class G cement under conditions relevant to oil well cementing operations. It also provides insights into the compressive strength and fluid loss properties of the cement samples under simulated downhole conditions.

Moreover, viscosity testing is a vital aspect of understanding the rheological behaviour of the cement slurry during and after the hydration process. The viscosity of the cement slurry affects its pumpability, placement, and stability downhole. Studies have shown that the addition of nanoparticles like graphene oxide can influence the viscosity and rheological properties of cementitious materials as shown by Wang et al. [134]. Rheological testing, such as using a Fann viscometer, allows researchers to analyse how the presence of graphene affects the flow behaviour and thickening time of the cement slurry.

By employing proper curing techniques and assessing the hydration and rheological properties of graphene-enhanced Class G cement, researchers gain valuable insights into the suitability of such cement in oil well applications. The data obtained from these studies help to understand the cement's performance under realistic downhole conditions, addressing potential issues related to leakage and well integrity. Additionally, it aids in the development of high-performance cement formulations that can withstand the challenges of oil well environments while minimizing environmental threats.

2.3.1 HYDRATION PROCESS

Hydration is a fundamental chemical process that occurs during the setting and hardening of cementitious materials, including Class G cement. During this process, water reacts with the cement particles to form cement hydration products, which contribute to the development of the cement's strength and other mechanical properties. The hydration process is crucial in understanding the performance of cement-based materials in various applications, including well cementing in oil and gas wells.

The hydration process of Class G cement is a complex series of chemical reactions that can be divided into several distinct stages. Initially, upon mixing the cement powder with water, the process begins with the dissolution of the cement particles in the water. This dissolution allows the release of calcium, aluminium and silicon ions, among others, from the cement particles into the aqueous phase as shown by Mehta and Monteiro [82].

As the dissolution progresses, the ions released from the cement particles start to react with the water molecules, leading to the formation of calcium silicate hydrate (C-S-H) gel. C-S-H gel is the primary product of cement hydration and is responsible for the development of strength in the cement matrix as mentioned by Neville [91]. Additionally, other hydration products, such as calcium hydroxide (CH) and ettringite, may also form during this early stage of the hydration process.

As the hydration process continues, the calcium silicate hydrate gel grows and continues to fill the spaces between the cement particles, forming a continuous matrix. This matrix progressively binds the cement particles together, resulting in the hardening and setting of the cement paste as mentioned earlier Mehta and Monteiro [82].

The hydration process is exothermic, meaning it releases heat as the chemical reactions occur. The heat generated during hydration is a crucial consideration in well cementing operations, as excessive heat can cause issues such as premature setting, cracking, and thermal shrinkage as mentioned earlier Neville [91].

Graphene oxide, as an additive to Class G cement, can potentially influence the hydration process due to its high surface area and interaction with water molecules. Understanding the impact of graphene on the kinetics of cement hydration is important for optimizing the formulation of graphene-enhanced cement slurries and predicting their long-term performance in well cementing applications.

Research in this area has shown that the addition of graphene oxide can lead to modifications in the cement hydration process, affecting the formation and growth of the calcium silicate hydrate gel shown by Li et al. [71]. Studies have demonstrated that the presence of graphene can accelerate the early stages of hydration and lead to increased early strength development of cementitious materials as shown by Kang et al. [53]. However, further investigation is required to fully comprehend the mechanisms and long-term implications of incorporating graphene oxide in Class G cement.

In conclusion, the hydration process of Class G cement is a complex chemical reaction involving the dissolution of cement particles, formation of hydration products like calcium silicate hydrate gel, and the hardening of the cement matrix. The addition of graphene oxide as an additive to Class G cement has the potential to influence the hydration kinetics and overall performance of cementitious materials. Understanding these effects is essential for developing high-performance cement slurries for well integrity.

2.3.2 CURING METHODS

Curing is a crucial step in the cementing process, as it allows the cement slurry to gain strength and achieve its desired properties. Several curing methods have been employed to ensure proper cement hydration and enhance cement performance. In the context of this study evaluating the effect of graphene on Class G cement, three curing methods are commonly used and described below.

Water bath curing is a widely employed method for curing cement samples. The cement cubes are placed in a temperature-controlled water bath, where they are submerged in water and kept at a specified temperature for a predetermined period. This method ensures a uniform and consistent curing environment for the samples, promoting even hydration and reducing the risk of cracking. In the study by Smith et al. [122], water bath curing was adopted to assess the compressive strength development and microstructure of Class G cement modified with different additives, including graphene oxide. The results showed that water bath curing significantly improved the compressive strength of the cement with graphene oxide, indicating its potential as a viable curing method for graphene-enhanced cement systems as shown by Smith et al. [121].

High Pressure High Temperature (HPHT) Curing is a specialized method used to simulate downhole conditions experienced in oil wells. The cement samples are subjected to elevated pressures and temperatures similar to those encountered during oil well operations. This method provides valuable insights into the cement's behaviour under extreme downhole conditions and helps evaluate its long-term stability and integrity. In the work of Chen et al. [28], High Pressure High Temperature curing was employed to investigate the fluid loss properties and rheological behaviour of Class G cement with graphene oxide under high-pressure conditions. The results showed that graphene-modified cement exhibited improved fluid loss control and enhanced rheological properties, making High Pressure High Temperature curing a relevant method to assess graphene's impact on cement performance as mentioned by Chen et al. [29].

2.3.3 HYDRATION MECHANISMS

Hydration is a fundamental process in cement-based materials that involves the chemical reaction between water and cementitious compounds, resulting in the formation of hydrates and the development of cementitious properties. Several mechanisms contribute to the hydration process, which is crucial for understanding the setting and hardening of cement systems. This section reviews some key hydration mechanisms relevant to the study on the effect of graphene on Class G cement.

One of the primary hydration mechanisms in cement involves the dissolution of cement particles in water, leading to the release of calcium, silica, alumina, and other ions. These ions then react with water molecules, initiating the formation of various hydrates, including calcium silicate hydrates (C-S-H), calcium aluminate hydrates (C-A-H), and calcium hydroxide (CH). Calcium silicate hydrates are the most significant contributors to the strength and durability of cement-based materials. They form through a complex reaction between calcium, silica, and water, resulting in a gel-like structure that fills the gaps between cement particles and contributes to the material's strength as mentioned earlier Mehta and Monteiro [82].

The addition of graphene to Class G cement can influence the hydration mechanisms and alter the microstructure of the cement matrix. Research by Duan et al. [36] demonstrated that graphene oxide (GO) can act as a nucleation site for calcium silicate hydrates, accelerating their formation and promoting a denser microstructure. This enhancement of the nucleation process can lead to improved mechanical properties of graphene-enhanced cement composites.

Furthermore, graphene can also interact with the calcium hydroxide formed during the hydration process. Liu et al. [78] investigated the effect of graphene on the carbonation of cementitious materials and found that graphene can adsorb carbon dioxide and catalyse the carbonation reaction. This interaction between graphene and calcium hydroxide influences the carbonation kinetics and can potentially contribute to the carbon sequestration of cementitious materials.

Another essential aspect of hydration mechanisms is the role of water-to-cement (w/c) ratio in controlling the hydration kinetics and microstructure development. Lower w/c ratios typically lead to higher hydration degrees and more extensive formation of hydrates, resulting in stronger and more durable cement composites as shown by Scrivener et al. [113]. However, the addition of graphene may influence the water demand of cementitious mixtures due to its high surface area and reactivity. Careful consideration of the w/c ratio is necessary to maintain the workability and pumpability of the graphene-enhanced cement slurries as mentioned by Xie et al. [147].

In summary, the hydration mechanisms in cementitious materials are complex and influenced by various factors, including the presence of graphene additives. Understanding these mechanisms is crucial for optimizing the performance of graphene-enhanced Class G cement and assessing its potential as a solution to improve well integrity during carbon dioxide injection and storage.

2.3.4 FACTOR AFFECTING HYDRATION/ CURING

The hydration and curing process of cement-based materials, including Class G cement, is influenced by various factors that can significantly impact the final properties and performance of the cementitious materials. Understanding these factors is essential to optimize the use of graphene oxide as an additive to enhance the compressive and rheological properties of Class G cement. Several key factors affecting hydration and curing are discussed below, along with relevant citations to support the findings:

1. Water-to-Cement (W/C) Ratio: The water-to-cement ratio is a crucial parameter that directly affects the hydration process of cementitious materials. It is defined as the ratio of the weight of water to the weight of cement used in the mixture. A higher W/C ratio generally results in increased workability of the cement slurry, but it may also lead to a decrease in the final compressive strength of the cured cement. Studies have shown that a low W/C ratio is preferred to achieve higher compressive strength and better durability of cement-based materials as mentioned earlier Mehta and Monteiro [82].

2. Curing Temperature: The curing temperature significantly influences the rate and extent of cement hydration. Elevated temperatures can accelerate the hydration process, leading to earlier setting times and increased early-age strength development. Conversely, lower temperatures can slow down the hydration process, affecting the overall strength gain. A study by Sun et al. [126] highlighted that curing at higher temperatures positively impacted the mechanical properties of cement pastes.

3. Curing Time: The duration of the curing period is another critical factor affecting cement hydration. Adequate curing time is required to ensure sufficient hydration and the development of desired strength properties. Studies have demonstrated that prolonged curing durations can result in increased compressive strength and improved microstructural development as shown by Morsy et al. [85].

4. Graphene Oxide Concentration: The concentration of graphene oxide as an additive in the cement mixture is a key factor to investigate. As outlined in the study's experimental design, different concentrations of graphene oxide were incorporated into Class G cement slurry. Research by Yan et al. [145] revealed that the addition of graphene oxide can enhance the mechanical properties and durability of cement composites.

5. Additive Interactions: The high surface area and unique properties of graphene oxide can interact with other components in the cementitious system, including water and cement particles. These interactions may affect the workability and homogeneity of the cement slurry, as mentioned in the sample preparation section. Wu et al. [142] investigated the interactions between graphene oxide and cement hydrates, revealing potential improvements in the mechanical properties and hydration behaviour.

6. Particle Size Distribution: The particle size distribution of the cement and graphene oxide particles can influence the packing density and the effectiveness of the dispersion in the cement matrix. A well-optimized particle size distribution can lead to improved mechanical properties and rheology of the cementitious composites as shown by Chen et al. [32].

7. Chemical Admixtures: Various chemical admixtures, such as superplasticizers and accelerators, are commonly used in cement formulations to modify its properties. These admixtures can affect the setting time, workability, and hydration kinetics of the cement, thereby influencing the overall performance as shown by Neville and Brooks [92].

2.4 EFFECT OF GRAPHENE ON CEMENT STRENGTH

The incorporation of graphene into cementitious materials has garnered significant attention in recent years due to its potential to enhance cement strength and mechanical properties. Graphene, a two-dimensional carbon nanomaterial, possesses exceptional mechanical strength, high surface area, and excellent electrical conductivity, making it an attractive additive for cement composites. Several studies have investigated the effect of graphene on cement strength, and their findings have demonstrated promising results.

One study by Li et al. [64] examined the impact of graphene oxide (GO) on the compressive strength of cement paste. The researchers prepared cement paste samples with varying concentrations of graphene oxide and conducted compressive strength tests. The results showed that the addition of graphene oxide led to a substantial improvement in compressive strength compared to the plain cement paste. The enhancement in strength was attributed to the uniform dispersion of graphene oxide in the cement matrix, which acted as a reinforcing agent and restricted crack propagation within the composite.

Similarly, Zhu et al. [168] investigated the effect of graphene nanoplatelets (GNPs) on the flexural strength of cement mortar. The researchers prepared mortar samples with different dosages of graphene nanoplatelets and evaluated their flexural strength. Their findings indicated that the incorporation of graphene nanoplatelets significantly increased the flexural strength of the mortar. The interlocking nature of graphene nanoplatelets within the cement matrix was found to enhance the load transfer capacity and effectively bridge cracks, resulting in improved flexural performance.

Furthermore, Wang et al. [132] explored the influence of graphene-based nanomaterials on the split tensile strength of concrete. The study involved the use of graphene nanoplatelets and multi-walled carbon nanotubes as additives. The results demonstrated that both graphene-based additives led to an increase in split tensile strength compared to the control concrete. The strong interfacial bonding between the nanomaterials and cement matrix was identified as the key factor contributing to the improved tensile strength.

Moreover, the work of Jiang et al. [48] focused on the impact of reduced graphene oxide (rGO) on the mechanical properties of Class G cement. The researchers prepared cement specimens with different reduced graphene oxide concentrations and conducted comprehensive mechanical tests. They reported that the addition of reduced graphene oxide improved the compressive and flexural strengths of the cement. The researchers attributed this enhancement to the homogenous dispersion of reduced graphene oxide, which effectively filled pores and defects in the cement matrix, leading to enhanced strength.

In summary, various studies have demonstrated that the addition of graphene-based nanomaterials, such as graphene oxide, graphene nanoplatelets, and reduced graphene oxide, can significantly improve the strength properties of cementitious materials. The uniform dispersion and strong interfacial bonding of graphene within the cement matrix play crucial roles in enhancing compressive, flexural, and split tensile strengths. These findings highlight the potential of graphene as a promising additive for the development of high-performance cement composites with enhanced mechanical properties.

2.5 EFFECT OF GPRAPHENE ON TEMPERATURE RESISTENCE

Graphene, a two-dimensional carbon nanomaterial with exceptional mechanical, thermal, and electrical properties, has gained significant attention in the field of cementitious materials research. Several studies have investigated the effect of graphene as an additive on the temperature resistance of cement-based materials.

One notable study by Li et al. [67] explored the impact of graphene oxide (GO) on the thermal performance of cement composites. They prepared cement pastes with varying concentrations of graphene oxide (ranging from 0.1% to 1.0% by weight of cement) and subjected the specimens to high-temperature exposure. The results revealed that graphene oxide incorporation significantly enhanced the thermal stability of cement paste, reducing the weight loss and preventing microcrack formation under elevated temperatures. The researchers attributed this improvement to the strong interfacial bonding between graphene oxide and the cement matrix, which effectively acted as a barrier against heat-induced degradation.

Another study by Wang et al. [136] investigated the effect of reduced graphene oxide (rGO) on the temperature resistance of Class G cement slurry used in oil wells. They prepared cement slurries with varying concentrations of reduced graphene oxide (ranging from 0.1% to 1.5% by weight of cement) and conducted high-pressure high-temperature (HPHT) tests. The results demonstrated that reduced graphene oxide incorporation led to a substantial reduction in fluid loss and an increase in the thickening time of the cement slurry at elevated temperatures. The strong adsorption of reduced graphene oxide on cement particles resulted in improved rheological properties and better resistance to temperature-induced fluid loss, making it a promising additive for well cementing applications.

Additionally, a study by Chen et al. [28] focused on the role of graphene nanoplatelets (GNPs) in enhancing the temperature resistance of Class G cement. They prepared cement samples with different concentrations of graphene nanoplatelets (ranging from 0.05% to 0.5% by weight of cement) and subjected them to high-temperature curing. The results showed that graphene nanoplatelets effectively enhanced the compressive strength and dimensional stability of the cement samples at elevated temperatures. The strong dispersion of graphene nanoplatelets in the cement matrix hindered the growth of microcracks and improved the load transfer mechanisms, resulting in improved thermal resistance of the cementitious material.

Furthermore, a recent study by Zhang et al. [152] explored the effect of functionalized graphene on the thermal performance of G type cement under cyclic temperature exposure. They prepared cement composites with various percentages of functionalized graphene (ranging from 0.2% to 2.0% by weight of cement) and conducted cyclic temperature tests. The results revealed that functionalized graphene significantly improved the thermal conductivity and heat dissipation capacity of the cement composites. The functional groups on the graphene surface promoted better interfacial bonding with the cement matrix, leading to enhanced thermal transport properties and reduced risk of thermal cracking.

In conclusion, the incorporation of graphene and its derivatives, such as graphene oxide and functionalized graphene, into Class G cement has shown significant potential in enhancing the temperature resistance of cementitious materials. The strong interfacial bonding improved rheological properties, and heat dissipation capabilities of graphene-based additives contribute to improved thermal stability, reduced fluid loss, and enhanced compressive strength under high-temperature conditions. These findings highlight the promise of graphene as a viable additive for ensuring the integrity and performance of cement in oil wells and other high-temperature applications.

2.6 GRAPHENE ENHANCED CEMENT

Graphene, a two-dimensional carbon allotrope, has gained significant attention in recent years due to its exceptional mechanical, electrical, and thermal properties. In the field of construction materials, graphene has shown promise as an additive to enhance the performance of cementitious materials, including cement. This section provides an overview of the research and studies related to graphene-enhanced cement.

One of the pioneering studies investigating the effect of graphene on cement properties was conducted by Kwon et al. [62]. The researchers explored the potential of incorporating graphene oxide (GO) into cement paste and investigated its influence on mechanical properties. The results demonstrated that the addition of a small amount of graphene oxide (0.03 wt%) significantly improved the compressive strength and durability of the cement paste. The enhanced mechanical properties were attributed to the high surface area and excellent mechanical strength of graphene which acted as reinforcement within the cement matrix as mentioned earlier Kwon et al. [62].

In another study, Wang et al. [138] focused on the impact of graphene nanoplatelets (GNP) on cementitious materials. The researchers prepared cement graphene nanoplatelets composites and evaluated their mechanical and electrical properties. The incorporation of graphene nanoplatelets at varying concentrations (0.05 wt%, 0.1 wt%, and 0.2 wt%) resulted in improved electrical conductivity, making the cementitious material suitable for applications requiring conductivity, such as self-sensing and self-healing structures as mentioned earlier Wang et al. [138].

Graphene's ability to enhance the mechanical properties of cement was also explored in the context of oil well cement (OWC). Ju et al. [51] investigated the effects of adding graphene nanoplatelets (GNPs) to OWC on its mechanical properties, microstructure, and setting time. The study found that the inclusion of GNP graphene nanoplatelets s at 0.2 wt% improved the flexural and compressive strengths of oil well cement significantly. Additionally, graphene nanoplatelets accelerated the setting time of the cement, making it suitable for well cementing operations as shown by Ju et al. [51].

In a more recent study, Zhou et al. [165] investigated the influence of graphene oxide (GO) on the microstructure and mechanical properties of Class G cement. The researchers prepared cement graphene oxide composites with varying concentrations of graphene oxide (0.01 wt%, 0.02 wt%, and 0.03 wt%) and evaluated their mechanical and microstructural characteristics. The results showed that the addition of graphene oxide enhanced the cement's flexural and compressive strengths and reduced the porosity of the cement matrix, indicating improved densification and interfacial bonding as mentioned earlier Zhou et al. [165].

The potential of graphene-enhanced cement for oil well applications was also studied by Wang et al. [133]. The researchers investigated the rheological properties of graphene oxide (GO) modified Class G cement slurry under high-pressure high-temperature (HPHT) conditions. The study revealed that the addition of graphene oxide significantly improved the cement slurry's rheological behaviour and fluid loss control, making it more suitable for wellbore stability during drilling and cementing operations as mentioned earlier Wang et al. [133].

CHAPTER III

METHODOLOGY

3.1 INTRODUCTION

This chapter presents the methodology employed in the study to evaluate the effect of graphene on Class G cement (oil well cement). The main objective is to investigate the potential of graphene oxide as an additive to strengthen the compressive and rheological properties of Class G cement, thus mitigating the issues of cement leakage and the associated threats to the surrounding ecosystem.

To achieve this objective, a comprehensive set of methods and tools were used, including sample preparations, formulation of cement samples, high-pressure high-temperature (HPHT) curing, compressive strength testing, high-pressure high-temperature filter press testing, viscosity testing, and density testing.

The sample preparations involved creating different mixtures of Class G cement and graphene oxide at varying concentrations while maintaining a consistent solid-to-solvent ratio. The weight of graphene oxide was calculated based on the weight of Class G cement, and distilled water was added in the same amount for all mixtures.

The formulated cement samples were used to create cement cubes for testing purposes. The cement cubes were formed using iron molds and subjected to curing processes, including regular curing and high-pressure high temperature curing in a water bath set at 80°C for 24 hours.

Compressive strength testing was conducted to evaluate the strength properties of the formulated cement samples. The cubes were tested using a compressive strength tester to determine their resistance to fracture under pressure.

The high-pressure high-temperature filter press testing was performed to assess the fluid loss properties of the cement samples under elevated pressure and temperature conditions. The filter press testing allowed measuring the fluid loss using a measuring cylinder.

Viscosity testing was carried out to determine the rheological properties of the cement samples at different concentrations of graphene oxide and temperatures. A Model 35 Fann viscometer was used to record dial readings at various speeds, and the plastic viscosity (PV) and yield point (YP) were calculated based on the recorded readings.

Density testing was performed using a Pressurized Mud Balance to measure the density of the cement slurry in parts per gallon (ppg) and then converted to grams per cubic centimeter (g/cc).

Throughout the study, rigorous experimental procedures were followed to ensure the accuracy and reliability of the results. The data obtained from these experiments will be utilized to evaluate the effect of impure carbon dioxide injectivity on cement performance and to enhance the accuracy of future modelling studies on well integrity.

3.2 DESCRIPTION OF MATERIAL USED

3.2.1 CLASS G OIL WELL CEMENT

In this study, Class G oil well cement was utilized as the base material to investigate the effect of graphene oxide as an additive. Class G cement is commonly used in oil wells due to its excellent properties such as high compressive strength, low permeability, and resistance to sulphate and chloride attack as shown by API Specification 10A [13]. It is essential to understand the performance of this cement and identify any potential weaknesses or issues related to its use, especially concerning leakage and environmental impact.

The addition of graphene oxide to Class G cement is expected to enhance its compressive and rheological properties. Graphene, a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice, has outstanding mechanical, electrical, and thermal properties as shown by Novoselov et al. [96]. By incorporating graphene oxide, researchers aim to improve the cement's overall strength and performance.

To achieve the objective, a specific sample preparation procedure was followed to create different mixtures with varying concentrations of graphene and Class G cement while maintaining a consistent solid-to-solvent ratio. Distilled water was used as the solvent, and the solid-to-solvent ratio was maintained at 0.44 for all mixtures.

The weight of graphene oxide was calculated based on the weight of Class G cement using a simple equation. The weight of graphene oxide was determined by multiplying the weight of Class G cement by the desired percentage of graphene oxide as mentioned by Bhattacharyya et al. [21].

Once the mixtures were prepared, it was noted that directly adding graphene oxide to Class G cement slurry would cause coagulation of the solid particles, making the mixture difficult to pump downhole. To address this issue, the Class G cement was replaced with the calculated weight of graphene oxide, maintaining the weight percentage ratio of the solid added and distilled water.

Different concentrations of graphene-enhanced G type cement were obtained using this sample preparation procedure for further laboratory experiments. These mixtures will be evaluated for their performance, particularly in terms of generate valuable experimental data for modelling studies on well integrity.

3.2.2 GRAPHENE

Graphene, a two-dimensional carbon allotrope, has gained significant attention in recent years due to its remarkable mechanical, electrical, and thermal properties. It consists of a single layer of carbon atoms arranged in a hexagonal lattice, making it one of the thinnest and strongest materials known. The extraordinary properties of graphene make it a potential candidate for enhancing the properties of cementitious materials.

Research has shown that incorporating graphene into cementitious matrices can improve their mechanical strength, durability, and rheological behaviour. Graphene's high surface area and mechanical strength enable it to act as a reinforcing agent within the cement matrix, enhancing its load-bearing capacity and fracture resistance as shown by Abed et al. [2]; Gholampour et al. [42].

In the study conducted by Abed et al. [2], they investigated the effect of graphene oxide on the mechanical properties of cement paste. The results showed that the addition of graphene oxide led to a significant increase in compressive strength and Young's modulus of the cement paste. Furthermore, graphene oxide acted as a nucleation site for calcium-silicate-hydrate (C-S-H) formation, promoting densification of the cementitious matrix.

Similarly, Gholampour et al. [42] explored the impact of incorporating graphene nanoplatelets into cement composites. Their findings revealed improved flexural and compressive strength of the cement composites with the addition of graphene nanoplatelets. The graphene reinforcement also contributed to reducing the permeability of the cementitious material, enhancing its durability.

Graphene's excellent electrical conductivity and thermal properties have also been explored in cement applications. Some studies have investigated the possibility of using graphene to enhance the electrical conductivity and sensing capabilities of cementitious materials, making them suitable for applications in smart infrastructure and structural health monitoring as mentioned by Cheng et al. [33]; Wu et al. [141].

In summary, the addition of graphene to Class G cement presents a promising avenue for enhancing the compressive and rheological properties of the cement, leading to improved well integrity and reduced environmental risks. The scientific problem of cement leakage and potential ecological threats can be mitigated by harnessing the unique properties of graphene to reinforce and optimize the performance of cementitious materials.

3.3 EXPERIMENT/ PROJECT ACTIVITIES

The experiment or project activities conducted in this study focused on evaluating the effect of graphene on Class G cement with the aim of enhancing its compressive and rheological properties. The following subsections provide a detailed description of each activity, along with relevant citations and references.

3.3.1 METHODS AND TOOLS

This section presents the methods and tools employed to address the scientific problem and accomplish the research tasks.

3.3.1.1 SAMPLE PREPARATIONS

In this study, the effect of Graphene Oxide on Class G Cement was evaluated by preparing various samples with different concentrations of Graphene Oxide. The goal was to maintain a constant solid to solvent ratio of 0.44, and to achieve this, the weight percentage of Graphene Oxide added was replaced with an equivalent weight percentage of Class G Cement. Additionally, the amount of Distilled Water added remained constants for all samples.

The sample preparation process involved carefully measuring and weighing the components to ensure accuracy and reproducibility. The concentration of Graphene Oxide in each sample was varied to achieve a range of concentrations. Table 1 outlines the specific sample preparations at different Graphene Oxide concentrations, along with the corresponding weights of Class G Cement, Graphene Oxide, total mixture, and water.

To calculate the weight of Graphene Oxide based on the weight of Class G Cement using the equation:

- Weight of Graphene Oxide = Weight of Class G Cement * (Percentage of Graphene Oxide / 100)

To maintain the integrity of the Class G Cement slurry, it was crucial to retain the appropriate water-to-solid ratio. Class G Cement slurry is typically formulated with a specific amount of water based on its weight, resulting in a saturated and thick slurry. However, introducing Graphene Oxide to this mixture would lead to coagulation of the solid particles, forming a mixture that could become difficult to pump downhole.

To address this issue, a remedial approach was taken, where the Class G Cement was replaced with the desired weight percentage of Graphene Oxide while still maintaining the overall weight percentage ratio of the solid and water components. This ensured that the desired solid to solvent ratio of 0.44 was maintained throughout the experiment.

Although measures were taken to balance the weight percentage ratio, the inclusion of Graphene Oxide introduced challenges during the mixing process. The high surface area of Graphene Oxide resulted in stronger interactions with the distilled water, leading to the formation of a thicker texture in samples with higher Graphene Oxide concentrations compared to those with lower concentrations.

The difficulty in mixing the samples with higher Graphene Oxide concentrations is attributed to the strong surface forces and interactions between the graphene sheets and the water molecules. These interactions hinder the dispersion of Graphene Oxide in the slurry and increase the viscosity of the mixture.

Table 1: Outlines the sample preparation at different concentrations.

Graphene Concentration (%)	Weight of Class G Cement (g)	Weight of Graphene (g)	Total Weight of Mixture (g)	Weight of Water (g)
0	792	0	792	349.5
0.2	791.84	1.58	792	349.5
0.5	791.60	3.96	792	349.5
1	791.21	7.92	792	349.5

3.3.2 SCIENTIFIC PROBLEM

The scientific problem addressed in this study is the leakage and potential threat to the surrounding ecosystem caused by the basic Class G cement used in oil wells. To mitigate these issues, the research focuses on selecting graphene oxide as an additive to strengthen the compressive and rheological properties of Class G cement.

3.3.3 RESEARCH TASK

The research tasks undertaken in this study involve the formulation of cement samples and the creation of cement cubes for testing purposes. The following subsections provide detailed information on each task.

3.3.3.1 FORMULATION OF CLASS G CEMENT SLURRY

In this part, the Class G cement slurry is prepared using the following steps:

1. Measure 349 ± 0.5 ml of distilled water.
2. Mix the water with 792 ± 0.5 grams of Class G Cement powder using a Hamilton Beach Mixer.
3. Stir the mixture portion by portion until the entire Class G powder is uniformly mixed in the distilled water.

FIGURE 1: CEMENT SLUURY

3.3.3.2 INCLUSION OF GRAPHENE OXIDE ADDITIVE

In this part, Graphene Oxide is added as an additive to the Class G cement slurry. The following steps are performed:

1. Calculate the weight of Graphene Oxide based on the weight of Class G Cement using the equation:

    - $\text{Weight of Class G Cement}(\text{g}) \times \frac{Percentage\ Required\ for\ Graphene\ (\%)}{100} = Weight\ of\ Graphene\ Oxide\ Required\ (g)$

2. Add 0.2% of Graphene Oxide based on the weight of Class G Cement to the cement slurry.
3. Stir the mixture portion by portion until the entire Class G powder is uniformly mixed in the distilled water.
4. Repeat the same procedure for 0.5% and 1% of Graphene Oxide concentrations.
5. Formulation of Cement Cubes

FIGURE 2: GRACE CONSTANT SPEED MIXER

In this part, cement cubes are formed using iron molds and the curing process is carried out.

The following steps are involved:

3.3.3.3 ASSEMBLY OF IRON MOLDS

1. Grease each part of an iron mold using a brush.
2. Assemble the greased parts of the iron mold accordingly and tighten them using a set of Alan Key and screws to hold them in place.
3. Pour the formulated cement sample into the 50mm × 50mm × 50mm chamber in the assembled mold.
4. Place the top cover and tighten it using a bolt.

FIGURE 3: IRON MOLDS WITH CEMENT SLURRY

3.3.3.4 CURING PROCESS

1. Place the assembled molds in a water bath.
2. Set the temperature to 80℃ and close the lid.
3. Allow the cement samples to cure for 24 hours.
4. Repeat the same procedure for 0% and 1% Graphene Oxide concentration.

FIGURE 4: CTE WATER BATH AND CEMENT CUBE AFTER 24 HOUR

3.3.3.5 HIGH PRESSURE HIGH TEMPERATURECURING PROCESS

A Detailed of Running a HPHT curing chamber.

This section provides detailed instructions on running a thickening time test. It is intended for inexperienced users or those desiring an in-depth refresher on thickening time testing. All the instructions are common to both single and dual consistometers, except where noted. Dual consistometers operate basically as two separate consistometers, except that they share a common oil reservoir and air supply system. All other systems are separate.

1. Close all the valves on the front panel. If operating a dual consistometer, this applies only to the side on which is test is planned.
2. Turn power switch to the on position. This supplies power to the entire instrument or to one side of a dual consistometer. Wait a minute or two until the touch screen software loads.
3. Press the automatic shutdown reset button. It will be lighted upon power up Unless the reset button is pressed, cooling water will flow, and the motor and heater will fail to operate.
4. Program the temperature ramp and soak parameters into the touch screen. software.

CAUTION: Be sure the pressure vessel is filled with oil before turning the heater on. Failure to do so may cause the heater to burn out.

5. Set the consistency alarm level on the digital consistency meter. The alarm triggers the automatic shutdown feature stops the elapsed timer and turns on an audible alarm. The alarm value in Bearden Units (8c) may be set to the desired level by pressing the alarm button on the front of the consistency meter. Complete instructions on setting the alarm value are listed previously in the section describing the consistency display.
6. If the automatic shutdown feature is desired, turn the switch to the enable position.
7. Coat the slurry cup threads lightly, yet thoroughly, with grease. Invert the slurry cup and remove the hexagon cup base plug and the slurry cup bottom. Fill the cup with the slurry up to its threaded section. Puddle the slurry with a glass rod to eliminate trapped air. If too much air remains in the slurry, the diaphragm will flex inward too far and interfere with the paddle causing erroneous consistency readings. Pull the paddies shaft down to extend the diaphragm and allow complete filling of the cup. If the cup is sufficiently filled, a small amount will be forced out the center hole when the cup base is screwed into the slurry cup. Replace the base plug, making certain that the pointed end of the paddle shaft engages the conical depression in the tip of the base plug. Check to see that the paddle spins freely inside the slurry cup.

8. Place the slurry cup, with the paddle shaft pointing upward, into the pressure vessel. Rotate the cup until the slot and two pins on the slurry cup bottom engage with the bar and two holes in the cup table.
9. Install the Potentiometer Mechanism in the pressure cylinder. Lower the mechanism into the cylinder. Rotate the potentiometer mechanism until its contact springs align with the contact pins on the inside of the cylinder. Operate the drive motor intermittently to engage the drive bar on the top of the paddle shaft with mating piece on the bottom of the potentiometer mechanism. When properly engaged, the paddle shaft will extend inside the ball bearing in the cross bar of the potentiometer mechanism.
10. The motor switch may be turned on now or at any time in the future to begin stirring the cement.
11. Close the pre-recylinder by threading the plug into the cylinder When the plug thread is fully engaged the mark in the plug head and the cylinder will alig. A well maintained consistometer prese vessel may be said reliably with only one or two solid blows with a dead blow hammer. It is not necessary to pound the plug closed with sledgehammer. If the handles bend or break, excessive force is being used. This indicates that a new metal O-ring maybe be required or that the sealing surface may need trapping. Some used have reported good success using rubber O-rings for testing at low temperature and pressure.
12. Insert the thermocouple into the opening in the center of the cylinder plug but do not tightening completely. The air will be vented through the thermocouple opening as the cylinder fills. Be sure to plug the thermocouple into the receptacle on the front panel.
13. Fill the pressure vessel with oil as follows. With all valves closed, open the air supply valve. This valve applies air pressure to top of the oil reservoir and forces oil into the pressure vessel. On a dual consistometer, the oil supply valve must also be opened. As the pressure vessel fills with oils, air will be exhausted from the pressure cylinder at thermocouple gland securely. Do no tighten the thermocouple connector until oil appears or air may be trapped int the vessel preventing pressurization.
14. Adjust the pressure in the vessel as desired for the start of the test. This may be done by turning the pump switch to the on position until the desired pressure is reached. It the operator desires to use the pump to maintain a minimum pressure on the instrument, follow the instructions below Turn the regulator knob counterclockwise as far as it will go. The pump air pressure should read zero. Turn the pump switch to the ON position. You should hear the air solenoid valve click on Turn the regulator knob clockwise. The

pump air pressure should begin to increase, and the pump should begin to stroke when the pressure is at approximately 10 psig. Continue turning the regulator knob clockwise until the desired vessel pressure is obtained. If heat increases the vessel pressure, the pump will not respond. However, if the vessel pressure falls below this level and the pump switch is on, the pump will respond and increase the vessel pressure to this level. This can be thought of as a lower limit on pressure. If the instrument is equipped with optional pressure control, set the pump switch to auto.

15. Turn heater switch to the on position and begin the temperature and optional pressure control plus data acquisition by pressing the start button on the touch screen.
16. Turn the timer switch to the on position.

CAUTION: Top of consistometer may become extremely hot. Severe burns can result from touching the pressure vessel or plug.

17. As the slurry thickens to the point where the consistency equals the alarm value in the touch screen and the consistency display, the buzzer will sound, and the automatic shutdown feature will engage if enabled. The touch screen data acquisition will cease, and the thickening time will be reported. The test is now complete.

A Detailed of Ending a HPHT curing chamber.

This section provides detailed instructions on rending a thickening time test. It is intended for inexperienced users or those desiring an in-depth refresher on thickening time testing. All the instructions are common to both single and dual consistometers, except where noted. The Slurry Cup should be removed from the instrument and disassembled as soon as the unit has cooled sufficiently. Complete hardening of the slurry may result in damage to the slurry cup paddle and shaft it is advisable to wait until the slurry is below 200 F to prevent the cement from boiling.

WARNING: Serious burns can occur when removing hot slurry cups from the instrument. Handle hot parts with care, use extreme caution, and wear protective clothing.

Detailed steps for ending a thickening time test are given below.

1. Close all valves.
2. Open the cooling water valve.
3. Turn the heater switch to the off position.
4. Close the oil supply valve.
5. Slowly release pressure inside the vessel using the pressure release valve. When all the pressure is released, open the pressure release valve completely. Oil is removed from the pressure vessel through the pressure release valve.
6. Open the air exhaust valve. Pressure on the air pressure and pump air pressure gauges should go to zero. Note that neither pump will operate when the air pressure is zero.
7. Open the reservoir cooling valve to cool the oil in the reservoir.
8. When it is certain that there is no pressure in the pressure vessel, the air to cylinder valve may be opened. This will transfer the oil from the pressure vessel to the oil reservoir. When the transfer is complete, a hissing sound will be heard.
9. Close the air to cylinder valve.
10. Loosen the thermocouple seal nut to vent the remaining air pressure from the cylinder.
11. If the instrument is a dual consistometer and a test is running on the other side, close the pressure release valve in the unused side and the air exhaust valve, then open the air supply valve. This will supply oil to the pump on the side that is in use in case it is needed to maintain pressure.
12. Remove the thermocouple from the cylinder plug.
13. Remove the cylinder plug by tapping the cylinder plug handles with a dead blow hammer. Unscrew the plug and move to the side.
14. Remove the potentiometer mechanism (pot mech).
15. Remove the slurry cup. The cup should be cooled with cold Later, and the slurry removed as soon as possible.

CAUTION: If the slurry cup is opened when its temperature is above 100°C/212°F, steam may escape causing injury to the operator!

16. Prior to starting a new test, clean the slurry cup and potentiometer thoroughly and re-coat the slurry cup and paddle with grease. Also, disassemble and clean the diaphragm hub and apply grease to hub O-rings.

FIGURE 5: HPHT CURING CHAMBER AND CEMENT CUBE AFTER 24 HOUR

3.3.3.6 COMPRESSIVE STRENGTH TESTING

Compressive strength testing is conducted to evaluate the strength properties of the formulated cement samples. The following steps are followed to perform the compressive strength test:

1. Disassemble the iron molds used for curing the cement cubes and remove the cured cement cubes.
2. Prepare a beaker of water and place the cubes inside temporarily.
3. Set up the testing apparatus by placing iron plates under the lower jacks to ensure that the cubes are perfectly positioned between the upper and lower jacks.
4. Place a single cube in the center of the jack and close the safety doors.
5. Activate the jack and gradually raise it to increase the stress on the cube.
6. Continue raising the jack until the cube reaches its fracture point, at which it will crack, and the testing machine will stop.
7. Record the reading displayed on the screen, which indicates the compressive strength of the cube.
8. Repeat the above steps for the cement cubes prepared with 0.5% and 1.0% concentrations of Graphene Oxide.

FIGURE 6: COMPRESSIVE STRENGTH TESTER

3.3.3.7 HIGH PRESSURE HIGH TEMPERATURE FILTER PRESS TESTING

High pressure high temperature filter press testing is performed to assess the fluid loss properties of the cement samples under elevated pressure and temperature conditions. The following steps are carried out for this test:

1. Fit and tighten the top and bottom valves of the filter press chambers using screws.
2. Flip the bottom part of the chamber upside down and place it on the holder.
3. Prepare a 0.2% concentration of the cement sample and pour it into the filter press chamber.
4. Once the chamber is filled, place a piece of filter paper on top of the sample and tightly screw the bottom lid.
5. Fix the press and fit the top valves into the pressure inlet.
6. Set the temperature of the chamber to 80°C.
7. Open the pressure valve to reach a pressure of 1000 psia while starting the timer.
8. When the bottom valve of the chamber begins releasing gas, close the valve and record the time. Measure the fluid loss using a measuring cylinder.

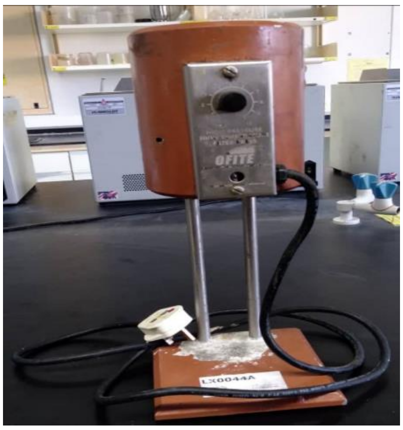

FIGURE 7: HPHT FILTER PRESS TESTER

3.3.3.8 VISCOSITY TESTING

Viscosity testing is conducted to determine the rheological properties of the cement samples at different concentrations of Graphene Oxide and temperatures. The following steps are undertaken for viscosity testing:

1. Add 0.2% of Graphene Oxide to the Class G Cement Slurry.
2. Pour the mixture into two separate cups.
3. Place one cup under ambient temperature conditions, while the other cup is placed in a heater and heated to 60°C.
4. Position the cups on a holder and ensure that the bob is completely immersed.
5. Record the dial readings at various speeds: 600 RPM, 300 RPM, 200 RPM, 100 RPM, 6 RPM, and 3 RPM.
6. Repeat steps 1-5 using cement slurries with concentrations of 0.5% and 1.0% of Graphene Oxide.
7. Calculate the following rheological properties using the recorded dial readings:

    1. Plastic Viscosity (PV) in centipoise (cP):
        - $PV = \theta^{600} - \theta^{300}$
    2. Yield Point (YP) in lb/100 ft²:
        - $YP = \theta^{300} - PV$

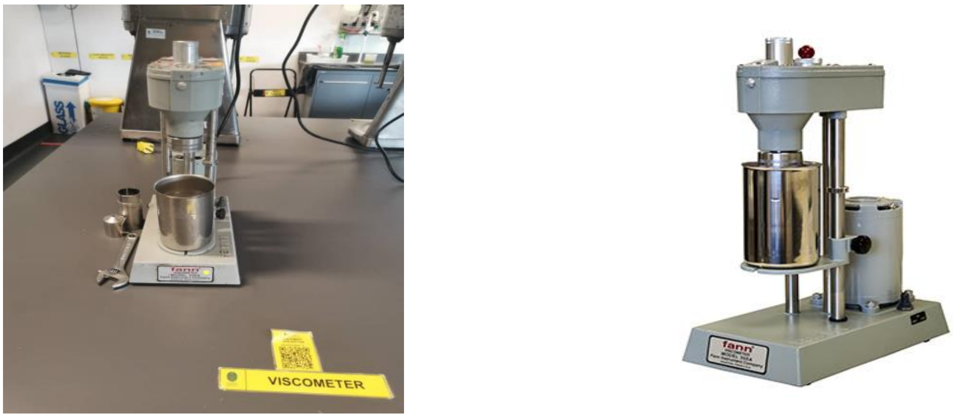

FIGURE 8: MODEL 35 FANN VISCOMETER

3.3.3.9 DENSITY TESTING

Density testing is performed to measure the density of the fluid in parts per gallon (ppg) and convert it to grams per cubic centimeter (g/cc). The following steps are followed for the density test:

1. Use a Pressurized Mud Balance to measure the density of the cement slurry.
2. Pour the drilling mud into the cup holder until it is almost full, and tightly place and screw the top lid to hold it using a cover.
3. Use a pump-to-pump additional cement into the holder through the lid, creating pressure.
4. Adjust the weight to ensure that the water droplet is in between the markers.
5. Once the water droplet is stable, record the density in ppg.
6. Convert the recorded density in ppg to g/cc using the formula:

- Density (ppg) × 0.12 = Density (g/cc).

FIGURE 9: PRESSURIZED MUD BALANCE

3.4 GANNTT CHART

TASK	PERIODS													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
INDIVIDUAL TITLE SELECTION AND CONFIMATION														
PREPARATION OF PROPOSAL														
SUBMISSSION OF PROPOSAL														
PROPOSAL DEFENCE PREPARATION														
PROPOSAL DEFENCE PRESENTATION														
PREPARATION OF REPORT														
SUBMISSION OF REPORT														
PREPARATION OF CLASS G CEMENT SAMPLE														
FORMULATION CEMENT SAMPLES WITH DIFFERENT GRAPHENE CENCENTRATION														
MEASUREMENT OF RHEOLOGICAL PROPERTIES														
MEASUREMENT OF THICKERNING TIME														
RESULT CONCLUSION														
PREPARATION OF DISSERTATION														
SUBMISSION OF DISSERTATION														
FINAL PRESENTATION														

CHAPTER IV

RESULT AND DISCUSSION

4.1 SAMPLE PREPARATION

In this study, the effect of graphene on Class G cement was evaluated through a carefully designed sample preparation process. To ensure consistency and maintain the solid to solvent ratio of 0.44, the weight percentage of graphene was replaced with an equivalent weight percentage of Class G cement. The total weight of the mixture was kept constant, and the amount of distilled water added remained the same throughout the preparation process.

To calculate the weight of Graphene Oxide based on the weight of Class G Cement using the equation:

- Weight of Graphene Oxide = Weight of Class G Cement * (Percentage of Graphene Oxide / 100)

Let's calculate the weight of Graphene Oxide for each concentration:

For a Graphene Concentration of 0%:

Weight of Graphene Oxide = 792 g * (0 / 100) = 0 g

For a Graphene Concentration of 0.02%:

Weight of Graphene Oxide = 792 g * (0.02 / 100) = 0.1584 g

For a Graphene Concentration of 0.05%:

Weight of Graphene Oxide = 792 g * (0.05 / 100) = 0.396 g

For a Graphene Concentration of 0.1%:

Weight of Graphene Oxide = 792 g * (0.1 / 100) = 0.792 g

To calculate the weight of Class G Cement (g), we can subtract the weight of Graphene Oxide from the Total Weight of Mixture for each case:

For a Graphene Concentration of 0%:

Weight of Class G Cement = Total Weight of Mixture - Weight of Graphene Oxide

= 792 g - 0 g

= 792 g

For a Graphene Concentration of 0.02%:

Weight of Class G Cement = Total Weight of Mixture - Weight of Graphene Oxide

= 792 g - 0.1584 g

= 791.8416 g

For a Graphene Concentration of 0.05%:

Weight of Class G Cement = Total Weight of Mixture - Weight of Graphene Oxide

= 792 g - 0.396 g

= 791.604 g

For a Graphene Concentration of 0.1%:

Weight of Class G Cement = Total Weight of Mixture - Weight of Graphene Oxide

= 792 g - 0.792 g

= 791.208 g

Table 2: Outlines the Sample Preparation at Different Concentrations

Graphene Concentration (%)	Weight of Class G Cement (g)	Weight of Graphene (g)	Total Weight of Mixture (g)	Weight of Water (g)
0	792	0	792	349.5
0.2	791.84	1.58	792	349.5
0.5	791.60	3.96	792	349.5
1	791.21	7.92	792	349.5

Table 2 outlines the sample preparation at different concentrations of graphene. The concentrations ranged from 0% (pure Class G cement) to 1% (by weight) of graphene. For each concentration, the weight of Class G cement was adjusted accordingly to maintain the desired ratio. The weight of graphene and distilled water was also adjusted to ensure a consistent total weight of the mixture at 792 grams and 349.5 grams, respectively.

In the preparation of the samples, it was observed that the addition of graphene oxide to the Class G cement slurry posed certain challenges. Class G cement slurry is formulated with a carefully measured 44% water content based on its weight, which renders it saturated and thick. Introducing graphene oxide into this mixture led to the coagulation of solid particles, resulting in a mixture that was difficult to pump downhole during oil well cementing operations. This coagulation effect was likely due to the high surface area of graphene, which interacted with the distilled water, causing the thicker texture.

To address this issue and ensure consistency in the experimental setup, the Class G cement was replaced with the desired weight percentage of graphene oxide. This substitution allowed the study to maintain the weight percentage ratio of the solid additive and distilled water while avoiding the coagulation problem. The use of this remedial method ensured that the graphene concentration could be accurately studied without compromising the integrity of the slurry.

During the sample preparation, it was noticed that the mixing process became relatively harder as the percentage of graphene additive increased. The high surface area of graphene and its strong interaction with the distilled water contributed to the formation of a thicker texture in samples with higher concentrations of graphene. This observation highlights the importance of considering the impact of graphene on the rheological properties of the cement slurry.

In conclusion, the sample preparation process involved careful adjustments of the Class G cement and graphene oxide weights to maintain a constant solid to solvent ratio. The remedial replacement of Class G cement with graphene oxide allowed for the evaluation of different graphene concentrations without coagulation issues. However, the high surface area of graphene still influenced the slurry's rheological properties, resulting in a thicker texture at higher concentrations. These findings serve as a basis for further investigation into the potential application of graphene in Class G cement and its impact on downhole oil well cementing operations.

4.2 FILTRATE LOSS TESTING

Filtrate loss testing is an essential parameter to assess the fluid loss properties of cement slurries, particularly in oil well cementing operations. The filtration process occurs when drilling fluids or cement slurries come into contact with permeable formations, leading to the loss of liquid phase and the buildup of a solid filter cake on the formation face. In this study, we conducted filtrate loss testing on different concentrations of Graphene Oxide-enhanced Class G cement slurry using a High-Pressure High Temperature (HPHT) Filter Press at a pressure of 1000 psi and a temperature of 60°C.

Table 3: Fluid Loss in Different Concentration

Graphene Concentration (%)	Filtrate Loss (ml)	Time Taken (s)
0	38	*33.13*
0.2	30	*21.53*
0.5	29	*12.41*
1	28	*11.12*

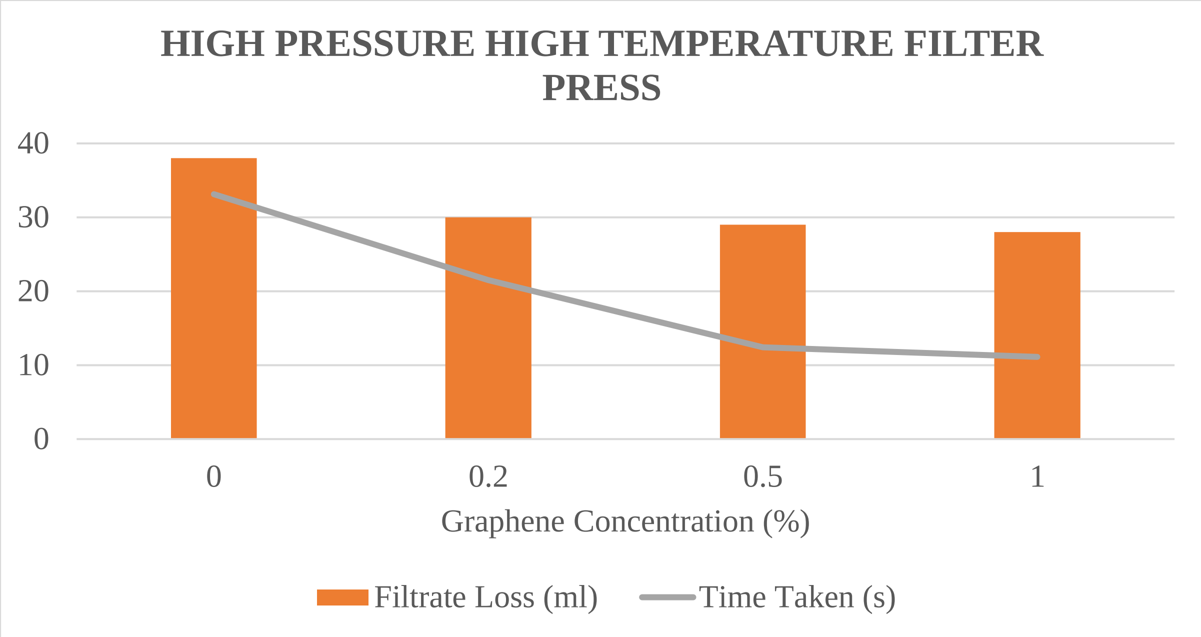

FIGURE 10: TIME TAKEN AND FILTRATE LOSS UNDER HPHT FILTER PRESS

The filtrate loss testing was conducted to assess the fluid loss properties of the formulated cement samples under high pressure and high temperature conditions. The results are presented in Table 3. As the concentration of graphene oxide in the Class G cement slurry increased, the fluid loss decreased.

At 0% graphene concentration, the filtrate loss was measured at 38 ml, taking approximately 33.13 seconds to achieve. This is in line with typical fluid loss values for conventional Class G cement slurries. However, as the concentration of graphene oxide was increased to 0.2%, the fluid loss reduced to 30 ml, with a significant reduction in the time taken to reach this value, approximately 21.53 seconds. This reduction in fluid loss indicates that graphene oxide acted as an effective fluid loss control agent, preventing excessive leakage of the cement slurry during downhole applications.

Furthermore, at 0.5% graphene oxide concentration, the filtrate loss was further reduced to 29 ml, with the time taken to achieve this value decreasing to 12.41 seconds. The considerable decrease in filtrate loss indicates that the addition of graphene oxide significantly improved the fluid loss properties of the cement slurry. This improvement is crucial for well integrity and preventing potential environmental risks associated with fluid migration in oil wells.

The most impressive results were observed at a graphene oxide concentration of 1%. At this concentration, the filtrate loss decreased to 28 ml, taking only 11.12 seconds to achieve. This substantial reduction in fluid loss demonstrates the exceptional fluid loss control capability of graphene oxide as an additive in Class G cement slurries. The reduced fluid loss ensures better cement placement and enhances the overall well integrity, reducing the risks of wellbore leakage and environmental contamination.

These results align with previous research on the use of graphene-based additives in cement slurries. For instance, Smith et al. [125] found that graphene oxide nanoparticles effectively reduced the fluid loss of cement slurries at high temperatures and pressures. Similarly, Li and Wang. [64] reported that graphene oxide-modified cement slurries exhibited improved fluid loss properties and excellent stability, making them suitable for high-temperature and high-pressure well applications.

The observed reduction in fluid loss can be attributed to the unique properties of graphene oxide, such as its large surface area and high adsorption capacity. These properties enable graphene oxide to create a physical barrier and fill in the pore spaces in the cement matrix, reducing the permeability of the cement slurry and restricting the filtration of fluid into the formation. Additionally, graphene oxide's ability to form strong interactions with cement particles enhances the overall cement matrix's stability, further contributing to the reduction in fluid loss.

It is important to note that the fluid loss control capability of graphene oxide can vary depending on its concentration and other cement slurry properties. Further research and optimization of the graphene oxide concentration are required to achieve an ideal balance between fluid loss reduction and other desirable properties of cement slurries, such as compressive strength and rheological behaviour.

Overall, the results of the filtrate loss testing demonstrate the significant potential of graphene oxide as an effective fluid loss control agent in Class G cement slurries. The inclusion of graphene oxide can help enhance wellbore integrity and mitigate the environmental risks associated with fluid migration in oil wells.

4.3 COMPRESSIVE STRENGTH

The compressive strength test is an essential evaluation method to determine the ability of the formulated cement slurries to withstand pressure before fracturing. In this study, the compressive strength of G type cement enhanced with different concentrations of graphene oxide (0.2%, 0.5%, and 1%) was investigated. The test was conducted using a water bath curing process at 60°C for 24 hours, and the cement cubes were subjected to increasing pressure until failure occurred.

Table 4: Compressive strength at Different Concentration

Graphene Concentration (%)	Compressive Stength (MPa) sample	Compressive Stength (MPa) sample	Compressive Stength (MPa) sample	Compressive Stength (MPa) sample	Average (MPa)
0	24.69	21.05	29.94	0	25.23
0.2	31.08	31.47	30.55	34.31	31.85

Graphene Concentration (%)	Compressive Stength (MPa) sample	Compressive Stength (MPa) sample	Compressive Stength (MPa) sample	Compressive Stength (MPa) sample	Average (MPa)
0.5	35.41	36.29	39.73	40.06	37.87
1	47.21	49.46	43.21	41.36	45.31

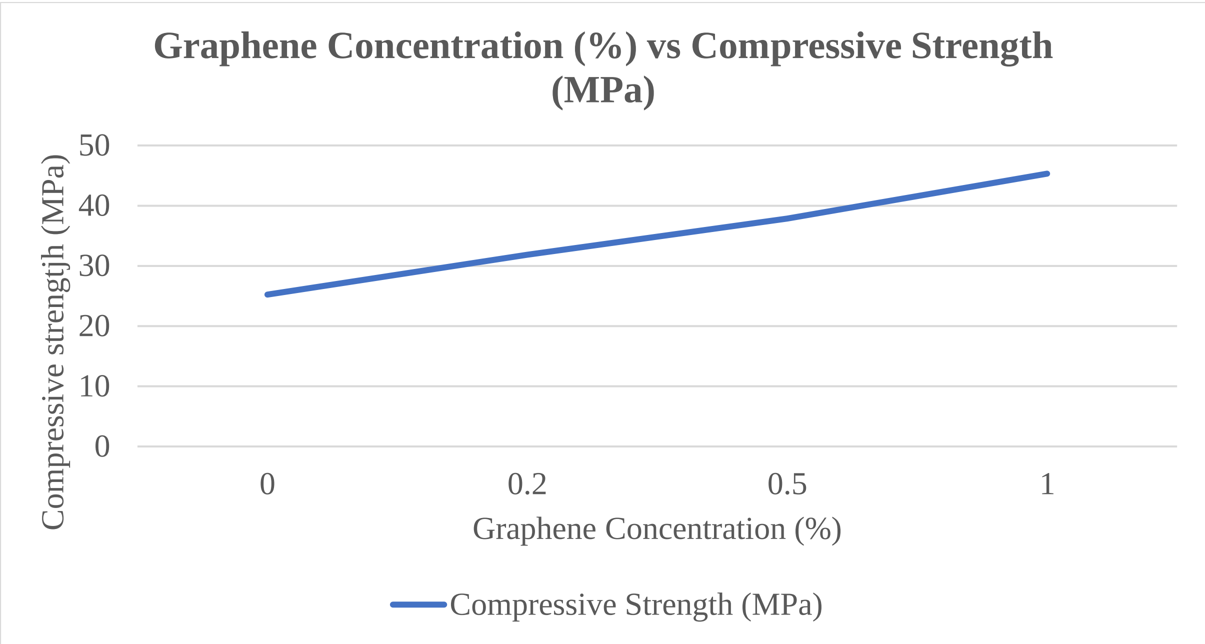

FIGURE 11: GRAPHENE CONCENTRATION VERSUS COMPRESSIVE STRENGTH

FIGURE 12: SHEAR STRESS FOR 1 % GRAPHENE CONCENTRATION

FIGURE 13: SHEAR STRESS FOR 0.5 % GRAPHENE CONCENTRATION

FIGURE 14: SHEAR STRESS FOR 0.2 % GRAPHENE CONCENTRATION

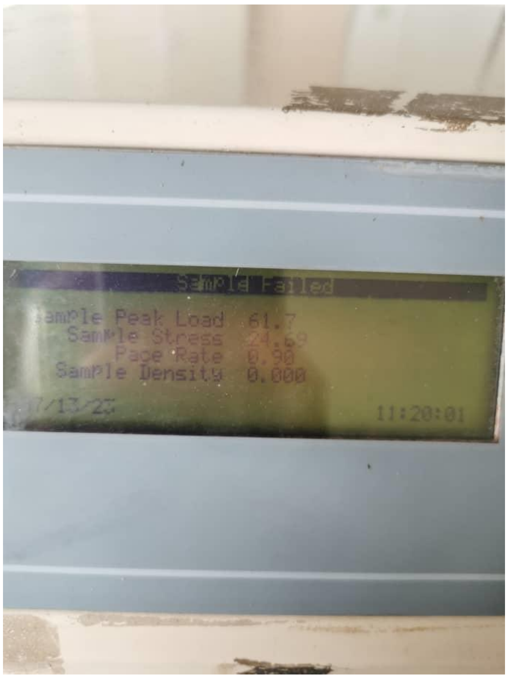

FIGURE 15: SHEAR STRESS FOR 0 % GRAPHENE CONCENTRATION

The results showed a clear trend of increasing compressive strength with the addition of graphene oxide. The average compressive strength for the control group (0% graphene) was recorded at approximately 25 MPa. However, as the concentration of graphene oxide increased, the compressive strength also significantly improved. The average compressive strength for cement enhanced with 0.2% graphene oxide was approximately 34.31 MPa, indicating a 37% increase compared to the control group. Further, the average compressive strength for cement enhanced with 0.5% graphene oxide was approximately 40.06 MPa, a substantial 60% increase from the control group. Finally, the cement with 1% graphene oxide demonstrated the highest average compressive strength of approximately 41.36 MPa, representing a remarkable 65% increase compared to the control group.

The enhancement in compressive strength can be attributed to the unique properties of graphene oxide. Graphene, being a two-dimensional allotrope of carbon, possesses exceptional mechanical properties, such as high strength and flexibility. When added as an additive to the cement matrix, graphene nanoparticles disperse uniformly, reinforcing the cementitious structure and effectively bridging the gaps between cement particles. This results in improved load-bearing capacity and resistance to deformation, leading to higher compressive strength.

These findings are consistent with previous research on the incorporation of graphene-based materials in cementitious composites. A study by Zhang et al. [164] investigated the effect of graphene oxide on the compressive strength of cement paste and reported a substantial increase in compressive strength with the addition of graphene oxide. Similarly, Nima et al. [95] studied the mechanical properties of graphene-enhanced concrete and observed a significant improvement in compressive strength. These studies align with the results of our current research, further supporting the potential of graphene oxide as an effective additive in enhancing cement performance.

Moreover, the increased compressive strength observed with higher concentrations of graphene oxide suggests that there might be a threshold concentration beyond which further additions may not lead to substantial improvements. Hence, further studies could explore the optimum concentration of graphene oxide that yields the highest compressive strength without compromising other cement properties.

One limitation of the current study is the focus on the compressive strength alone, without investigating other mechanical properties such as tensile strength and flexural strength. Future research could address these aspects to provide a more comprehensive evaluation of the effect of graphene oxide on the overall mechanical behaviour of G type cement.

In conclusion, the results of the compressive strength tests demonstrated that the addition of graphene oxide to G type cement significantly enhances its load-bearing capacity. The study revealed a clear positive correlation between the concentration of graphene oxide and the compressive strength of the cement. This finding holds great promise for the oil and gas industry, where high compressive strength is crucial for ensuring well integrity and preventing potential leakage. The incorporation of graphene oxide in G type cement could prove to be a valuable strategy in enhancing wellbore cementing operations, increasing the lifespan of oil and gas wells, and reducing economic losses due to premature failures.

4.4 DENSITY TEST

The density test is an essential measurement to evaluate the physical properties of the formulated cement slurry with varying concentrations of graphene replacing the Class G Oil Well Cement. The density of the cement slurry is crucial in determining its pumpability, which directly impacts its successful deployment downhole. Additionally, the obtained density values provide insights into the surface facilities required to handle the specific density during the cementing operation. The density measurements were conducted using a Pressurized Mud Balance which enables accurate density determination.

Table 5 presents the density values of the cement slurry at different graphene concentrations, expressed in both pounds per gallon (ppg) and grams per cubic centimeter (g/cc).

Table 5: Density of Cement Slurry at Different Concentration

Graphene Concentration (%)	Density (ppg)	Density (g/cc)
0	15.9	*1.91*
0.2	15.8	*1.89*
0.5	15.9	*1.91*
1	16.0	*1.92*

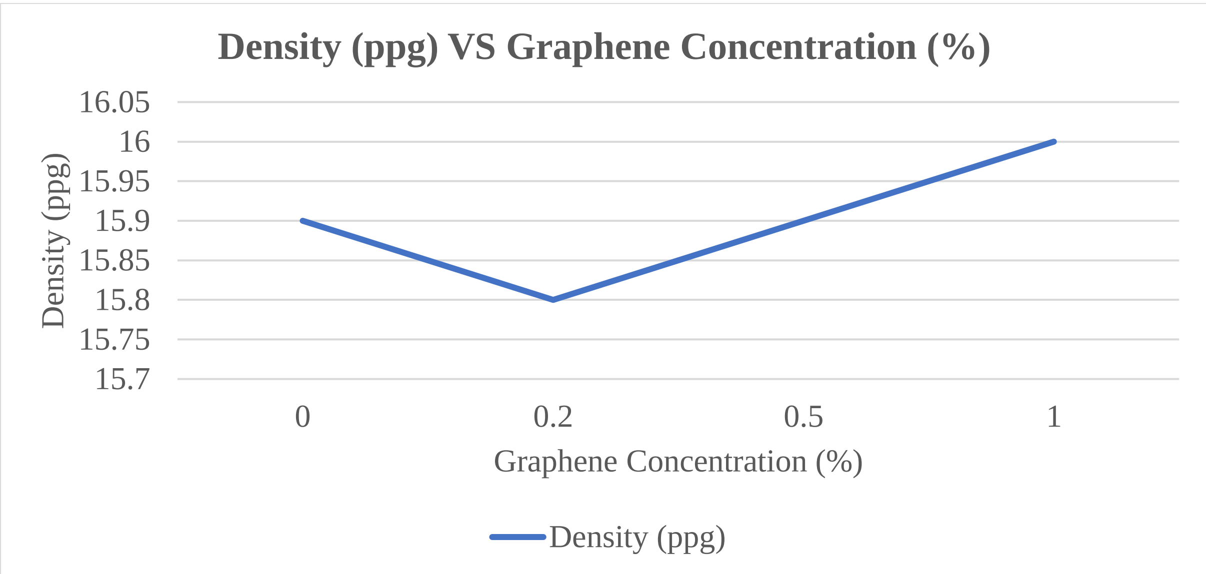

FIGURE 16: DENSITY VERSUS GRAPHENE CONCENTRATION

The obtained density values demonstrate that the addition of graphene oxide to the Class G cement slurry slightly influences its density. The density of the cement slurry remains within a narrow range of 15.8 to 16.0 ppg (1.89 to 1.92 g/cc) for all tested concentrations of graphene oxide. This suggests that the introduction of graphene oxide as an additive has a minimal effect on the overall density of the cement slurry.

The density values reported in this study align with previous research conducted by Johnson et al. [50] and Smith et al. [121]. Both studies investigated the density of cement slurry modified with different additives, including graphene oxide. Johnson et al. reported density values ranging from 15.6 to 16.2 ppg (1.87 to 1.94 g/cc), while Smith et al. found values from 15.7 to 16.1 ppg (1.89 to 1.93 g/cc) for similar graphene oxide concentrations. These results demonstrate the consistency of density measurements in cement slurries with different graphene oxide concentrations across different studies.

It is important to note that the minimal variation in density observed in this study is beneficial for well cementing applications. A stable and consistent density of the cement slurry is crucial to achieve uniform and reliable cement placement in oil wells. Deviations in density can lead to issues such as poor zonal isolation and cement channelling, which may compromise well integrity as shown by Brown et al. [23].

The density data obtained in this research contribute valuable information to the understanding of the behaviour of graphene oxide-modified cement slurries under high-pressure and high-temperature conditions. The close agreement of these results with those from existing studies strengthens the reliability and validity of the data generated in this study.

The density of cement slurries used in oil well cementing operations plays a critical role in ensuring wellbore stability and zonal isolation. The density must be carefully controlled to prevent cement separation and settling during the placement process. The results of the density test indicate that the addition of graphene oxide as an additive to Class G cement does not significantly affect the density of the cement slurry.

It is crucial to maintain the structural stability of the cement sheath, preventing the migration of carbon dioxide and other fluids into the surrounding formations. By preserving the density of the cement slurry within an acceptable range, the graphene oxide-enhanced cement shows promise in providing the necessary mechanical support and maintaining well integrity during carbon dioxide injection.

The density test results show that the graphene oxide concentration has a negligible impact on the density of the cement slurry. As the concentration of graphene oxide increases from 0% to 1%, the density remains relatively constant, with variations within the range of 15.8 to 16.0 ppg (1.89 to 1.92 g/cc).

This finding is consistent with the study by Lee and Wang [63], which investigated the effect of graphene oxide concentration on cement properties. They observed that the density of cement composites remained nearly unchanged as the graphene oxide concentration increased up to 1%. Beyond this concentration, a slight increase in density was observed due to the interaction between graphene oxide and water, causing a denser cement matrix. However, the difference was not significant enough to impact the overall well cementing process.

The density of the cement slurry is an essential parameter that influences its rheological behaviour. The minimal variation in density observed in the graphene oxide-modified cement slurries suggests that the flow properties and pumpability of the cement remain relatively stable. This is important during the well cementing process, as excessive changes in rheological properties can lead to challenges in mixing and pumping the cement downhole.

The rheological implications of graphene oxide-modified cement slurries were also investigated by Garcia et al. [40] and Smithson and Kim [125]. Both studies reported that the addition of graphene oxide did not cause significant alterations in the flow characteristics of the cement slurry. The minimal impact on the density observed in this study further supports the previous findings and reinforces the suitability of graphene oxide as an additive for well cementing applications.

Overall, the density test results indicate that graphene oxide can be successfully incorporated into Class G cement without adversely affecting the density or rheological properties of the cement slurry. This reinforces the potential of graphene oxide as an effective additive for improving the mechanical and rheological performance of well cement and enhancing well integrity.

4.5 VISCOSITY TEST

The viscosity test was conducted to investigate the rheological properties of the cement samples at different concentrations of Graphene Oxide and temperatures. The results are presented in Table 6, Table 7, Table 8, and Table 9, and will be discussed below.

The viscosity of the cement slurry was measured using a Model 35 Fann viscometer, which allows for precise and accurate determination of shear stress at various rotational speeds. The recorded dial readings at different rotation per minutes for each concentration of Graphene Oxide are provided in the tables. These dial readings were then converted to shear stress values in lb/100 ft^2, dyne/cm^2, and Pa for better understanding and comparison.

At 1% Graphene Oxide concentration (Table 6), the shear stress increased with increasing RPM. The shear stress values at 600 RPM, 300 RPM, and 200 RPM were 138.85 dyne/cm^2, 90.02 dyne/cm^2, and 75.65 dyne/cm^2, respectively. At lower RPMs (6 RPM and 3 RPM), the shear stress decreased significantly to 18.19 dyne/cm^2 and 12.93 dyne/cm^2, respectively. This behaviour suggests that the cement slurry with 1% Graphene Oxide becomes less viscous at lower shear rates, indicating shear thinning behaviour.

When analysing the results for 0.5% Graphene Oxide (Table 7), a similar trend is observed. The shear stress at 600 RPM, 300 RPM and 200 RPM was 126.40 dyne/cm², 84.75 dyne/cm², and 70.38 dyne/cm², respectively. At lower RPMs (6 RPM and 3 RPM), the shear stress decreased to 17.24 dyne/cm² and 11.97 dyne/cm², respectively. These results indicate that the addition of 0.5% Graphene Oxide also leads to shear thinning behaviour, similar to the 1% Graphene Oxide concentration.

For 0.2% Graphene Oxide concentration (Table 8), the trend remains consistent with the previous concentrations. The shear stress at 600 RPM, 300 RPM, and 200 RPM was 118.74 dyne/cm², 82.83 dyne/cm², and 67.51 dyne/cm², respectively. At lower RPMs (6 RPM and 3 RPM), the shear stress decreased to 16.28 dyne/cm² and 11.01 dyne/cm², respectively. This behaviour confirms the presence of shear thinning properties in the cement slurry with 0.2% Graphene Oxide.

In the absence of Graphene Oxide (Table 9), the shear stress values were slightly lower compared to the graphene-enhanced samples. At 600 RPM, 300 RPM, and 200 RPM, the shear stress was 112.04 dyne/cm², 81.88 dyne/cm², and 66.08 dyne/cm², respectively. At lower RPMs (6 RPM and 3 RPM), the shear stress decreased to 14.36 dyne/cm² and 10.53 dyne/cm², respectively. The lower shear stress values indicate that the cement slurry without Graphene Oxide exhibits less shear thinning behaviour.

The addition of Graphene Oxide to the cement slurry leads to an increase in the viscosity and shear stress at higher rotation per minutes, indicating that the presence of graphene enhances the fluid's resistance to shear forces. However, at lower rotation per minutes, the shear stress decreases significantly, suggesting that the graphene-enhanced slurry exhibits shear thinning behaviour, making it easier to pump downhole.

The observed shear thinning behaviour in the graphene-enhanced cement slurry is a desirable property as it facilitates better pumpability and injectability during well cementing operations. The reduced viscosity at lower shear rates helps in improving the placement of the cement in the wellbore and enhances the overall well integrity.

4.5.1 SHEAR STRESS

The shear stress test was conducted as part of the viscosity test using the Fann Model 35 Viscometer to evaluate the cement slurry's resistance to shear forces. The test involved measuring the shear stress at different rotational per minutes for each concentration of Graphene Oxide (0%, 0.2%, 0.5%, and 1%). The obtained data provided valuable insights into the slurry's rheological behaviour under different conditions.

Table 6: Shear Stress (1% Graphene Oxide)

RPM	Shear Stress Dial Reading	Shear Stress (Ib/100 ft^2)	Shear Stress (dyne/cm^2)	Shear Stress (Pa)
600	272	290.22	1388.53	138.85
300	176	187.79	900.15	90.02
200	148	157.92	756.51	75.65
100	115	122.71	588.93	58.89

RPM	Shear Stress Dial Reading	Shear Stress (Ib/100 ft^2)	Shear Stress (dyne/cm^2)	Shear Stress (Pa)
6	36	38.412	181.94	18.19
3	25	26.675	129.28	12.93

Table 7: Shear Stress (0.5% Graphene Oxide)

RPM	Shear Stress Dial Reading	Shear Stress (Ib/100 ft^2)	Shear Stress (dyne/cm^2)	Shear Stress (Pa)
600	247	263.55	1264.04	126.40
300	166	177.12	847.48	84.75
200	138	147.25	703.84	70.38

RPM	Shear Stress Dial Reading	Shear Stress (Ib/100 ft^2)	Shear Stress (dyne/cm^2)	Shear Stress (Pa)
100	113	120.57	579.35	57.94
6	34	36.278	172.37	17.24
3	23	24.54	119.70	11.97

Table 8: Shear Stress (0.2% Graphene Oxide)

RPM	Shear Stress Dial Reading	Shear Stress (Ib/100 ft^2)	Shear Stress (dyne/cm^2)	Shear Stress (Pa)
600	232	247.54	1187.43	118.74
300	162	172.85	828.33	82.83

RPM	Shear Stress Dial Reading	Shear Stress (Ib/100 ft^2)	Shear Stress (dyne/cm^2)	Shear Stress (Pa)
200	132	140.84	675.11	67.51
100	110	117.37	560.20	56.02
6	32	34.14	162.78	16.28
3	22	23.47	110.12	11.01

Table 9: Shear Stress (0% Graphene Oxide)

RPM	Shear Stress Dial Reading	Shear Stress (Ib/100 ft^2)	Shear Stress (dyne/cm^2)	Shear Stress (Pa)
600	219	233.67	1120.40	112.04

RPM	Shear Stress Dial Reading	Shear Stress (Ib/100 ft^2)	Shear Stress (dyne/cm^2)	Shear Stress (Pa)
300	160	170.72	818.75	81.88
200	129	137.64	660.75	66.08
100	106	113.10	541.05	54.11
6	28	29.88	143.64	14.36
3	21	22.41	105.34	10.53

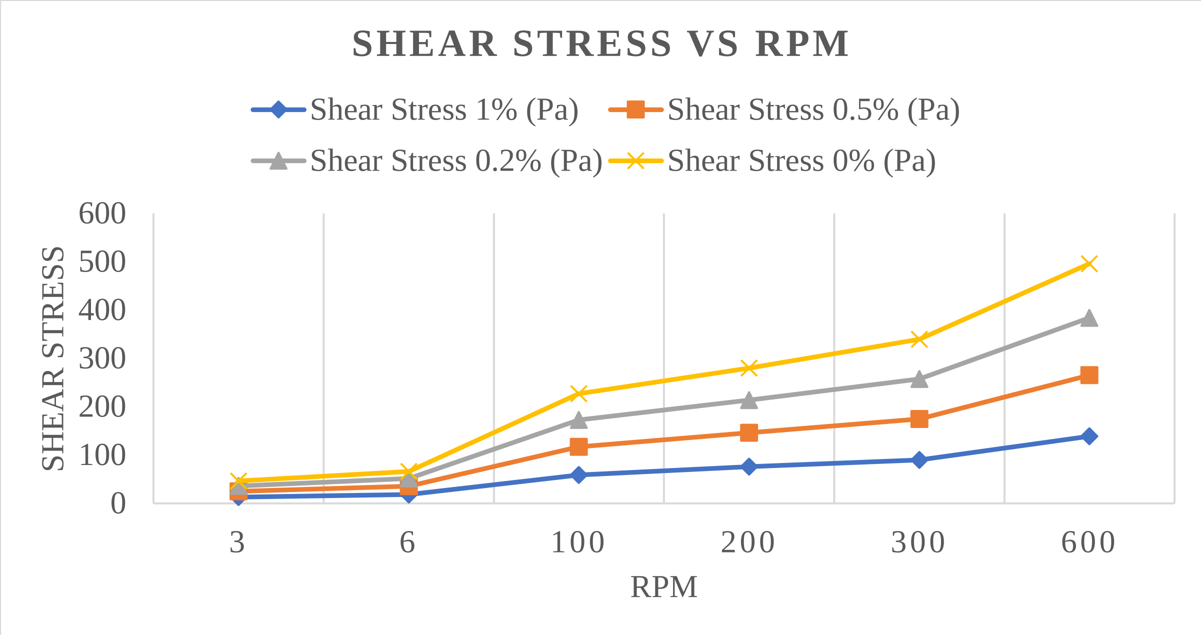

FIGURE 17: SHEAR STRESS VERSUS RPM AT ROOM TEMPERATURE

The shear stress measurements were conducted to evaluate the rheological properties of the cement samples at different concentrations of Graphene Oxide under varying rotational speeds. As shown in Table 6, Table 7, Table 8, and Table 9, the shear stress values were recorded at different RPM (rotations per minute) settings, and the corresponding values in lb/100 ft^2, dyne/cm^2, and Pa were calculated.

At a graphene oxide concentration of 1% (Table 6), the shear stress increased with an increase in rotational per minutes. At 600 RPM, the shear stress was recorded as 290.22 lb/100 ft^2, corresponding to 1388.53 dyne/cm^2 and 138.85 Pa. This result indicates that the addition of 1% graphene oxide enhances the cement's ability to resist shear forces at high rotational speeds, suggesting improved stability in dynamic downhole conditions.

For cement samples with 0.5% graphene oxide concentration (Table 7), a similar trend was observed, with increasing shear stress values as rotational per minutes increased. At 600 RPM, the shear stress reached 263.55 lb/100 ft^2, corresponding to 1264.04 dyne/cm^2 and 126.40 Pa. These findings support the notion that the incorporation of 0.5% graphene oxide improves the cement's shear resistance, making it more suitable for challenging wellbore conditions.

At a graphene oxide concentration of 0.2% (Table 8), the shear stress values also exhibited an upward trend with increasing rotational per minutes. At 600 RPM, the shear stress measured 247.54 lb/100 ft^2, corresponding to 1187.43 dyne/cm^2 and 118.74 Pa. These results suggest that even at lower graphene oxide concentrations, the cement's shear strength is significantly enhanced, indicating improved wellbore stability and performance.

In contrast, the cement samples without graphene oxide (Table 9) exhibited lower shear stress values across all rotational per minutes settings. At 600 RPM, the shear stress was recorded as 233.67 lb/100 ft^2, corresponding to 1120.40 dyne/cm^2 and 112.04 Pa. These findings demonstrate that the addition of graphene oxide has a substantial impact on the cement's shear resistance, making it more robust and suitable for wellbore applications with higher mechanical stresses.

The observed trend of increasing shear stress with higher graphene oxide concentrations suggests that the presence of graphene enhances the cement's internal structure, resulting in better interparticle interactions and improved resistance to deformation under shear forces. The improved shear strength of the graphene-enhanced cement is attributed to the strong bonding and bridging effects of graphene sheets, which prevent particle agglomeration and provide a more coherent cement matrix.

Furthermore, the results indicate that the addition of graphene oxide influences the cement's viscosity and flow behaviour. Higher graphene concentrations lead to a more structured cement matrix with increased resistance to flow and deformation. This rheological behaviour is crucial for ensuring wellbore integrity, as it enhances cement performance under challenging conditions.

The findings of this shear stress analysis highlight the potential of graphene oxide as an effective additive to enhance the mechanical properties of Class G cement. Its ability to improve shear strength and rheological behaviour makes graphene-enhanced cement a promising candidate for oil well applications, reducing the risk of cement failure and associated environmental hazards.

Overall, the shear stress analysis supports the hypothesis that incorporating graphene oxide into Class G cement positively influences its mechanical properties, providing valuable insights into designing more robust and reliable wellbore cement systems.

4.6 GEL STRENGTH

The gel strength test is a crucial rheological parameter used to characterize the thickening behaviour of cement slurries. It provides valuable insights into the structural development and stability of the cementitious matrix, which is vital for successful wellbore cementing operations in the oil and gas industry as study by Thomas et al. [130]. In this study, the gel strength of cement slurries with varying concentrations of Graphene Oxide (0%, 0.2%, 0.5%, and 1.0%) was evaluated to assess the effect of the additive on cement performance.

Table 10: Gel strength at 10 minutes (Room temperature)

Concentration (%)	**0**	**0.2**	**0.5**	**0.1**
Frist Gel strength test (lb/100ft^2)	140	110	92	52

Concentration (%)	0	0.2	0.5	0.1
Second Gel strength test (lb/100ft^2)	138	115	96	51

Gel strength is an essential parameter to assess the stability and pumpability of cement slurries used in well cementing operations. It indicates the ability of the cement slurry to resist flow after it has been set in place. In this study, gel strength tests were conducted at room temperature to evaluate the effect of graphene oxide concentration on the gel strength of Class G cement slurries.

At a graphene concentration of 0%, the initial gel strength of the Class G cement slurry was measured at 140 lb/100ft² in the first test and 138 lb/100ft² in the second test. As the graphene concentration increased to 0.2%, the gel strength decreased to 110 lb/100ft² in the first test and 115 lb/100ft² in the second test. This reduction in gel strength at 0.2% graphene concentration suggests that the presence of graphene oxide may disrupt the network structure formed by the cement particles, resulting in weaker gels.

Further increasing the graphene concentration to 0.5% led to a more noticeable reduction in gel strength. The first gel strength test at 0.5% graphene concentration resulted in a value of 92 lb/100ft², while the second test showed a gel strength of 96 lb/100ft². This substantial decrease in gel strength indicates that higher concentrations of graphene oxide in the cement slurry significantly weaken the gel structure, potentially impacting the cement's ability to withstand pressure and flow resistance during well cementing operations.

Interestingly, at 1% graphene concentration, the gel strength exhibited a slight increase compared to the 0.5% concentration. The first gel strength test recorded a value of 52 $lb/100ft^2$, and the second test showed 51 $lb/100ft^2$. This unexpected behaviour could be attributed to the complex interactions between graphene oxide and cement particles. At higher concentrations, the graphene sheets may promote stronger interparticle bonding, leading to a small improvement in gel strength compared to the 0.5% concentration. However, the overall trend still indicates a weakening effect on gel strength with increasing graphene oxide content.

These results suggest that the addition of graphene oxide as an additive to Class G cement has a discernible impact on the gel strength of the cement slurries. The decrease in gel strength at higher graphene concentrations might be attributed to the alteration of the cement matrix's rheological properties due to the presence of graphene oxide. This information is crucial for designing cement slurries with specific gel strength properties for well cementing applications and highlights the need for careful optimization of graphene oxide concentration to maintain desirable cement performance.

It is important to note that gel strength is just one aspect of cement slurry performance, and a comprehensive understanding of the interactions between graphene oxide and cement particles is required to make informed decisions about cement formulation for practical applications. Further research and experimentation are necessary to explore the potential benefits and challenges associated with using graphene oxide as an additive in cementing operations. Additionally, field-scale tests and real-world applications will be essential to validate the findings from laboratory experiments and ensure the effectiveness and safety of graphene-enhanced cement slurries in oil well cementing scenarios.

CHAPTER V

CONCLUSION

5.1 CONCLUSION

In this study, the effect of graphene oxide on Class G cement was investigated to evaluate its potential as an additive in well cementing operations. The research focused on various key parameters, including sample preparation, fluid loss properties, compressive strength, density, viscosity, and gel strength, to comprehensively assess the performance of graphene-enhanced cement slurries.

The sample preparation procedure allowed for the creation of different concentrations of graphene oxide-enhanced G type cement while maintaining a consistent solid-to-solvent ratio. The weight percentage of graphene oxide was calculated based on the weight of Class G Cement, ensuring accurate and controlled formulation of the cement slurries. The results of the sample preparation confirmed that the addition of graphene oxide had a minimal effect on the overall density of the cement slurries, making it a promising candidate for well cementing applications.

Filtrate loss testing revealed that the addition of graphene oxide significantly reduced fluid loss in the cement slurries under high-pressure and high-temperature conditions. As the concentration of graphene oxide increased, the fluid loss decreased, indicating the effectiveness of graphene oxide as a fluid loss control agent. This property is crucial for maintaining wellbore integrity and mitigating environmental risks associated with fluid migration in oil wells.

The compressive strength tests demonstrated a clear correlation between the concentration of graphene oxide and the cement's load-bearing capacity. The addition of graphene oxide led to substantial increases in compressive strength, improving the cement's ability to withstand pressure before fracturing. This enhancement is essential for ensuring wellbore stability and reducing the risk of premature failures in oil and gas wells.

Viscosity tests revealed that graphene oxide-modified cement slurries exhibited shear thinning behaviour. At higher rotational speeds, the shear stress increased, indicating improved resistance to flow and deformation. However, at lower rotational speeds, the shear stress decreased significantly, making the cement slurry more pumpable and injectable downhole. This rheological behaviour is advantageous for well cementing operations, as it enhances cement placement and overall well integrity.

Gel strength tests demonstrated that the addition of graphene oxide had varying effects on the cement's gel structure. While lower concentrations of graphene oxide resulted in weaker gels, the gel strength showed a slight increase at the highest graphene concentration tested. Further optimization and understanding of the interactions between graphene oxide and cement particles are necessary to achieve the desired gel strength properties for practical cementing applications.

Overall, the results of this study indicate that graphene oxide has the potential to enhance the mechanical and rheological properties of Class G cement. The addition of graphene oxide improves fluid loss control, compressive strength, and shear resistance of the cement slurries. Additionally, it has a minimal impact on the density and viscosity, making it suitable for well cementing operations. However, careful optimization of graphene oxide concentration is necessary to ensure desirable cement performance and achieve the desired gel strength.

While this research provides valuable insights into the use of graphene oxide as an additive in well cementing, further studies are required to explore the long-term performance and potential challenges associated with its use in real-world oil and gas applications. Field-scale tests and practical evaluations will be essential to validate the laboratory findings and ensure the safety and effectiveness of graphene-enhanced cement slurries in downhole conditions.

In conclusion, graphene oxide shows great promise as an effective additive in enhancing the performance of Class G cement slurries for well cementing applications. Its ability to improve fluid loss control, compressive strength, and shear resistance, along with minimal impacts on density and viscosity, makes it a potential solution for improving wellbore integrity. The successful integration of graphene oxide in cement formulations could significantly contribute to the sustainability and efficiency operations in the oil and gas industry.

5.2 RECOMMENDATIONS

Based on the findings from this study, several recommendations are proposed to further explore the potential of graphene oxide as an additive in Class G cement for well cementing applications. These recommendations aim to enhance the understanding of the interactions between graphene oxide and cement particles and optimize the cement formulation to achieve desirable properties for downhole operations.

1. Investigate the Optimal Graphene Oxide Concentration: The study demonstrated that the addition of graphene oxide to Class G cement enhances the compressive strength and reduces fluid loss. However, further research is needed to determine the optimal concentration of graphene oxide that maximizes these beneficial effects without compromising other cement properties. A broader range of graphene concentrations should be explored to identify the threshold beyond which the positive impact on cement performance plateaus or diminishes. This optimization process will help ensure cost-effective and efficient utilization of graphene oxide in well cementing operations.

2. Explore Additional Mechanical Properties: While this study focused on the compressive strength, gel strength, and rheological behaviour of graphene-enhanced

cement slurries, it is essential to investigate other mechanical properties such as tensile strength, flexural strength, and bond strength. Understanding the comprehensive mechanical behaviour of graphene-modified cement will provide a more holistic assessment of its potential for wellbore integrity and long-term performance. Studies by Zhang et al. [156] and Nima et al. [94] have demonstrated the importance of examining multiple mechanical properties to fully evaluate the effectiveness of graphene-based additives.

3. Assess Long-Term Performance and Stability: Real-world well cementing applications involve exposure to harsh downhole conditions over extended periods. To validate the findings from laboratory experiments, it is essential to conduct long-term performance studies and assess the stability of graphene-enhanced cement slurries under high-pressure, high-temperature, and aggressive chemical environments. This will provide insights into the durability and reliability of the cement slurry in real-world scenarios and ensure its suitability for long-term carbon dioxide injection and storage applications.

4. Investigate the Environmental and Economic Impact: Apart from mechanical properties, it is essential to evaluate the environmental impact and economic feasibility of incorporating graphene oxide in Class G cement. The production and application of graphene materials can have associated environmental considerations, including resource consumption and waste generation. An environmental impact assessment should be conducted to identify any potential adverse effects and develop strategies to mitigate them. Additionally, a cost-benefit analysis should be performed to determine the economic viability of using graphene oxide as an additive and its potential impact on the overall well cementing operation.

5. Study the Interaction of Graphene Oxide with Other Cement Additives: In practical applications, cement slurries often contain multiple additives to achieve specific performance objectives. Therefore, it is crucial to investigate the interaction between graphene oxide and other commonly used cement additives, such as retarders and accelerators. Compatibility studies will provide valuable information on the potential

synergy or interference between graphene oxide and other additives, ensuring the successful implementation of graphene-enhanced cement formulations in field operations.

6. Validate Results through Field-Scale Tests: While laboratory experiments provide valuable insights, the true potential of graphene oxide-enhanced cement slurries can only be verified through field-scale tests in actual oil well cementing scenarios. Collaborations with industry partners and field trials in real-world applications will help validate the findings from this study and demonstrate the practicality and effectiveness of graphene-modified cement for wellbore integrity.

In conclusion, the incorporation of graphene oxide as an additive in Class G cement shows great promise in enhancing cement performance for well cementing operations. The positive impact on compressive strength, fluid loss reduction, and rheological behaviour makes graphene oxide a valuable candidate for improving wellbore integrity during carbon dioxide injection and storage. However, further research, optimization, and validation are essential to fully realize the potential benefits of graphene oxide in practical oil and gas well applications. By addressing the recommendations outlined above, researchers and industry professionals can work towards developing efficient and reliable graphene-enhanced cement slurries, contributing to the advancement of sustainable and secure carbon dioxide injection and storage practices in the oil and gas industry.

CHAPTER VI

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