

UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

AN EXPERIMENTAL STUDY ON THE EFFECT OF ADDITIVES ON CASING-CEMENT
BONDING STRENGTH

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

Degree of

MASTER OF SCIENCE

By

KAYODE JOSHUA SANNI

Norman, Oklahoma

2024

AN EXPERIMENTAL STUDY ON THE EFFECT OF ADDITIVES ON CASING-CEMENT
BONDING STRENGTH

A THESIS APPROVED FOR THE
MEWBOURNE SCHOOL OF PETROLEUM AND GEOLOGICAL ENGINEERING

BY THE COMMITTEE CONSISTING OF

Dr. Catalin Teodoriu, Chair

Dr. Ahmed Ramadan

Dr. Saket Srivastava

© Copyright by KAYODE JOSHUA SANNNI 2024

All Rights Reserved.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my advisor, Professor Catalin Teodoriu, for his unwavering support, guidance, and encouragement throughout the course of my research. His expertise and mentorship have been invaluable to the completion of this thesis. I am also grateful to the lab manager, Gary Stowe, with whom I had the pleasure of working as a teaching assistant. His dedication and insights greatly enhanced my understanding and proficiency in the laboratory. My sincere thanks go to Professor Ahmed Ramadan and Dr. Saket Srivastava, my thesis committee members, for their constructive feedback and for challenging me to broaden my research perspectives. Their contributions have significantly enriched the quality of this work. I am profoundly grateful to Tenaris for their generous support in providing the specialized equipment essential for the success of this research. Their partnership has been vital to achieving the goals of this study.

A special thank you to my dear friends whose companionship and support made this journey all the more rewarding. Their encouragement and friendship have been a constant source of motivation.

Lastly, I am profoundly grateful to my parents and family for their endless love, patience, and encouragement. Their unwavering belief in me has been the foundation upon which I have built my academic pursuits.

This thesis would not have been possible without the support of all these individuals, and I am truly thankful for their contributions to my personal and professional growth.



Kayode Joshua Sanni

Content

Abstract.....	xii
1 Introduction.....	1
1.1 Problem statement.	1
1.2 Objectives.....	8
1.2.1 General Objective.	8
1.2.1 Specific Objectives.	8
1.3 Scope of work.	9
2 Literature review.	10
2.1 Well Integrity.	10
2.2 Well cementing.....	13
2.2.1 Primary Cementing Techniques.....	15
2.2.2 Importance of Well Cementing.....	16
2.3 Portland cement.	17
2.3.1 Types of Cement according to the API.	19
2.3.2 Cement Additives.	23
2.4 Bonding.....	43
2.4.1 Effect of casing roughness on shear bond.	47
2.4.2 Effect of mud contamination.....	48
2.4.3 Effect of casing centralization on cement bond.....	50
2.4.4 Shear bonding experimental methods.....	52
3 Methodology.....	59
3.1 Materials and Methods.....	59
3.2 Sample preparation.	59
3.3 Compressive strength measurement.	63
3.4 Ultrasonic measurements.	65
3.4 Ultrasonic Hardware.	65
3.5 Interfacial Bonding Shear Strength	67
3.6 Density measurement.....	70
4 Results and Discussions.....	72
4.1 Debonding and Post debonding Analysis.....	72
4.1.1 Maximum Debonding Force.	74
4.1.2 Minimum Bonding Force after Debonding.....	82

4.1.3 Average Bonding Force after Debonding.	86
4.1.4 Bonding Force Loss due to Debonding.	91
4.1.5 Initial Displacement after Debonding.	95
4.1.6 Scoring Metric based on Impact of Additives, ...	100
4.2 Unconfined Compressive Strength Analysis.....	108
4.2.1 Unconfined Compressive Strength Analysis at room and elevated temperatures.	108
4.2.2 Comparison of IBSS and UCS.	113
5 Conclusions	120
6 Recommendations	123
Bibliography	126

Figures

Figure 1. World population prospects (Hannah Ritchie, 2023).	2
Figure 2. Energy Consumption Per Capita Around the World (Bhutada, 2022).	3
Figure 3. share of primary energy (BP, 2023).	4
Figure 4. Total U.S. Wells by production rate brackets (The U.S. Energy Information Administration, 2023).	5
Figure 5 Possible leakage pathways in a cased wellbore (Wu B, 2020).	7
Figure 6: Portland Cement Production Workflow (Ichim, 2015)	18
Figure 7: Relative Volume Evolution of Cement Components During Hydration in a Dry Environment (Left) and Under Water (Right) (Aïtcin, 2016)	36
Figure 8: Hydration Reaction Progress Over Time (Gutteridge & Dalziel, 1990)	38
Figure 9: Heat Flow vs. Hydration Time in Cement (Aïtcin, 2016)	39
Figure 10: Pressure and Temperature Influence on UCS over One Day (Fink, 2015)	41
Figure 11: Bond model with continuous contact (left). A bond with discontinuous contact but collection of small bonds (right) (Wilson et al., 2018).	44
Figure 12: Failure under shear stress conditions. Continuous bond model complete failure (left). Irregular failure in discontinuous bond yet still intact (right). (Wilson et al., 2018)	45
Figure 13: Effect of mud contamination on tensile strengths of three types of oil well cements (Morgan & Dumbauld, 1952).	49
Figure 14: Schematics of casing placements in a wellbore: concentric (left) and eccentric (right) (Salehabadi et al., 2010).	51
Figure 15: Pure shear strength (left) and shear bonding strength (right) set ups (Teodoriu et al., 2018a)	53
Figure 16: Schematic of setup using hydraulic press to measure shear bond strength (Jadhav et al., 2017)	54
Figure 17: Experiment setup for shear bond strength test of geopolymers cement (Salehi et al., 2017)	55
Figure 18: Digital balance.	59
Figure 19: Ofite high shear mixer.	62
Figure 20: Metallic molds.	63
Figure 21: Experimental set up in water bath.	63
Figure 22: Test Mark CM-2500 (Romanowski et al., 2018).	64
Figure 23: Proceq™ Ultrasonic Device.	66
Figure 24: Schematic of the Mold assembly for the shear bond testing.	68
Figure 25: Mold assembly for the shear bond testing.	68
Figure 26: Hydraulic Bond Shear Testing Machine Frame.	69
Figure 27: Interfacial Bonding Shear Strength Result	73
Figure 28. Maximum Debonding force for cement recipes at 1-day curing.	75
Figure 29: Interfacial Bonding Shear Strength for cement recipes at 1-day curing.	75
Figure 30. Maximum Debonding force for cement recipes at 3-days curing.	77
Figure 31: Interfacial Bonding Shear Strength for cement recipes at 3-days curing.	77
Figure 32. Comparison of Debonding Force between 1- and 3-day curing time at room temperature.	79
Figure 33: Comparison of Interfacial Bonding Shear Strength between 1- and 3-day curing time at room temperature.	80
Figure 34. Comparison of Debonding Force between 1- and 3-day curing time at elevated temperature.	81

<i>Figure 35: Comparison of Interfacial Bonding Shear Strength between 1- and 3-day curing time at elevated temperature.</i>	82
<i>Figure 36. Minimum Bonding force after debonding for cement recipes at 1-day curing.</i>	83
<i>Figure 37. Minimum Bonding force after debonding for cement recipes at 3-day curing.</i>	84
<i>Figure 38: Comparison of the Minimum Debonding Force between 1- and 3-day curing time at room temperature after Debonding.</i>	85
<i>Figure 39: Comparison of the Minimum Debonding Force between 1- and 3-day curing time at elevated temperature after Debonding.</i>	86
<i>Figure 40. Average Bonding force after debonding for cement recipes at 1-day curing.</i>	87
<i>Figure 41. Average Bonding force after debonding for cement recipes at 3-day curing.</i>	88
<i>Figure 42. Comparison of the Average Debonding Force between 1- and 3-day curing time at room temperature after Debonding.</i>	89
<i>Figure 43. Comparison of the Average Debonding Force between 1- and 3-day curing time at elevated temperature after Debonding.</i>	90
<i>Figure 44. Bonding force loss after debonding for cement recipes at 1-day curing.</i>	92
<i>Figure 45. Bonding force loss after debonding for cement recipes at 3-day curing.</i>	93
<i>Figure 46. Comparison of the Bonding Loss Force between 1- and 3-day curing time at room temperature after Debonding.</i>	94
<i>Figure 47. Comparison of the Bonding Loss Force between 1- and 3-day curing time at room temperature after Debonding.</i>	95
<i>Figure 48. Initial Displacement after debonding for cement recipes at 1-day curing.</i>	97
<i>Figure 49. Initial Displacement after debonding for cement recipes at 3-day curing.</i>	98
<i>Figure 50. Comparison of the Initial Displacement between 1- and 3-day curing time at room temperature after Debonding.</i>	99
<i>Figure 51. Comparison of the Initial Displacement between 1- and 3-day curing time at elevated temperature after Debonding.</i>	100
<i>Figure 52. Unconfined Compressive Strength for cement recipes at 1-day curing.</i>	109
<i>Figure 53. Unconfined Compressive Strength for cement recipes at 3-day curing.</i>	110
<i>Figure 54. Unconfined Compressive Strength between 1- and 3-day curing time at room temperature.</i>	111
<i>Figure 55. Unconfined Compressive Strength between 1- and 3-day curing time at elevated temperature.</i>	112
<i>Figure 56. Relationship between UCS and IBSS at 1 Day curing at room temperature.</i>	114
<i>Figure 57. Relationship between UCS and IBSS at 1 Day curing at elevated temperature.</i>	115
<i>Figure 58. Relationship between UCS and IBSS at 3 Days curing at room temperature.</i>	116
<i>Figure 59. Relationship between UCS and IBSS at 3 Days curing at elevated temperature.</i>	118

Tables

Table 1: Portland Cement Composition (Fink, 2015).....	19
Table 2:API Cement Classes and Their Applications.....	22
Table 3. Composition of fly ash obtained from different coals (Gollakota et al., 2019).	34
Table 4: Limitations of various wellbore logs (Kiran et al., 2017).....	44
Table 5: Effect of surface roughness on shear bond adapted from Carter and Evans (1964)	47
Table 6: Effect of mud type on shear bond strength adapted from (Carter & Evans, 1964)	49
Table 7: The percentage of casing-cement and cement-formation bonding in the centralized casing scenario and 50% stand-off scenario respectively.	52
Table 8: Summary of authors' findings on UCS using different cement recipes.	56
Table 9: Summary of authors' findings on IBSS using different cement recipes	57
Table 10. Samples and recipes.....	60
<i>Table 11: Scoring metric for 1 day curing at room temperature.....</i>	<i>102</i>
<i>Table 12: Scoring metric for 1 day curing at elevated temperature.</i>	<i>104</i>
<i>Table 13: Scoring metric for 3 days curing at room temperature.</i>	<i>106</i>
<i>Table 14: Scoring metric for 3 days curing at elevated temperature.</i>	<i>107</i>
Table 15: Summary of Cement Recipes based on different selection criteria and curing days.	119

Equations

$C_3A + 3CSH_2 + 26H \rightarrow C_6AS_3H_{32}$ (Equation 1).....	37
$2C_3A + C_6AS_3H_{32} + 4H \rightarrow 3C_4ASH_{12}$ (Equation 2).....	37
$2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH$ (Equation 3)	37
$2C_2S + 4H \rightarrow C_3S_2H_3 + CH$ (Equation 4)	37
$2C_3S + 7H \rightarrow C_3S_2H_8 + 3CH$ Equation 5.....	39
$2C_2S + 7H \rightarrow C_3S_2H_8 + CH$ Equation 6.....	39
$C_3A + 3CSH_2 + 26H \rightarrow C_6AS_3H_{32}$ Equation 7	40
$2C_3A + C_6AS_3H_{32} + 22H \rightarrow 3C_4ASH_{18}$ Equation 8.....	40
$\text{Eccentricity}\% = \frac{\delta}{(R_w - r_c)} * 100$ Equation 9.....	51
$\sigma = \frac{F_{max}}{2\pi * ID_B * SL}$ Equation 10.....	53
$\sigma = \frac{F_{max}}{2\pi * ID_A * CL}$ Equation 11.....	53
Equation 12	70
Equation 13	70

Abstract

Well integrity is a critical concern in the petroleum industry, as compromised integrity can lead to severe consequences, including loss of life, equipment failure, hydrocarbon leakage, and environmental pollution. Studies reveal that a significant percentage of oil and gas wells in the United States exhibit sustained casing pressure (SCP) or casing vent flow (CVF) during their operational lifespan, with occurrences ranging from 0.3% to 26.5% in key states like Pennsylvania, Colorado, and New Mexico. These findings highlight the importance of effective cementing practices to ensure well safety, prevent fluid migration, and maintain zonal isolation throughout a well's lifecycle. Cementing operations play a pivotal role in securing wellbore integrity by providing structural support and preventing the migration of formation fluids. However, the complex nature of wellbore cementing necessitates a deeper understanding of the factors influencing bonding strength and compressive strength performance under various environmental and operational conditions.

This thesis presents an experimental study investigating the effect of various additives on the bonding strength between casing and cement, using API Class G cement as the base material. The study explores six additives: microblock, silica flour, fly ash, iron powder, iron oxide, and gilsonite, each incorporated at specified percentages. Cement samples were cured for both 1 and 3 days at room temperature and at elevated temperatures of 75°C, reflecting real-world operational scenarios. The research evaluates the interplay between Unconfined Compressive Strength (UCS) and Interfacial Bonding Shear Strength (IBSS), two critical metrics that govern cement's mechanical behavior and its ability to maintain bonding integrity with casing. UCS tests were performed on cubic cement molds to assess the compressive strength, while IBSS measurements

were carried out to determine the bonding strength at the cement-casing interface under various curing conditions and durations.

The results of this study provide insights into the additive-specific trade-offs between compressive strength and bonding performance. Some additives, such as fly ash, demonstrated superior UCS but at the expense of reduced IBSS, suggesting strong structural support but weaker bonding under certain conditions. In contrast, additives like microblock offered a balanced performance between UCS and IBSS, highlighting their potential for maintaining both strength and bonding integrity. The study underscores that high compressive strength does not always translate to strong bonding, necessitating careful additive selection to meet the specific requirements of wellbore operations. Additionally, the research explores the post-debonding characteristics of each cement recipe, providing valuable information on displacement behavior and force loss after debonding.

1 Introduction.

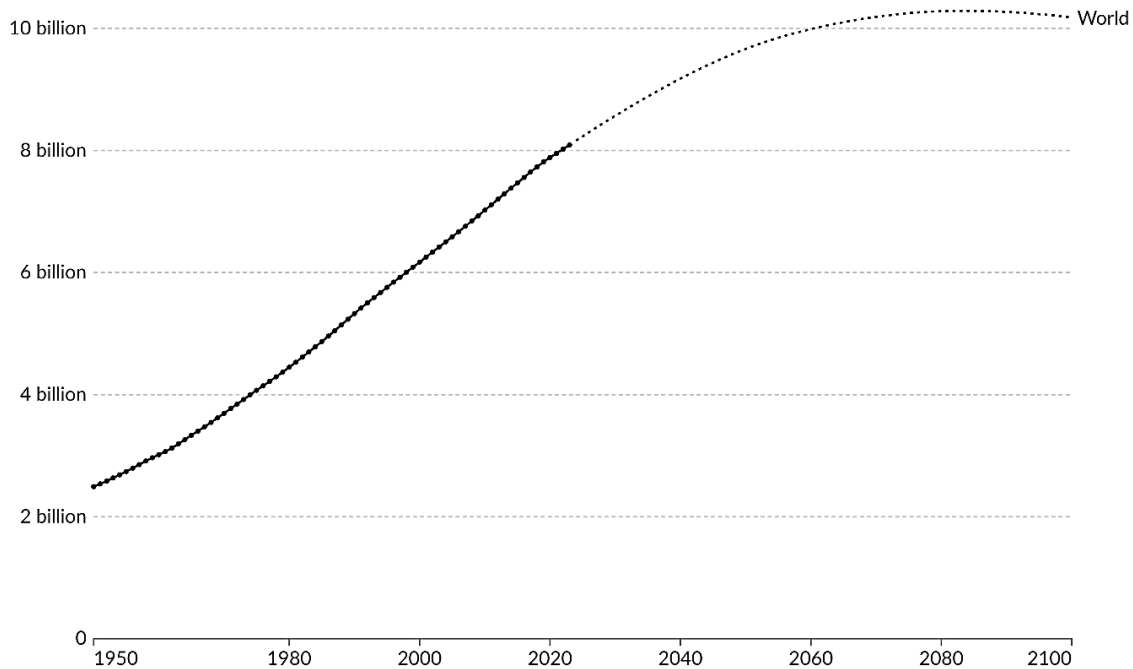
This chapter addresses the main ideas that have been examined in the research thesis, providing a complete outline and explanation of the topic at hand. Subsequently, the key objectives aimed at addressing this topic are introduced. Ultimately, the scope of research to achieve the proposed objectives is clarified.

1.1 Problem statement.

Over the past 30 years, the world population has grown significantly, tripling since the mid-20th century. From an estimated 2.5 billion people in 1950, the global population reached 8 billion by mid-November 2022, with a sharp increase of 2 billion since 1998 and an additional billion since 2010. Future projections by the **United Nations (2023)** estimate that the world population will continue to grow, reaching 9.7 billion by 2050 and peaking at approximately 10.4 billion by the mid-2080s, as illustrated in **Figure 1**. Such rapid population growth places increasing pressure on global resources, including energy, water, and food supplies. It also highlights the need for sustainable energy production and efficient resource management to support an expanding and urbanizing global population.

Population, 1950 to 2100

Future projections are based on the UN medium scenario¹.



Data source: UN, World Population Prospects (2024)

OurWorldinData.org/population-growth | CC BY

1. **UN projection scenarios:** The UN's World Population Prospects provides a range of projected scenarios of population change. These rely on different assumptions in fertility, mortality and/or migration patterns to explore different demographic futures. [Read more: Definition of Projection Scenarios \(UN\)](#)

Figure 1. World population prospects (Hannah Ritchie, 2023).

In addition to population growth, the global demand for energy has also increased, outpacing the rate of population expansion. According to the U.S. Energy Information Administration (EIA), the rise in global power consumption has led to a notable increase in per capita electricity consumption, which refers to the average amount of electricity used per person (The U.S. Energy Information Administration, 2023). This trend is depicted in Figure 2 and underscores the growing energy requirements of an expanding and increasingly industrialized population. As industrialization continues, particularly in developing nations, energy demand will likely keep

rising, further emphasizing the importance of developing diverse and resilient energy sources that can keep pace with consumption.

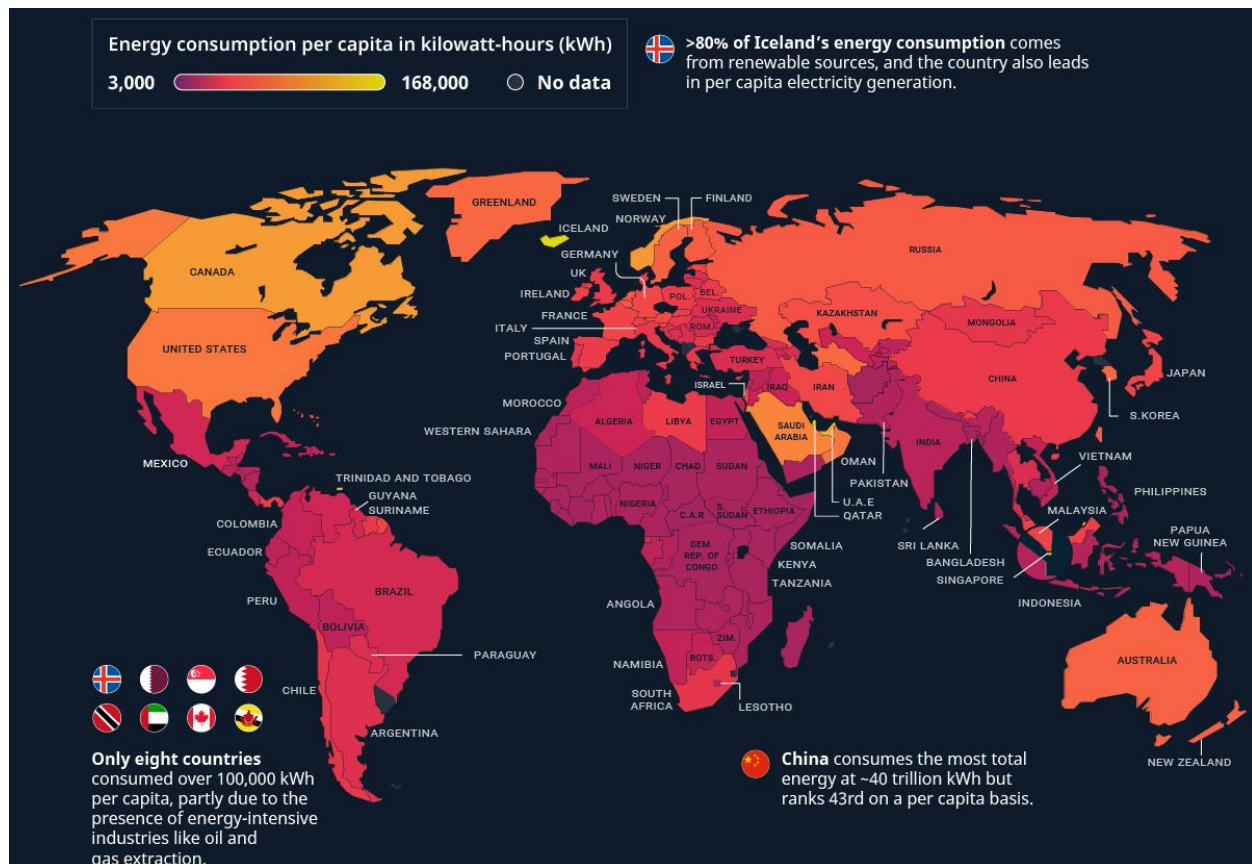


Figure 2. Energy Consumption Per Capita Around the World (Bhutada, 2022).

Despite this escalating demand for energy, the composition of the world's energy sources is currently undergoing a major transition. Historically, oil and gas have played a dominant role, contributing to more than 45% of global energy consumption in 2020 (BP, 2023). However, their share in the energy mix is gradually declining, with projections indicating that they will constitute less than 25% of global energy use by 2050. BP's forecast (BP, 2023) suggests that renewable energy will surpass coal by 2030, and by 2035, renewable sources are expected to overtake oil and gas to become the largest contributors to the global energy landscape, as shown in **Figure 3**. This

shift towards renewable energy is being driven by factors such as climate change concerns, technological advancements in renewable technologies, and government policies promoting cleaner energy sources. Solar, wind, hydroelectric, and other renewable sources are increasingly becoming cost-competitive alternatives, and their adoption is being accelerated by global efforts to mitigate greenhouse gas emissions.

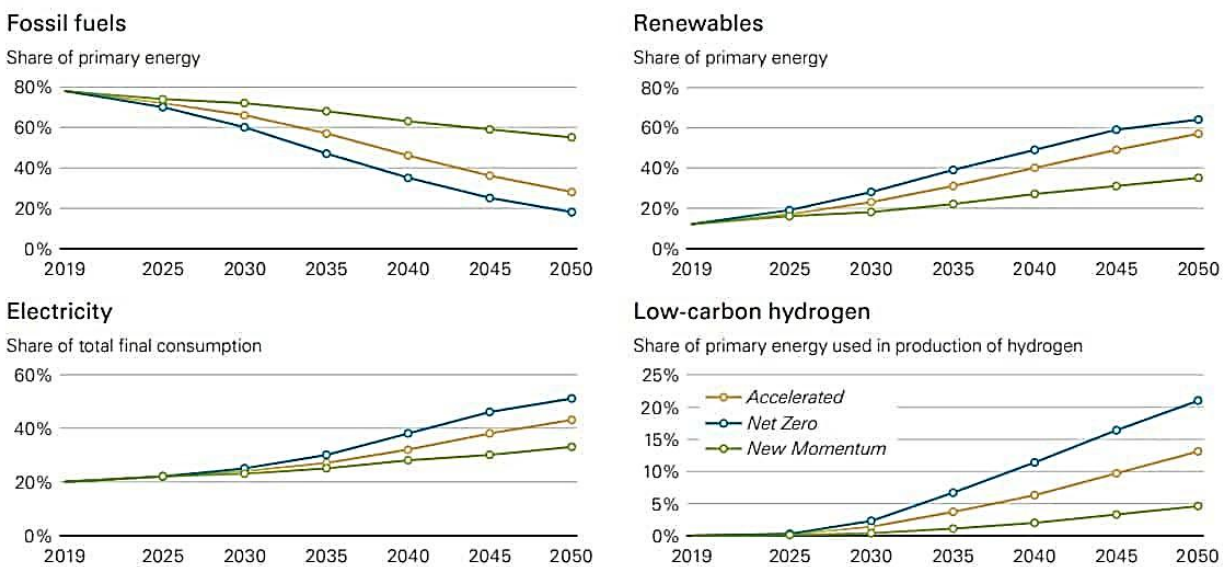


Figure 3. share of primary energy (BP, 2023).

While the share of oil and gas in the energy market is expected to decline, they will still play a significant role in meeting energy demand, especially in industries where alternatives are not yet widely available, such as aviation, shipping, and certain industrial processes. The more than 900,000 wells currently in production across the United States (**Figure 4**) highlight the importance of maintaining well integrity for sustainable energy production. Ensuring the integrity of these wells is crucial for continued oil and gas extraction and future opportunities in geothermal energy production and carbon sequestration using existing infrastructure. Maintaining well integrity

minimizes risks such as leaks, blowouts, and environmental contamination, which can have significant economic, environmental, and social impacts.

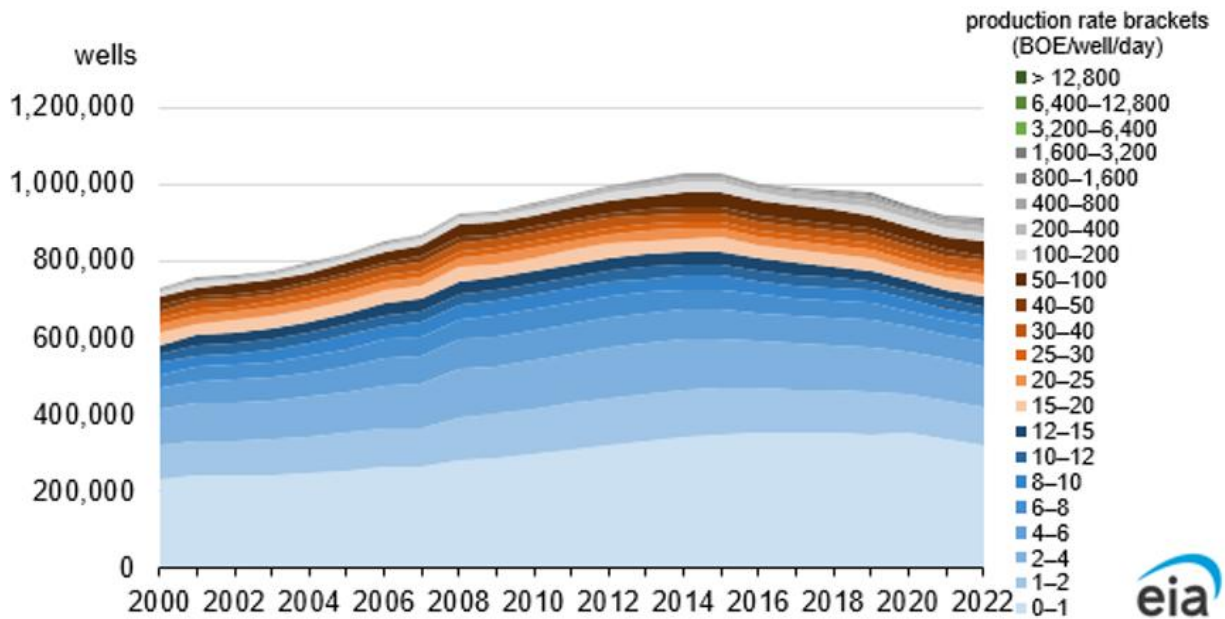


Figure 4. Total U.S. Wells by production rate brackets (The U.S. Energy Information Administration, 2023).

Drilling and well completion are complex and costly processes carried out to establish a connection between the reservoir and the surface for the production of hydrocarbons. These procedures involve drilling from the surface to the target reservoir, cementing the annular space, and completing the well to achieve various objectives, such as hydrocarbon recovery, geothermal energy production, or carbon sequestration. However, these processes often present significant challenges, including loss of circulation of drilling mud or cement due to naturally fractured formations, highly permeable zones, or caverns. Such issues can lead to increased drilling and completion times, subsequently raising costs at the rig.

As demand for fossil fuels continues to grow, the need to explore new frontiers has become more pressing, prompting drilling and well completion activities in increasingly challenging environments. In conventional well design, the cement sheath serves as one of the primary barriers in the well integrity framework, providing structural support and isolation. Once set, the wellbore cement is subjected to various environmental conditions throughout the well's life, which can impact its integrity and effectiveness as a barrier.

Cementing plays a critical role in ensuring well integrity, serving as the primary barrier for casing, isolating problematic formations, and protecting the casing from corrosion while also providing structural support. Therefore, the quality of cement must meet the required standards for fluid loss, thickening time, mechanical strength, transfer properties (such as permeability and porosity), and rheological characteristics to ensure long-term integrity under subsurface conditions. Poor cementing can lead to the need for costly remedial work, including squeeze cementing, and may result in non-productive time. In the worst-case scenario, inadequate cementing could lead to catastrophic blowouts, resulting in the complete loss of the well and even casualties (Al-Yami et al., 2017). Consequently, cement properties can be enhanced through the use of additives. While conventional additives are well-studied, unconventional materials like Gilsonite and Microblock have not been extensively examined, particularly concerning their mechanical behavior and compressive strength under varying temperature conditions.

Data from various energy outlooks indicate that drilling activities, as well as plugging and abandonment operations, are increasing in both complexity and frequency. These operations encompass exploration and production activities in geothermal wells, oil and gas wells, water wells, and carbon capture and storage projects, all of which require effective well construction and production management. To achieve the desired outcomes, it is imperative to carry out these

operations in a cost-effective and safe manner, which necessitates a comprehensive understanding of the key well components.

One of the most critical components in well construction and integrity is oilwell cement. Whether it is used in hydrocarbon wells to ensure safe production and structural support, in geothermal wells to provide project viability, in gas storage wells to withstand high cyclic loads, or in carbon storage wells to ensure sealing of underground deposits, the properties of cement are key to the success of the project. The ability of cement to maintain integrity over time and under changing temperature conditions is essential for long-term well performance. Figure 5 shows the possible leakage pathways in a cased wellbore that could impact the integrity of the well negatively.

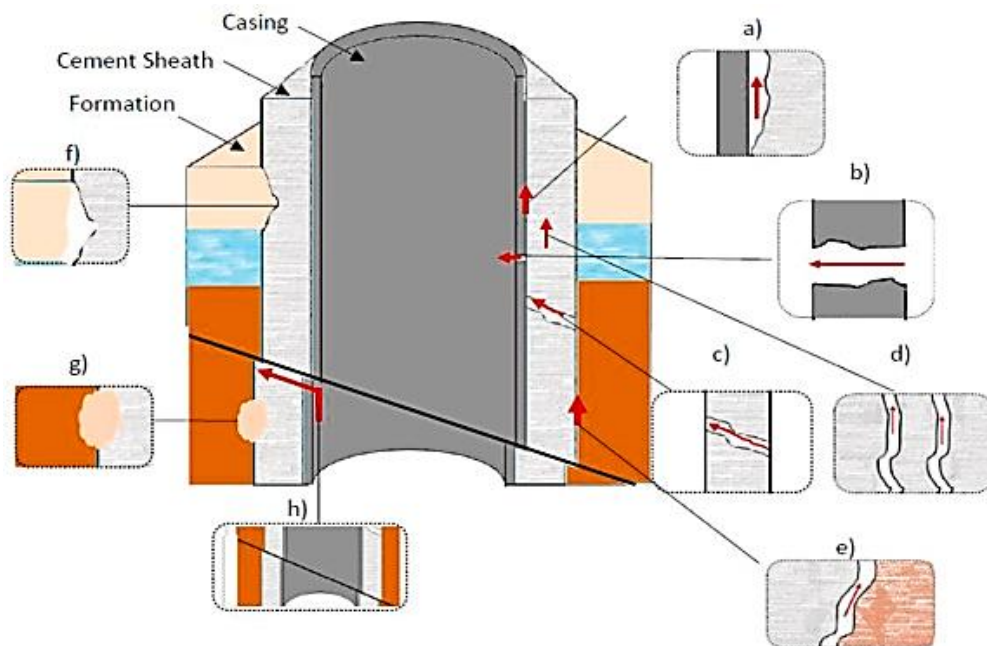


Figure 5 Possible leakage pathways in a cased wellbore (Wu B, 2020)

A lack of understanding of how the mechanical properties of cement develop over time and with temperature changes can compromise the proper selection of cement for well integrity. This research aims to provide a deeper understanding of the evolution of cement's mechanical properties

over time, under different temperature conditions, and to assess the mechanisms involved in setting. Ultimately, this will lead to better assessments of well integrity.

The subsequent sections of this thesis will begin with a description of the well construction process, followed by a detailed explanation of oilfield cement, its characteristics, and its manufacturing process. This will be followed by an overview of the testing methods, with a specific focus on the experimental approaches used in this research. Chapters 5 and 6 will present a discussion of the results, their implications, recommendations for future work, and final conclusions.

1.2 Objectives.

1.2.1 General Objective.

The general objective of this thesis is to evaluate the effects of various additives on the mechanical properties of well cement, specifically focusing on their impact on casing-cement bonding strength, compressive strength, and the evolution of these properties over time and under different temperature conditions. This research aims to enhance well integrity by providing insights into how unconventional additives can improve cement performance, thereby supporting safer and more effective well construction, production, and abandonment.

1.2.1 Specific Objectives.

- Conduct a comprehensive literature review focused on well cementing and well integrity, along with an overview of cement and additives in the oil and gas industry.
- Elaborate a methodology aligned with API 10B for the conduction of laboratory testing pertaining to the compressive strength of the different class G cement composites, likewise for the measurement of the interfacial debonding shear strength.

- Conduct laboratory testing of the different class G composites in order to assess both their respective interfacial debonding shear strength and their compressive strength.
- Analyze the change in the interfacial debonding shear strength and compressive strength of the different class G cement composites by the addition and variation of the percentage by weight of different additives cured at room and high temperature.
- Analyze the post-debonding characteristics of the different class G cement composites by the addition and variation of the percentage by weight of different additives cured at room and high temperatures.
- Compare the results obtained through laboratory testing to highlight the change of the compressive strength by the addition of different additives to class G.
- Compare the results obtained through laboratory testing to highlight the change of interfacial bonding shear strength by the addition of different additives to class G cement.

1.3 Scope of work.

The scope of this thesis encompasses an in-depth investigation into the mechanical properties of oilwell cement under different temperature conditions, with a particular focus on the use of various additives to enhance cement performance. The research aims to assess the impact of cement additives on improving cement properties, such as interfacial bonding shear strength and compressive strength, which evolve over time and under different environmental conditions. By exploring the role of conventional and unconventional additives like Silica, Fly Ash, Iron Powder, Iron Oxide, Gilsonite and Microblock, this study seeks to improve well integrity for various well applications, including hydrocarbon production, geothermal energy, and carbon sequestration.

2 Literature review.

2.1 Well Integrity.

Well integrity is a pivotal aspect of the oil and gas industry, essential for the safe and efficient extraction of hydrocarbons and other subsurface resources. According to the (D-010, 2013), well integrity involves "the application of technical, operational, and organizational solutions to reduce the risk of uncontrolled release of formation fluids throughout the well's life cycle." Similarly, the American Petroleum Institute (API) defines well integrity as the condition of a well that has competent mechanical barriers to prevent the unintended flow of fluids—both liquids and gases—from one geological formation to another or to the surface ((API), 2016). The (Association, 2019) emphasizes that well integrity encompasses all activities, processes, and barriers employed during operations to mitigate the hazard of uncontrolled fluid release over the well's lifespan.

Failures in well integrity are complex issues influenced by a multitude of factors, including environmental conditions like geographical location, subsurface geology, pressure, and temperature. Human elements such as engineering practices and regulatory frameworks also play significant roles (Cahill et al., 2019; Sandl et al., 2021; Trudel et al., 2019). These failures can lead to severe consequences, including environmental contamination, safety hazards, and substantial financial losses.

Maintaining well integrity involves multiple barriers and systems designed to contain fluids within the wellbore and prevent leaks. These barriers include casing strings, cement sheaths, wellheads, and various downhole equipment, all of which must function synergistically to ensure a secure well environment. The primary barriers are generally categorized into mechanical barriers—such as casing and tubing—and pressure barriers, including cement and packers (King & King, 2013).

A failure in any of these barriers can result in a loss of well control, posing risks to personnel, assets, and the environment.

Historically, well integrity issues have been linked to various factors in well construction and operation. Poor cementing practices, casing damage, pressure fluctuations, and insufficient maintenance are common contributors to integrity failures (Dusseault et al., 2000). Cementing plays a crucial role in establishing zonal isolation, which is essential for maintaining pressure control and preventing crossflow between different geological formations. When cementing operations are not executed properly, it can compromise zonal isolation, creating pathways for fluid migration and jeopardizing the overall safety of the well (Bourgoyne et al., 1991).

Studies indicate that well integrity failures can occur at any stage of a well's life cycle—from drilling and completion to production and abandonment (Davies et al., 2014). The increasing complexity of modern wells, coupled with the trend of drilling in challenging environments such as deepwater locations, ultra-deep reservoirs, and high-temperature/high-pressure (HTHP) conditions, has intensified the focus on effective well integrity management (R, 2012). The risks associated with poor well integrity extend beyond safety concerns; they can also result in significant financial losses due to production downtime, remediation costs, and regulatory fines (Brufatto et al., 2003).

In recent years, advancements in technology and well integrity management practices have contributed to reducing the frequency of well integrity issues. Innovations such as enhanced cement formulations, the use of nano-additives, improved monitoring techniques like real-time downhole sensors, and advanced downhole tools have all played roles in mitigating risks and ensuring that wells maintain their integrity over time (Bai et al., 2016). Additionally, the development of well integrity standards by organizations like the API and the International

Organization for Standardization (ISO) has been instrumental in providing guidelines for the consistent application of best practices in well construction and maintenance ((ISO), 2017; Institute, 2010).

Casing is a fundamental component in maintaining well integrity. According to (Schlumberger, 2024), casing is a large-diameter steel pipe inserted into the drilled wellbore and cemented in place, designed to withstand various loads such as burst, collapse, and tensile stresses under harsh downhole conditions. The primary purposes of casing include providing structural integrity to the wellbore, isolating different geological formations to prevent fluid crossflow, protecting freshwater aquifers, and facilitating pressure control during drilling operations. Different types of casing—surface casing, intermediate casing, production casing, and liner strings—are used depending on the specific requirements of the well design (Larry W. Lake, 2006).

In completion operations, casing continues to play a crucial role. It serves as a major structural component that stabilizes the wellbore, prevents the formation walls from caving in, and provides a conduit for hydrocarbons to be safely brought to the surface. The casing also allows for the installation of equipment like blowout preventers (BOPs), which are critical for maintaining control over the well during drilling and production (H., 2001). Ensuring the integrity of the casing through proper material selection, design, and installation is vital for the overall integrity of the well.

The importance of well integrity cannot be overstated. Effective well integrity management ensures the safety of personnel, protects the environment, and maximizes the economic value of hydrocarbon resources. Continuous improvements in technology, adherence to industry standards, and rigorous operational practices are essential components in achieving and maintaining well integrity throughout the life of a well.

2.2 Well cementing.

Well cementing is a critical operation in the construction of oil and gas wells, serving as a cornerstone for well integrity and longevity. It involves pumping a cement slurry into the annular space between the casing and the wellbore wall, where it hardens to form a solid sheath. This cement sheath performs multiple essential functions: it stabilizes the casing, protects it from corrosive formation fluids, prevents the unwanted migration of fluids between different geological layers, and supports the overall structural integrity of the well (Erik B Nelson, 2006).

The primary objectives of well cementing are to achieve effective zonal isolation, provide structural support to the casing, and prevent fluid movement between distinct geological formations. Zonal isolation is crucial because it ensures that hydrocarbons and other subsurface fluids remain confined to their respective reservoirs, thereby preventing cross-contamination and preserving the productive capacity of the well. Inadequate cementing practices can compromise well integrity, leading to issues such as fluid migration, casing corrosion, and even catastrophic events like blowouts (Bourgoyne et al., 1991).

The cementing process begins with the meticulous design of the cement slurry, tailored to meet the specific conditions of the well. Factors such as temperature, pressure, well depth, and formation characteristics influence the selection of cement types and additives. The most commonly used cement in the industry is API Class G cement, renowned for its versatility and compatibility with various additives that enhance performance under specific well conditions ((API), 2010). Additives are incorporated to modify the slurry's properties, including setting time, density, rheology, and mechanical strength. Typical additives encompass retarders, accelerators, weighting agents, fluid loss additives, and extenders (Fink, 2015).

Effective mud removal is a pivotal step in the cementing operation, as residual drilling fluids can impede the bonding between the cement and the formation, creating channels for fluid migration. To facilitate uniform cement placement, centralizers are installed on the casing to keep it centered within the wellbore. The pumping schedule must be precisely planned to ensure that the cement slurry reaches the desired location before it begins to set, thereby maximizing the quality of the cement job (Smith, 1990).

Cementing challenges become more pronounced in complex well environments, such as high-temperature/high-pressure (HTHP) wells, deepwater settings, and wells with significant deviations or horizontal sections. These conditions complicate slurry design and placement, necessitating specialized additives and advanced cementing techniques. Common issues like loss of circulation, gas migration, and cement shrinkage can undermine cement integrity in these challenging scenarios (Erik B Nelson, 2006).

Technological advancements have led to the development of innovative cement systems and placement methodologies. Solutions such as self-healing cements, foamed cements, and microfine cement slurries have been engineered to enhance performance under demanding conditions. These materials address specific challenges like gas migration and micro-annulus formation, which can compromise zonal isolation (Bois et al., 2011).

There are two primary types of cementing operations: **primary cementing** and **secondary (remedial) cementing**. Primary cementing involves placing cement in the annulus between the casing and the wellbore to achieve zonal isolation and support the casing. According to (Fink, 2015), the objectives of primary cementing are to:

- Support axial and radial casing loads

- Isolate porous formations
- Seal formation fluid influx
- Protect casing from corrosion.

Secondary cementing, which includes techniques like squeeze cementing and plug cementing, is performed to maintain or enhance well integrity after the initial cement job. Squeeze cementing can repair issues from a faulty primary cementation, stop drilling fluid losses, seal off depleted or abandoned formations, and mend casing leaks (Erik B Nelson, 2006).

2.2.1 Primary Cementing Techniques.

There are three main techniques for primary cementing:

1. **Through-the-Casing Cementing:** This traditional method involves pumping cement slurry down the casing and up the annulus. A pair of wiper plugs (bottom and top) and a float collar are used to displace the cement. Centralizers and scratchers are employed to ensure good casing-to-cement and cement-to-formation bonds (Hole, 2008).
2. **Inner-String Cementing:** In this technique, a modified float collar allows tubing or drill pipe to be run inside the casing to the bottom of the well. This setup enables the cement to be pumped more efficiently, reducing the time and potential for fluid loss at the joints (Fink, 2015).
3. **Reverse Circulation Cementing:** Used primarily when weak formations are present near the wellbore shoe, cement slurry is pumped down the annulus and displaces the drilling mud back up through the casing as shown in Figure 6. Special tools like float collars and wellheads are required. Since wiper plugs cannot be used, detecting the end of the cement

displacement is challenging, often leading to over-displacement as a precaution (Bourgoyne et al., 1991).

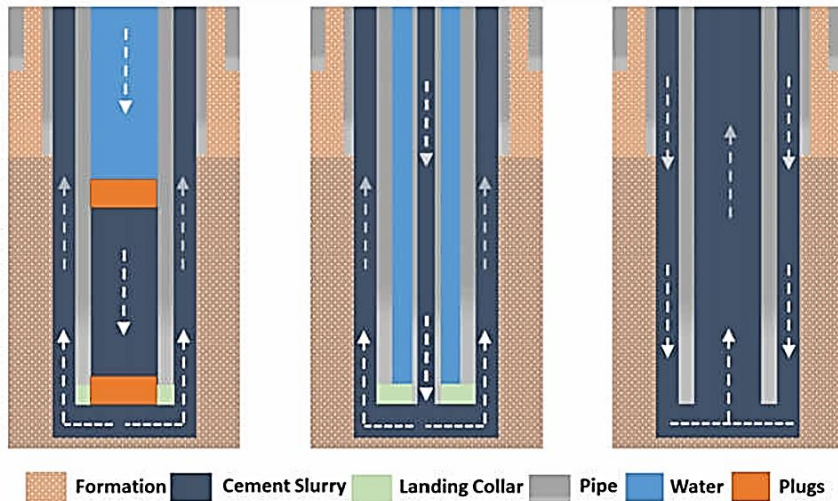


Figure 6 – Two plugs (left), inner-string (center), and reverse circulation cementing (right) (Ichim, 2017)

After cement placement and the "wait-on-cement" (WOC) period, the cement sets and bonds to both the casing and the formation. This bond acts as a crucial barrier, ensuring well integrity. The ability of the cement sheath to withstand the stresses encountered throughout the well's life depends significantly on the quality of the primary cementing job. Factors influencing this quality include casing centralization (standardized by API Spec 10D and ISO 10427), curing time, well inclination, slurry design, and operational practices ((API), 2002; (ISO), 2001).

2.2.2 Importance of Well Cementing.

Primary cementing is not just a procedural step but a critical component in well construction that has long-term implications for safety and efficiency. A successful cement job ensures a hydraulic seal that prevents fluid communication between different zones and to the surface, safeguarding against environmental contamination and resource loss. Failure to achieve effective zonal isolation

can lead to severe consequences, including costly remediation efforts, operational delays, environmental incidents, and safety hazards for personnel (Bois et al., 2011).

The industry continuously seeks to improve cementing practices through research and technological innovation. Recent developments include:

- **Nanotechnology in Cementing:** Incorporating nanoparticles into cement slurries has shown promise in enhancing mechanical properties, reducing permeability, and improving overall durability of the cement sheath (Zhe & Yuxiu, 2018).
- **Real-Time Monitoring:** Advanced monitoring tools and software allow for real-time analysis of cement placement, enabling immediate adjustments to optimize the cement job (Anunciação Jaculli et al., 2022).
- **Environmentally Friendly Additives:** There is a growing emphasis on using eco-friendly additives that meet performance requirements while minimizing environmental impact (Fink, 2015).

Adhering to industry standards and guidelines, such as those provided by the American Petroleum Institute (API) and the International Organization for Standardization (ISO), is essential for ensuring consistency and reliability in cementing operations. These standards cover aspects ranging from material specifications to operational procedures, contributing to overall well integrity and safety ((API), 2010; (ISO), 2004).

2.3 Portland cement.

Portland cement is a cornerstone material in the construction and petroleum industries, renowned for its versatility and strength. The manufacturing process begins with the selection of calcareous (calcium-rich) and argillaceous (clay-rich) rocks, which are dried, ground, and mixed in precise

proportions under dry or wet conditions. This mixture is then heated in a rotary kiln to extremely high temperatures, typically between 1,426°C and 1,540°C (2,600°F to 2,800°F). The intense heat induces chemical reactions that form clinker—hard, nodular material. After cooling, the clinker is ground again and combined with additives like gypsum to produce Portland cement (Nelson, 1990).

The name "Portland cement" originates from its resemblance to Portland stone, a high-quality building stone quarried on the Isle of Portland in Dorset, England. When Joseph Aspdin patented the product in 1824, he noted its similarity to this natural stone (Taylor, 1997).

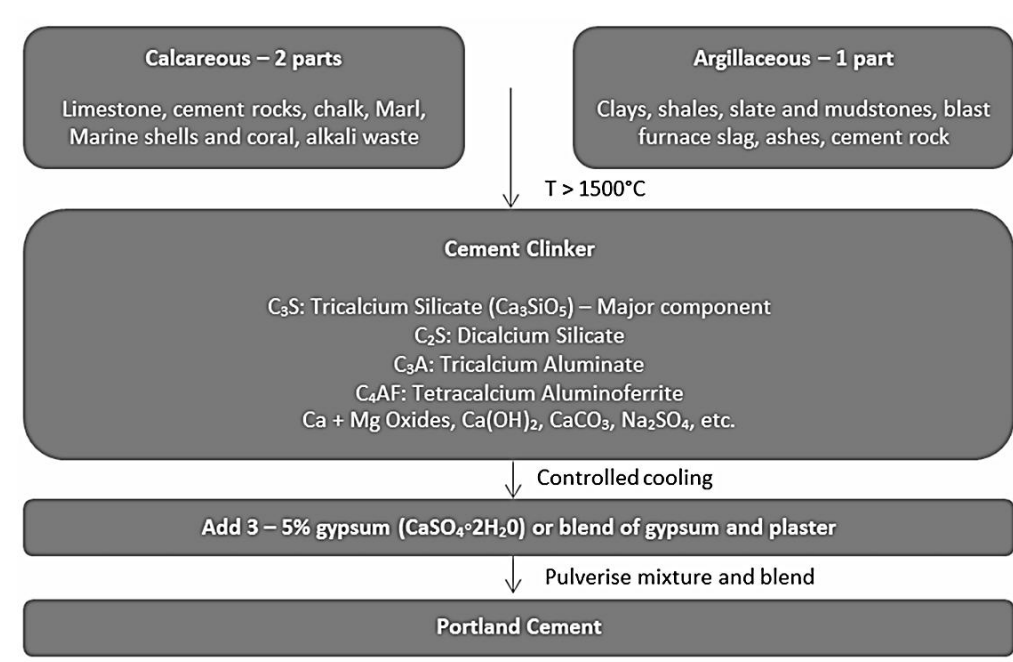


Figure 6: Portland Cement Production Workflow (Ichim, 2015)

The following table shows the typical composition of Portland cement.

Table 1: Portland Cement Composition (Fink, 2015)

Compound	Percentage
CaO – Calcium oxide (burnt lime)	60-69
SiO ₂ – Silicon dioxide (silica)	18-24
Al ₂ O ₃ + TiO ₂ - Aluminum + Titanium oxide (alumina and titania)	4-8
Fe ₂ O ₃ – Iron oxide (ferric oxide)	1-8
MgO – Magnesium oxide (magnesia)	<5
K ₂ O, Na ₂ O – Potassium and Natrium oxide	<2
SO ₃ – Sulfur trioxide (sulfite)	<3

Depending on the intended application, Portland cement can be mixed with various substances to create different materials:

- **Concrete:** A composite material consisting of cement powder, water, fine aggregates (sand), and coarse aggregates (gravel or crushed stone like limestone or granite). Concrete is the most widely used construction material globally due to its durability and versatility (Mehta & Monteiro, 2014).
- **Mortar:** A mixture of cement powder, water, and fine sand, often enhanced with a plasticizer such as hydrated lime or an organic wetting agent. Mortar is primarily used for binding building blocks like bricks and stones (Neville, 2011).
- **Cement Paste:** A simple blend of cement powder and water. In civil engineering, it's commonly referred to as grout, while in petroleum engineering, it's known as cement slurry—the focus of well cementing operations ((API), 2010).

2.3.1 Types of Cement according to the API.

In the oil and gas industry, cementing plays a crucial role in ensuring well integrity under challenging downhole conditions, such as high pressures, high temperatures, corrosive fluids, and variable geological formations. The cements used in this sector are specialized to withstand these

harsh environments, distinguishing them from cements used in general construction (Erik B Nelson, 2006).

The American Petroleum Institute (API) provides a classification system for oilwell cements in API Specification 10A, categorizing them into classes based on their composition and suitability for different well conditions ((API), 2010). These cements are also graded according to their sulfate resistance: Ordinary (O), Moderate Sulfate Resistant (MSR), and High Sulfate Resistant (HSR).

The primary API cement classes are:

- **Class A:** Suitable for use when special properties are not required. Available only in Grade O, it's used for depths up to 6,000 feet (1,830 meters) and temperatures up to 170°F (77°C) (Renpu, 2011).
- **Class B:** Designed for conditions requiring moderate to high sulfate resistance. Available in Grades MSR and HSR, it is also used for depths up to 6,000 feet and temperatures up to 170°F (77°C) (Renpu, 2011).
- **Class C:** Characterized by high early strength development, making it ideal for situations where rapid strength gain is necessary. Available in Grades O, MSR, and HSR, suitable for depths up to 6,000 feet and temperatures up to 170°F (77°C) (Renpu, 2011).
- **Class D:** Intended for moderately high temperatures and pressures. Available in Grades MSR and HSR, it can be used at depths from 6,000 to 10,000 feet (1,830 to 3,050 meters) and temperatures up to 230°F (110°C) (Renpu, 2011).

- **Class E:** Designed for high-temperature and high-pressure environments. Available in Grades MSR and HSR, suitable for depths from 10,000 to 14,000 feet (3,050 to 4,270 meters) and temperatures up to 290°F (143°C) ((API), 2010).
- **Class F:** Intended for extremely high temperatures and pressures. Available in Grades MSR and HSR, it is used for depths from 10,000 to 16,000 feet (3,050 to 4,880 meters) and temperatures up to 320°F (160°C) ((API), 2010).
- **Class G:** A basic well cement that can be modified with additives for a wide range of well depths and temperatures. Available in Grades MSR and HSR, it's commonly used for depths up to 8,000 feet (2,440 meters) but can be extended with additives for deeper wells (Renpu, 2011).
- **Class H:** Similar to Class G but with coarser grind size, making it suitable for deeper and hotter wells. Available in Grades MSR and HSR, it's used for depths up to 8,000 feet and beyond when enhanced with additives (Renpu, 2011).

Table 2 summarizes the API cement classes, their grades, and typical application depths and temperatures ((API), 2010).

Table 2:API Cement Classes and Their Applications

Cement Class	Grades Available	Depth Range	Temperature Range
Class A	O	0 – 6,000 ft	Up to 170°F (77°C)
Class B	MSR, HSR	0 – 6,000 ft	Up to 170°F (77°C)
Class C	O, MSR, HSR	0 – 6,000 ft	Up to 170°F (77°C)
Class D	MSR, HSR	6,000 – 10,000 ft	Up to 230°F (110°C)
Class E	MSR, HSR	10,000 – 14,000 ft	Up to 290°F (143°C)
Class F	MSR, HSR	10,000 – 16,000 ft	Up to 320°F (160°C)
Class G	MSR, HSR	0 – 8,000 ft (extendable)	Wide range
Class H	MSR, HSR	0 – 8,000 ft (extendable)	Wide range

The selection of a particular cement class and grade depends on various factors, including:

- **Depth of the Well:** Deeper wells require cements that can withstand higher pressures and temperatures (Smith, 1990).
- **Temperature:** High downhole temperatures can accelerate the setting time of cement and affect its strength development. Specialized cements and additives are used to control these effects (Erik B Nelson, 2006).
- **Formation Conditions:** The presence of sulfates or other aggressive chemicals in the formation fluids necessitates the use of sulfate-resistant cements to prevent deterioration over time (Taylor, 1997).
- **Pressure Conditions:** Higher pressures demand cements with appropriate mechanical properties to maintain integrity under stress (Thiercelin et al., 1998).

Importance of Sulfate Resistance

Sulfate attack is a common issue that can compromise the durability of cement in subsurface environments. Sulfate ions react with components of the cement paste, leading to expansion and cracking. API grades MSR and HSR are formulated to resist sulfate attack, enhancing the longevity of the cement sheath (Taylor, 1997).

Recent developments in cement technology have led to the creation of specialized cements and additives that address specific challenges in well cementing. For instance:

- **Microfine Cements:** These cements have finely ground particles that can penetrate narrow gaps and are used for remedial cementing operations (Xing et al., 2024).
- **Self-Healing Cements:** Formulated to repair microcracks autonomously, enhancing long-term zonal isolation (Rod et al., 2020).
- **High-Temperature Cements:** Designed to maintain strength and stability at temperatures exceeding traditional limits (Carter & Smith, 1958).

2.3.2 Cement Additives.

The use of chemical additives in the oil and gas industry can modify the rate of hydration that occurs when water and cement are mixed. Those additives are chemicals or materials that are blended into the neat cement slurries in order to change their performance to achieve the needs of the operation (Broni-Bediako, 2016). The incorporation of various additives into cement formulations has been extensively studied to enhance properties such as bonding strength, compressive strength, mechanical durability, and pumpability. Commonly used chemical additives in oil and cementing procedures encompass accelerators, retarders, extenders, additives for loss circulation, and dispersants, among others (Roshan, 2010).

- **Accelerators:** chemical additives used to speed up the thickening time of the cement, increasing the early development of the compressive strength. Those accelerators can be calcium chloride, and sodium chloride among others.
- **Retarders:** It is a chemical additive that is used to delay cement hydration; hence the development of the compressive strength is much slower. Some of the retarders are lignosulfonate, cellulose derivatives, and hydroxycarboxylic acids.
- **Extenders:** Material or chemical used to lower the density of the mixture; hence, the hydrostatic pressure of the same is going to be lower. Bentonite and sodium silicate are the common extenders that are used in the oil and gas industry.
- **Heavy-weight agents:** The requirement for an additive to be considered a heavy-weight agent is to have a greater specific gravity than the cement, even particle size, and low water requirements in order to restrain high formation pressure. Hematite and ilmenite are commonly used for this purpose.
- **Fluid loss additive:** commonly used to reduce the rate at which water from the cement is absorbed by the formation due to differential pressure. The most common additive for fluid loss is hydroxyethyl cellulose.
- **Dispersants:** This additive is used to improve the flow properties of cement slurries. It is particularly used to compensate for high viscosity and the tendency to gel of some cement slurries.

Other Unconventional additives are.

2.3.2.1 Iron Powder Filings.

Iron powder filings are fine particles of elemental iron that can be added to cement mixtures to modify their physical and mechanical properties. The addition of iron powder filings has been

investigated for its potential to enhance the thermal conductivity, density, and mechanical strength of cement composites.

Compressive and Mechanical Strength

Studies have shown that incorporating iron powder filings into cement can significantly improve its compressive strength. This enhancement is attributed to the filler effect, where iron particles fill voids within the cement matrix, leading to a denser and more homogeneous material (Wang et al., 2023). The iron particles also contribute to the formation of additional hydration products through pozzolanic reactions, further strengthening the cement structure.

Bonding Strength

The presence of iron powder filings can enhance the bonding strength between the cement and the casing or formation. The metallic nature of iron improves the interfacial adhesion due to increased surface roughness and potential chemical interactions at the interface (Feng et al., 2020). This improved bonding is crucial for maintaining well integrity by preventing fluid migration and ensuring zonal isolation.

Thermal Conductivity and Heat Generation

Iron has high thermal conductivity, and its inclusion in cement can facilitate better heat dissipation during the exothermic hydration process. This property is beneficial in high-temperature wellbore environments, as it reduces the risk of thermal cracking and enhances the durability of the cement sheath (Wang et al., 2023).

Pumpability

The addition of iron powder filings can affect the rheological properties of the cement slurry. While increased density might pose challenges for pumpability, adjusting the particle size distribution and optimizing the slurry design can mitigate these issues. The use of superplasticizers and dispersants can help maintain acceptable flow characteristics (Niu et al., 2022).

2.3.2.2 Iron Oxide.

Iron oxide, commonly available as hematite (Fe_2O_3) or magnetite (Fe_3O_4), is used as a weighting agent and functional additive in cement formulations.

Density Enhancement

Iron oxide is often added to cement to increase its density, which is essential for controlling formation pressures and preventing well blowouts in high-pressure zones (Erik B Nelson, 2006). A higher-density cement slurry can counterbalance formation pressures, enhancing well control during cementing operations.

Mechanical Properties

The inclusion of iron oxide can improve the mechanical strength of the set cement. The iron oxide particles act as fillers that enhance the microstructure of the cement matrix. This improvement leads to increased compressive and tensile strengths, which are critical for the structural integrity of the cement sheath under downhole stresses (Onaizi et al., 2024).

Thermal Stability

Iron oxide additives contribute to the thermal stability of cement. They can withstand high temperatures without decomposing, making them suitable for high-temperature well conditions. The thermal properties of iron oxide help in maintaining the integrity of the cement sheath over the well's lifespan (Shadbad et al., 2022).

Bonding and Durability

Iron oxide can enhance the bonding between the cement and casing or formation by improving the microstructure and reducing porosity. A denser cement matrix with fewer microcracks leads to better durability and resistance to aggressive downhole fluids (Valizadeh Kiamahalleh et al., 2020).

2.3.2.3 Microblock.

Microblock is a term that may refer to micro-sized particulate additives or proprietary materials designed to enhance specific properties of cement. These materials are engineered to interact at the microstructural level, improving various aspects of cement performance.

Permeability Reduction

Microblock additives can effectively reduce the permeability of cement by filling microvoids and capillaries within the cement matrix. This reduction is crucial for preventing gas migration and fluid intrusion, thereby maintaining zonal isolation (Maagi et al., 2020).

Mechanical Strength Enhancement

By refining the pore structure and enhancing the packing density, microblock additives contribute to increased compressive and tensile strengths. The improved particle packing leads to a more uniform stress distribution within the cement, enhancing its mechanical performance under load (Murtaza et al., 2019).

Rheological Properties and Pumpability

Microblock additives can influence the rheology of cement slurries. Their fine particle size helps in achieving a stable slurry with good flow characteristics, which is essential for efficient

placement during cementing operations. Properly designed microblock-containing slurries can exhibit reduced viscosity and improved pumpability (Souza et al., 2016).

Bonding Improvements

The incorporation of microblock materials enhances the interfacial transition zone between the cement and the casing or formation. By improving the microstructure at the interface, these additives lead to stronger adhesive bonds and reduced chances of debonding under thermal and mechanical stresses (Arefi et al., 2011).

2.3.2.4 Silica Flour.

Silica flour, a finely divided form of crystalline silica, is extensively used as an additive in oil well cementing to enhance the performance and durability of cement slurries, especially under high-temperature conditions. Its inclusion in cement formulations addresses several challenges associated with well integrity and longevity (Erik B Nelson, 2006).

Role of Silica Flour in Oil Well Cementing

Silica flour is primarily added to prevent strength retrogression—a phenomenon where the cement loses strength over time when exposed to temperatures above 110°C. At elevated temperatures, the calcium hydroxide produced during cement hydration can react to form detrimental compounds that weaken the cement matrix. Silica flour reacts with calcium hydroxide to form additional calcium silicate hydrate (C-S-H) phases that are stable at high temperatures, thereby maintaining the cement's structural integrity (Eilers & Nelson, 1979).

Effects on Cement Properties

1. Prevention of Strength Retrogression

The addition of silica flour mitigates strength retrogression by forming thermally stable C-S-H phases. Eilers and Nelson (1979) demonstrated that incorporating silica flour into cement slurries helps maintain compressive strength after prolonged exposure to high temperatures, which is critical for deep wells and geothermal applications.

2. Enhancement of Mechanical Strength

Silica flour improves the mechanical properties of set cement, including compressive and tensile strengths. By refining the microstructure and reducing porosity, it leads to a denser and more durable cement sheath capable of withstanding the mechanical stresses encountered during the well's lifecycle (Arefi et al., 2011).

3. Improvement of Bonding

The presence of silica flour enhances the bonding between the cement and the casing or formation. A stronger bond is essential to prevent fluid migration and ensure effective zonal isolation. This improvement is attributed to the formation of a more cohesive and homogeneous cement matrix (Erik B Nelson, 2006).

4. Influence on Rheology and Pumpability

Silica flour affects the rheological properties of cement slurries due to its fine particle size and high surface area. While it may increase the slurry's viscosity, appropriate adjustments with dispersants and fluid-loss additives can optimize pumpability without compromising performance (Aïtcin, 2016).

Applications in High-Temperature Wells

In high-temperature wells, such as deep oil and gas wells and geothermal wells, the use of silica flour is crucial. It ensures that the cement maintains its mechanical integrity over time, preventing failures that could lead to safety hazards and environmental issues. By stabilizing the cement matrix at temperatures exceeding 110°C, silica flour extends the service life of the well (Erik B Nelson, 2006).

Considerations and Limitations

While silica flour offers significant benefits, its incorporation requires careful slurry design. The increased water demand due to its fine particles can affect the slurry's density and set time. Additionally, overuse may lead to excessive viscosity, making placement more challenging. Therefore, optimizing the concentration of silica flour and using appropriate admixtures is essential for successful cementing operations (Erik B Nelson, 2006).

2.3.2.5 Gilsonite.

Gilsonite is a naturally occurring, crystallized hydrocarbon bitumen found in geological formations such as dikes, sills, fracture fillings, and disseminated blebs, particularly within oil shale and tar sands (Taylor Boden, 2012). Elemental analysis indicates that Gilsonite comprises approximately 74% carbon, 7.1% hydrogen, 0.67% nitrogen, 3.1% oxygen, and 4% sulfur, reflecting its rich hydrocarbon content (Akbari Nasrekani et al., 2016). High-quality deposits are notably present in the Uinta Basin of Utah and Colorado (Taylor Boden, 2012).

Initially, Gilsonite was employed as a lost circulation material in water-based drilling fluids and subsequently utilized as a low-density additive in cement formulations for lost circulation control (Slagle KA, 1958). Various studies have highlighted its diverse applications and benefits in cementing operations:

- **Lost Circulation Control and Density Reduction:** Slagle and Carter (1959) demonstrated that Gilsonite effectively reduces the density of cement slurries and acts as a lost circulation control agent. Its scouring action aids in removing mud cake from the borehole, enhancing cement placement efficiency (Slagle KA, 1958).
- **Filtration Reduction:** Radenti and Ghiringhelli (1972) observed that incorporating Gilsonite into cement slurries reduced filtration rates by 40%, improving the slurry's overall performance (Radenti & Ghiringhelli, 1972).
- **High-Temperature Performance Improvement:** Vural K k et al. (2011) used Gilsonite as a modifier to enhance the high-temperature performance of unmodified binders, indicating its suitability for thermal stability in cementing applications (K k et al., 2011).
- **Enhancement of Mechanical Properties and Gas Migration Control:** Raha (2016) reported that Gilsonite aids in density control, mud removal, and enhances both compressive and cement bond strength. It also improves isolation characteristics while reducing gas migration through the cement matrix (Raha, 2016).
- **Self-Healing Properties:** Due to its composition containing light hydrocarbons, Gilsonite exhibits self-healing capabilities when encountering gas or light hydrocarbons, sealing microcracks and preventing fluid migration (Didier et al., 2018).
- **Hydrocarbon Migration Restriction:** William et al. (2019) found that Gilsonite-modified cement composites can restrict hydrocarbon migration at the cement-casing and cement-formation interfaces, thereby enhancing zonal isolation (William, 2019).

Additionally, Gilsonite offers advantages over traditional additives like fly ash. While fly ash is a common pozzolanic material used to improve compressive strength, it has limitations. The

inclusion of Gilsonite not only boosts compressive strength but also mitigates issues associated with fly ash. According to the American Gilsonite Company (2022), Gilsonite-modified cement reduces cracking tendencies, acts as a bridging material to heal micro-fissures, decreases permeability, improves cement bond strength, and ensures zonal isolation. It also eliminates the need for on-site blenders or batch mixers, prevents pump cavitation, and removes the requirement for wetting and defoaming agents (Company, 2022).

Applications of Gilsonite in Cementing Operations (Slagle KA, 1958):

- Primary cementing in lost-circulation zones.
- Squeeze cementing to repair casing leaks or poor primary cement jobs.
- Re-cementing above zones with inadequate cement fill.
- Plugging operations to reestablish drilling fluid circulation.

The properties of Gilsonite make it a promising additive for high-pressure, high-temperature (HPHT) and geothermal wells, particularly where severe lost circulation is a challenge due to naturally fractured formations (William, 2019). Its affinity for hydrocarbons provides a solution for mitigating hydrocarbon migration through cement interfaces.

However, while some data on mechanical properties like unconfined compressive strength (UCS) are available, comprehensive studies on both short-term and long-term mechanical characterization are limited. Current research primarily focuses on Gilsonite's fluid loss control properties and other operational benefits, indicating a need for further investigation into its mechanical performance over time.

2.3.2.6 Fly ash.

Fly ash is a waste product resulting from the combustion of coal in coal-fired thermal power plants. Annually, about 750 million tons of fly ash are produced worldwide, posing significant disposal challenges (Kabir et al., 2016). Although fly ash is a valuable source of engineering materials, its full potential remains largely untapped.

The characteristics of fly ash depend on the technology used during its production. It is formed and released before the flue gases are expelled, using two main types of boilers: fluidized bed boilers and conventional pulverized coal boilers (Kar et al., 2022). Understanding the types and varieties of coal is crucial, as they play a significant role in determining the properties of the resulting fly ash (Matsunaga et al., 2002).

In coal-fired thermal power plants, 60% to 88% of fly ash is collected using particle pollution control equipment like electrostatic precipitators. This fly ash is produced by burning coal at high temperatures ranging from 1200°C to 1700°C and comprises various organic and inorganic components. Due to its complex composition, variable particle size and shape, and fine particles, identifying, specifying, characterizing, and utilizing fly ash can be challenging processes (Kar et al., 2022).

Chemical composition of fly ash.

The fundamental difference between geopolymers and traditional cement lies in their chemical bonding. Cement is based on hydration and ionic bonding, whereas geopolymers consist of three-dimensional covalent bonds formed through the polycondensation of inorganic aluminosilicate solutions (Abd Rahman et al., 2021). The performance variations in geopolymers are primarily due to their chemical composition and the activation of their constituent compounds (Romero et al., 2023).

Geopolymers are synthesized by the alkaline activation of aluminosilicate-based materials like fly ash, differing from cement, which relies on hydration reactions (Salehi et al., 2016). The chemical composition of fly ash can vary significantly depending on the type of coal used and the combustion process employed (Kar et al., 2022), as illustrated in **Table 3** (Gollakota et al., 2019).

Table 3. Composition of fly ash obtained from different coals (Gollakota et al., 2019).

Component (mass %)	Bituminous	Subbituminous	Anthracite	Lignite
Al ₂ O ₃	5–35	20–30	25.1–29.2	10–25
MgO	0–5	1–6	0.7–0.9	3–10
Fe ₂ O ₃	10–40	4–10	3.8–4.7	4–15
SiO ₂	20–60	40–60	43.5–47.3	15–5
CaO	1–12	5–30	0.5–0.9	15–40
Na ₂ O	0–4	0–2	0.2–0.3	0–6
K ₂ O	0–3	0–4	3.3–3.9	0–4
SO ₃	0–4	0–2	–	0–10
TiO ₂	0.5	1.1–1.2	1.5–1.6	0.23–1.68
P ₂ O ₅	0.02	0.3–0.5	0.2	–
MnO	0.02	0.1	0.1	0.04–0.21
S	0.08–0.67	0.7	0.1	–
Loss on ignition	0–15	1.8–2.7	8.2	0–5

Class F fly ash

The American Society for Testing and Materials (ASTM) classifies fly ash into two categories: Class C (high calcium) and Class F (low calcium) fly ash (T & Ramaswamy, 2017). Class F fly ash is widely used due to its abundant availability and technical advantages, such as reduced heat of hydration, decreased bleeding and segregation, lower permeability, and enhanced resistance to sulfates and acids. However, it also presents drawbacks like poorer carbonation resistance and higher water absorption when used in concrete (Rashad, 2015).

Activation of Fly ash.

Chemical activation of fly ash primarily involves two processes: sulfate activation and alkali activation (Lee et al., 2003; Poon et al., 2001). Various alkali activators are employed to activate fly ash, typically using calcium hydroxide (Ca(OH)_2), sodium hydroxide (NaOH), or other oxides to increase the mixture's alkalinity. This increased alkalinity corrodes the densified outer glassy layer of the fly ash particles, exposing the reactive core and facilitating a faster reaction (T & Ramaswamy, 2017).

2.3.3 Hydration of cement.

Portland cement is classified as a hydraulic cement because it gains strength through chemical reactions with water—a process known as hydration. This reaction results in hardening and solidification, providing rigidity to the cement matrix (Abid, 2018).

When cement is mixed with water in specified ratios recommended by manufacturers, the clinker components react with water, leading to the formation of hydrates and hydroxides. These products contribute to the cement's strength but also introduce internal porosity. The "wait-on-cement" (WOC) time—the period required for the cement to achieve a minimum compressive strength of about 3.5 MPa (500 psi)—varies depending on the water-to-cement (w/c) ratio, cement composition, and additives used.

As a hydraulic cement, Portland cement sets and hardens in both dry and wet environments, whether left in air or submerged underwater (Nelson, 1990). Hydration leads to mechanical bonding, heat generation, and volume changes in the cement paste, all influenced by curing conditions (Aïtcin, 2016). Due to its volumetric instability during hydration, cement paste can experience a chemical contraction—also known as Le Chatelier's contraction—losing between 1% and 8% of its absolute volume (Aïtcin, 2016; Keating et al., 1989).

According to Powers (1958), achieving full hydration requires a minimum w/c ratio of 0.42. Water in the cement paste can be categorized as reactive—forming a "solid gel" responsible for the bonding properties—or non-reactive "gel water," which adheres to the hydrated cement paste. Hydration can occur in closed systems or those open to external water sources (POWERS, 1958). As illustrated in **Figure 7**, chemical contraction in a sample with a 0.42 w/c ratio shows that in a dry environment, the relative volume of air increases over time, whereas in a wet environment, water enters the sample through the pore network.

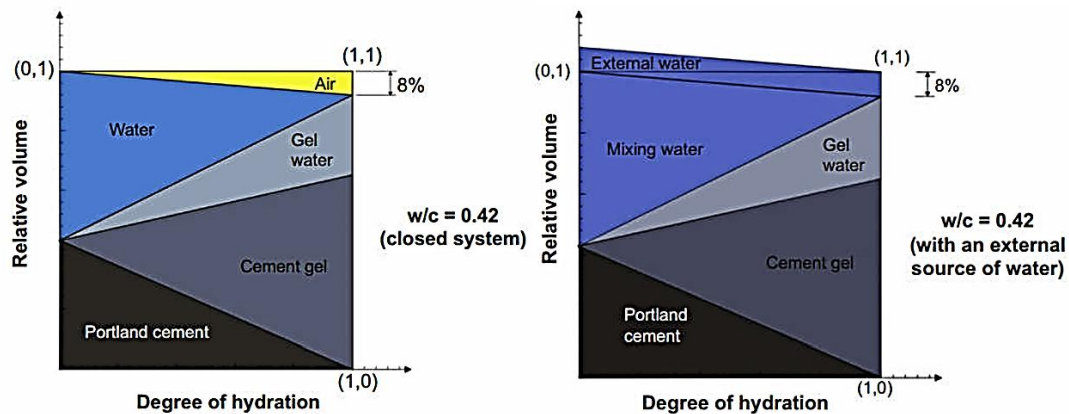


Figure 7: Relative Volume Evolution of Cement Components During Hydration in a Dry Environment (Left) and Under Water (Right) (Aïtcin, 2016)

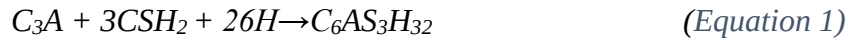
The hydration process involves dissolution and precipitation in a complex chemical system, resulting in hydrate formation and cement hardening. This reaction is an example of an inhibited autocatalytic or chemical clock reaction, initiated when water contacts the anhydrous cement powder (Luke et al., 1995). Therefore, proper storage conditions for cement powder are crucial to prevent premature hydration.

The primary products of cement hydration are (Aïtcin, 2016):

- Calcium Silicate Hydrate (C-S-H), a gel-like substance.

- Calcium Hydroxide (CH), also known as portlandite, a crystalline phase.
- Trisulfoaluminoferrite hydrates (AFt), with ettringite being the most significant.
- Monosulfoaluminoferrite hydrates (AFm).

The hydration of tricalcium aluminate (C_3A) is significant during the early stages and affects the mechanical and rheological properties of cement. C_3A reacts rapidly with water, causing "flash setting" due to the formation of calcium aluminate hydrate platelets on the clinker surface. To control this, calcium sulfate (gypsum) is added during clinker production, leading to the precipitation of ettringite:



Once the sulfate is depleted, ettringite reacts with remaining C_3A to form monosulfoaluminate:



Silicate hydration, primarily involving alite (C_3S) and belite (C_2S), dominates the hydration kinetics due to their abundance in cement clinkers. The reaction stages include dissolution (I), induction (II), acceleration (III), deceleration (IV), and diffusion (V) phases (Aïtcin, 2016; Nelson, 1990):



These reactions result in the formation of C-S-H gel and CH (portlandite). Tricalcium silicate (C_3S) contributes to early strength development, while dicalcium silicate (C_2S) influences strength at later stages (Fink, 2015).

Gutteridge and Dalziel (1990) investigated the hydration over 100 days for individual cement clinker phases mixed with a w/c ratio of 0.71. Using X-ray diffraction, they measured phase

consumption in a cement with the following composition: 68% C₃S, 14% C₂S, 6% C₃A, 7% C₄AF, and 2% calcium sulfate. The cement had a density of 3,160 kg/m³ and a Blaine fineness of 320 m²/kg. Their findings, depicted in **Figure 8**, show a logarithmic behavior for hydration reactions of all phases except C₂S, with most reactions occurring within the first 40 days.

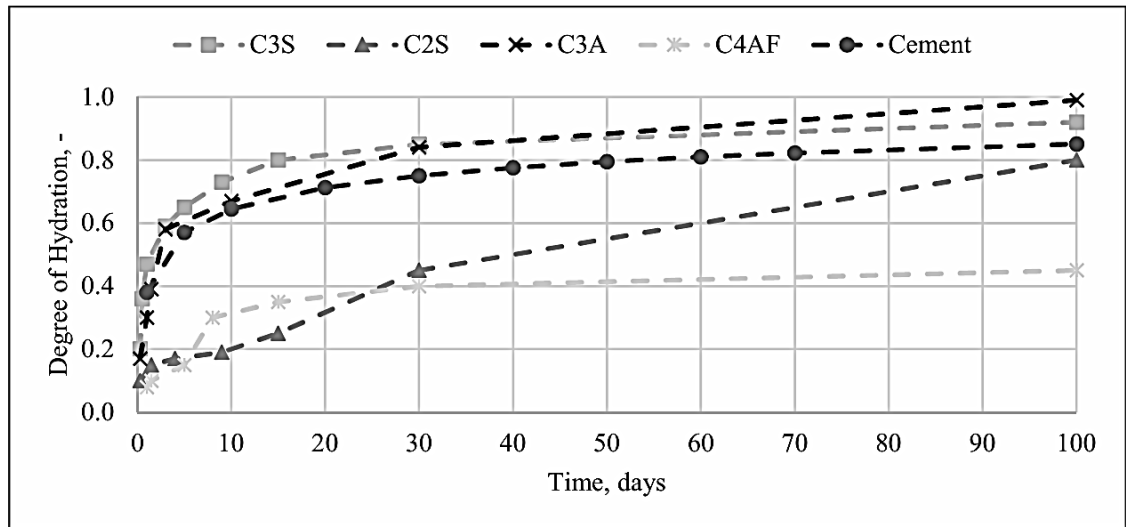


Figure 8: Hydration Reaction Progress Over Time (Gutteridge & Dalziel, 1990)

Monitoring the heat generated during cement hydration reveals that, although hydration continues over extended periods, significant heat flow and temperature increases occur mainly during the dissolution and acceleration phases within the initial hours after mixing as shown in **Figure 9**.

Dissolution (I), induction (II), acceleration (III), deceleration (IV), and diffusion (V)

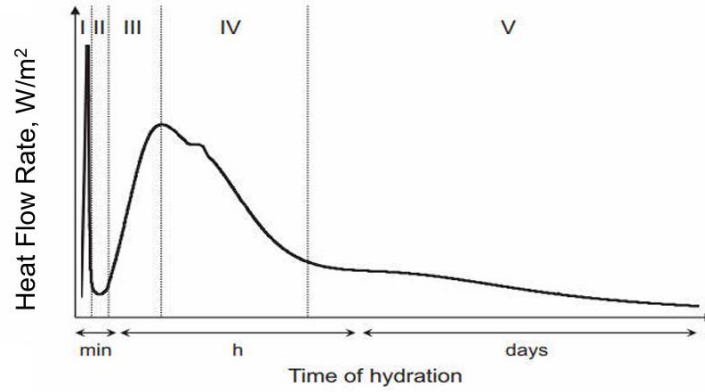


Figure 9: Heat Flow vs. Hydration Time in Cement (Aïtcin, 2016)

2.3.4 Hydration of silicates.

Silicates constitute approximately 80% of Portland cement's composition, making them the predominant phase (Nelson, 1990). Specifically, about 70% is tricalcium silicate (C_3S), and around 20% is dicalcium silicate (C_2S). The hydration reactions of these silicates with water are as follows (Michael S. Mamlouk, 2011; Mindess, 2008):

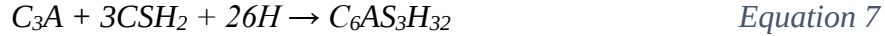


Both reactions produce Calcium Silicate Hydrate (C-S-H) and Calcium Hydroxide (CH). However, C_3S hydrates more rapidly than C_2S , contributing to early strength development in cement. In contrast, C_2S hydration occurs more slowly, influencing strength at later stages (Abid, 2018).

2.3.5 Hydration of Aluminate Phase.

Although the aluminate phase is less abundant than silicates, it significantly affects the rheology and early strength of cement. Tetracalcium aluminoferrite (C_4AF) hydrates at a rate similar to

tricalcium aluminate (C_3A) but much slower (Nelson, 1990). Initially, C_3A reacts with gypsum (CSH_2) and water to form ettringite ($C_6AS_3H_{32}$):



The stability of ettringite depends on the availability of gypsum. Ettringite does not contribute to cement strength development. Once gypsum is depleted, ettringite reacts with any remaining C_3A to form monosulfoaluminate hydrate crystals:



In sulfate-deficient conditions, monosulfoaluminate crystals are stable. However, in the presence of additional sulfate, these crystals can revert to ettringite. The ettringite crystals are about two and a half times larger than monosulfoaluminate crystals and can cause cement cracking when exposed to sulfate environments (Michael S. Mamlouk, 2011; Mindess, 2008).

2.3.6 Temperature on cement setting.

Temperature plays a pivotal role in the setting, hardening, and overall performance of cement composites used in well cementing operations. Accurate determination of downhole temperatures is essential for designing cement slurries that can withstand the specific thermal conditions of a reservoir. This factor comes into play for the reason that temperature fluctuation has a significant impact on the cement composite behavior and performance. This is due to the initial exothermic reaction that the cement has within the first 24 to 36 hours, and the endothermic process that cement goes through after that initial time. Temperature fluctuations can significantly influence the hydration reactions of cement, thereby affecting its mechanical properties, setting time, and long-term durability (Batista da Silva et al., 2018; Luke, 2004; Vu et al., 2012; Wang, 2017).

In high-temperature environments, such as those encountered in deep wells, the rate of cement hydration accelerates. This acceleration leads to a shorter setting time and rapid development of

early compressive strength. However, elevated temperatures can also cause substantial chemical and microstructural changes in the cement matrix, which may impact the long-term integrity of the wellbore (Bahafid et al., 2018; Batista da Silva et al., 2018; Karim et al., 2018; Mahmoud & Elkatatny, 2024; Rincon et al., 2022).

Figure 10 presents the influence of temperature and pressure on cement strength development in the first 24 hours of curing. As temperature and pressure increase—from 35°C to 77°C and from 3.5 MPa to 30 MPa, respectively—cement samples exhibit higher initial strength in less time, effectively reducing the required "wait-on-cement" (WOC) time. This relationship, however, is not linear and can vary at higher temperatures where phenomena such as strength retrogression may occur (Erik B Nelson, 2006; Rincon et al., 2022).

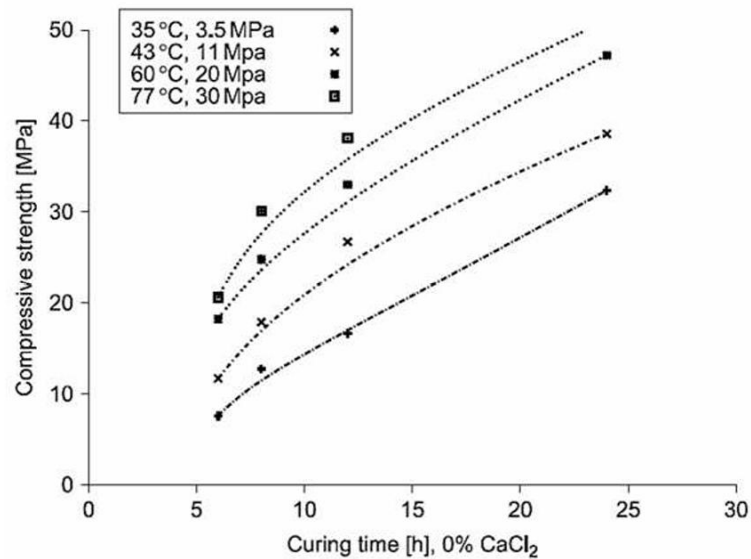


Figure 10: Pressure and Temperature Influence on UCS over One Day (Fink, 2015)

Research by Elkhadiri et al. (2009) demonstrated that curing temperature significantly affects cement hydration and mechanical strength development. At lower temperatures (e.g., 22°C), the hydration process is slower, allowing for controlled precipitation of hydration products within the

cement's pore structure. This controlled process contributes to gradual strength gain over time. In contrast, higher curing temperatures (e.g., 85°C) accelerate hydration reactions, leading to higher initial strengths but can result in a decline in strength over extended periods due to the formation of less stable hydration products (DeBruijn et al., 2010).

The exothermic nature of the initial cement hydration within the first 24 to 36 hours contributes to the temperature rise within the cement matrix (Luke, 2004). This self-heating can exacerbate the effects of already high downhole temperatures, potentially leading to issues such as thermal cracking or strength retrogression (Vu et al., 2012; Wang, 2017).

Strength retrogression is a phenomenon where cement loses strength over time when exposed to temperatures typically above 110°C (Eilers & Nelson, 1979). This loss occurs due to the conversion of strength-contributing phases like calcium silicate hydrates into less stable, high-temperature phases such as alpha-dicalcium silicate hydrate. To mitigate strength retrogression, silica additives like silica flour or microsilica are incorporated into the cement slurry. These additives react with free lime released during hydration to form additional calcium silicate hydrate phases that are stable at high temperatures (Eilers & Nelson, 1979; Scrivener et al., 2004).

At lower temperatures, neat Portland cement can achieve satisfactory strength development without additives. However, at temperatures exceeding 110°C, the inclusion of silica is essential to maintain mechanical integrity and low permeability (Rincon et al., 2022; Saunders & Walker, 1954).

In addition to mechanical properties, temperature influences the permeability and porosity of the set cement. High temperatures can lead to increased pore pressure and microcracking, which may compromise the zonal isolation capabilities of the cement sheath (DeBruijn et al., 2010; Karakosta

et al., 2015; Wu et al., 2020). Therefore, thermal stresses must be considered in cement design to ensure long-term well integrity.

Advanced cement formulations are being developed to address these thermal challenges. High-temperature cements with specialized additives can enhance thermal stability, reduce shrinkage, and improve resistance to thermal degradation (Mahmoud & Elkatatny, 2024). These formulations often include nanomaterials, fibers, and other additives that enhance the cement's thermal and mechanical properties (M. R. Islam, 2011).

2.4 Bonding

Effective bonding between the cement and the steel casing or geological formation is crucial for maintaining zonal isolation and ensuring the integrity of a well throughout its lifespan. This bond is established primarily through adhesion at the interface of the two contacting materials. The strength of this adhesive bond depends on the resistance to separation between the surfaces. Measuring the displacement across the interfacial bond provides valuable insights into the bond's strength and performance (Wilson et al., 2018).

However, traditional assessments often focus on macro-scale bonding, which may not accurately represent the complex stress distributions and bonding mechanisms occurring at the micro-scale interface. The limitations of several commonly used wellbore logging tools in evaluating cement bonding are summarized in **Table 4** (Kiran et al., 2017). Notably, the adhesive bond between the cement and the casing or formation is not a singular, uniform bond but rather a collection of numerous smaller bonds distributed across the interface (Wilson et al., 2018), as illustrated in **Figure 11**.

Table 4: Limitations of various wellbore logs (Kiran et al., 2017).

Logs/Surveys	Uses	Limitations
Cement Bond and Variable Density Logs	Predicts well-bonded cement, debonding at wet casing and formation	No prediction of mud channels, vertical cracks, gas chimney, and radial variation in cement
Ultra-sonic imaging log	Shows well-bonded cement, mud channel in good cement, gas chimney, and debonding at wet casing	Unable to figure out mud channels in weak cement, vertical cracks, debonding at dry casing and formation, and radial variation in cement
Isolation Scanner	Capable of showing good cement, mud channels, gas chimneys, thick vertical cracks, debonding at wet casing and formation, and cement radial variation	No prediction on thin vertical cracks and debonding at dry casing

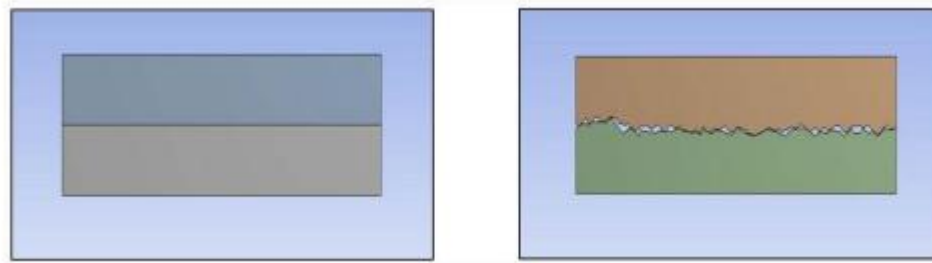


Figure 11: Bond model with continuous contact (left). A bond with discontinuous contact but collection of small bonds (right) (Wilson et al., 2018).

These two bonding models—the continuous contact and the discontinuous contact—exhibit distinct failure behaviors under applied stress conditions. In a continuous contact interface, the bond is likely to experience a complete failure when subjected to certain shear stress levels, potentially leading to a loss of zonal isolation and compromising well integrity (Goodwin & Crook, 1992). In contrast, a discontinuous contact model, composed of multiple smaller adhesive bonds, tends to fail progressively as individual bonds break at varying stress thresholds. Under similar stress conditions, the discontinuous bond may weaken but can remain partially intact, providing

residual bond strength and a degree of redundancy that prevents immediate catastrophic failure (Bosma et al., 1999), as shown in **Figure 12**.

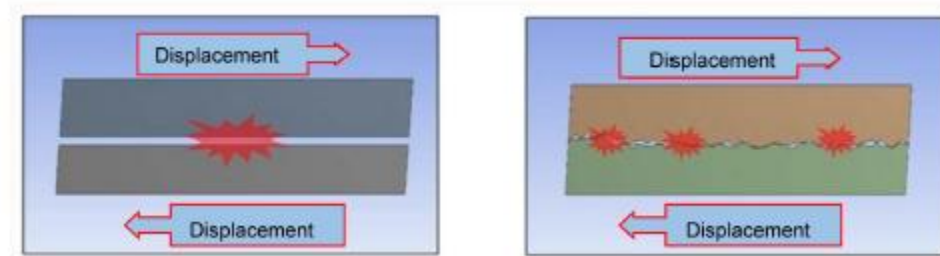


Figure 12: Failure under shear stress conditions. Continuous bond model complete failure (left). Irregular failure in discontinuous bond yet still intact (right). (Wilson et al., 2018)

The bonding between the cement and the casing or formation adheres to the principles of mechanical bonding theory. This bond is formed when the cement slurry infiltrates surface irregularities—such as cavities, pores, and asperities—on the casing or formation surfaces and then hardens, creating a mechanical interlock. The effectiveness of this process is significantly influenced by the rheological properties of the cement slurry, which determine its ability to flow into and fill these surface features. Adequate wetting of the surfaces is essential to displace air and ensure intimate contact between the cement and the substrate (H, 2015).

Surface roughness plays a critical role in enhancing adhesion. Rougher surfaces provide greater opportunities for mechanical interlocking due to increased surface area and the presence of more peaks and valleys (Fjær et al., 2008). The higher the number of these surface irregularities on the casing or formation, the greater the likelihood of forming a stronger mechanical bond with the cement. Surface preparation techniques, such as sandblasting or chemical treatments, can be employed to increase surface roughness and thereby improve bond strength (Alshahrani et al., 2021).

The enhanced adhesive bond resulting from increased surface roughness requires higher shear forces to overcome the friction and disrupt the bond compared to a smooth surface. However, this advantage is realized only if the cement slurry can adequately wet the rough surface initially (H, 2015). Therefore, the wetting properties and overall quality of the cement slurry are critical factors influencing the formation of a strong frictional adhesive bond.

The mechanical properties of the cement, such as tensile strength, Young's modulus, and Poisson's ratio, significantly affect the cement sheath's ability to withstand operational stresses and prevent failure (Thiercelin et al., 1998). Matching the elastic properties of the cement to those of the surrounding formation can help minimize stress concentrations at the interface, thereby enhancing bond integrity (Bosma et al., 1999). Williams et al. (2011) recommend that for a cement system to endure operational load cycling over time—especially under conditions of elevated temperature, pressure, and cyclic stresses—it should exhibit the following mechanical characteristics:

- **High Tensile Strength to Young's Modulus Ratio:** A higher ratio indicates that the cement is more resilient and better able to accommodate deformation without failing. This property makes the cement more favorable for withstanding the mechanical stresses associated with temperature and pressure fluctuations, as well as cyclic loading conditions common in well operations.
- **Optimal Young's Modulus Ratio Between Cement and Formation:** An ideal ratio of the cement's Young's modulus to that of the formation is approximately 0.5. This balance ensures that the cement is neither too rigid nor too flexible compared to the formation, reducing the risk of debonding or fracturing due to differential strains (Thiercelin et al., 1998).

Furthermore, the chemical composition and microstructure of the cement can influence its bonding properties. Additives such as latex, silica fume, and nano-materials have been shown to enhance bonding by improving the cement's mechanical properties and its ability to adhere to casing and formation surfaces (M. R. Islam, 2011; Saunders & Walker, 1954).

2.4.1 Effect of casing roughness on shear bond.

The roughness of the casing surface significantly influences the shear bond strength between the cement and the casing. Shear bond strength is defined as the force required to overcome the mechanical bond at the interface of the cement and the casing (Carter & Evans, 1964). This bond is crucial for maintaining well integrity, as it ensures proper adhesion and prevents fluid migration.

In their experimental study, Evans and Carter (1964) investigated the effects of temperature, surface roughness, and mud contamination on the shear bond strength of Portland cement with steel pipe. They found that increased temperature leads to thermal expansion of the casing, imposing additional stress on both the shear bond and the casing itself. Regarding surface roughness, their results indicated that rusty pipes exhibited a much higher bonding strength compared to smoother, mill-finished pipes. This is illustrated in **Table 6**.

Table 5: Effect of surface roughness on shear bond adapted from Carter and Evans (1964)

Steel Type of finish	Bond Strength	
	Shear (psi)	Hydraulic (psig)
New (Mill Varnish)	74	200-250
New (Varnish chemically removed)	104	300-400
New (Sandblasted)	123	500-700
Used (rusty)	141	500-700
New (sandblasted-resin-sand coated)	2400	1100-1200

Similarly, Scott and Brace (1966) observed that enhancing the roughness of the casing surface improves the bond strength between the casing and the cement. They utilized resin-sand coatings

to artificially increase surface roughness, which maintained excellent bond strength even under high-temperature conditions of 300°F to 400°F (Scott J B, 1966).

The increased shear bond strength due to surface roughness is attributed to the mechanical interlocking between the cement and the irregularities on the casing surface. Rough surfaces provide more surface area and more cavities (peaks and valleys) for the cement to penetrate and harden, resulting in a stronger mechanical bond (Li et al., 2016). This interlocking requires greater shear force to overcome, enhancing the overall bond strength between the cement and the casing.

2.4.2 Effect of mud contamination.

Mud contamination during cementing operations can adversely affect the quality and integrity of the cement sheath. Morgan and Dumbauld (1952) investigated the harmful effects of treated mud sheaths contaminating cement slurries during placement. Their research revealed a significant reduction in the tensile strength of the hardened cement due to chemicals in the treated muds altering the cement's structural and rheological properties (Morgan & Dumbauld, 1952). This led to lower cement strength and poor bonding to the casing, as shown in **Figure 13**.

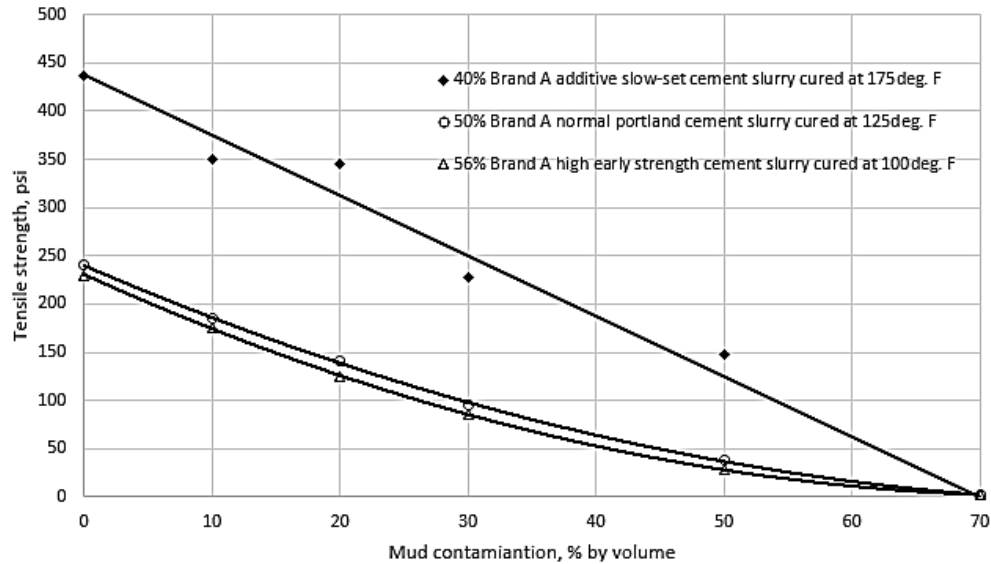


Figure 13: Effect of mud contamination on tensile strengths of three types of oil well cements (Morgan & Dumbauld, 1952).

In recent decades, there has been increased use of oil-based muds (OBMs) in unconventional reservoirs and deep high-pressure/high-temperature (HPHT) zones due to their stability at elevated temperatures (Amani et al., 2012). However, research indicates that contamination of cement by OBMs can be detrimental to the integrity of the cement sheath. Studies have shown an increase in porosity and a significant decrease in compressive and shear bond strength when cement is contaminated with OBMs (Carter & Evans, 1964; Li et al., 2016). Additionally, OBM contamination can alter the thickening time of the slurry and reduce the likelihood of the cement slurry adequately wetting the substrate surfaces, leading to weaker bonds with the casing and formation (Peterson, 1963). **Table 7** presents shear bond test results for different drilling fluid systems, highlighting the pronounced negative effect of oil-based mud.

Table 6: Effect of mud type on shear bond strength adapted from (Carter & Evans, 1964)

Type of Mud	Shear Bond (psi)
None	141
Water base	97
Inverted Oil Emulsion	66
Oil base	63

The presence of a mud cake layer along the formation walls or on the outer surface of the casing during cement placement can hinder the formation of a proper cement bond seal (Nath et al., 2018). This issue critically affects both the short-term and long-term integrity of the well, as it can lead to micro-annuli and channels that allow fluid migration (Amani et al., 2012; Shadravan & Amani, 2012). Consequently, there has been a concerted effort to improve drilling fluid displacement and enhance the cleaning of casing and formation surfaces before cementing operations (Erik B Nelson, 2006).

Advanced spacer fluids and mechanical cleaning tools are being utilized to effectively remove residual drilling fluids and mud cake. The design of spacer fluids that are compatible with both the drilling mud and the cement slurry is crucial for efficient mud removal and to prevent contamination (Erik B Nelson, 2006). Moreover, optimizing the rheological properties of the cement slurry can enhance its ability to displace mud and wet the casing and formation surfaces, thereby improving bond strength (Shadravan et al., 2015).

2.4.3 Effect of casing centralization on cement bond.

Casing centralization is a critical factor in achieving a successful primary cementing operation. Proper centralization ensures that the casing is centered within the wellbore, facilitating uniform placement of cement in the annulus and preventing mud channeling. To effectively displace drilling mud and avoid channeling, the frictional pressure drop of the cement slurry must overcome the gel strength of the mud (Xie et al., 2015).

In deviated and horizontal wells, the casing tends to become eccentric due to gravitational forces and wellbore geometry. This eccentricity results in an uneven annular space, where the narrow side experiences slower mud flow, leading to gelation and ineffective mud displacement by preflush or spacer fluids. Consequently, cleaning the wellbore and preparing it for cementing

becomes more challenging, potentially compromising the quality of the cement bond (Cooper & Birch, 1990; Kerunwa et al., 2021; Kettl et al., 1993).

Casing eccentricity can also occur due to hole enlargement or formation caving. Limited use of centralizers increases the likelihood of casing eccentricity, which can lead to well integrity issues throughout the well's lifespan (Akgun & Al-Ghadban, 2004). Additionally, eccentric casing can result in non-uniform loading during various well operations, increasing the risk of casing collapse (Guohua et al., 2012). **Figure 14** illustrates the difference between concentric and eccentric casing placements in a wellbore.

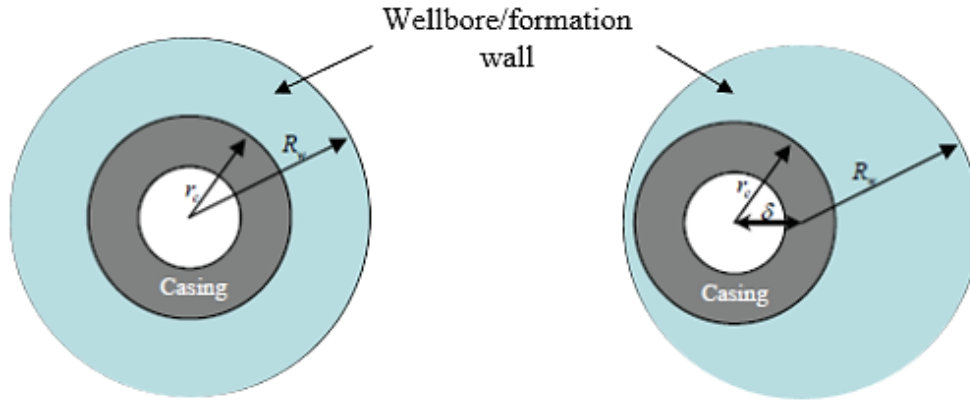


Figure 14: Schematics of casing placements in a wellbore: concentric (left) and eccentric (right) (Salehabadi et al., 2010)

The degree of eccentricity is calculated using Equation 2, yielding a value between 0% (perfectly concentric) and 100% (casing touching the wellbore wall) (Salehabadi et al., 2010):

$$\text{Eccentricity}\% = \frac{\delta}{(R_w - r_c)} * 100$$

Equation 9

Cementing calculations often assume a concentric casing, which can be inaccurate, especially in deviated wells (Akgun & Al-Ghadban, 2004). Since the 1940s, using spacers or preflushes has been recommended to separate drilling mud from cement slurry and improve mud removal.

Couturier et al. (1990) investigated mud removal in eccentric annuli and found that the rheology (density, viscosity, and gel strength) of the spacer relative to the drilling mud and cement is critical for effective displacement (Couturier et al., 1990).

Andrade et al. (2014) studied the relationship between casing centralization and cement bonding. Their results, summarized in **Table 8**, indicate that centralized casing negatively affects bonding at both the casing-cement and cement-formation interfaces, even without considering thermal effects (De Andrade et al., 2014). After thermal cycling, the deterioration of the casing-cement bond was more severe in the scenario with 50% casing stand-off. This phenomenon can be explained by the uniform thermal loading on the cement, making areas with high tensile radial stress more likely to exceed the bond strength compared to a centralized casing.

Table 7: The percentage of casing-cement and cement-formation bonding in the centralized casing scenario and 50% stand-off scenario respectively.

Sample	Bonding	Before cycling	After cycling
Centralized	Casing-cement (%)	79	77
	Cement-formation (%)	97	96
50% stand-off	Casing-cement (%)	93	82
	Cement-formation (%)	99	99

2.4.4 Shear bonding experimental methods.

Over the past decades, significant research has focused on studying and improving the shear bond strength between cement and casing to enhance well integrity. Teodoriu et al. (2018) investigated the shear failure and bonding stresses of neat Class H cement using two experimental setups depicted in **Figure 15**. They found that the pure shear strength of neat Class H cement is higher than the shear bond strength at the cement-casing interface. The pure shear strength (τ_{pure}) was calculated using Equation 10, and the shear bond strength (τ_{bond}) was calculated using Equation

11. Their findings imply that debonding along the cement-casing interface occurs before the cement sheath itself fails under shear stress (Teodoriu et al., 2010; Teodoriu et al., 2018a).

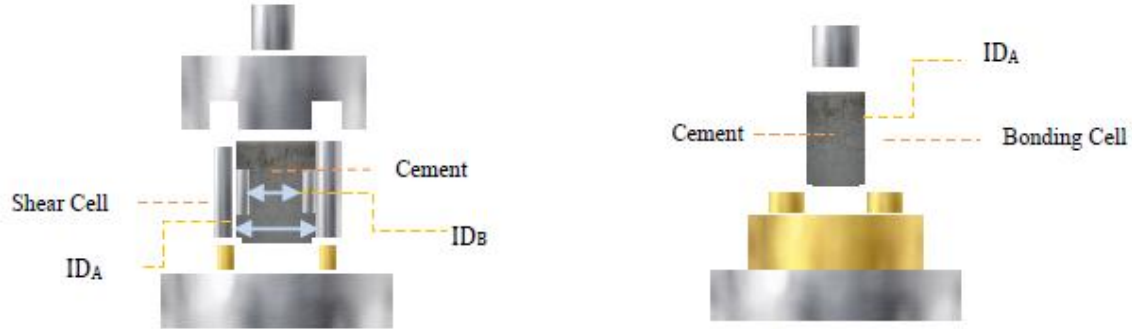


Figure 15: Pure shear strength (left) and shear bonding strength (right) set ups (Teodoriu et al., 2018a)

$$\sigma = \frac{F_{max}}{2\pi * ID_B * SL}$$

Equation 10

$$\sigma = \frac{F_{max}}{2\pi * ID_A * CL}$$

Equation 11

Jadhav et al. (2017) conducted experiments to measure the effect of casing coating on the shear bond strength of Class G cement containing a defoamer and free water control agent. Their experimental setup was similar to that of Teodoriu et al. (2018), as shown in **Figure 16**. They discovered that the shear bond strength of cement to casing with an inorganic coating was twice that of uncoated pipe (Jadhav et al., 2017). Based on their results, they recommended coating casing pipes in the field to enhance shear bond strength.

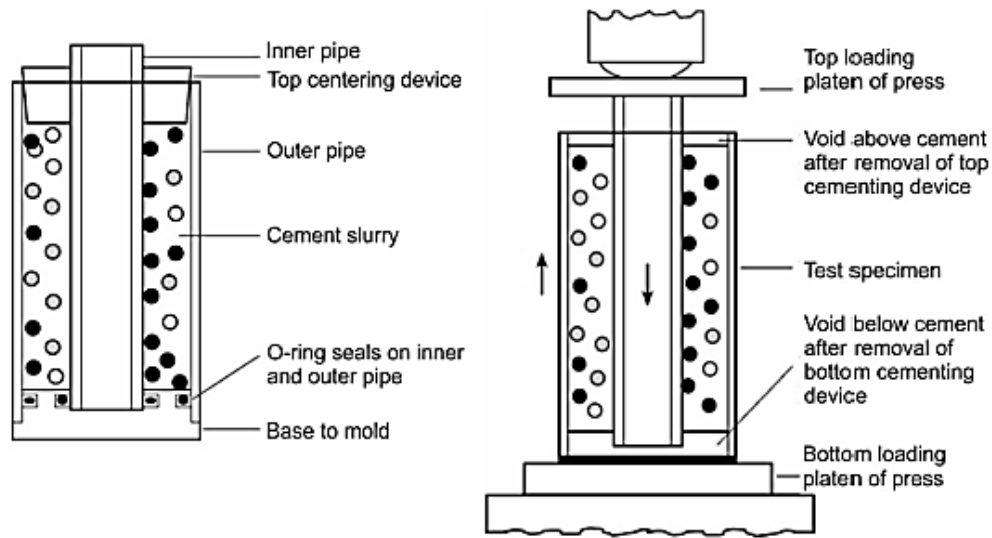


Figure 16: Schematic of setup using hydraulic press to measure shear bond strength (Jadhav et al., 2017)

Salehi et al. (2017) explored the characterization and shear bond strength of geopolymer cements using different molar concentrations of alkali activators. They tested the bond strength using two types of pipes: one with mill varnish coating and one without. The experimental setup is illustrated in **Figure 17**. Their findings indicated that geopolymer cements could provide comparable or improved shear bond strength compared to traditional Portland cements, especially when optimized with appropriate activator concentrations.

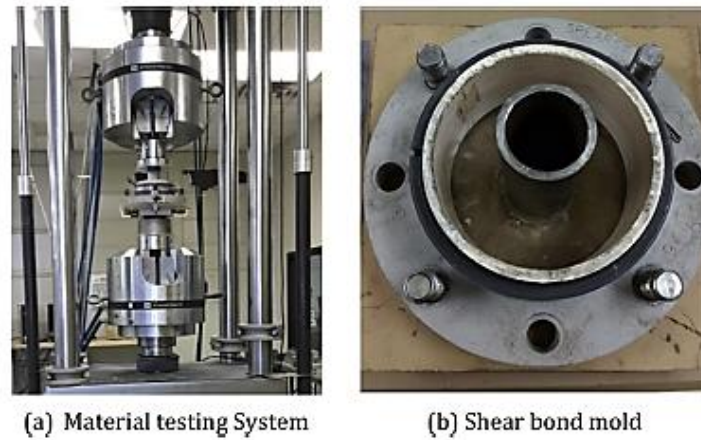


Figure 17: Experiment setup for shear bond strength test of geopolymer cement (Salehi et al., 2017)

Neto et al. (2014) investigated the bond strength between Portland cement and steel substrates prepared using three different surface treatments:

- **a)** Washed with water and dried with ethanol.
- **b)** Chemically treated with NaCl solution on the surface.
- **c)** Coated with a layer of cement dried before placement in a mold.

Their research showed that steel chemically treated with NaCl exhibited the strongest shear bond strength. They suggested that chloride ions influenced the corrosion process of the steel, creating a rougher substrate surface, which enhanced mechanical interlocking and resulted in a stronger adhesive bond.

Recent advancements have focused on improving cement-casing bonding through various methods:

- **Surface Texturing:** Enhancing casing surface roughness using mechanical or chemical methods to improve mechanical interlocking (Li et al., 2016).

- **Nanomaterial Additives:** Incorporating nanoparticles into cement slurries to improve rheological properties and bonding characteristics (Li et al., 2022).
- **Advanced Coatings:** Developing specialized casing coatings that promote better adhesion and resist corrosion, further enhancing bond strength (Zhe & Yuxiu, 2018).

Table 8: Summary of authors' findings on UCS using different cement recipes.

Authors	Cement Recipe	Curing Time	Temperature (°C)	UCS (MPa)
(Erik B Nelson, 2006)	Class G	24 hours	60	13.8-20.7
(Erik B Nelson, 2006)	Class H	24 hours	60	12.4-19.3
Benge & Poole (2005)	Foamed cement (density 1.2 g/cm ³)	24 hours	60	2.1-6.9
Benge & Poole (2005)	Latex-modified Class G	24 hours	60	17.2-24.1
Mahmoudkhani et al. (2010)	CO ₂ -resistant cement	7 days	93	34.5-41.4
Mahmoudkhani et al. (2010)	CO ₂ -resistant cement	28 days	93	41.4-48.3
Choolaei et al. (2012)	Class G + 0.5% carbon nanotubes	7 days	25	36.5-42.1
Choolaei et al. (2012)	Class G + 0.5% carbon nanotubes	28 days	25	45.5-51.7
Shahriar & Nehdi (2012)	Class G + 40% fly ash	28 days	23	31.5-38.6
Shahriar & Nehdi (2012)	Class G + 40% fly ash	28 days	60	41.2-48.3

Authors	Cement Recipe	Curing Time	Temperature (°C)	UCS (MPa)
Pang et al. (2014)	Class G + 10% metakaolin	24 hours	60	18.6-24.8
Pang et al. (2014)	Class G + 10% metakaolin	72 hours	60	27.6-34.5
Salehi et al. (2016)	Class H + 1% nanosilica	24 hours	60	22.1-27.6
Salehi et al. (2016)	Class H + 1% nanosilica	72 hours	60	31.0-37.9
Elhard et al. (2017)	Geopolymer cement	7 days	85	20.7-34.5
Elhard et al. (2017)	Geopolymer cement	28 days	85	27.6-41.4
Salehi et al. (2017)	Class G + 35% silica flour	72 hours	149	27.6-41.4
Salehi et al. (2017)	Class G + 35% silica flour	28 days	149	34.5-55.2
Bois et al. (2019)	Ultra-lightweight cement (0.9 g/cm ³)	24 hours	60	3.4-6.9
Bois et al. (2019)	Ultra-lightweight cement (0.9 g/cm ³)	7 days	60	6.9-10.3

Table 9: Summary of authors' findings on IBSS using different cement recipes

Authors	Curing Time	Cement Recipe	Temperature	IBSS (MPa)
(Salehi et al., 2016)	24 hours	Optimized fly ash geopolymer	Up to 300°C	0.56
(Alexandre Lavrov, 2016)	-	Portland Cement	-	0.1 – 1.0
(Zhao et al., 2015)	6 – 60 hours	Portland Cement with Sand	20°C	1.0 – 2.5
(Zhao et al., 2015)	6 – 60 hours	Portland Cement (Added sand to casing)	20°C	2.5 – 7.5

(Teodoriu et al., 2018b)	1, 35, 82	Class H Cement	Room Temp	0.47 – 1.0
(Tabatabaei et al., 2020)	24 hours	Portland Cement	-	0.271
(Lambrescu & Teodoriu, 2022)	1, 3, 7 days	Class G Cement	Room Temp	1.6 - 5.1
(Lambrescu et al., 2024)	Not specified	Portland Cement	Up to 65°C	1.0 – 4.0

3 Methodology.

3.1 Materials and Methods.

In this section, we present a detailed account of the experimental procedures, including the materials used, the methods for sample preparation, and the specific equipment employed to conduct the tests throughout the research.

3.2 Sample preparation.

The initial step in preparing the samples involved accurately measuring the weights of all materials using a digital balance, as depicted in **Figure 18**.

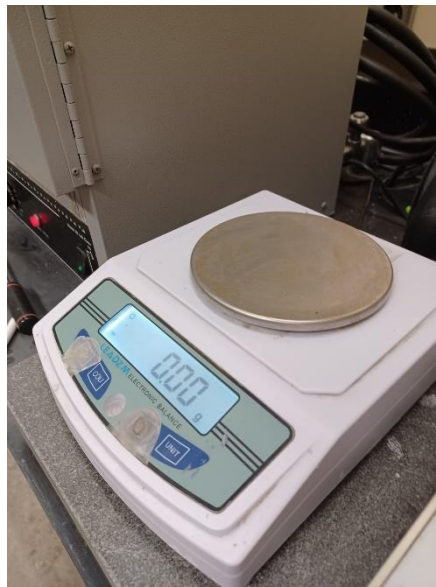


Figure 18: Digital balance.

For the control samples, we precisely weighed 792.72 grams of Class G cement and 348.53 grams of distilled water to produce 600 ml of cement slurry. This mixture served as the baseline for our research.

In order to assess the effects of various additives on the cement properties, we prepared additional samples by incorporating 5% by weight of each additive relative to the cement content. This means

that for each additive—fly ash, silica flour, microblock, gilsonite, iron powder filings, and iron oxide—we added 39.6 grams to the original 792.72 grams of cement. This consistent percentage allowed for a fair comparison of the impact each additive had on the desired properties.

To further explore the influence of higher additive concentrations, we prepared two additional samples:

- For silica flour, we created a sample with a 10% addition, which involved adding 79.2 grams to the cement.
- For fly ash, we prepared a sample with a 30% addition, equating to 237.82 grams added to the cement.

These variations enabled us to observe how increasing the proportion of specific additives might affect the cement slurry's characteristics.

By standardizing the additive percentages and varying them strategically for selected materials, we aimed to systematically evaluate and compare the effects on bonding strength, compressive strength, mechanical properties, and pumpability of the cement slurries. Table 4 shows the cement recipe composition.

Table 10. Samples and recipes.

Sample	Materials		
	Distilled water (grams)	Class G Cement (grams)	Additives (grams)
Class G	348.53	792.72	-
Class G + 5% Fly Ash	348.53	792.72	39.64

Class G + 5% Silica Flour	348.53	792.72	39.64
Class G + 5% Microblock	348.53	792.72	39.64
Class G + 5% Gilsonite	348.53	792.72	39.64
Class G + 5% Iron Powder	348.53	792.72	39.64
Class G + 5% Iron Oxide	348.53	792.72	39.64
Class G + 10% Silica Flour	348.53	792.72	79.27
Class G + 30% Fly Ash	348.53	792.72	237.82

Next, after measuring all the materials, the handling procedures varied based on the experimental set being prepared. For the **first set of samples**, the materials were left in their original state without any additional processing.

For the **second set of samples**, we initiated a manual mixing process. Here, the Class G cement and the respective additives were thoroughly blended by hand until a homogeneous mixture was achieved. This step ensured uniform distribution of the additives within the cement.

In the **third set of samples**, we introduced an additional step to the mixing process. The dry materials—Class G cement and the additives—were first blended together to achieve uniformity. This dry mixture was then gradually added to the distilled water during mixing. This method promotes better interaction between the cement particles and additives with the water, potentially enhancing the properties of the final slurry.

After completing the specific preparation procedures for each experimental set, the dry material mixtures were poured into the mixer, as depicted in **Figure 19**.



Figure 19: Ofite high shear mixer.

Subsequently, the mixing process is initiated promptly. During the first 15 seconds, the neat Class G cement or the pre-blended mixture is carefully added into the mixer, which is set to operate at a shear rate of 4,000 RPM. Just before the 15-second mark, the lid of the mixer is closed to commence high-shear mixing at 12,000 RPM for an additional 35 seconds. Once the prescribed mixing time is completed, the cement slurry is poured into pre-greased metallic molds, as shown in **Figure 20**. These molds are designed to produce three 2-inch by 2-inch cubes, adhering to API-10B2 guidelines corroborated by Rincon et al. (2022). The decision to use cube molds is based on Rincon's findings, which indicate that cylindrical samples do not accurately represent the mechanical properties of cement and do not efficiently correlate Ultrasonic Pulse Velocity (UPV) with Unconfined Compressive Strength (UCS) measurements (Rincon et al., 2022).



Figure 20: Metallic molds.

After the molding process, the cement cubes are carefully submerged in water baths, which are either at room temperature or maintained at an elevated temperature of 75°C, as shown in **Figure 21**. Immersing the samples initiates the curing process, allowing the cement to harden adequately within the molds. Once the samples have reached sufficient hardness, they are removed from the molds and placed back into their respective water baths to continue the curing process.



Figure 21: Experimental set up in water bath.

3.3 Compressive strength measurement.

To determine the unconfined compressive strength of the cement cube specimens, we employed a CM-2500 compression testing machine (**Figure 22**), which is manufactured and calibrated by Test

Mark Industries. According to the manufacturer, this machine has an accuracy of $\pm 0.5\%$. The device applies a uniaxial load to the cement cubes at a rate of $72 \text{ kN} \pm 7 \text{ kN}$ per minute, measuring the force required to produce a permanent (plastic) deformation in the sample.

The compressive strength is calculated by dividing the maximum force applied by the surface area of the cube that was in complete contact with the load-bearing plate of the testing machine. In accordance with API RP 10B-2 guidelines, the results are reported to the nearest 0.3 MPa (50 psi) and are averaged among samples made from the same slurry and tested simultaneously, when applicable.



Figure 22: Test Mark CM-2500 (Romanowski et al., 2018).

3.4 Ultrasonic measurements.

In the 1980s, ultrasonic measurements emerged as a non-destructive technique for estimating the strength of oilfield cement, with foundational work by Rao et al. (1980). This method relies on the emission and reception of high-frequency longitudinal and transverse waves that travel through the length of the sample.

The practice of measuring ultrasonic wave velocity in materials is governed by standards such as ASTM E494, ASTM C597, and API 10B-2. These procedures are recommended for samples thicker than 5 mm with smooth, parallel surfaces. They enable the determination of mechanical properties including modulus of elasticity, Poisson's ratio, acoustic impedance, shear modulus, bulk modulus, as well as reflection and transmission coefficients.

Ultrasonic measurements can be performed both in situ—such as downhole assessments using modern logging tools—and in laboratory settings. In oilfield cements and when using ultrasonic cement analyzers, the speed at which waves propagate through the material varies based on the medium and correlates with the sample's strength. Beyond oilfield applications, this technique is also utilized for estimating the strength of concrete and measuring the thickness of various components, such as the wall thickness of steel pipes.

3.4 Ultrasonic Hardware.

An ultrasonic testing apparatus typically comprises several essential components: a time base, a transmitter and receiver pair, and an A-scan indicator circuit responsible for generating, receiving, and displaying electrical signals associated with ultrasonic waves. To facilitate efficient energy transfer between the transmitter, the sample, and the receiver, a couplant is employed. For the measurement of longitudinal waves, we used the PosiTector™ ultrasonic couplant. In the case of

transverse wave measurements, we utilized a viscous shear gel produced by Magnaflux for Sonotech.



Figure 23: ProceqTM Ultrasonic Device.

Our experiments involved transducers operating at a frequency of 250 kHz. Before initiating each set of measurements, we calibrated the system using a reference sample with a known transit time of 25.4 microseconds (μs). **Figure 23** showcases the ProceqTM device utilized in this research. It is important to note that this device has specific limitations regarding testing frequency, temperature, and pressure, operating optimally at temperatures up to 35°C and under atmospheric pressure conditions.

3.5 Interfacial Bonding Shear Strength

To simulate a wellbore environment for shear bond strength testing, a 2 7/8-inch outer diameter (OD) steel casing pipe was inserted into a 4-inch inner diameter (ID) casing pipe, which represents the wellbore. **Figure 24** illustrates the schematic of the mold assembly used to create the bond between the casing and the cement. **Figure 25** shows the actual mold assembly utilized for the shear debonding tests.

The cement slurry was poured into the annulus between the outer casing and the inner casing. After pouring the slurry, a layer of free water was added on top to prevent dehydration during curing. For elevated temperature tests, the samples were cured in a water bath maintained at 75°C under ambient pressure for durations of 1 and 3 days. The temperature was carefully controlled within a range of $\pm 2^{\circ}\text{C}$. Occasionally, when fresh water was added to the bath, there was a temporary temperature drop of 5–8°C. It is important to note that all tests adhered to consistent procedural standards. After the curing period, the temperature was gradually reduced to avoid introducing thermal stresses into the system.

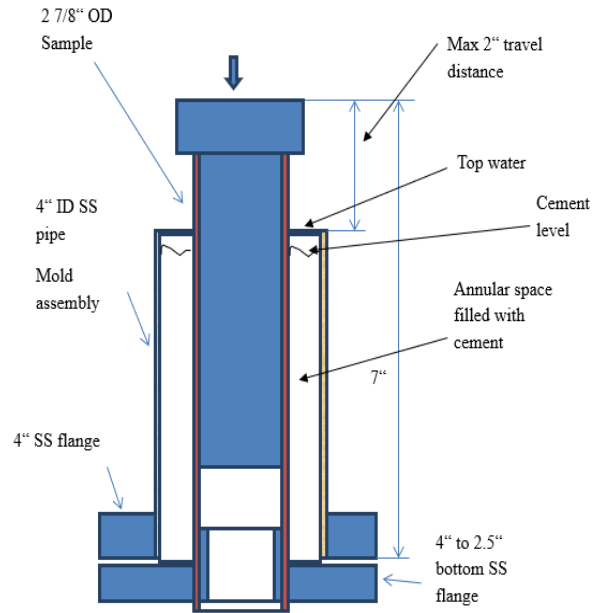


Figure 24: Schematic of the Mold assembly for the shear bond testing.



Figure 25: Mold assembly for the shear bond testing.

A hydraulic press machine, depicted in **Figure 26**, was employed to apply force to the inner casing until debonding occurred. The machine applied load at a rate of 1,000 psi per minute. Using DasyLab software, the displacement of the inner casing and the corresponding force were recorded

every 0.1 seconds. When debonding occurred—often indicated by an audible sound—the inner casing was further advanced through the cement sheath by an additional 40 mm to ensure complete debonding. Subsequently, the entire cement sheath and inner casing were extracted using the hydraulic press.

To calculate the interfacial bonding shear strength, we identified the peak force from the force-displacement plots, which represented the force required to break the bond and initiate movement of the casing sample. The shear bond strength was then determined by dividing this peak force by the known interfacial area between the cement and the casing.

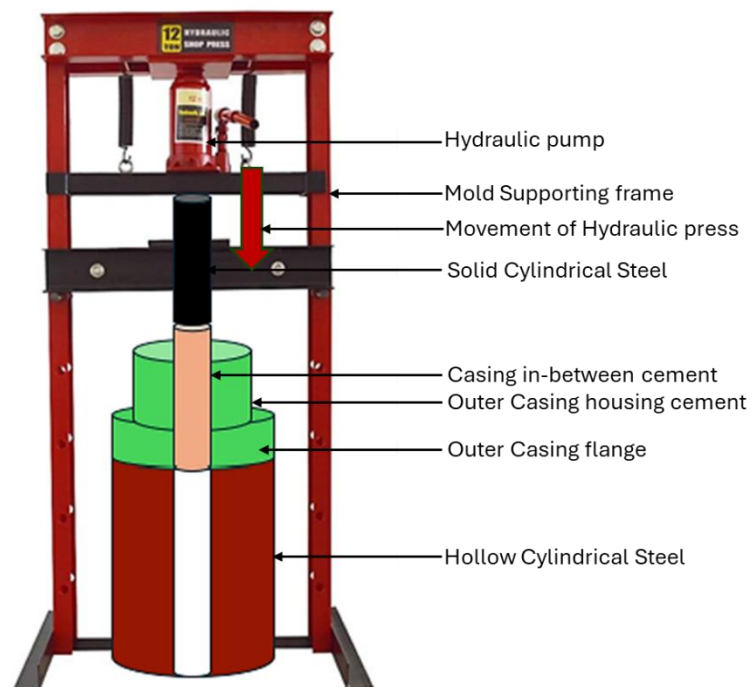


Figure 26: Hydraulic Bond Shear Testing Machine Frame.

3.6 Density measurement.

To determine the density of the samples, we used an analytical method that accounts for the specific geometry of the specimens. Each cube designated for measuring thermal properties had precise dimensions recorded, taking into consideration that a hole was drilled through the cube. To calculate the volume of each sample, we subtracted the volume of the cylindrical hole from the total volume of the cube. This calculation is represented by **Equation 5**:

$$V = (L_1 * L_2 * L_3) - (\pi * r^2 * L_1)$$

Equation 12

In this equation:

- V is the volume of the sample.
- L₁, L₂, L₃ are the length, width, and height of the cube, respectively.
- r is the radius of the cylindrical hole drilled through the cube.
- π is a constant (approximately 3.1416).

After calculating the volume, we measured the weight of each sample using a digital balance, as shown in **Figure 18**.

Finally, we calculated the density (ρ) of each sample by dividing the measured weight (W) by the previously calculated volume (V), as indicated in **Equation 13**:

$$\rho = \frac{V}{W}$$

Equation 13

By following this procedure, we obtained accurate density values for each sample, effectively accounting for the material removed by the drilled hole. This method ensures that the calculated densities reflect the true material properties of the specimens under study.

4 Results and Discussions.

The following section will show the results obtained for the compressive strength measurements and the measurements for the thermal properties of all the different cement composites used throughout the research. All these results are going to be shown mainly through graphs showing the change of the different properties during the period of testing, as well as the mention of the main effects that the additive had on the property that was measured on the respective graph.

4.1 Debonding and Post debonding Analysis.

Figure 27 provides a representation of the Interfacial Bonding Shear Strength (IBSS) testing result, where the relationship between force and displacement is analyzed to evaluate the bonding performance of cement. The graph plots force (measured in lbf) on the vertical axis against displacement (measured in mm) on the horizontal axis, illustrating the progression of bonding strength and its decline during debonding.

The parameter **FMAX** represents the maximum bonding force, which corresponds to the peak point on the graph. This value indicates the highest load the cement-casing bond can withstand before debonding begins. It is critical for understanding the initial strength of the bond and how effectively the cement can maintain integrity under stress. Following **FMAX**, there is a rapid drop in force to a point termed **FMIN**, which represents the minimum bonding force remaining after the debonding process has started. This drop demonstrates the initial weakening of the bond.

The average bonding force, denoted as **FAVG**, provides insight into the bond's stability after debonding. It is calculated from the steady-state region following the sharp drop and reflects the ability of the bond to retain consistent strength during continued displacement. This parameter is significant for evaluating the post-debonding behavior of the cement and how well it can sustain residual loads.

The schematic also highlights **IDFL**, the initial displacement that occurs immediately after the bond begins to fail. Lower values of IDFL signify a more stable bond, as they indicate minimal displacement after debonding starts. Additionally, the **FBFL**, which measures the bonding force loss, is derived as the difference between FMAX and FAVG. This value quantifies the extent of strength loss due to debonding and is a critical indicator of how much bonding performance is compromised after the initial peak force is reached.

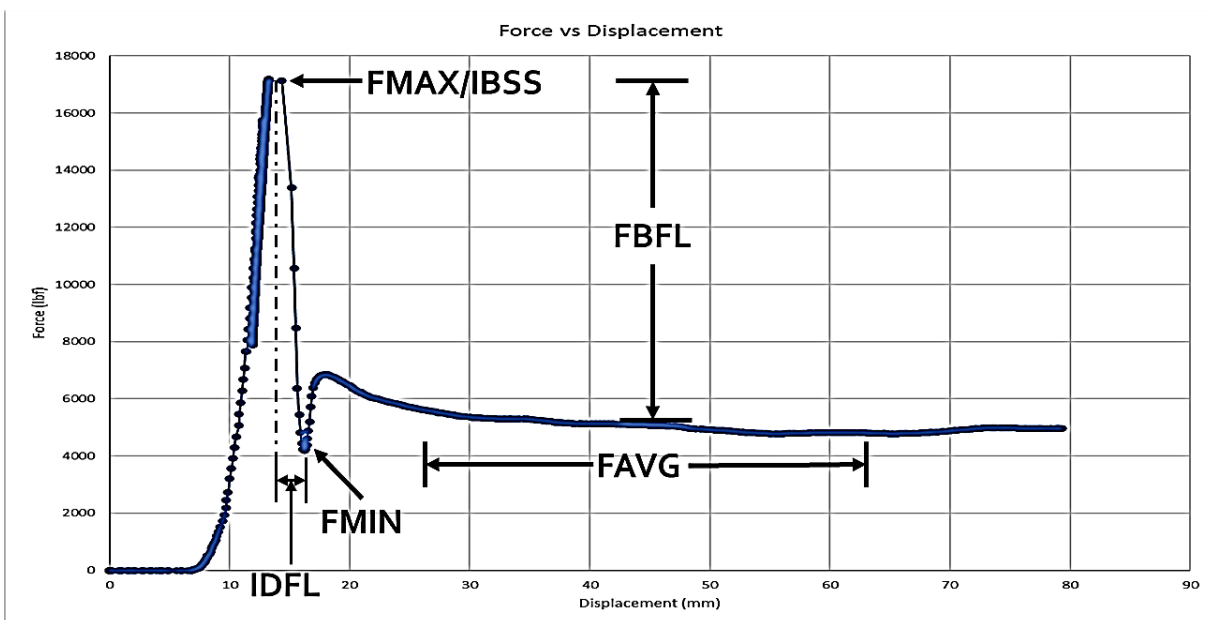


Figure 27: Interfacial Bonding Shear Strength Result

Overall, this schematic illustrates the mechanical response of the cement-casing bond under stress, capturing the transition from maximum strength to post-debonding stability. The parameters extracted from this graph—FMAX, FMIN, FAVG, IDFL, and FBFL—offer a comprehensive understanding of the bonding performance, enabling detailed assessment of the effectiveness of various cement recipes in enhancing wellbore integrity under different conditions.

4.1.1 Maximum Debonding Force.

Figure 28 presents the FMAX (debonding force) for various cement recipes with additives compared to the control sample (Class G cement) after 1 day of curing, measured at both room temperature (RT) and elevated temperature (HT). A consistent trend emerges, showing that elevated temperatures (HT) generally enhance bonding strength, as reflected by higher FMAX values, except for Class G + 30% Fly Ash. Notably, the cement recipe with 5% Fly Ash demonstrates a significant increase in FMAX at HT, outperforming other additives, suggesting that increasing Fly Ash concentration at HT may weaken the Interfacial Bonding Shear Strength (IBSS) as seen in **Figure 29**. Similarly, recipes with 5% Gilsonite and 10% Silica Flour exhibit minimal variation in IBSS across both temperature conditions. Among the additives, Class G + 5% Microblock achieves the highest IBSS at both RT and HT. However, Class G + 5% Silica Flour shows the most pronounced improvement in IBSS with temperature rise. These results highlight the dual importance of curing temperature and additive selection in optimizing debonding force and bond strength.

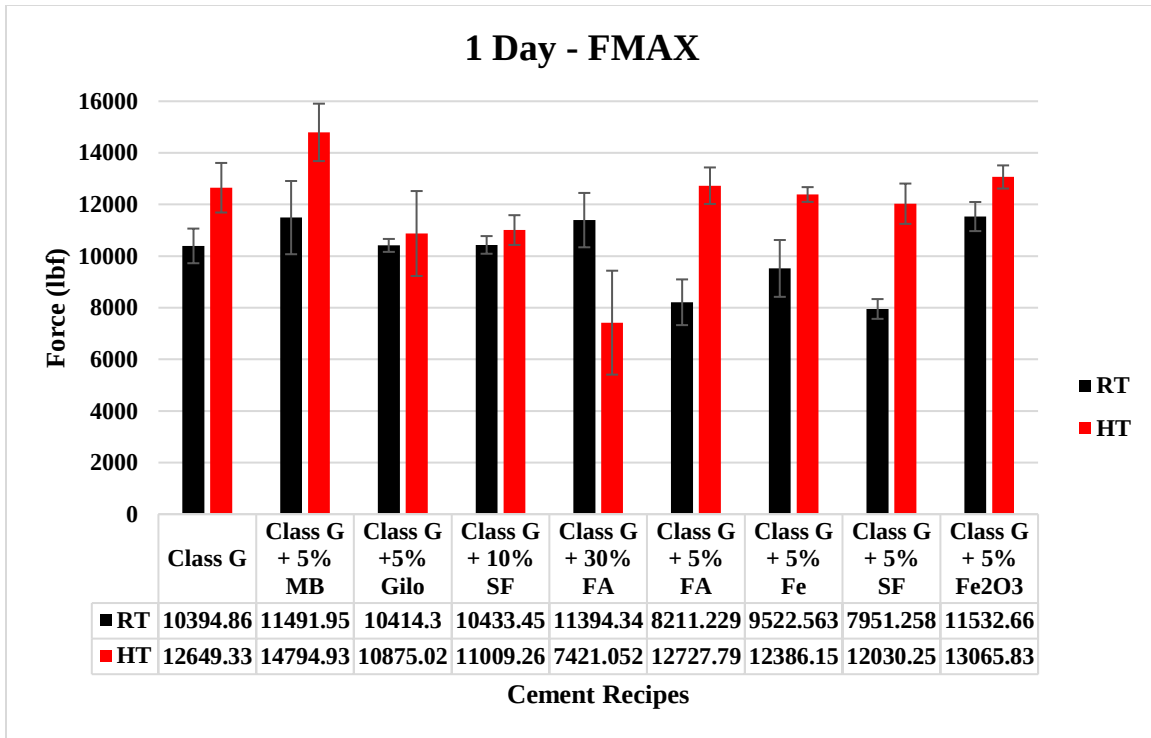


Figure 28. Maximum Debonding force for cement recipes at 1-day curing.

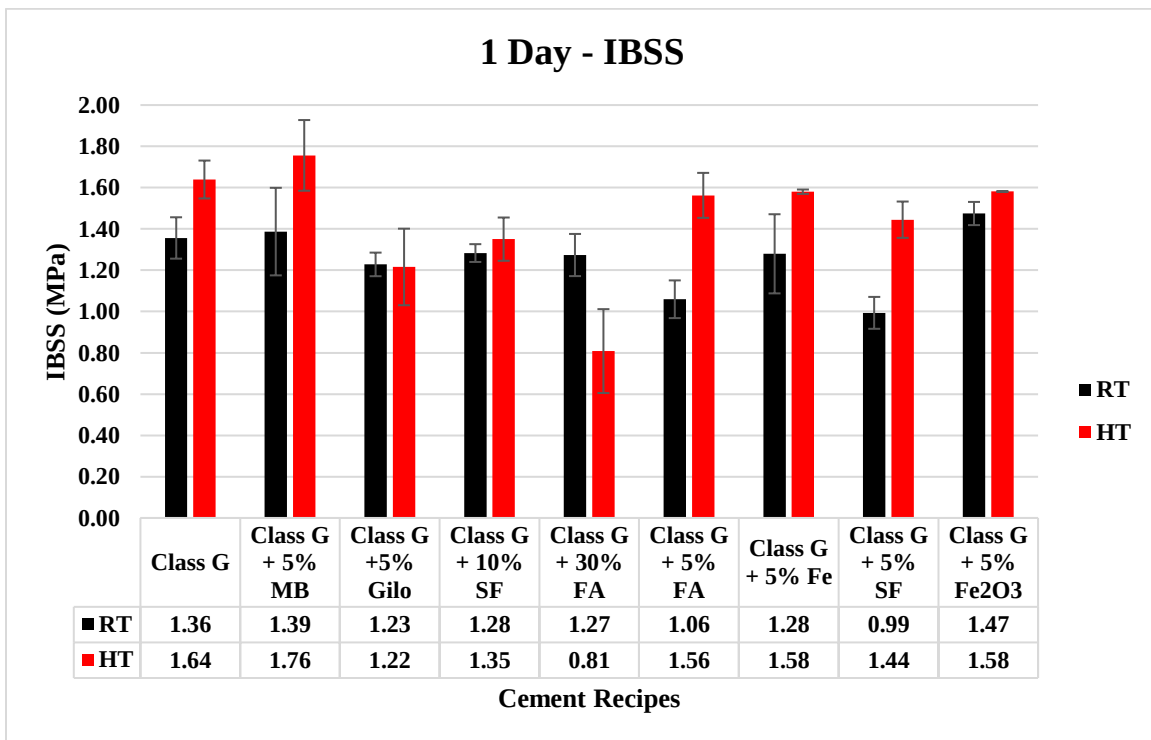


Figure 29: Interfacial Bonding Shear Strength for cement recipes at 1-day curing.

The results for FMAX after 3 days of curing reveal interesting variations across the cement recipes at room temperature (RT) and elevated temperature (HT), as seen in **Figure 30** and **Figure 31**. While most additives show improved bonding strength over time, there are noticeable differences in performance between RT and HT conditions. Notably, the control sample (Class G) maintains high FMAX values at both temperatures, indicating strong baseline performance. The addition of 30% fly ash (FA) performs exceptionally well at RT, recording the highest FMAX value among all samples. However, its performance drops significantly at HT, suggesting that temperature affects the bonding properties of this specific recipe negatively.

On the other hand, additives like 5% silica flour (SF) and 5% iron oxide (Fe_2O_3) exhibit more consistent performance across both temperature ranges, highlighting their stability under elevated temperatures. The recipes with 5% microblock (MB) and 5% Gilsonite (Gilo) also show solid performance, with marginal decreases at HT, but they remain competitive overall. This indicates that while certain additives enhance bonding strength at RT, others maintain better stability at elevated temperatures, suggesting that temperature resilience varies with the type of additive used.

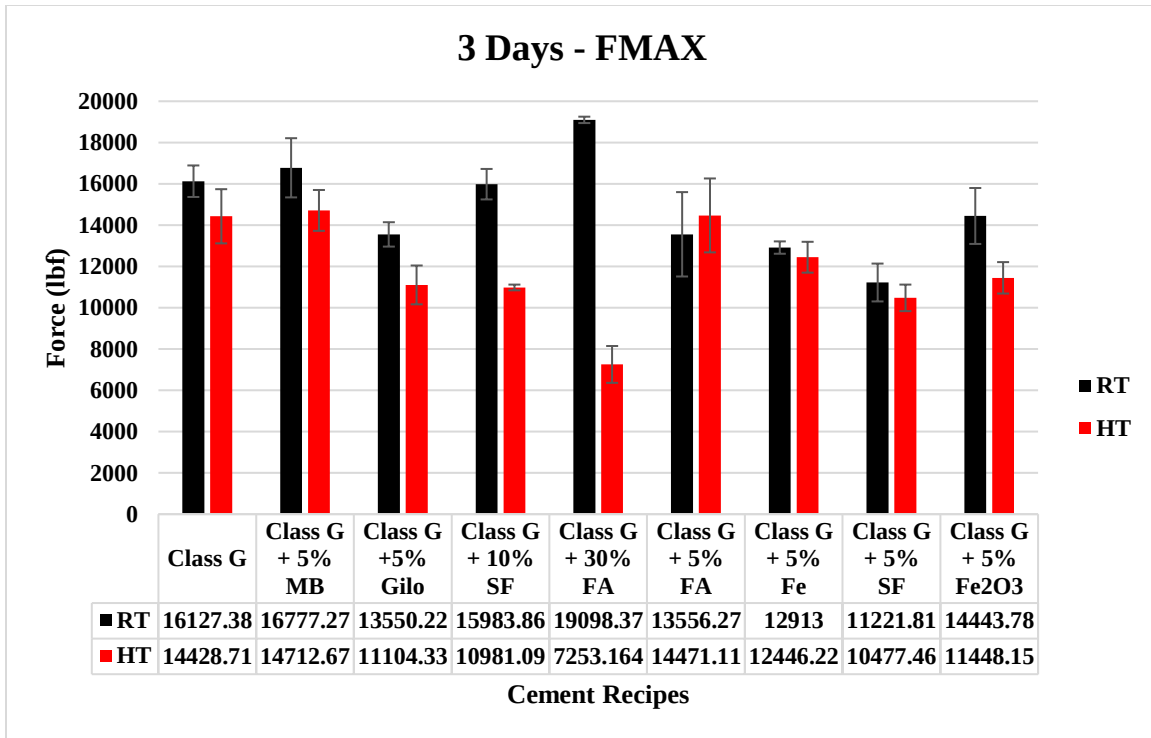


Figure 30. Maximum Debonding force for cement recipes at 3-days curing.

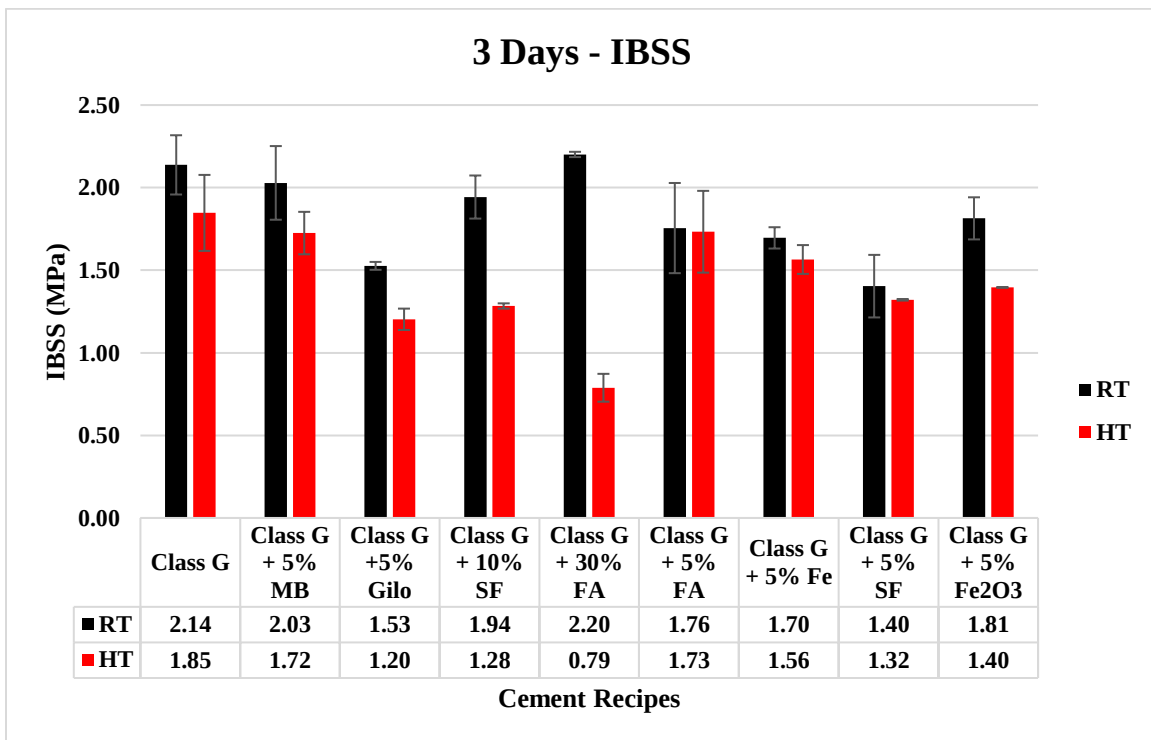


Figure 31: Interfacial Bonding Shear Strength for cement recipes at 3-days curing.

Figure 32 and **Figure 33** show the comparison of FMAX between 1-day and 3-day curing for various cement recipes at room temperature (RT), revealing key trends. Across the board, the 3-day curing period significantly enhances the bonding strength, as evidenced by the higher FMAX values for all cement compositions compared to their 1-day counterparts. This improvement over time highlights the role of extended curing in strengthening the cement matrix and improving the bond between the casing and cement. Among the additives, the 30% fly ash (FA) sample stands out, showing the most significant increase in FMAX after 3 days. This suggests that fly ash may benefit from longer curing times, potentially enhancing its bonding performance over time. On the other hand, while the 5% Gilsonite (Gilo) and 5% iron oxide (Fe_2O_3) mixtures show improvements over time, the differences are less pronounced, indicating these additives may reach peak performance earlier. Overall, this comparison emphasizes the importance of curing duration in maximizing bonding strength, with some additives—such as fly ash—demonstrating a particularly strong response to longer curing times.

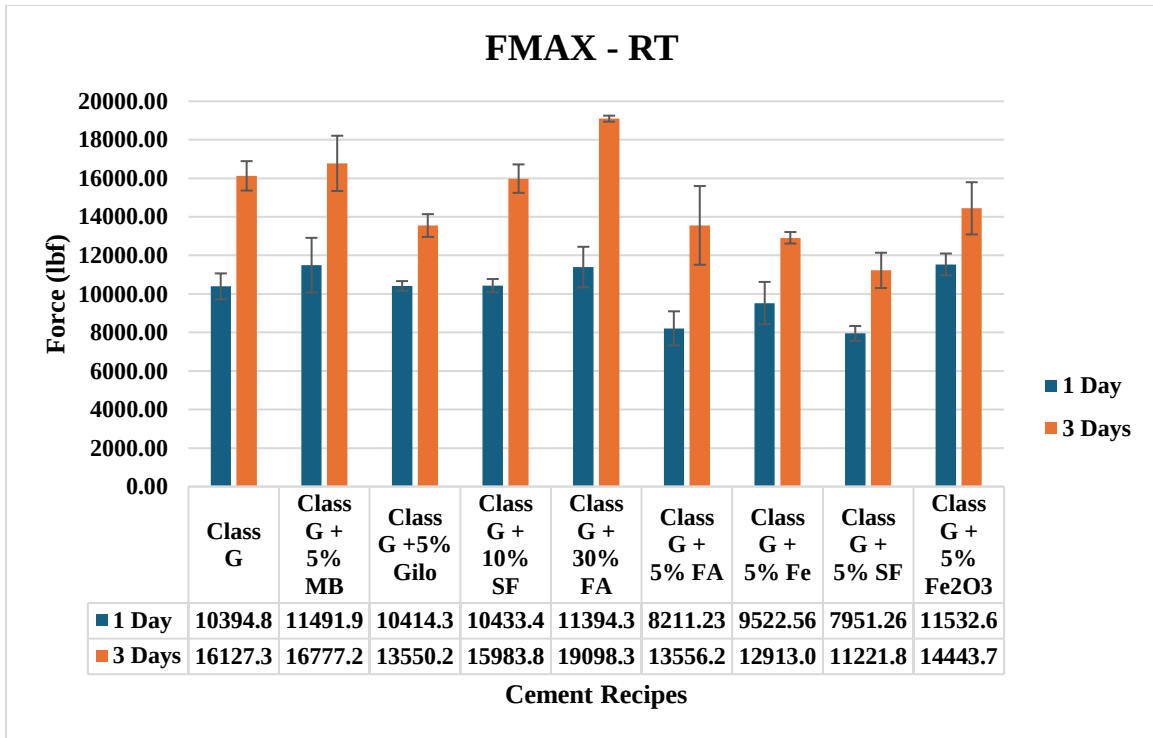


Figure 32. Comparison of Debonding Force between 1- and 3-day curing time at room temperature.

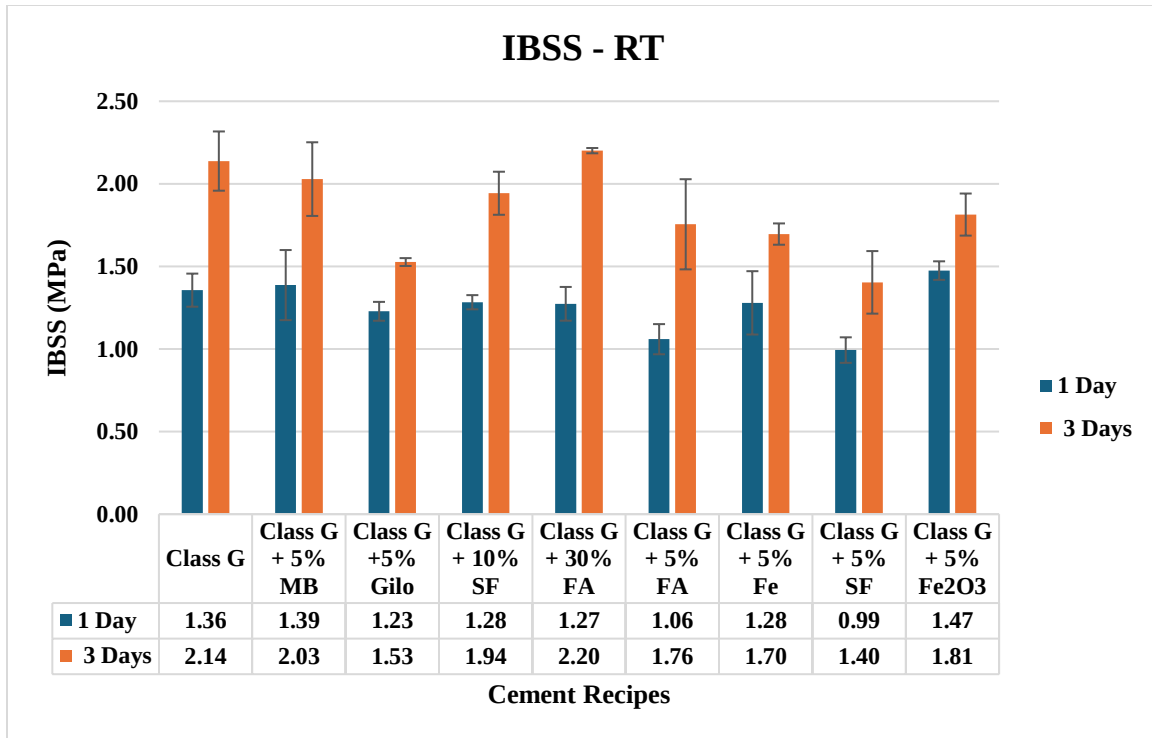


Figure 33: Comparison of Interfacial Bonding Shear Strength between 1- and 3-day curing time at room temperature.

Figure 34 and **Figure 35**, a comparison of FMAX between 1-day and 3-day curing at elevated temperatures (HT), highlights varying trends in the bonding strength across the different cement recipes. Unlike the room temperature curing results, where extended curing significantly enhanced performance, the impact of additional curing time at HT is less pronounced for several additives. In some cases, the performance after 3 days remains nearly identical to the 1-day results, suggesting that certain additives may achieve optimal bonding strength more quickly under high-temperature conditions. For example, the Class G control sample and the 5% Fly Ash blend maintain consistently high FMAX values across both curing durations, indicating that these mixtures are well-suited for HT environments.

On the other hand, the Microblock, Gilsonite (Gilo), 10% Silica Flour, 30% fly ash (FA), and 5% iron filings (Fe) recipes exhibit little to no improvements after 3 days. Interestingly, the mixture

with 5% Silica Flour and 5% iron oxide (Fe_2O_3) shows deterioration from 1 to 3 days, indicating that its bonding strength may be sensitive to extended curing at high temperatures. Overall, the data demonstrates that while HT curing accelerates strength development for certain additives, others benefit only marginally from longer curing periods, underscoring the importance of additive selection based on specific well conditions.

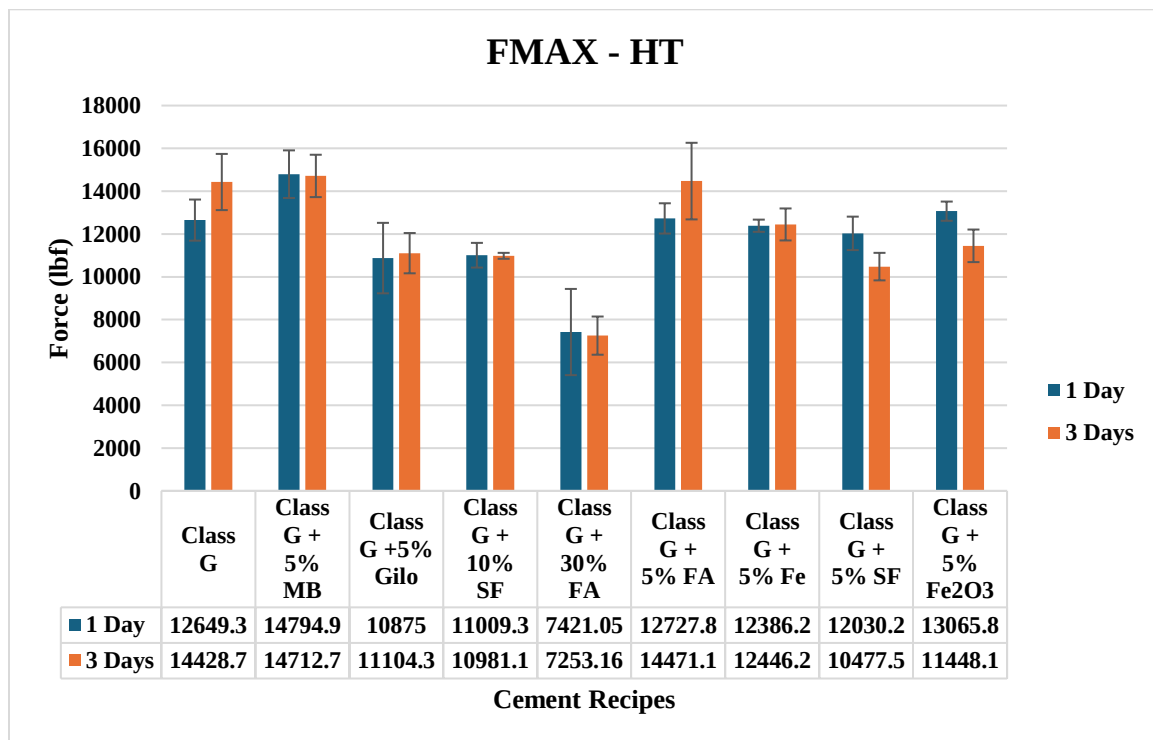


Figure 34. Comparison of Debonding Force between 1- and 3-day curing time at elevated temperature.

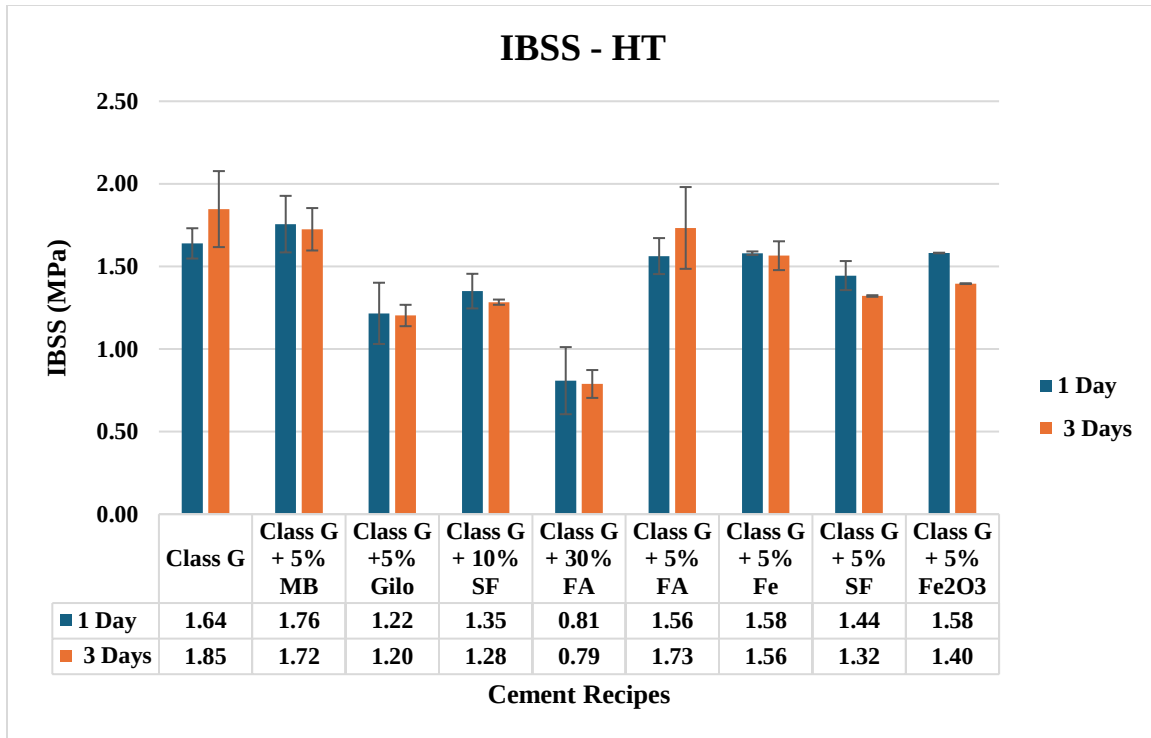


Figure 35: Comparison of Interfacial Bonding Shear Strength between 1- and 3-day curing time at elevated temperature.

4.1.2 Minimum Bonding Force after Debonding.

The 1-day FMIN results offer meaningful insights into how temperature impacts the ability of various cement recipes to maintain casing stability post-debonding, as shown in **Figure 36**. Overall, most additives demonstrate higher FMIN values at room temperature (RT), indicating improved post-debonding strength under RT conditions. Notably, the Class G + 5% Fly Ash (FA) mixture maintains comparable force at both RT and elevated temperature (HT), suggesting temperature stability. Meanwhile, the control sample (Class G), Class G + 5% Microblock (MB), and Class G + 5% iron oxide (Fe_2O_3) exhibit stronger bonding at HT, aligning with the FMAX trends observed for these recipes after 1 day of curing. However, the effect of temperature on the minimum bonding force is not consistent across all recipes, highlighting variability in how different cement compositions respond to thermal conditions after debonding.

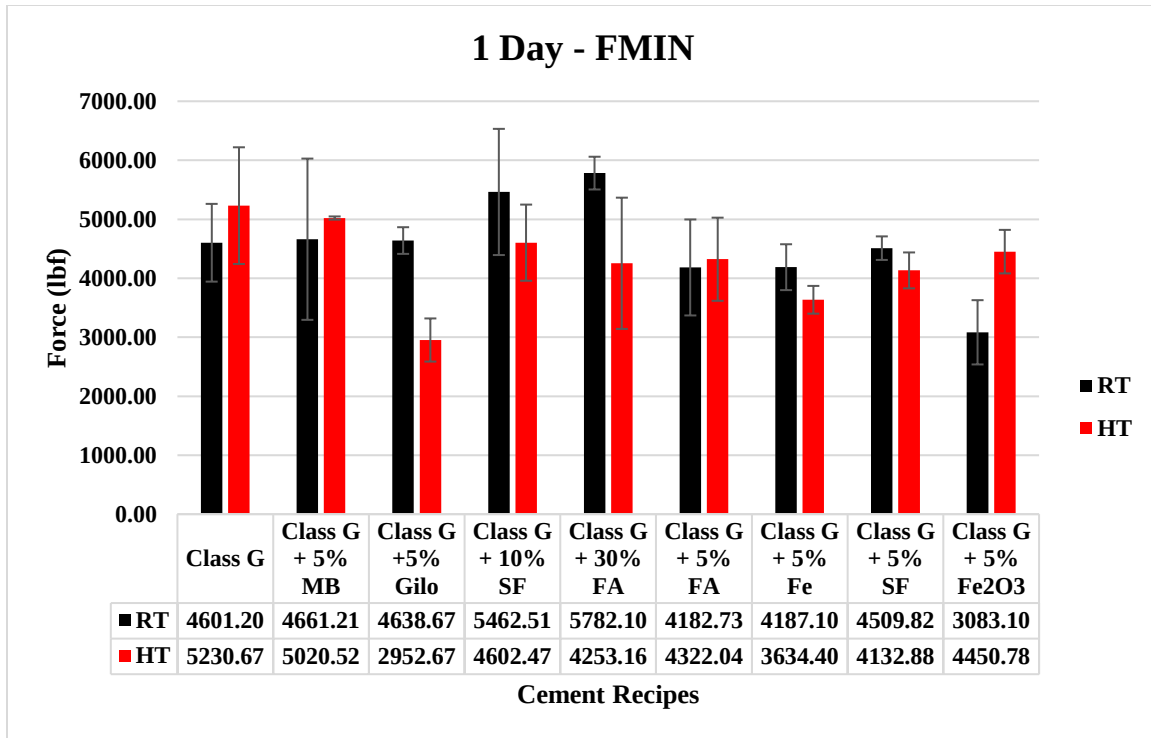


Figure 36. Minimum Bonding force after debonding for cement recipes at 1-day curing.

The 3-day FMIN results highlight the impact of temperature on the post-debonding stability of various cement recipes as seen in **Figure 37**. Unlike the 1-day results, a more distinct pattern emerges, with several additives showing divergent behaviors at room temperature (RT) and elevated temperature (HT). The control sample (Class G) demonstrates the most significant increase in FMIN at HT, suggesting that its bonding strength improves substantially with higher temperatures over time. Similarly, the 5% microblock (MB) blends exhibit stable performances across both temperatures, with only slight differences, indicating consistent bonding behavior.

In contrast, all other recipes—such as 5% (Gilosnite, Fly Ash, Silica Flour, iron filings), 10% Silica Flour, and 30% fly ash (FA)—display notably higher FMIN values at RT, suggesting that these additives are more effective under ambient conditions. This indicates that elevated temperatures may negatively affect their post-debonding bonding strength. Overall, the results

emphasize the importance of both curing time and temperature in determining the optimal performance of specific additives, with some compositions excelling at RT while others perform better under HT.

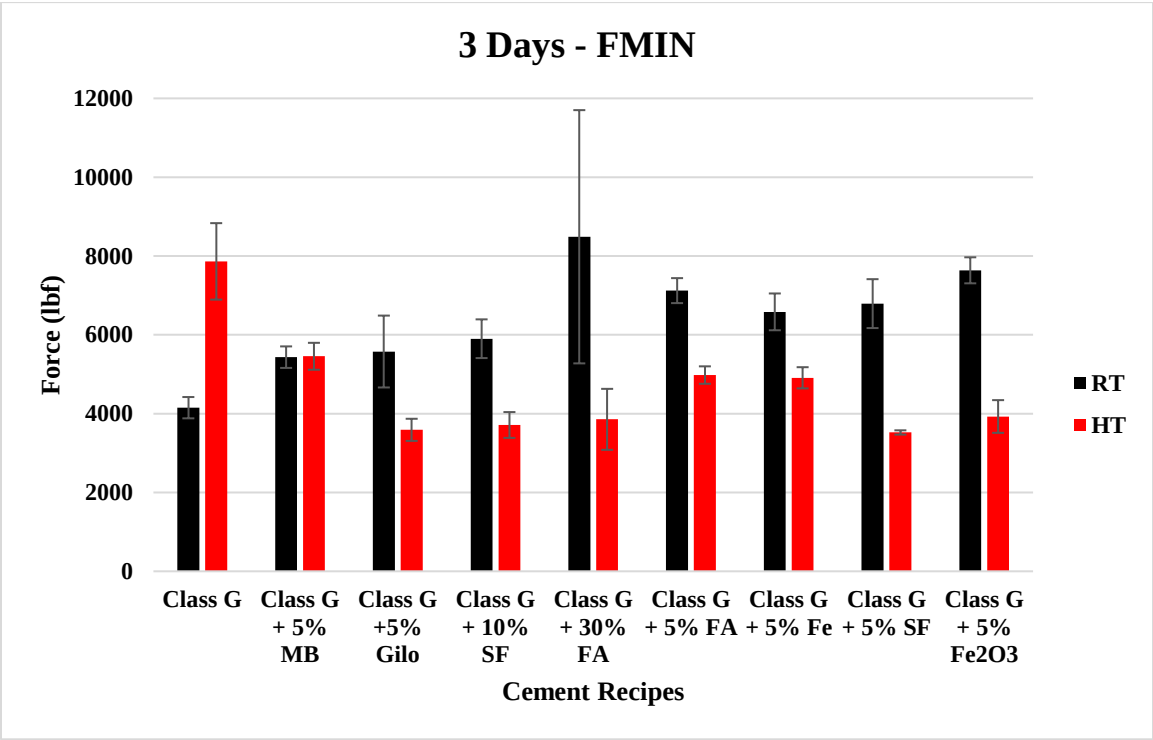


Figure 37. Minimum Bonding force after debonding for cement recipes at 3-day curing.

Figure 38 compares FMIN between 1-day and 3-day curing at room temperature (RT), revealing distinct trends in the post-debonding strength of various cement recipes. All additives except the control sample exhibit higher FMIN values after 3 days of curing, indicating that extended curing enhances these cement formulations' bonding properties and stability. Notably, the 5% iron oxide (Fe₂O₃) sample shows the most significant improvement, with FMIN increasing substantially over time, demonstrating the additive's effectiveness in maintaining casing stability with longer curing durations. On the other hand, while the 5% microblock (MB), Gilsonite, and 10% Silica Flour

blend show slight improvements over time, their FMIN values remain relatively stable, reflecting their consistent bonding performance even with shorter curing.

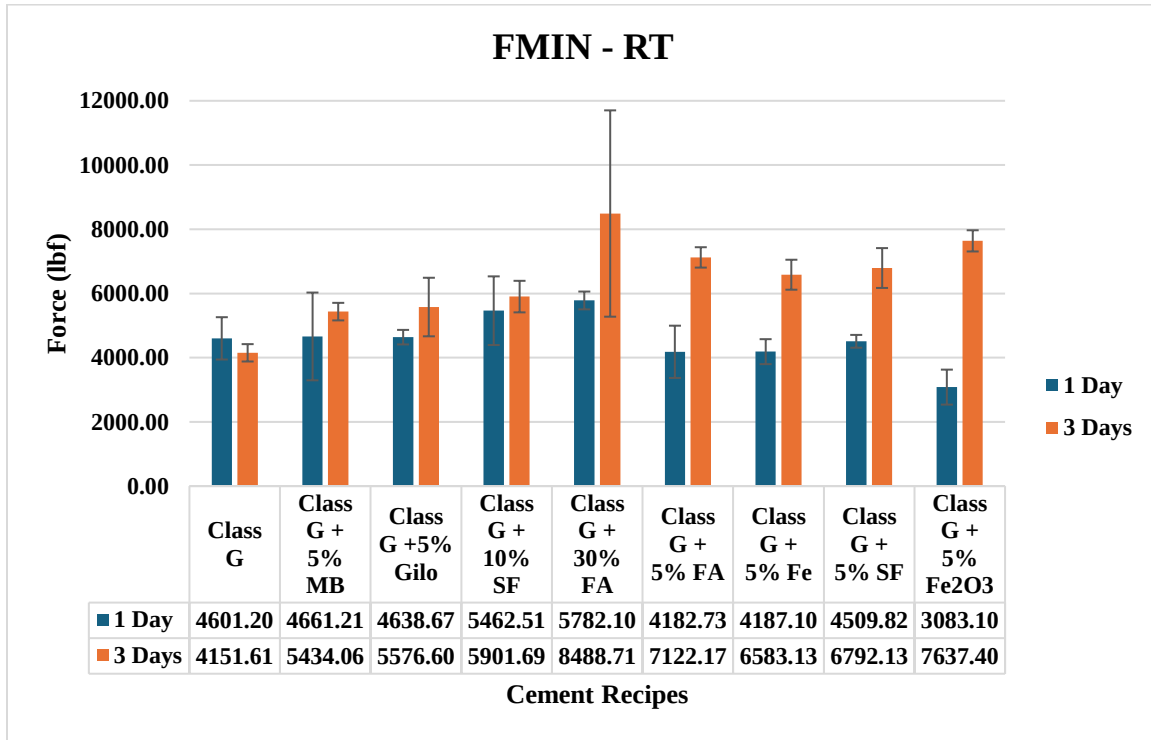


Figure 38: Comparison of the Minimum Debonding Force between 1- and 3-day curing time at room temperature after Debonding.

The comparison of FMIN between 1-day and 3-day curing at elevated temperatures provides valuable insights into the influence of time and additives on post-debonding strength, as seen in **Figure 39**. The control sample, Class G cement, exhibited a notable increase in FMIN from 5230.67 lbf at 1 day to 7863.90 lbf at 3 days, demonstrating the positive impact of extended curing on bonding performance under elevated temperatures. Similarly, Class G + 5% Microblock, Gilsonite, Fly Ash, and Iron filings showed moderate gains in FMIN over time, indicating enhanced stability and strength as curing progressed. However, other additives, such as 30% fly ash, 5% Fe₂O₃, 5%, and 10% silica flour (SF), exhibited a more moderate decrease in FMIN over 3 days. The results suggest that while elevated temperature improves post-debonding resistance

for most cement blends, the effectiveness varies depending on the additive used. These trends emphasize the importance of selecting appropriate additives based on specific operational requirements, as the performance under prolonged curing can differ significantly across formulations.

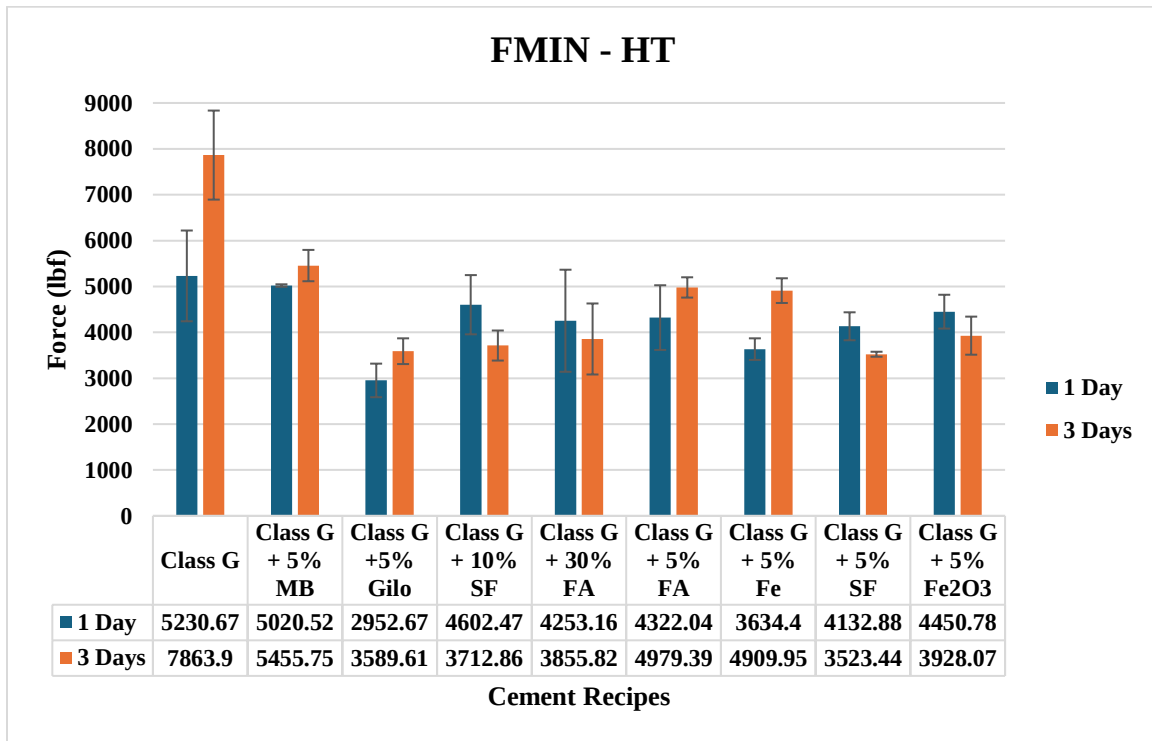


Figure 39: Comparison of the Minimum Debonding Force between 1- and 3-day curing time at elevated temperature after Debonding

4.1.3 Average Bonding Force after Debonding.

The 1-day FAVG results highlight the impact of temperature on the average force required to maintain casing stability post-debonding. As seen in **Figure 40**, most cement recipes, including Class G + 5% Microblock (MB) and Class G + 10% Silica Flour (SF), exhibit higher FAVG values at room temperature (RT) than at elevated temperature (HT), indicating a stronger average holding capacity under ambient conditions. Notably, Class G + 30% Fly Ash (FA) demonstrated the highest average force across both temperature conditions, suggesting superior bonding

performance, though it experienced a decline at HT. Conversely, Gilsonite-modified cement (Class G + 5% Gilo) showed the lowest average force at both RT and HT, suggesting its limited effectiveness in enhancing post-debonding stability. The control sample (Class G) also followed a similar trend with decreased FAVG under HT. These results suggest that while certain additives like FA significantly enhance cement performance, the influence of temperature is not uniform, with many recipes experiencing a noticeable reduction in their average holding force under elevated temperature conditions.

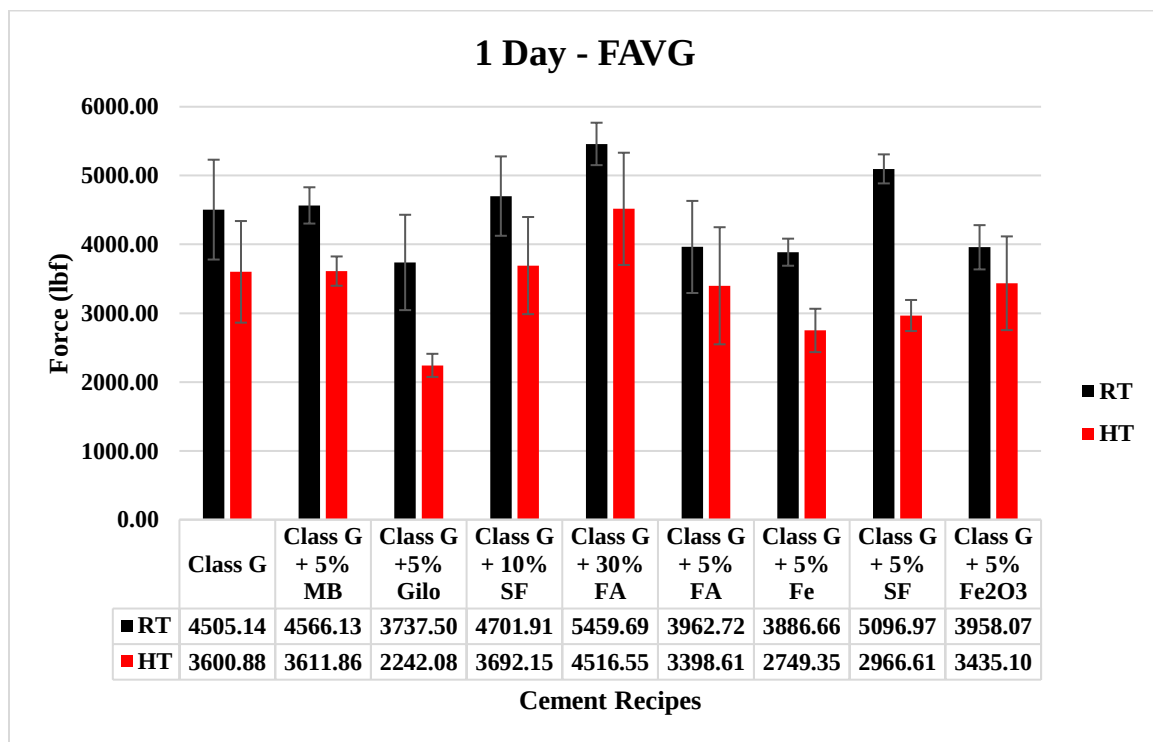


Figure 40. Average Bonding force after debonding for cement recipes at 1-day curing.

The 3-day FAVG results demonstrate a shift in the performance of cement recipes at elevated temperatures (HT) compared to room temperature (RT), as shown in **Figure 41**. Unlike the 1-day curing results, the average force required to maintain casing stability after debonding generally declines under HT conditions for most additives. Class G cement, however, maintains a relatively

stable performance, with minimal differences between RT (5568 lbf) and HT (5768 lbf), indicating resilience to temperature changes. On the other hand, significant reductions are observed in Class G + 30% Fly Ash and Class G + 10% Silica Flour (SF) under HT conditions, suggesting that these compositions may be more vulnerable to thermal stress. Overall, the results emphasize that all additives experience significant deterioration at higher temperatures.

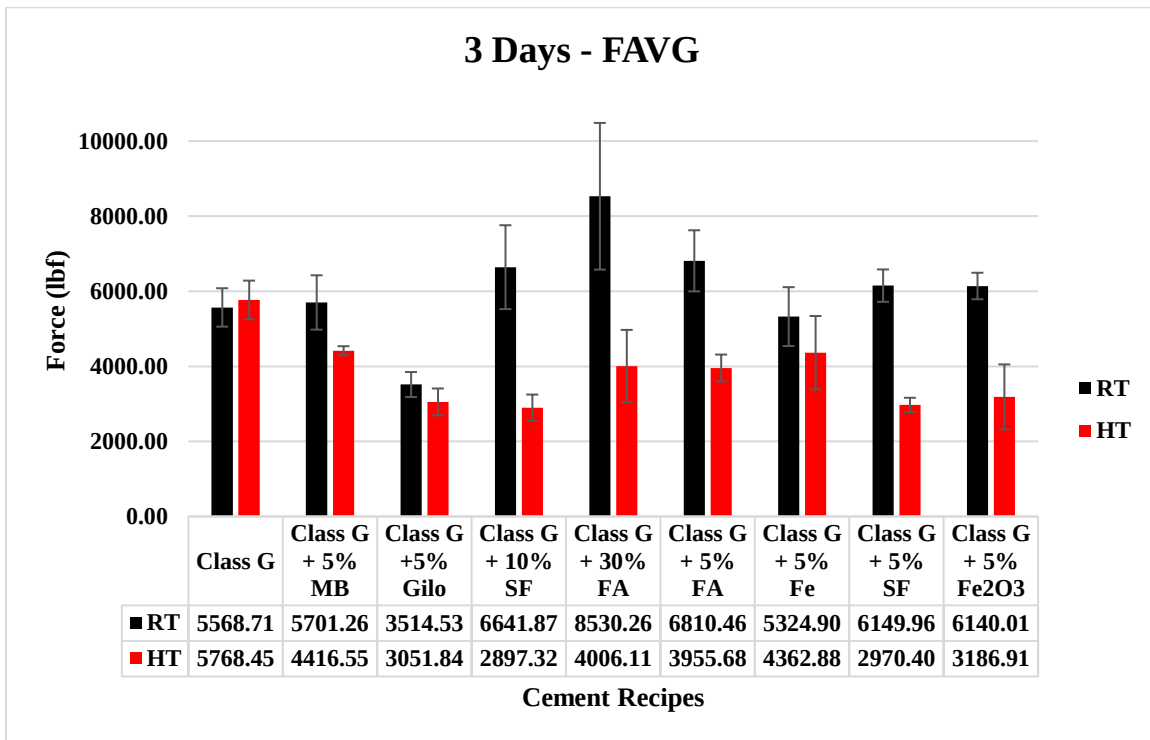


Figure 41. Average Bonding force after debonding for cement recipes at 3-day curing.

The comparison of FAVG values between 1-day and 3-day curing at room temperature highlights significant improvements in bonding strength over time for most cement recipes as seen in **Figure 42**. Notably, the control sample (Class G) exhibits a substantial increase from 4505 lbf on day 1 to 5568 lbf on day 3, demonstrating improved performance with prolonged curing. The addition of 5% Microblock (MB) also enhances performance consistently, with an increase from 4566 lbf to 5701 lbf, reflecting the additive's contribution to better bonding over time. A standout observation

is the significant growth in the performance of Class G + 30% Fly Ash, which jumps from 5459 lbf to 8530 lbf, indicating the high efficacy of this additive in long-term stabilization. Conversely, 5% Gilsonite presents a slight decline between day 1 and day 3, suggesting it may not offer the same durability as other additives over extended curing. Similarly, the 10% Silica Flour mixture shows notable improvement, moving from 4701 lbf to 6642 lbf, reinforcing silica's role in enhancing long-term mechanical strength. Overall, most additives benefit from extended curing, with fly ash and silica-based recipes performing exceptionally well, demonstrating their effectiveness in improving long-term bonding at room temperature.

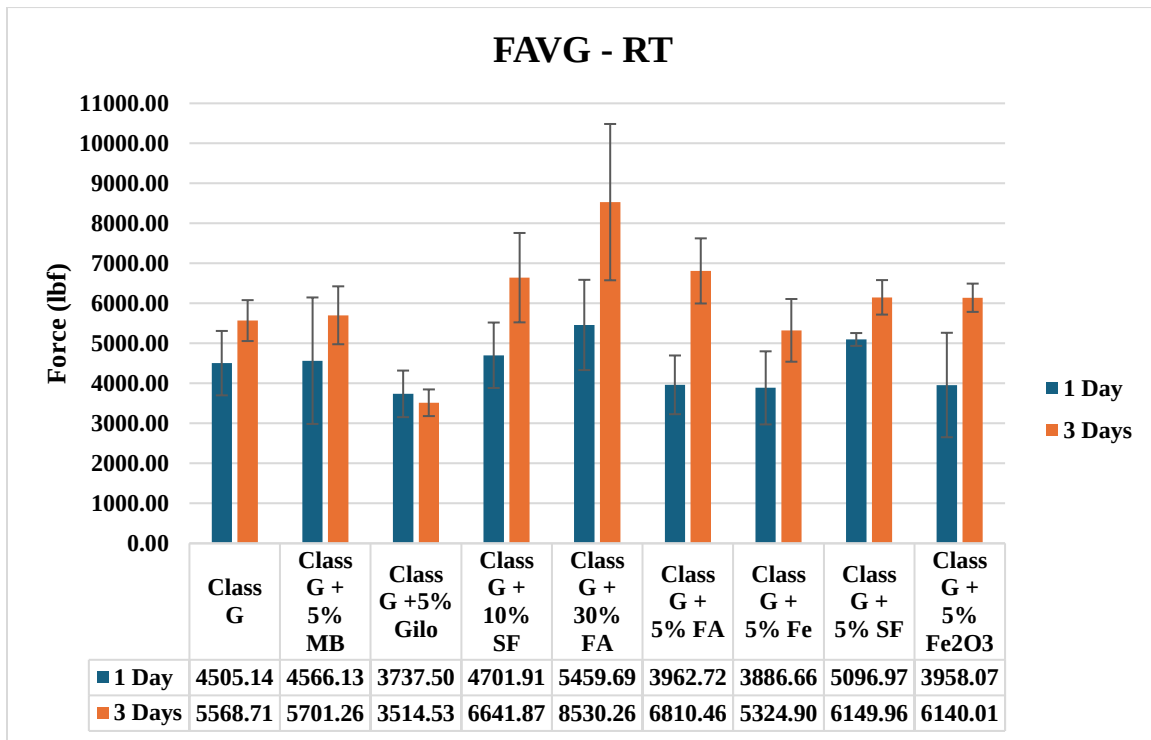


Figure 42. Comparison of the Average Debonding Force between 1- and 3-day curing time at room temperature after Debonding.

The 3-day FAVG results at elevated temperatures, as shown in **Figure 43**, reveal diverse trends in the force required to maintain casing stability across different cement recipes. The Class G control

sample exhibits a significant increase in FAVG from day 1 to day 3, indicating improved bonding performance over time under heat exposure. In contrast, some additives such as 5% Microblock (MB) and 5% Fly Ash show moderate improvements in FAVG between the two curing durations, but their overall performance is still lower than the control sample at 3 days. Notably, recipes like Class G + 5% Fe₂O₃ and Class G + 10% Silica Flour demonstrate relatively weak performance at elevated temperatures, with a decrease in FAVG over time. Interestingly, while the Class G + 5% Silica approximately the same strength at day 1 and day 3 of curing. These results suggest that while some additives can enhance bonding performance over time at elevated temperatures, others may exhibit less stability or effectiveness under similar conditions.

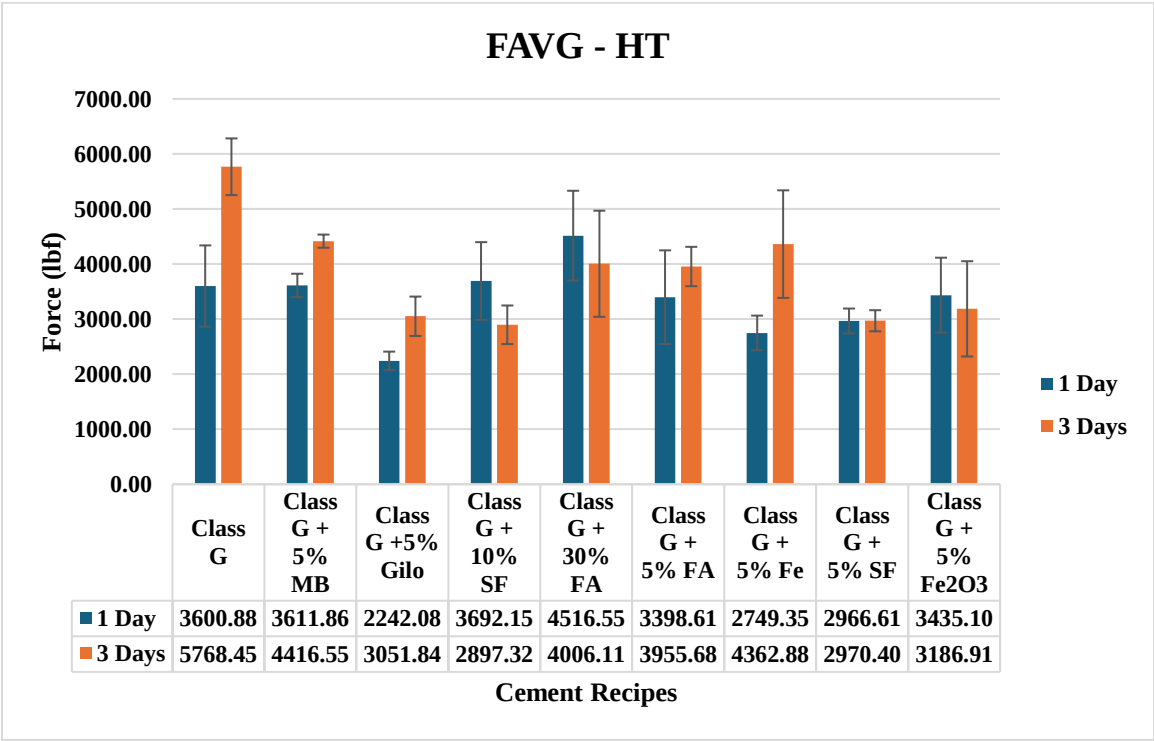


Figure 43. Comparison of the Average Debonding Force between 1- and 3-day curing time at elevated temperature after Debonding.

4.1.4 Bonding Force Loss due to Debonding.

The 1-day bonding force loss (**BFBL**) results provide critical insights into how various cement additives perform under different temperature conditions (**Figure 44**). Notably, most cement recipes exhibit higher bonding force loss at elevated temperatures (HT), suggesting greater instability in post-debonding conditions at higher temperatures. For example, Class G + 5% Microblock (MB) and Class G + 5% iron filings (Fe) show significantly greater BFBL at HT (11,184 lbf and 9,730 lbf, respectively) compared to their RT values, indicating their tendency to lose more bonding capacity at elevated temperatures. Interestingly, Class G + 30% FA exhibits the lowest **BFBL** at HT (3,029 lbf), marking it as an exceptional additive in maintaining post-debonding stability at high temperatures. On the other hand, recipes such as Class G + 10% Silica Flour (SF) and Class G + 5% Gilsonite (Gilo) show relatively moderate losses, but still with higher values at HT than RT. The control Class G cement performs adequately, though it also experiences a significant increase in BFBL from 5,926 lbf at RT to 8,998 lbf at HT. Overall, these results highlight that while certain additives, like 30% FA, perform well under HT, others may compromise post-debonding stability, especially under elevated temperatures.

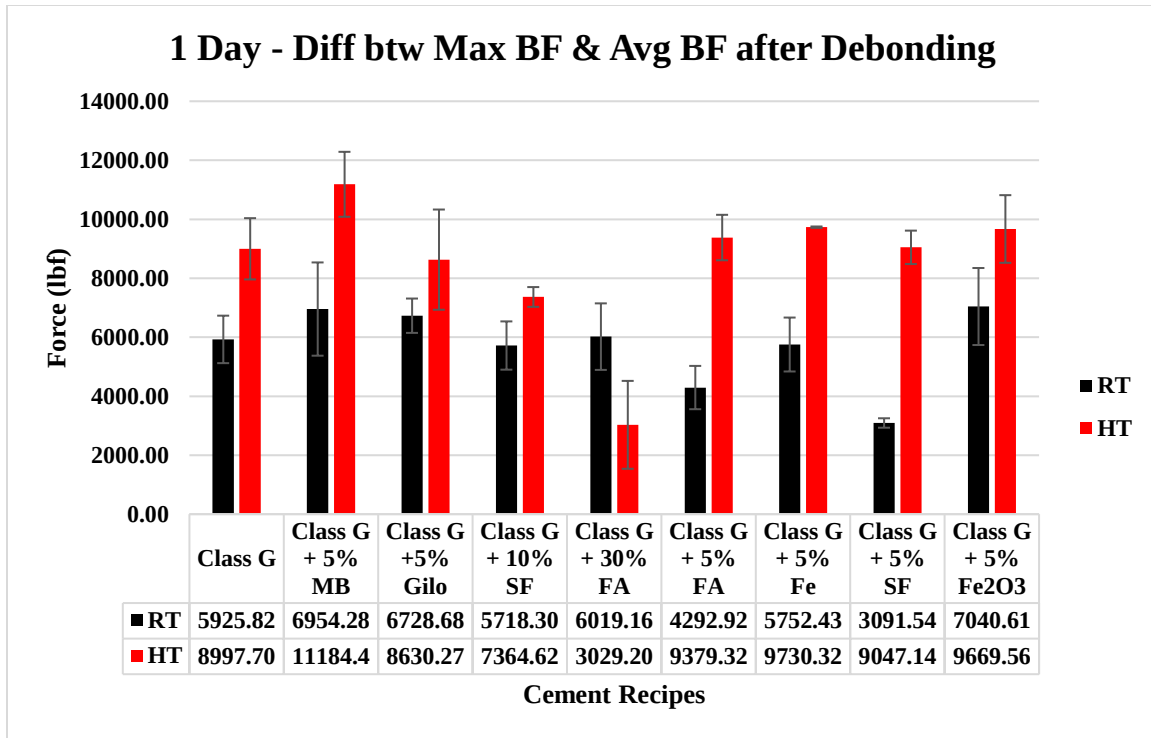


Figure 44. Bonding force loss after debonding for cement recipes at 1-day curing.

The 3-day curing results for Bonding Force Loss (FBFL) reveal significant insights into the ability of various cement recipes to maintain casing bonding after debonding at both room temperature (RT) and high temperature (HT). As seen in **Figure 45**, Class G cement without additives showed a notable difference in FBFL between RT and HT, with higher values at RT (10408 lbf) compared to HT (8531 lbf). Interestingly, the Class G + 5% Microblock (MB) recipe demonstrated the highest bonding force across both RT and HT, maintaining an FBFL of over 10,000 lbs in both conditions, indicating a high loss in the bonding force. However, the Class G + 30% Fly Ash (FA) sample exhibited a sharp decrease at HT (3345 lbf) compared to RT (10494 lbf), reflecting significant bonding force loss at elevated temperatures. Overall, cement recipes that maintained lower FBFL values, such as Class G + 5% Fe₂O₃, Class G + 5% Fe and Class G + 5% Silica Flour,

performed better at high temperatures, suggesting these additives may enhance the cement's ability to hold the casing in place after debonding.

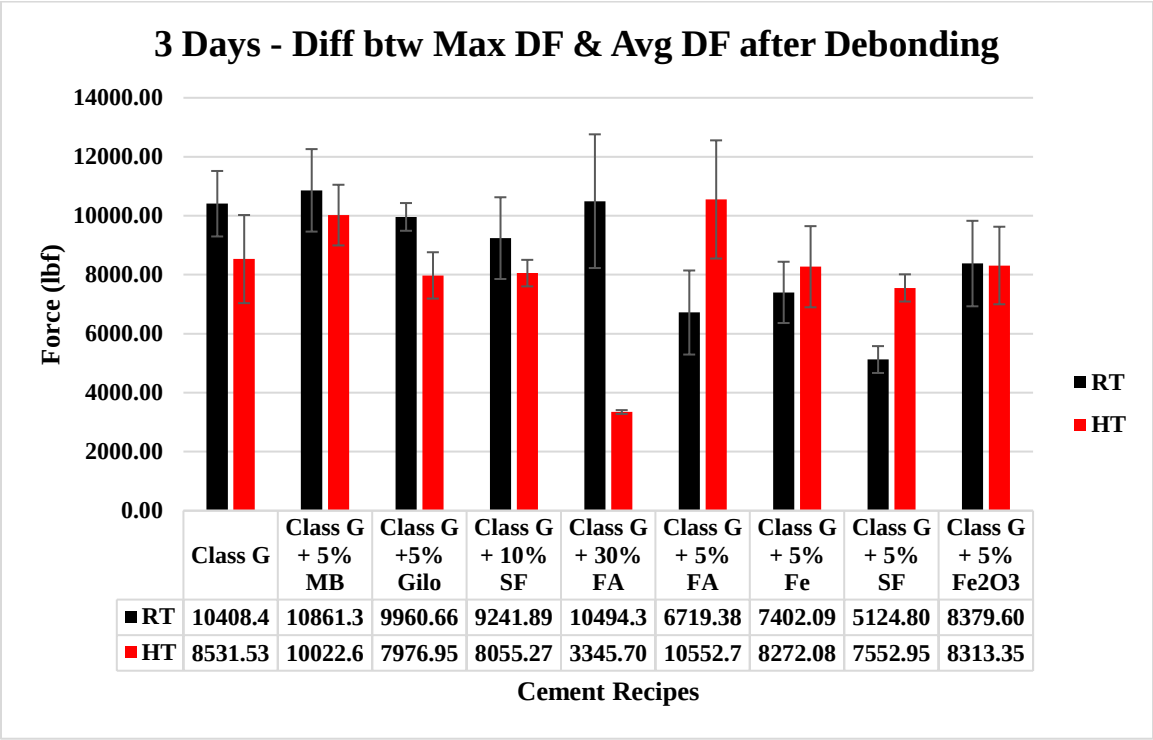


Figure 45. Bonding force loss after debonding for cement recipes at 3-day curing.

The 1-day and 3-day comparison of Bonding Force Loss (FBFL) at room temperature (**Figure 46**) highlights the influence of different additives on the cement's capacity to maintain stability post-debonding. Across all recipes, bonding forces generally increase at 3 days compared to 1 day, indicating improved stability over time. However, Class G + 5% Microblock (MB) and Class G + 30% Fly Ash (FA) exhibit notably high bonding loss at 3 days, suggesting a more rapid reduction in bonding force, which could compromise long-term performance. In contrast, Class G with 5% Fly Ash (FA), 5% Iron (Fe), and 5% Iron Oxide (Fe₂O₃) demonstrate minimal changes in FBFL between 1 and 3 days, reflecting their ability to mitigate bonding loss more effectively over time. These additives exhibit steady bonding behavior, making them reliable for reducing the rate of

bonding force decline. Overall, additives that balance high bonding forces with low FBFL at 3 days—such as 5% FA, 5% Fe, and Fe_2O_3 —offer the most promising performance for ensuring sustained casing stability after debonding.

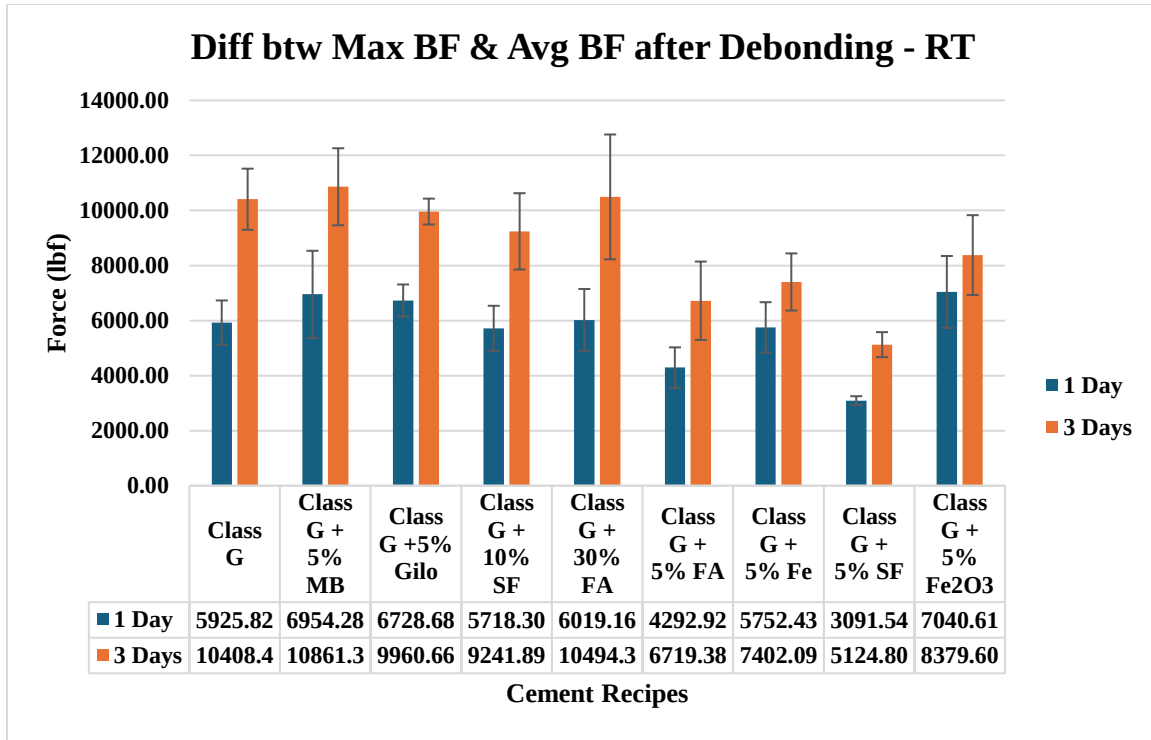


Figure 46. Comparison of the Bonding Loss Force between 1- and 3-day curing time at room temperature after Debonding.

The 1-day and 3-day comparison of Bonding Force Loss (FBFL) at elevated temperatures reveals valuable insights into the thermal stability of various cement additives, as seen in **Figure 47**. Notably, Class G + 5% Microblock (MB) and Class G + 5% Fly Ash (FA) display higher bonding loss forces initially at 1 day, but their FBFL decreases significantly over 3 days, indicating an enhanced ability to retain casing stability with extended curing. In contrast, Class G + 30% FA shows a slight increase in bonding force at 3 days, suggesting that prolonged exposure to heat optimizes its performance. Additives such as 5% Iron (Fe) and 5% Iron Oxide (Fe_2O_3) demonstrate

moderate reductions in FBFL over time, showcasing consistent long-term reliability. Although some additives exhibit minor reductions in bonding loss at 3 days, the general trend underscores the role of thermal curing in improving stability, with Class G + 30% FA achieving the lowest FBFL by the end of the curing period, making it especially effective for maintaining casing integrity. These findings highlight that different additives respond uniquely to elevated temperatures, with several demonstrating superior long-term performance under thermal conditions.

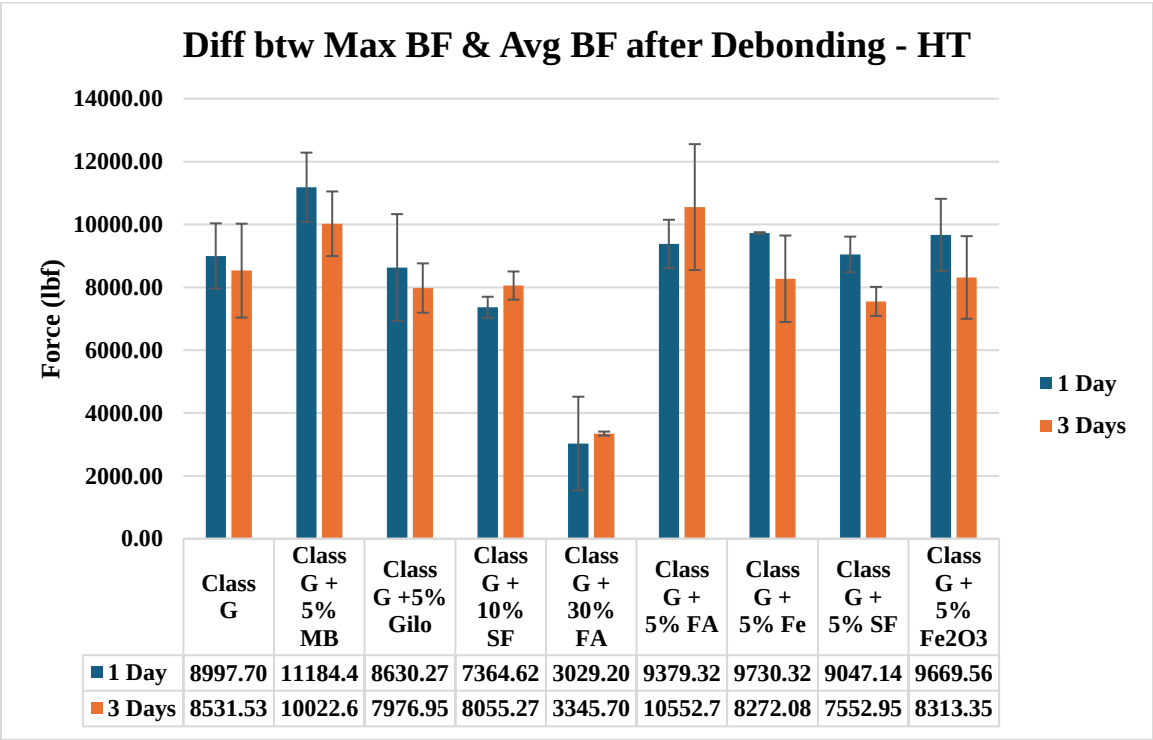


Figure 47. Comparison of the Bonding Loss Force between 1- and 3-day curing time at room temperature after Debonding.

4.1.5 Initial Displacement after Debonding.

The 1-day displacement analysis following debonding provides critical insights into the secondary support capacity of each cement recipe at both room temperature (RT) and high temperature (HT)

as seen in **Figure 48**. In general, higher displacement values indicate weaker secondary support, potentially compromising well integrity by allowing significant movement of the casing. Notably, Class G cement at elevated temperature shows a significant increase in displacement from 1.67 mm (RT) to 2.39 mm (HT), suggesting reduced support under thermal conditions. Similarly, Class G + 5% Fly Ash (FA) and Class G + 5% Silica Flour (SF) exhibit some of the highest displacements at HT, indicating poor post-debonding stability. On the other hand, Class G + 10% SF and Class G + 5% Fe exhibit relatively low displacements at both RT and HT, reflecting their potential to maintain well integrity by providing better secondary support. The smallest displacement at RT is observed with Class G + 5% SF (1.20 mm), but it increases significantly at HT, demonstrating temperature sensitivity. Overall, recipes with minimal displacement under both conditions, such as those with iron additives, are more effective at stabilizing casing positions post-debonding, ensuring better long-term well integrity.

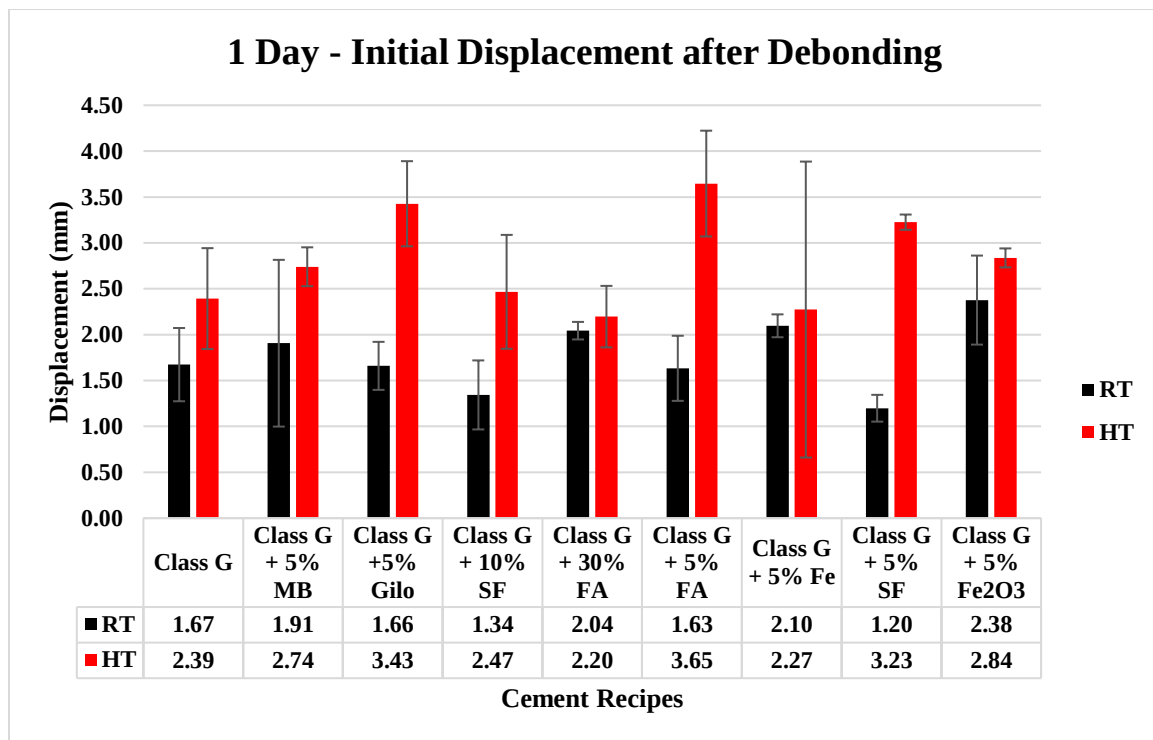


Figure 48. Initial Displacement after debonding for cement recipes at 1-day curing.

The 3-day comparison of casing displacement after debonding, under both room temperature and elevated temperature, highlights key differences in how cement additives perform over time (**Figure 49**). While several additives, such as Class G + 30% FA, exhibit consistent displacement between both temperatures, others, like Class G + 5% Fly Ash (FA), show a sharp increase in displacement at elevated temperatures, indicating diminished secondary support as heat exposure increases. On the other hand, Class G + 5% MB and Class G + 10% SF, though experiencing slightly higher displacement at high temperatures, display controlled movement at room temperature, signifying their better ability to maintain well integrity under standard conditions. Notably, Class G + 5% SF achieves the least displacement at room temperature, marking it as a promising candidate for maintaining casing stability. However, elevated temperatures tend to increase displacement across most recipes, revealing the challenge of maintaining secondary

support in thermal environments. This underscores the importance of optimizing cement additives for both temperature conditions to ensure consistent well integrity over time.

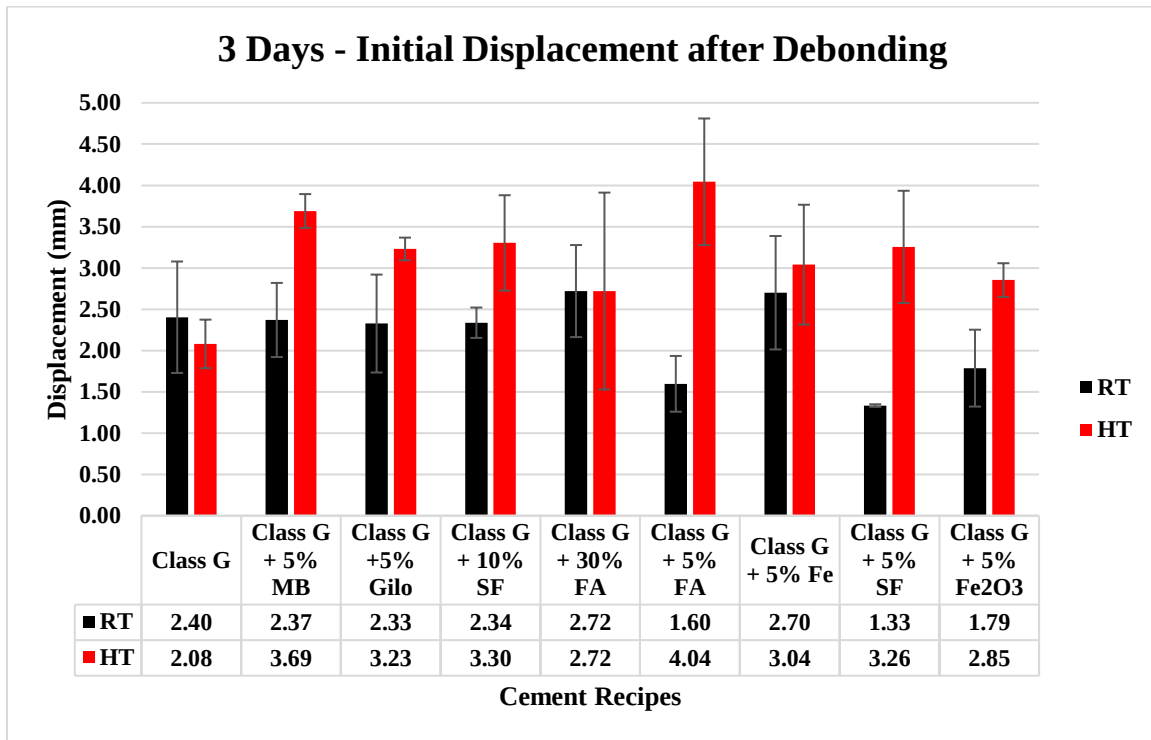


Figure 49. Initial Displacement after debonding for cement recipes at 3-day curing.

The comparison of displacement between 1 day and 3 days of curing at room temperature reveals the impact of curing days on how well each cement recipe supports the casing after primary support has been lost due to debonding, as seen in **Figure 50**. Notably, most cement recipes, including the control (Class G), show an increase in displacement over the three days, implying that extended curing does not always enhance secondary support. However, Class G + 5% Fly Ash (FA) and Class G + 5% Iron Oxide (Fe₂O₃) exhibit reductions in displacement over time, indicating improved secondary stability with prolonged curing. The lowest displacement is observed for Class G + 5% Silica Flour (SF), suggesting it provides the most reliable secondary support among the recipes, both at 1 day and 3 days. On the other hand, Class G + 30% FA shows the highest

displacement at both curing stages, highlighting its limitation in offering effective structural integrity under room temperature conditions. These results emphasize the importance of selecting additives that maintain minimal displacement over time to ensure long-term.

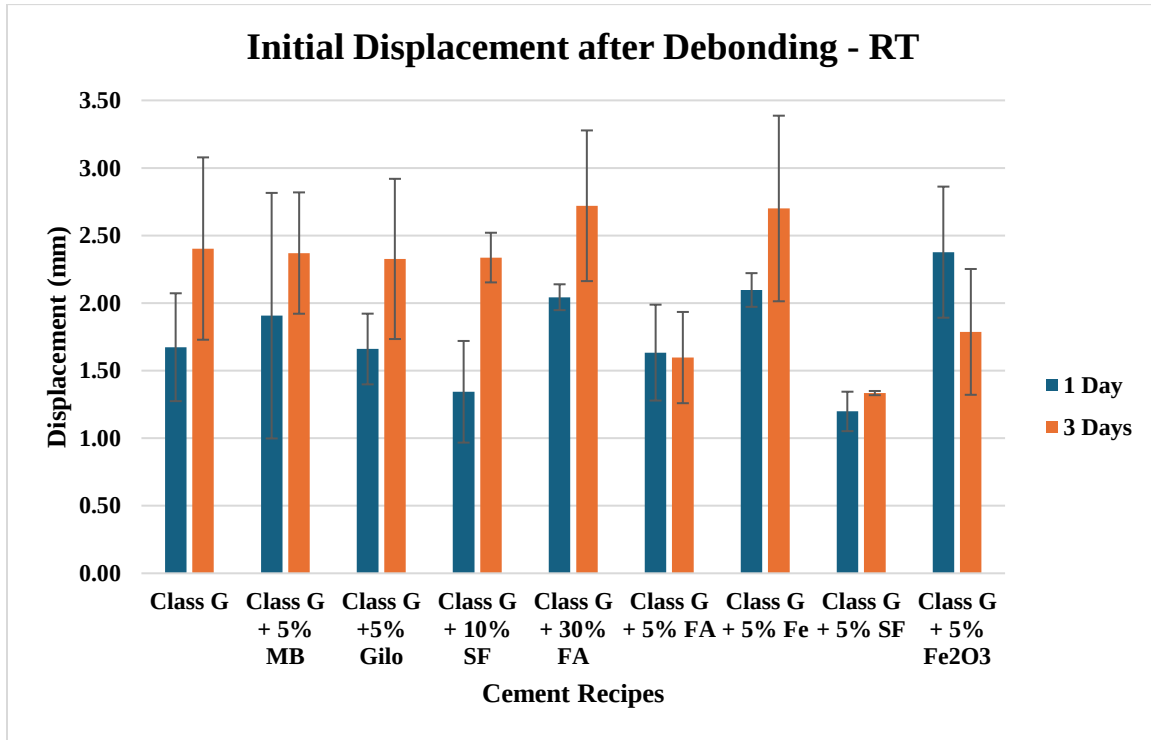


Figure 50. Comparison of the Initial Displacement between 1- and 3-day curing time at room temperature after Debonding.

The comparison of displacement between 1 day and 3 days of curing at high temperature highlights the performance of different cement recipes in providing secondary support after debonding, as seen in **Figure 51**. Notably, Class G cement shows improves performance over time, with displacement decreasing from 2.39 mm to 2.08 mm after 3 days, indicating enhanced stability with curing. Conversely, additives such as Class G + 5% Microblock (MB) and Class G + 5% Fly Ash (FA) exhibit increased displacement over time, suggesting their ability to maintain secondary support deteriorates at elevated temperatures. Class G + 30% Fly Ash maintains a moderate

displacement with little change, demonstrating consistent but limited secondary support. Meanwhile, Class G + 5% Silica Flour (SF) and Iron Oxide (Fe_2O_3) display stable performances with moderate displacement values, suggesting these additives retain structural integrity reasonably well under thermal conditions. In contrast, Class G + 5% FA shows the highest displacement values at both curing days, implying it may be less reliable for maintaining well integrity over extended curing at high temperatures. These results indicate that while elevated temperatures can challenge secondary support, certain additives perform more consistently than others, with recipes like Class G + Fe_2O_3 showing balanced performance over time.

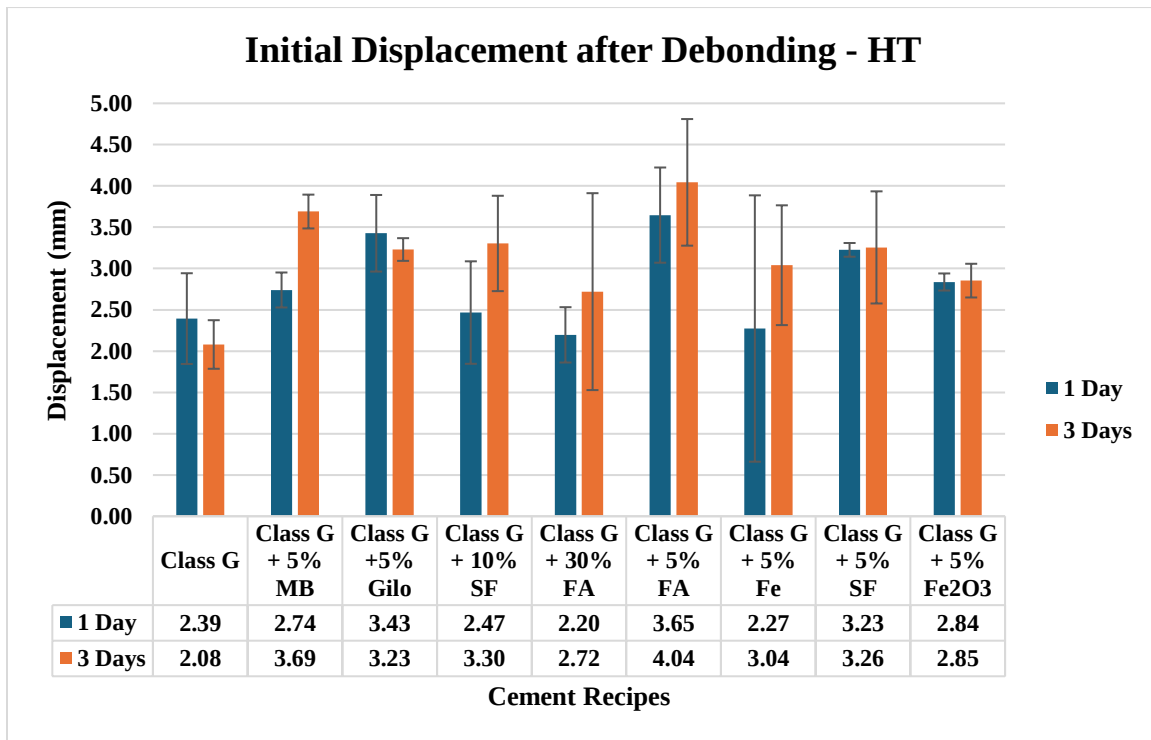


Figure 51. Comparison of the Initial Displacement between 1- and 3-day curing time at elevated temperature after Debonding.

4.1.6 Scoring Metric based on Impact of Additives,

1 Day Room Temperature

Table 9 evaluates the performance of various cement recipes based on key mechanical and bonding properties after 1 day of curing at room temperature. The results are weighted across six critical parameters to determine the most effective additives for maintaining well integrity under these conditions. Each property contributes differently to the overall score, reflecting its relative importance in wellbore stability.

Unconfined Compressive Strength (UCS) and Maximum Force at Debonding (FMAX) each contribute 25% to the total score, highlighting their significance in assessing both the structural support provided by the cement and its ability to resist debonding. Among the recipes, Class G + 30% Fly Ash (FA) emerges as a top performer with a total weighted score of 7.55, demonstrating a strong balance between UCS, FMAX, and other parameters. This recipe's ability to sustain compressive forces while resisting debonding underscores its reliability in maintaining casing stability during early-stage curing.

Class G + 5% Microblock (MB) and Class G + 10% Silica Flour (SF) display a balanced performance across multiple parameters, with relatively strong scores in UCS, FMAX, and IDFL. This indicates its suitability for applications where both structural integrity and displacement control are critical. Meanwhile, Class G + 5% Silica Fume (SF) demonstrates robust performance in FBFL (Bonding Force Loss), indicating its ability to retain bonding strength post-debonding, although its overall performance is slightly lower due to weaker UCS and IDFL scores.

At the lower end of the spectrum, Class G + 5% Gilsonite (Gilo) achieves the poorest total score, indicating limitations in both compressive strength and bonding properties. This suggests that its application may be unsuitable in scenarios demanding high structural integrity or bonding reliability. Other recipes, such as Class G + 5% Iron Oxide (Fe_2O_3) and Class G + 5% Iron (Fe), exhibit moderate performance.

Table 11: Scoring metric for 1 day curing at room temperature.

Property	Selection Criteria	Score Trends	Weight Score (%)	Class G	Class G + 5% MB	Class G + 5% Gilso	Class G + 5% FA	Class G + 5% Fe	Class G + 5% SF	Class G + 5% Fe ₂ O ₃	Class G + 10% SF	Class G + 30% FA
UCS	High	3, 8, 1, 7, 5, 2, 4, 6, 9	25	0.75	2	0.25	1.75	1.25	0.5	1	1.5	2.25
FMAX	High	4, 8, 5, 2, 3, 1, 9, 6, 7	25	1	2	1.25	0.5	0.75	0.25	2.25	1.5	1.75
FAVG	Moderate	5, 6, 1, 4, 2, 8, 3, 7, 9	18	0.9	1.08	0.18	0.72	0.36	1.44	0.54	1.26	1.62
FMIN	Moderate	5, 7, 6, 2, 3, 4, 1, 8, 9	15	0.75	1.05	0.9	0.3	0.45	0.6	0.15	1.2	1.35
IDFL	Low	5, 4, 6, 7, 2, 9, 1, 8, 3	10	0.5	0.4	0.6	0.7	0.2	0.9	0.1	0.8	0.3
FBFL	Low	5, 2, 3, 8, 6, 9, 1, 7, 4	7	0.35	0.14	0.21	0.56	0.42	0.63	0.07	0.49	0.28
Total scores			100	4.25	6.67	3.39	4.53	3.43	4.32	4.11	6.75	7.55

Scoring metric

9 – Excellent

1 – Poor

1 Day Elevated Temperature

Table 10 presents the performance of various cement recipes in maintaining stability under elevated temperature conditions after one day of curing. Class G + 10% Silica Flour (SF) emerges as the best performer with a weighted score of 6.4, demonstrating its ability to maintain compressive strength and bonding integrity in high-temperature environments. This composition performed averagely in FMAX but excels in metrics like UCS, FAVG, FMIN, IDFL and FBFL, suggesting its reliability in sustaining casing stability under thermal conditions after debonding.

Class G + 30% Fly Ash (FA), despite achieving the highest UCS, FAVG, IDFL, and FBFL in this group, scores relatively lower in bonding metrics like FMAX and FMIN. This indicates that while

it offers exceptional compressive strength, its bonding performance is limited, which may affect its ability to prevent debonding-related displacement. This makes it more suitable for applications where compressive strength is the primary requirement. As the temperature increased, the FMAX and FMIN dropped significantly at one day of curing.

Class G + 5% Microblock (MB) and Class G achieve a solid balance across most parameters, showing relatively high-performance bonding metrics like FAVG and FMIN but low performance in UCS. This balance makes it a versatile option for scenarios requiring high bonding strength but low to moderate compressive strength. Conversely, Class G + 5% Gilsonite (Gilo) records the lowest overall score, reflecting weaker performance across critical parameters such as FMAX and FMIN, which indicates its limited applicability in high-temperature wellbore conditions.

Interestingly, Class G + 5% Iron Oxide (Fe_2O_3) performs moderately well, particularly in FMAX and UCS, indicating its potential for maintaining structural integrity under thermal conditions. However, its slightly weaker scores in FBFL and IDFL suggest it may not excel in minimizing force loss or displacement after debonding. Class G + 5% FA shows a similar trend, with high scores in UCS and bonding metrics but slightly lower in displacement control.

The data underscore the importance of selecting cement additives based on specific wellbore requirements. While recipes like 10% SF and 30% FA offer high compressive strength performance, others like Class G provide a better balance between strength and bonding. This nuanced evaluation highlights the interplay between various mechanical properties and serves as a valuable framework for optimizing cement systems in high-temperature applications.

Table 12: Scoring metric for 1 day curing at elevated temperature.

Property	Selection Criteria	Score Trends	Weight Score (%)	Class G	Class G + 5% MB	Class G + 5% Gilso	Class G + 5% FA	Class G + 5% Fe	Class G + 5% SF	Class G + 5% Fe ₂ O ₃	Class G + 10% SF	Class G + 30% FA
UCS	High	4, 3, 1, 7, 5, 2, 6, 8, 9	25	1	0.75	0.25	1.75	1.25	0.5	1.5	2	2.25
FMAX	High	6, 9, 2, 7, 5, 4, 8, 3, 1	25	1.5	2.25	0.5	1.75	1.25	1	2	0.75	0.25
FAVG	Moderate	6, 7, 1, 4, 2, 3, 5, 8, 9	18	1.08	1.26	0.18	0.72	0.36	0.54	0.9	1.44	1.62
FMIN	Moderate	9, 8, 1, 5, 2, 3, 6, 7, 4	15	1.35	1.2	0.15	0.75	0.3	0.45	0.9	1.05	0.6
IDFL	Low	7, 5, 2, 1, 8, 3, 4, 6, 9	10	0.7	0.5	0.2	0.1	0.8	0.3	0.4	0.6	0.9
FBFL	Low	6, 1, 7, 4, 2, 5, 3, 8, 9	7	0.42	0.07	0.49	0.28	0.14	0.35	0.21	0.56	0.63
Total scores			100	6.05	6.03	1.77	5.35	4.1	3.14	5.91	6.4	6.25

3 Days Room Temperature

Table 11 shows the performance of cement recipes after three days of curing at room temperature offers valuable insights into the stability and effectiveness of different additives. Notably, Class G + 30% Fly Ash (FA) emerges as the top-performing recipe with a total weighted score of 7.71, excelling in categories like UCS, FMAX, FAVG, and FMIN. Its performance demonstrates that high fly ash concentrations significantly enhance both compressive strength and bonding, making it a superior choice for applications requiring robust wellbore integrity. The recipe, however, scores poorly in displacement control (IDFL) and bonding force loss (FBFL), hence providing a shortcoming for wells in high tectonic movement areas.

Class G + 5% Iron Oxide (Fe₂O₃) and Class G + 10% Silica Flour (SF) achieve strong performances in UCS and FMAX, showcasing their ability to sustain high compressive forces and resist debonding under room temperature conditions. Their relatively high scores in FMIN and FAVG indicate good bonding capacity, making them suitable for applications where both compressive and bonding performance are critical.

Class G + 5% Fly Ash (FA) also performs well, securing a close third position. It demonstrates balanced strength across UCS and bonding metrics such as FMIN and FAVG, indicating that lower concentrations of fly ash still provide a solid combination of compressive strength and bonding stability. It provides moderate FMAX. This recipe stands out as a cost-effective alternative to 30% FA for cases where slightly lower performance is acceptable.

Class G + 5% Gilsonite (Gilo) records the lowest total score, underperforming in UCS and bonding metrics such as FMIN and FBFL. This highlights its limitations in both structural and bonding strength, making it less suitable for scenarios demanding high wellbore integrity.

Class G + 5% Gilsonite (Gilo) records the lowest total score, underperforming in UCS and bonding metrics such as FAVG and FMIN. This highlights its limitations in both structural and bonding strength, making it less suitable for scenarios demanding high wellbore integrity.

The scoring trends emphasize that recipes with fly ash (30% and 5%) consistently outperform others, demonstrating superior performance across compressive strength and bonding metrics. Additives like iron oxide and silica flour, while effective in enhancing UCS and FMAX, show moderate bonding performance, indicating their potential for targeted applications. Conversely, recipes like Gilsonite require further optimization to meet the demands of wellbore integrity under room temperature curing.

Table 13: Scoring metric for 3 days curing at room temperature.

Property	Selection Criteria	Score Trends	Weight Score (%)	Class G	Class G + 5% MB	Class G + 5% Gilso	Class G + 5% FA	Class G + 5% Fe	Class G + 5% SF	Class G + 5% Fe ₂ O ₃	Class G + 10% SF	Class G + 30% FA
UCS	High	2, 7, 1, 5, 4, 3, 8, 6, 9	25	0.5	1.75	0.25	1.25	1	0.75	2	1.5	2.25
FMAX	High	7, 8, 3, 4, 2, 1, 5, 6, 9	25	1.75	2	0.75	1	0.5	0.25	1.25	1.5	2.25
FAVG	Moderate	3, 4, 1, 8, 2, 6, 5, 7, 9	18	0.54	0.72	0.18	1.44	0.36	1.08	0.9	1.26	1.62
FMIN	Moderate	1, 2, 3, 7, 5, 6, 8, 4, 9	15	0.15	0.3	0.45	1.05	0.75	0.9	1.2	0.6	1.35
IDFL	Low	3, 4, 6, 8, 2, 9, 7, 5, 1	10	0.3	0.4	0.6	0.8	0.2	0.9	0.7	0.5	0.1
FBFL	Low	3, 4, 1, 8, 7, 9, 6, 5, 2	7	0.21	0.28	0.07	0.56	0.49	0.63	0.42	0.35	0.14
Total scores			100	3.45	5.45	2.3	6.1	3.3	4.51	6.47	5.71	7.71

3 Days Elevated Temperature

Table 12 shows the elevated temperature test after three days of curing reflects the effectiveness of each cement recipe across multiple performance indicators. Class G is the highest-performing recipe, with a total weighted score of 6.83. This result underscores its exceptional capability in maintaining structural integrity under thermal conditions. However, the recipe achieves a moderate score in UCS, making it ideal for high-temperature wellbore applications where moderate strength and high bonding are critical.

Class G + 5% Microblock (MB) follows closely, with competitive total scores but low UCS and the highest FMAX scores. This recipe provides a very good bonding strength, with high FMAX, FAVG, and FMIN scores, indicating its potential for applications requiring reliable debonding resistance. However, it slightly underperforms in FBFL and IDFL, suggesting some limitations in minimizing force loss and displacement post-debonding.

Class G + 5% Fe₂O₃ delivers a robust performance, excelling in bonding parameters such as FMIN and FAVG. While its UCS score is not the highest, the combination of strong bonding and

displacement control makes it a reliable choice for thermal environments demanding sustained bonding strength.

Class G + 5% Fly Ash (FA) demonstrates solid overall performance, scoring consistently across UCS, FAVG, and FMAX. While its bonding metrics (FMIN and FBFL) are slightly lower than the top performers, it offers a balanced profile suitable for applications requiring both strength and moderate bonding capabilities.

Class G + 5% Silica Flour (SF) records the lowest total score, with weaker performance across all key metrics, particularly in UCS and FAVG. This indicates its limited suitability for high-temperature environments, as it struggles to maintain sufficient bonding strength and structural integrity under thermal stress.

Table 14: Scoring metric for 3 days curing at elevated temperature.

Property	Selection Criteria	Score Trends	Weight Score (%)	Class G	Class G + 5% MB	Class G + 5% Gilso	Class G + 5% FA	Class G + 5% Fe	Class G + 5% SF	Class G + 5% Fe ₂ O ₃	Class G + 10% SF	Class G + 30% FA
UCS	High	4, 3, 1, 7, 5, 2, 6, 8, 9	25	1	0.75	0.25	1.75	1.25	0.5	1.5	2	2.25
FMAX	High	7, 9, 4, 8, 6, 2, 5, 3, 1	25	1.75	2.25	1	2	1.5	0.5	1.25	0.75	0.25
FAVG	Moderate	9, 8, 3, 5, 7, 2, 4, 1, 6	18	1.62	1.44	0.54	0.9	1.26	0.36	0.72	0.18	1.08
FMIN	Moderate	9, 8, 2, 7, 6, 1, 5, 3, 4	15	1.35	1.2	0.3	1.05	0.9	0.15	0.75	0.45	0.6
IDFL	Low	9, 2, 5, 1, 6, 4, 7, 3, 8	10	0.9	0.2	0.5	0.1	0.6	0.4	0.7	0.3	0.8
FBFL	Low	3, 2, 7, 1, 5, 8, 4, 6, 9	7	0.21	0.14	0.49	0.07	0.35	0.56	0.28	0.42	0.63
Total scores			100	6.83	5.98	3.08	5.87	5.86	2.47	5.2	4.1	5.61

4.2 Unconfined Compressive Strength Analysis.

4.2.1 Unconfined Compressive Strength Analysis at room and elevated temperatures.

The Unconfined Compressive Strength (UCS) data for different cement recipes reveals valuable insights into the performance of the cement formulations under both room temperature (RT) and high-temperature (HT) conditions after one day of curing as seen in **Figure 52**. The UCS values, which measure the material's ability to withstand compressive stress along a single axis, vary significantly between room and elevated temperatures, showcasing the influence of thermal conditions on cement stability.

From the data, it is clear that all cement recipes exhibit significantly higher UCS at elevated temperatures. Class G cement alone achieves a UCS of 12.48 MPa at room temperature, which rises dramatically to 43.04 MPa under high-temperature conditions. Among the additives, the standout performer is Class G + 30% Fly Ash (FA), which reaches the highest UCS value of 70.62 MPa at HT, indicating exceptional strength under thermal conditions. However, at RT, this recipe shows moderate performance with 17.28 MPa, which suggests the additive greatly benefits from high-temperature curing.

Other additives such as Class G + 5% MB, Class G + 5% Fe, and Class G + 5% Fe₂O₃ also demonstrate strong UCS at HT, with values ranging from 39.20 MPa to 44.20 MPa. This indicates that these additives provide consistent structural reinforcement when exposed to heat. On the contrary, Class G + 5% Gilo exhibits the lowest UCS at both RT (8.80 MPa) and HT (24.94 MPa), highlighting its limited effectiveness in enhancing cement strength under either condition.

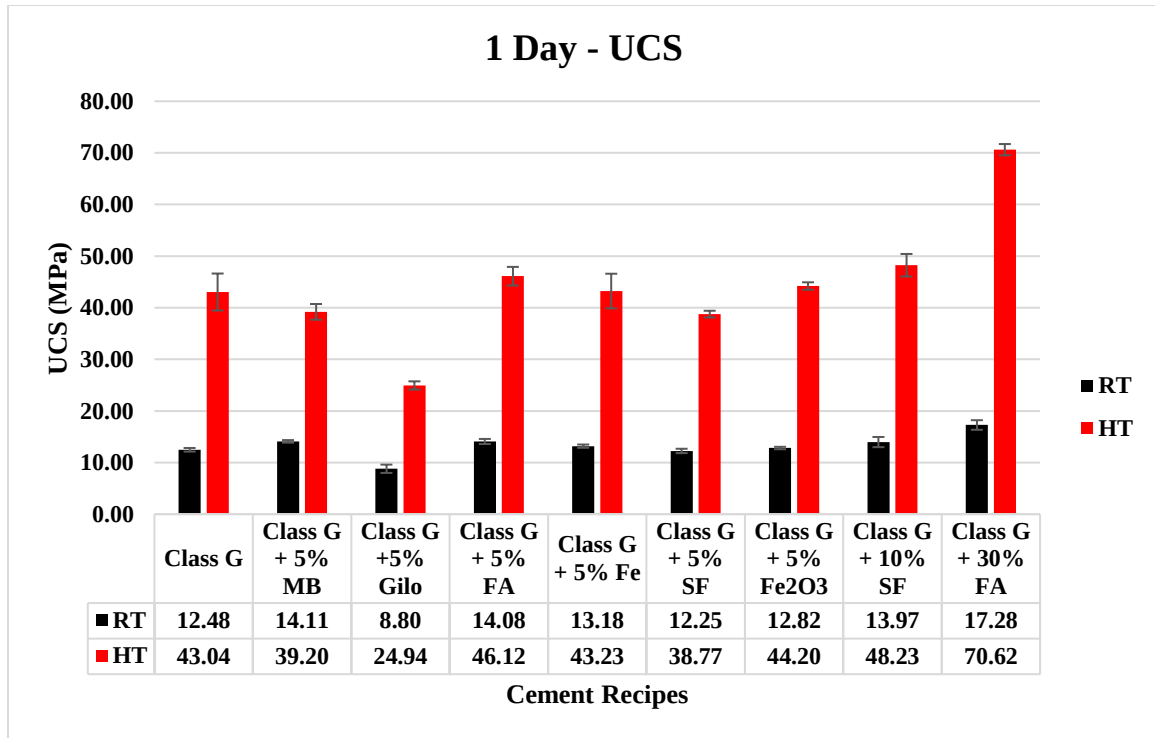


Figure 52. Unconfined Compressive Strength for cement recipes at 1-day curing.

The 3-day Unconfined Compressive Strength (UCS) results at both room and elevated temperatures reveal distinct trends in how different cement recipes respond to curing conditions, as seen in **Figure 53**. Cement compositions generally exhibit significantly higher UCS under high-temperature conditions, indicating that heat accelerates the hydration process and improves material strength. Notably, Class G + 30% Fly Ash (FA) achieved the highest UCS (67.21 MPa) at elevated temperatures, reflecting its potential to enhance cement strength with heat exposure significantly. Class G + 5% Fe₂O₃ and Class G + 5% Fe also performed exceptionally well, both maintaining strong UCS values under high temperatures. On the other hand, Class G + 5% Gilo showed the lowest UCS values under both room and high-temperature conditions, suggesting limited effectiveness in improving strength. The comparison across additives suggests that while certain additives, such as fly ash or iron-based compositions, respond positively to heat, others,

like Gilo, may require more optimal curing conditions or longer curing periods to achieve competitive strength. This trend underscores the importance of additive selection when optimizing cement performance, especially in thermal environments.

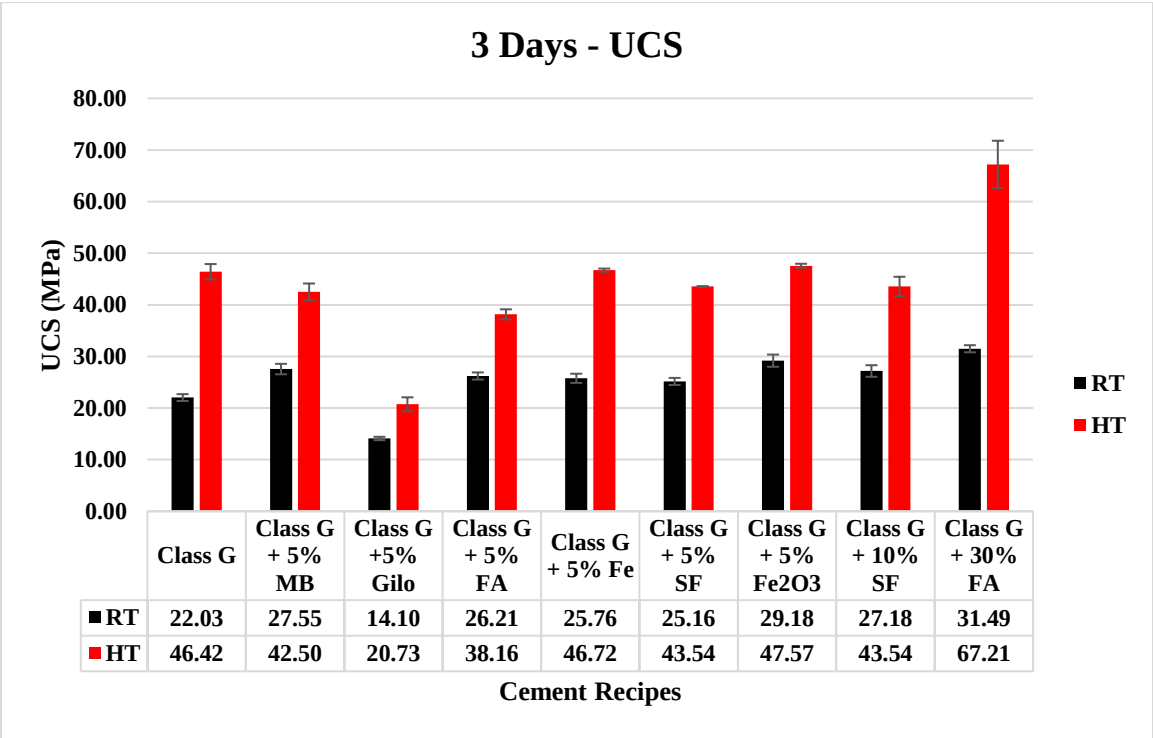


Figure 53. Unconfined Compressive Strength for cement recipes at 3-day curing.

The comparison of unconfined compressive strength (UCS) for different cement recipes at room temperature (RT) over 1 day and 3 days highlights the significant improvement achieved through extended curing, as seen in **Figure 54**. Across most cement recipes, UCS increases between the first and third day, showcasing the time-dependent strength gain of cement. Notably, ****Class G + 30% Fly Ash (FA)**** exhibits the highest UCS values at both 1 day (17.28 MPa) and 3 days (31.49 MPa), indicating superior strength development over time. Similarly, ****Class G + 5% Fe2O3**** also performs well, increasing to 29.18 MPa by the third day, suggesting that these additives promote consistent strength gains. In contrast, ****Class G + 5% Gilo**** shows the lowest UCS

values, with only a modest increase from 8.80 MPa to 14.10 MPa, reflecting limited compressive strength improvement with time. Overall, cement recipes with additives such as Fly Ash (both 5% and 30%) and iron-based compounds (Fe and Fe₂O₃) show substantial strength benefits with curing time, suggesting they offer enhanced structural integrity when allowed adequate curing, particularly under room temperature conditions.

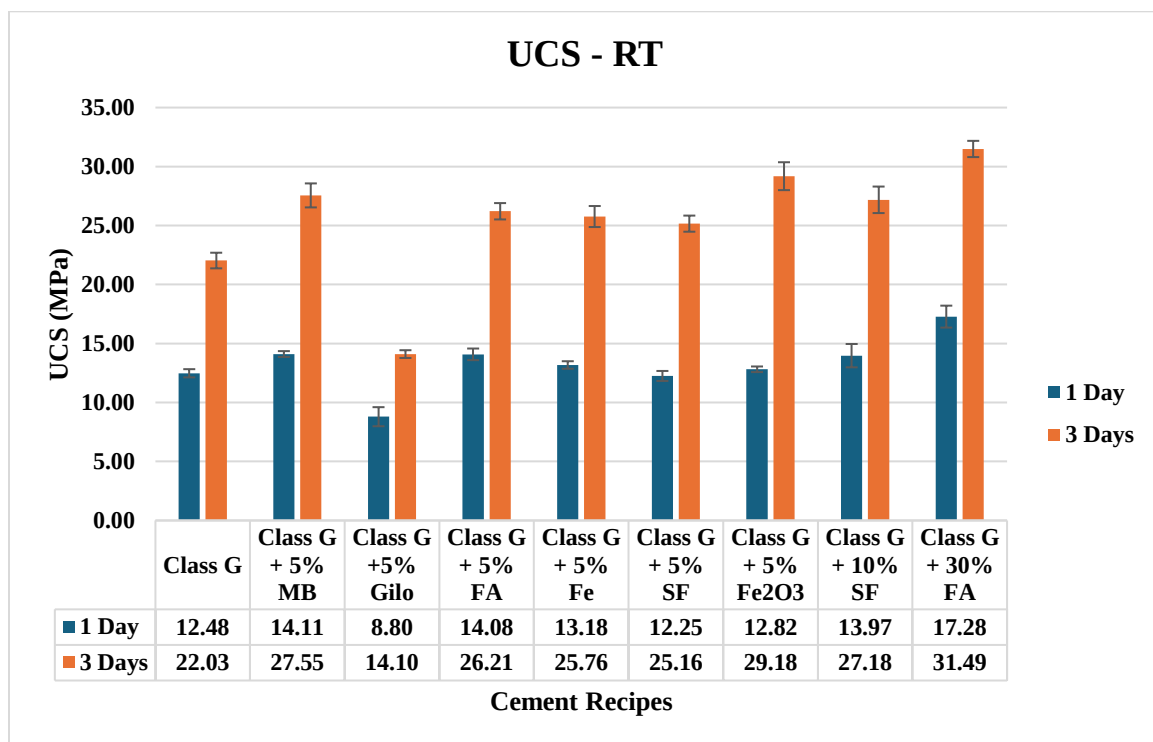


Figure 54. Unconfined Compressive Strength between 1- and 3-day curing time at room temperature.

The unconfined compressive strength (UCS) trends observed under elevated temperatures for one and three days reveal insightful variations in cement performance with prolonged curing, as seen in **Figure 55**. Class G + 30% Fly Ash (FA) exhibits exceptional initial strength, maintaining the highest UCS value among all recipes at both curing intervals, although with a slight decline from 70.62 MPa to 67.21 MPa. Interestingly, some recipes, such as Class G + 5% FA, display a

noticeable drop in strength after extended curing, suggesting sensitivity to longer curing at elevated temperatures. On the other hand, additives like Class G + 5% Fe and Class G + 5% Fe₂O₃ demonstrate improved stability, maintaining or slightly increasing their UCS over time, indicating their resilience under thermal conditions. Class G + 5% Gilo, however, shows a reduction in strength from 24.94 MPa to 20.73 MPa, indicating potential limitations when subjected to prolonged heat exposure. This comparative analysis emphasizes that while certain additives excel in maintaining integrity, others may experience performance degradation with extended curing under high temperatures, offering valuable insights into optimal cement selection for thermal applications.

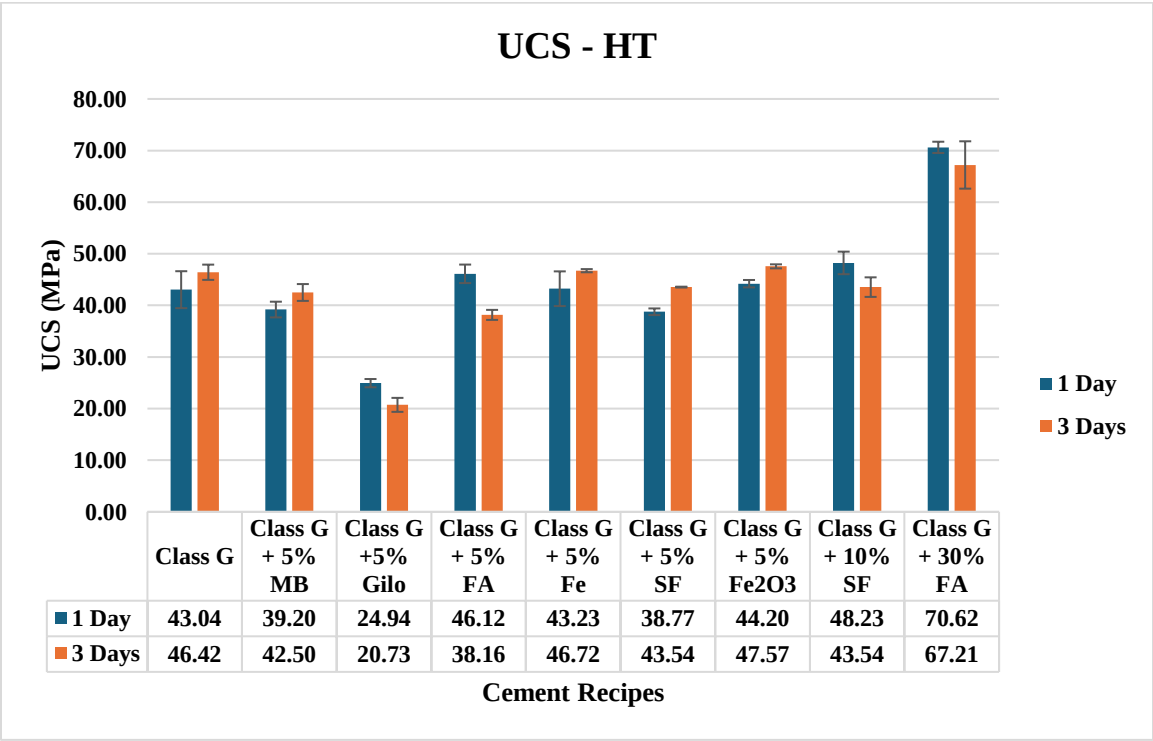


Figure 55. Unconfined Compressive Strength between 1- and 3-day curing time at elevated temperature.

4.2.2 Comparison of IBSS and UCS.

The relationship between Unconfined Compressive Strength (UCS) and Initial Bond Shear Strength (IBSS) in this analysis offers insights into the performance of different cement recipes after 1 day of curing at room temperature, as seen in **Figure 56**. The trend shows that while UCS measures the maximum stress the cement can withstand without lateral confinement, IBSS reflects the initial bonding force between the cement and casing before any displacement occurs. Class G + 30% Fly Ash (FA) exhibits the highest UCS at 17.28 MPa, but with a relatively moderate IBSS of 1.27 MPa, suggesting strong compressive performance but average bonding at early stages. On the other hand, Class G + 5% Microblock (MB) achieves a slightly improved balance between UCS (14.11 MPa) and IBSS (1.39 MPa), indicating it maintains both strength and bonding capabilities well. Interestingly, Class G + 5% Silica Fume (SF) shows the lowest IBSS (0.99 MPa) despite a reasonable UCS of 12.25 MPa, hinting that while it contributes to compressive strength, it may not enhance bonding sufficiently. Recipes with additives like 5% FA and 5% Fe₂O₃ display diverse trade-offs, excelling either in UCS or IBSS but not both simultaneously, which could suggest selective use based on whether strength or bonding is more critical for specific applications. The interplay between UCS and IBSS highlights that high compressive strength does not always equate to strong bonding, underscoring the importance of additive selection based on wellbore integrity requirements.

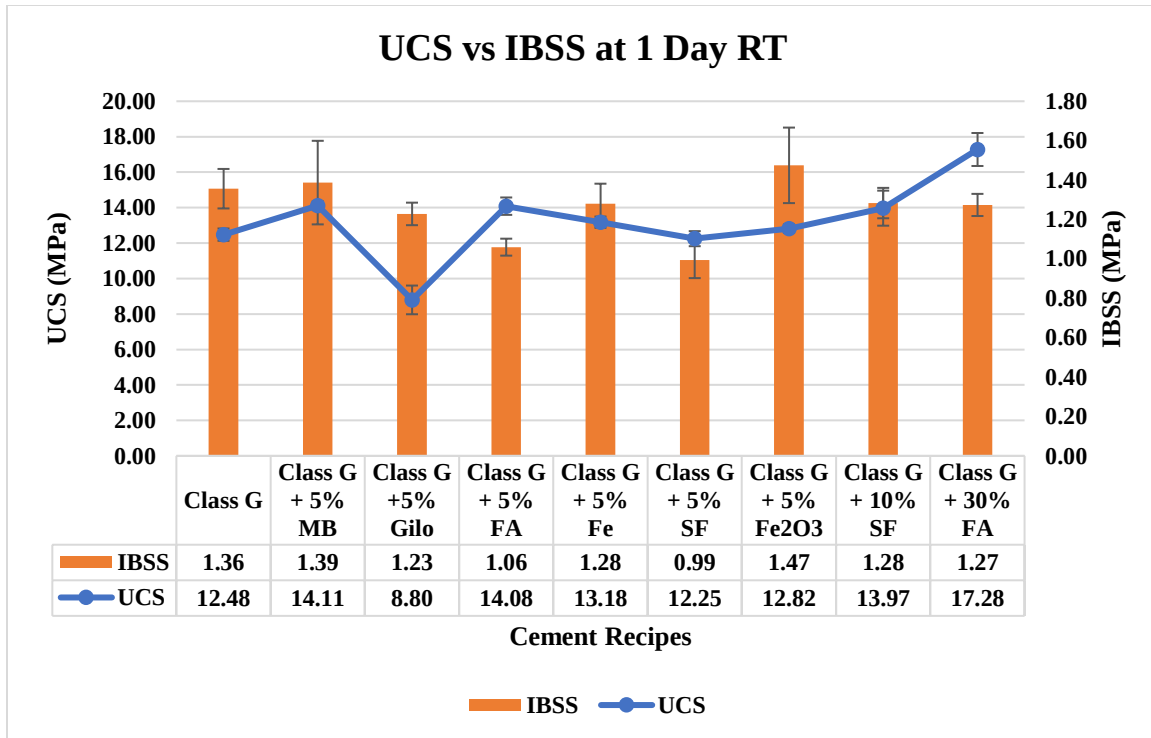


Figure 56. Relationship between UCS and IBSS at 1 Day curing at room temperature.

The 1-day elevated temperature analysis presents interesting trends between the Unconfined Compressive Strength (UCS) and the Initial Bond Strength Score (IBSS) across the cement recipes, as seen in **Figure 57**. Notably, Class G + 30% Fly Ash (FA) delivers the highest UCS at 70.62 MPa but scores the lowest IBSS at 0.81, suggesting that while the cement gains significant compressive strength, it may not perform well in bonding strength, which can be problematic for wellbore integrity. On the other hand, Class G + 5% Microblock (MB) achieves a balanced performance, maintaining a relatively strong IBSS of 1.76 along with a UCS of 39.20 MPa, indicating it offers a good compromise between bonding strength and compressive performance. Class G + 10% Silica Flour (SF) stands out with one of the highest UCS values (48.23 MPa) while maintaining a reasonable IBSS (1.35), making it suitable for applications requiring higher compressive strength with moderate bonding capacity. Meanwhile, additives like Class G + 5%

Gilo exhibit weaker UCS (24.94 MPa) but still maintain acceptable bonding with an IBSS of 1.22. Overall, this table demonstrates that while some recipes boost UCS effectively, such as Class G + 30% FA, they may sacrifice bonding performance, requiring a thoughtful selection of additives based on the specific demands of casing stability and compressive strength in elevated-temperature environments.

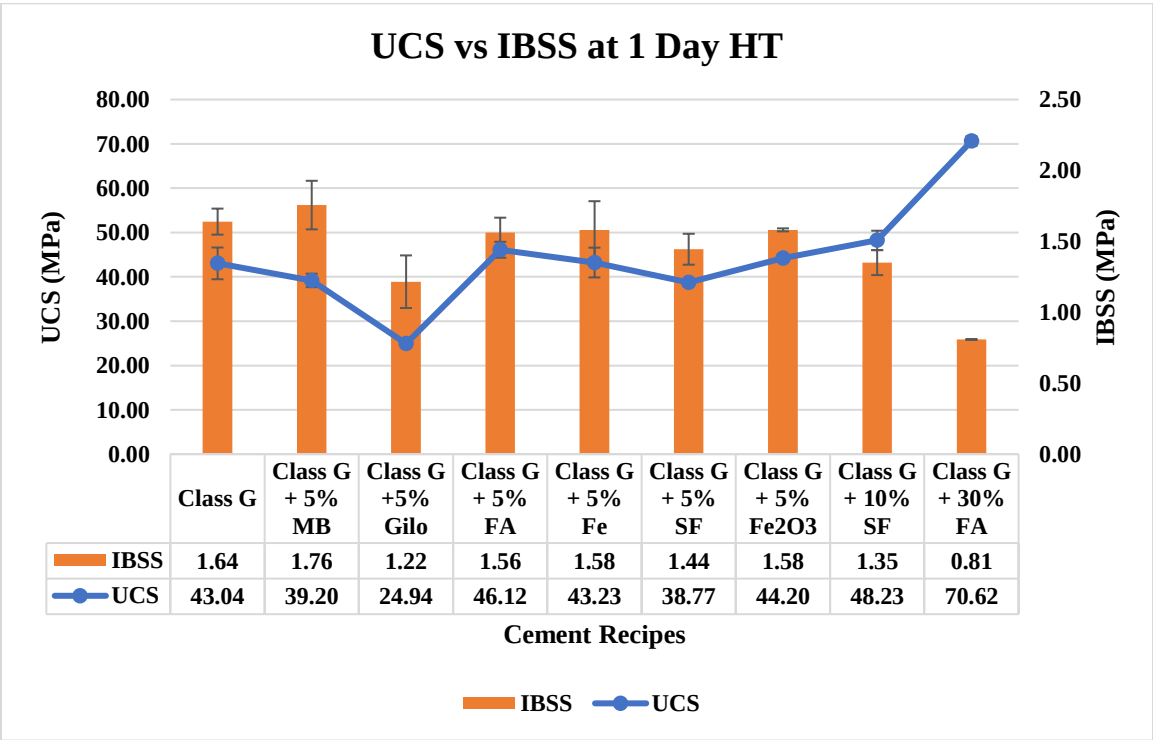


Figure 57. Relationship between UCS and IBSS at 1 Day curing at elevated temperature.

Figure 58 compares UCS (Unconfined Compressive Strength) and IBSS (Initial Bond Shear Strength) for different cement recipes after three days of curing at room temperature offers meaningful insights into the relationship between compressive strength and bonding capability. Notably, the cement recipes show varied behaviors, with Class G + 30% FA exhibiting the highest UCS at 31.49 MPa, alongside an impressive IBSS of 2.20 MPa, indicating robust mechanical and

bonding performance. On the other hand, Class G + 5% Gilo presents the lowest UCS (14.10 MPa) and the weakest IBSS (1.53 MPa), highlighting its limited performance under these conditions.

Interestingly, additives like Class G + 5% Fe₂O₃ and Class G + 10% SF maintain a balance between moderate UCS and reasonably strong IBSS, showing potential for applications requiring both structural integrity and bonding stability. Class G + 5% SF, despite having a UCS of 25.16 MPa, shows the lowest IBSS among the group (1.40 MPa), suggesting its compressive strength may not fully translate into bonding efficiency. Overall, the data suggests that cement recipes with fly ash additives (particularly 30% FA) perform exceptionally well across both metrics, implying their suitability for applications demanding higher compressive strength and enhanced bonding after curing.

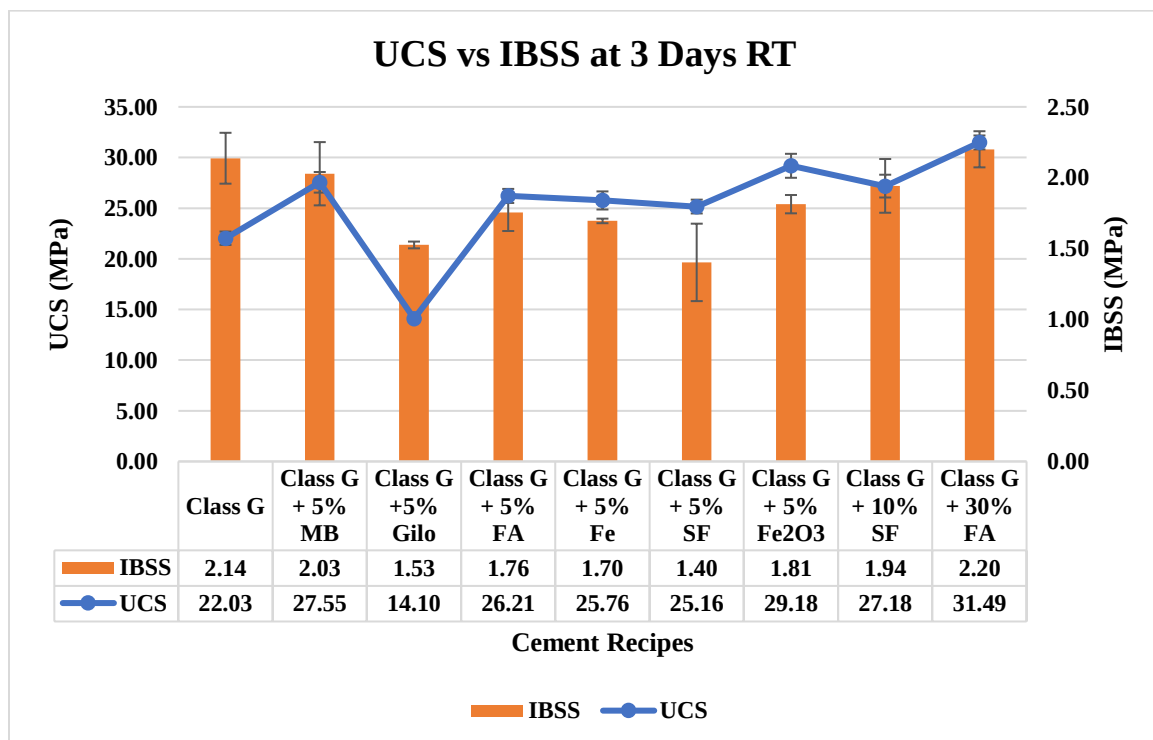


Figure 58. Relationship between UCS and IBSS at 3 Days curing at room temperature.

Figure 59 compares UCS (Unconfined Compressive Strength) and IBSS (Initial Bond Shear Strength) at elevated temperatures over three days and offers meaningful insights into the performance of different cement recipes under thermal curing. Class G + 30% Fly Ash (FA) stands out with a remarkably high UCS of 67.21 MPa, indicating exceptional compressive strength, but this comes at the cost of a very low IBSS of 0.79 MPa, suggesting a weaker bonding performance. Conversely, recipes like Class G + 5% Fe₂O₃ achieve a good balance, with a strong UCS of 47.57 MPa and a moderate IBSS of 1.40 MPa, highlighting its potential for applications that demand both compressive and bonding strength. Recipes such as Class G + 5% Gilo show poor compressive strength (20.73 MPa) and relatively low bonding (1.20 MPa), making them less ideal under high temperatures. It is interesting to observe that Class G + 5% Fe maintains both a high UCS (46.72 MPa) and a relatively solid IBSS (1.56 MPa), indicating it can perform well in maintaining structural integrity and casing bonding. Overall, the trade-off between UCS and IBSS across recipes reflects the diverse mechanical behaviors influenced by curing conditions, with some additives favoring compressive strength at the expense of bonding and vice versa.

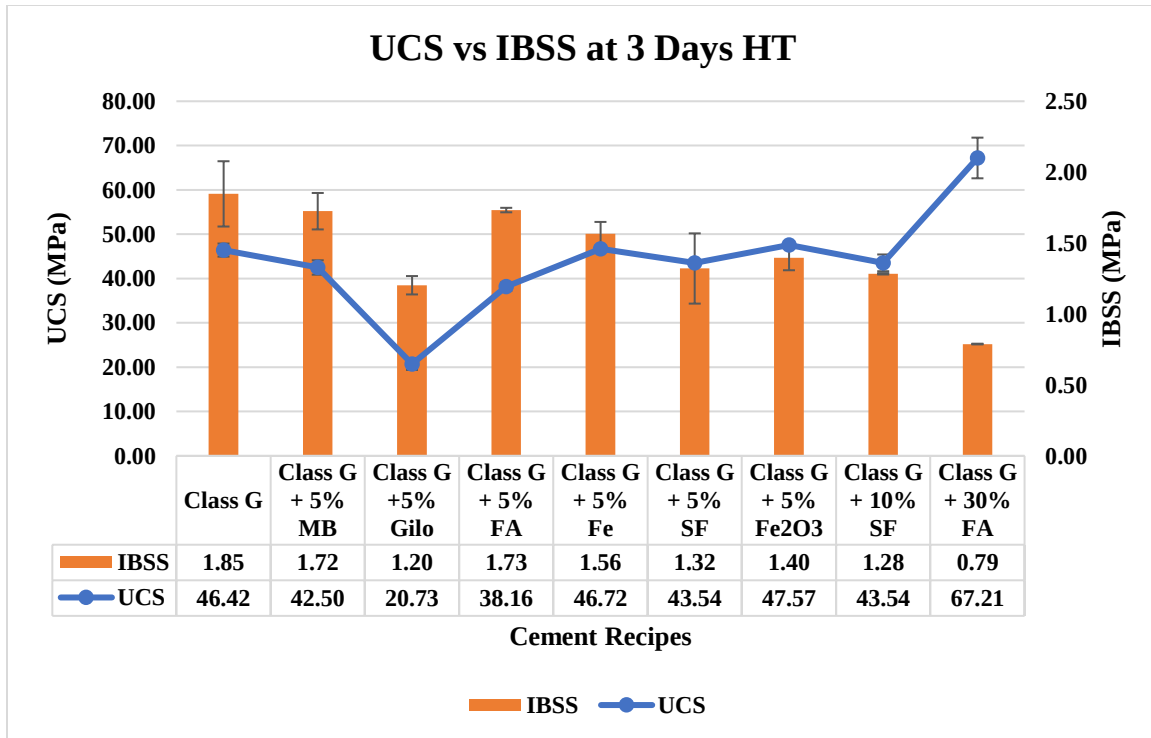


Figure 59. Relationship between UCS and IBSS at 3 Days curing at elevated temperature.

Table 15 summarizes the selection criteria and corresponding cement recipes identified as optimal under different curing conditions based on bonding and compressive strength. For one day of curing at room temperature (RT), Class G + 30% Fly Ash (FA) emerged as the best-performing recipe, offering both high bonding and compressive strength, highlighting its suitability for early-stage wellbore integrity. Under elevated temperature (HT) conditions for one day, Class G + 10% Silica Flour (SF) demonstrated high bonding and moderate compressive strength, making it effective in thermally stressed environments. For moderate bonding combined with high compressive strength, Class G + 5% Microblock (MB) was preferred under the same elevated temperature conditions. After three days of curing, Class G + 30% FA consistently excelled under both room and elevated temperature conditions, achieving a balance of high compressive strength and bonding performance. Similarly, Class G + 5% Iron Oxide (Fe₂O₃) provided moderate bonding

and high compressive strength after three days of curing at room temperature. This table effectively categorizes the cement recipes by their performance, offering a clear guide for selecting appropriate additives tailored to the specific curing conditions and performance requirements of wellbore cementing operations.

Table 15: Summary of Cement Recipes based on different selection criteria and curing days.

Selection Criteria	1 Day - RT	1 Day - HT	3 Days - RT	3 Days - HT
High Bonding and High Compressive Strength	Class G + 30% FA	Class G + 10% SF	N/A	N/A
High Bonding and Moderate Compressive Strength	Class G + 10% SF	N/A	N/A	N/A
Moderate Bonding and High Compressive Strength	Class G + 5% MB	Class G + 30% FA	Class G + 5% Fe ₂ O ₃	Class G + 30% FA
Moderate Bonding and Moderate Compressive Strength	N/A	N/A	N/A	N/A

5 Conclusions

This research has provided a comprehensive evaluation of the impact of various additives on the mechanical and bonding properties of API Class G cement under different curing conditions. The investigation focused on both room temperature and elevated temperature scenarios, with curing durations of one and three days. The outcomes of this study are highly insightful for optimizing cementing practices in the petroleum industry, particularly for ensuring wellbore integrity.

From the analysis, it is evident that the interplay between Unconfined Compressive Strength (UCS) and Initial Bond Shear Strength (IBSS) is crucial for determining the overall performance of cement recipes. While UCS reflects the capacity of the cement to withstand compressive forces, IBSS measures the bonding capability between the cement and the casing, which is essential for mitigating casing displacement and maintaining well stability. A key observation across all curing conditions is the trade-off between UCS and IBSS, where some additives enhance compressive strength at the expense of bonding performance, while others achieve a better balance between the two.

At room temperature after one day of curing, Class G + 30% Fly Ash (FA) emerged as the top-performing recipe with the highest total weighted score. This recipe demonstrated exceptional compressive strength and bonding properties, making it suitable for early-stage wellbore integrity. However, its performance was slightly limited in displacement control (IDFL) and bonding force loss (FBFL), which could pose challenges in scenarios with significant tectonic movements. Class G + 10% Silica Flour (SF) and Class G + 5% Microblock (MB) also performed well, offering a balance of strength and bonding properties. On the other hand, Class G + 5% Gilsonite (Gilo) showed the weakest performance due to poor UCS and bonding metrics, underscoring its limited applicability under room temperature conditions.

The performance trends under elevated temperature conditions after one day of curing highlighted Class G + 10% Silica Flour (SF) as the best overall recipe, achieving a strong balance between UCS and bonding metrics. However, Class G + 30% Fly Ash (FA) displayed the highest UCS but underperformed in IBSS, indicating its suitability for applications prioritizing compressive strength over bonding. Interestingly, Class G + 5% Microblock (MB) provided moderate UCS and excellent bonding properties, making it a versatile choice for high-temperature wellbore operations. Conversely, Class G + 5% Gilsonite (Gilo) again exhibited the lowest scores, emphasizing its unsuitability for thermally stressed environments.

After three days of curing at room temperature, the results revealed that Class G + 30% Fly Ash (FA) consistently outperformed other recipes, achieving high UCS, FMAX, and FAVG scores. This confirms the effectiveness of fly ash as an additive for long-term wellbore integrity. Class G + 5% Iron Oxide (Fe_2O_3) and Class G + 10% Silica Flour (SF) also demonstrated strong performance, particularly in bonding metrics, indicating their potential for applications where both compressive strength and bonding are critical. However, Class G + 5% Gilsonite (Gilo) remained the poorest performer, further highlighting its limitations in maintaining structural integrity and bonding strength under room temperature conditions.

Under elevated temperature conditions after three days of curing, Class G + 30% Fly Ash (FA) achieved the highest UCS, underscoring its exceptional compressive strength. However, its IBSS remained low, indicating potential issues with bonding in thermal environments. Class G + 5% Microblock (MB) and Class G + 5% Iron Oxide (Fe_2O_3) emerged as reliable options, achieving strong bonding metrics and moderate UCS, making them suitable for thermally stressed applications. Conversely, Class G + 5% Silica Flour (SF) recorded the lowest total score, reflecting its limited suitability for elevated temperature conditions.

The study also compared UCS and IBSS for various recipes under different curing conditions, highlighting the importance of selecting additives based on specific wellbore requirements. Recipes like Class G + 30% Fly Ash (FA) excelled in UCS across all scenarios but often sacrificed IBSS, making them ideal for applications requiring high compressive strength. Conversely, recipes like Class G + 5% Microblock (MB) and Class G + 5% Iron Oxide (Fe_2O_3) offered a balanced performance, excelling in bonding metrics while maintaining moderate compressive strength.

Overall, this study underscores the importance of tailoring cement recipes to the specific conditions and requirements of wellbore operations. While some additives like 30% Fly Ash enhance compressive strength, others like Microblock and Iron Oxide provide a balance of strength and bonding, ensuring sustained well integrity. The insights gained from this research provide a valuable framework for optimizing cement systems in the petroleum industry, paving the way for improved wellbore stability and operational safety. Future studies could further refine these findings by exploring additional additives and varying curing conditions to address the dynamic challenges of wellbore cementing.

6 Recommendations

Based on the findings of this study, several recommendations can be made for future research to further improve the performance evaluation and optimization of cement recipes for well integrity under diverse operational conditions. These recommendations aim to address potential limitations in the current research and open avenues for deeper exploration.

1. **Extended Curing Periods:** While this study evaluated the cement recipes at 1 and 3 days of curing, future research could explore longer curing periods, such as 7, 14, and 28 days. This would provide insights into the long-term performance and bonding behavior of the cement compositions, especially in wells that require extended setting times under both room and elevated temperature conditions.
2. **Real-Field Well Conditions:** The experiments in this study were conducted in controlled laboratory environments. Future work could replicate these tests under field-like conditions by simulating downhole pressure, temperature variations, and dynamic casing movements to better reflect real operational challenges. This would enhance the practical relevance of the findings.
3. **Exploration of New Additives:** Although this study focused on traditional additives like Fly Ash, Silica Flour, Iron Oxide, and Gilsonite, further research can investigate emerging additives, including nanomaterials, polymers, and geopolymer cement blends. Such additives may offer novel ways to enhance both compressive strength and bonding performance simultaneously.
4. **Integration with Fracture and Flow Simulations:** Future studies could incorporate fracture modeling and fluid flow simulations to assess how these cement recipes perform

in fractured reservoirs and in wells subject to hydraulic fracturing treatments. This would provide insights into how fractures impact bonding strength and compressive performance.

5. **Mechanical Cycling and Thermal Cycling Tests:** To better understand the durability of the cement recipes, future research could introduce mechanical cycling (repeated loading and unloading) and thermal cycling (fluctuations in temperature) experiments. This would evaluate the recipes' ability to maintain well integrity under fluctuating stresses over time.
6. **Chemical Compatibility with Well Fluids:** Further studies should assess the chemical interaction between the cement recipes and different types of well fluids (e.g., brines, hydrocarbons, CO₂-rich fluids). This would help determine the chemical durability of the recipes and their suitability for use in wells with aggressive chemical environments.
7. **Cost-Benefit Analysis for Field Deployment:** While this study focused on mechanical and bonding performance, future research could incorporate a cost-benefit analysis for each additive to determine the economic feasibility of scaling the optimized recipes for field applications. This would provide operators with a clearer picture of the trade-offs between performance and cost.
8. **Advanced Characterization Techniques:** Future research could use advanced characterization methods, such as scanning electron microscopy (SEM) or X-ray computed tomography (CT), to gain deeper insights into the microstructure of the cement matrices. This would help in understanding the structural changes that contribute to bonding and strength properties.
9. **Multi-Scale Modeling for Predictive Analysis:** Developing multi-scale predictive models that integrate both experimental data and numerical simulations would enhance the ability to predict the long-term performance of cement recipes under various scenarios.

This approach would offer a more comprehensive understanding of the interplay between UCS, IBSS, and operational variables.

10. Environmental Impact Assessment: Lastly, future research should explore the environmental impact of the additives used in the cement compositions. Investigating sustainable alternatives, such as eco-friendly binders or recycled materials, would align with the industry's growing focus on sustainability and carbon reduction.

By implementing these recommendations, future research can build on the foundation laid by this study, addressing potential gaps and enhancing the practical applicability of cement recipes in wellbore operations. These improvements will not only contribute to the advancement of cementing technologies but also ensure safer, more sustainable, and cost-effective well operations.

Bibliography

- (API), A. P. I. (2002). API Specification 10D. In *Specification for Bow-Spring Casing Centralizers*: API Publishing Services.
- (API), A. P. I. (2010). API Specification 10A. In *Specification for Cements and Materials for Well Cementing*: API Publishing Services.
- (API), A. P. I. (2016). Well Integrity. In: API Publishing.
- (ISO), I. O. f. S. (2001). Petroleum and natural gas industries—Equipment for well cementing. In *Part 1: Casing bow-spring centralizers*. (Vol. ISO 10427-1:2001). Geneva, Switzerland: ISO.
- (ISO), I. O. f. S. (2004). Petroleum and natural gas industries—Equipment for well cementing. In *Part 2: Centralizer placement and stop-collar testing*. (Vol. ISO 10427-2:2004). Geneva, Switzerland: ISO.
- (ISO), I. O. f. S. (2017). Petroleum and natural gas industries—Well integrity. In *Part 1: Life cycle governance*. Geneva, Switzerland: ISO.
- Abd Rahman, S. H., Medvedev, A., Yakovlev, A., Sazali, Y. A., Jain, B., Hassan, N., & Thompson, C. (2021). Development of New Geopolymer-Based System for Challenging Well Conditions. International Petroleum Technology Conference,
- Abid, K. (2018). *Designing a New Cement Composition Using Agricultural Wastes for Underground Gas Storage* Curtin University].
- Aïtcin, P. C. (2016). 3 - Portland cement. In P.-C. Aïtcin & R. J. Flatt (Eds.), *Science and Technology of Concrete Admixtures* (pp. 27-51). Woodhead Publishing. <https://doi.org/https://doi.org/10.1016/B978-0-08-100693-1.00003-5>
- Akbari Nasrekani, A., Naderi, K., Nakhaei, M., & Mahmoodinia, N. (2016). High-temperature performance of gilsonite-modified asphalt binder and asphalt concrete. *Petroleum Science and Technology*, 34, 1783–1789. <https://doi.org/10.1080/10916466.2016.1230750>
- Akgun, F., & Al-Ghadban, H. H. (2004). Simulation Investigation of Casing Eccentricity Estimation for Different Inclination Angles and Tensile Forces Using Finite Element Method. SPE International Petroleum Conference in Mexico,
- Alexandre Lavrov, M. T. (2016). *Physics and Mechanics of Primary Well Cementing*. Springer International Publishing.
- Alshahrani, A., Albaqami, M., Naji, Z., Al-Khunein, Y., Alsubaie, K., Alqahtani, A., & Al-Thobity, A. M. (2021). Impact of different surface treatment methods on bond strength between fiber post and composite core material. *Saudi Dent J*, 33(6), 334-341. <https://doi.org/10.1016/j.sdentj.2020.03.010>
- Amani, M., Al-Jubouri, M., & Shadravan, A. (2012). Comparative Study of Using Oil-Based Mud Versus Water-Based Mud in HPHT Fields.
- Anunciação Jaculli, M., Choueri Jr, N., da Mata, C. R., Aparecida Silva Leite, A. G., Pelaquim Mendes, J. R., & Colombo, D. (2022). Well safety and integrity evaluation of offshore wells: A review of past, present, and future. *Journal of Petroleum Science and Engineering*, 212, 110329. <https://doi.org/https://doi.org/10.1016/j.petrol.2022.110329>

- Arefi, M. R., Javaheri, M. R., Mollaahmadi, E., Zare, H., Abdollahi, B., & Eskandari, M. (2011). Silica nanoparticle size effect on mechanical properties and microstructure of cement mortar. *Journal of American Science*, 7, 231-238.
- Association, U. O. a. G. I. (2019). Well Integrity Guidelines. In: Oil & Gas UK.
- Bahafid, S., Ghabezloo, S., Faure, P., Duc, M., & Sulem, J. (2018). Effect of the hydration temperature on the pore structure of cement paste: Experimental investigation and micromechanical modelling. *Cement and Concrete Research*, 111, 1-14. <https://doi.org/https://doi.org/10.1016/j.cemconres.2018.06.014>
- Bai, M., Zhang, Z., & Fu, X. (2016). A review on well integrity issues for CO₂ geological storage and enhanced gas recovery. *Renewable and Sustainable Energy Reviews*, 59, 920-926. <https://doi.org/10.1016/j.rser.2016.01.043>
- Batista da Silva, Í., Martinelli, A. E., Medeiros de Souza, W. R., Cezar de Oliveira Freitas, J., & Felipe Rodrigues, M. A. (2018). Dilatometric behavior and crystallographic characterization of Portland-polyurethane composites for oilwell high-temperature cementing applications. *Journal of Petroleum Science and Engineering*, 169, 553-559. <https://doi.org/https://doi.org/10.1016/j.petrol.2018.06.014>
- Bhutada, G. (2022). *Mapped: Energy Consumption Per Capita Around the World*. Retrieved 10/16/2024 from <https://elements.visualcapitalist.com/energy-consumption-per-capita/>
- Bois, A.-P., Garnier, A., Rodot, F., Sain-Marc, J., & Aimard, N. (2011). How To Prevent Loss of Zonal Isolation Through a Comprehensive Analysis of Microannulus Formation. *SPE Drilling & Completion - SPE DRILL COMPLETION*, 26, 13-31. <https://doi.org/10.2118/124719-PA>
- Bosma, M., Ravi, K., Driel, W. v., & Schreppers, G. J. (1999). Design Approach to Sealant Selection for the Life of the Well. SPE Annual Technical Conference and Exhibition,
- Bourgoynne, J., A T, Millheim, K. K., Chenevert, M. E., & Young, J., F S. (1991). *Applied drilling engineering*. Richardson, TX (United States); Society of Petroleum Engineers. <https://www.osti.gov/biblio/5050497>
- BP. (2023). *Energy Outlook*. BP.
- Brufatto, C., Cochran, J., Conn, L., Power, D., El-Zeghaty, S. Z. A. A., Fraboulet, B., Griffin, T., James, S., Munk, T., Justus, F., Levine, J. R., Montgomery, C., Murphy, D., Pfeiffer, J., Pornpoch, T., & Rishmani, L. (2003). From Mud to Cement - Building Gas Wells. 15, 62-76+77.
- Cahill, A. G., Beckie, R., Ladd, B., Sandl, E., Goetz, M., Chao, J., Soares, J., Manning, C., Chopra, C., Finke, N., Hawthorne, I., Black, A., Ulrich Mayer, K., Crowe, S., Cary, T., Lauer, R., Mayer, B., Allen, A., Kirste, D., & Welch, L. (2019). Advancing knowledge of gas migration and fugitive gas from energy wells in northeast British Columbia, Canada. *Greenhouse Gases: Science and Technology*, 9(2), 134-151. <https://doi.org/https://doi.org/10.1002/ghg.1856>

- Carter, G., & Smith, D. K. (1958). Properties of Cementing Compositions at Elevated Temperatures and Pressure. *Transactions of the AIME*, 213(01), 20-27. <https://doi.org/10.2118/892-g>
- Carter, L. G., & Evans, G. W. (1964). A Study of Cement-Pipe Bonding. *Journal of Petroleum Technology*, 16, 157-160.
- Company, A. G. (2022). *American Gilsonite Company*. <https://www.americangilsonite.com/end-markets/oil-gas/cementing/>
- Cooper, R. E., & Birch, G. (1990). 15 Horizontal Well Cementing. In E. B. Nelson (Ed.), *Developments in Petroleum Science* (Vol. 28, pp. 15-11-15-15). Elsevier. [https://doi.org/https://doi.org/10.1016/S0376-7361\(09\)70313-9](https://doi.org/https://doi.org/10.1016/S0376-7361(09)70313-9)
- Couturier, M., Guillot, D., Hendriks, H., & Callet, F. (1990). Design Rules And Associated Spacer Properties For Optimal Mud Removal In Eccentric Annuli. Annual Technical Meeting, D-010, N. S. (2013). Well Integrity in Drilling and Well Operations. In: Standards Norway.
- Davies, R. J., Almond, S., Ward, R. S., Jackson, R. B., Adams, C., Worrall, F., Herringshaw, L. G., Gluyas, J. G., & Whitehead, M. A. (2014). Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation. *Marine and Petroleum Geology*, 56, 239-254. <https://doi.org/https://doi.org/10.1016/j.marpetgeo.2014.03.001>
- De Andrade, J., Torsæter, M., Todorovic, J., Opedal, N., Stroisz, A., & Vrålstad, T. (2014). Influence of Casing Centralization on Cement Sheath Integrity During Thermal Cycling. IADC/SPE Drilling Conference and Exhibition,
- DeBruijn, G., Loiseau, A., Chougnet-Sirapian, A., Piot, B., Pershikova, E., Khater, W., Evoy, K., & Wilson, G. (2010). Innovative Cementing Solution for Long-Term Steam Injection Well Integrity. SPE EUROPEC/EAGE Annual Conference and Exhibition,
- Didier, A., Radonjic, M., & Du, H. (2018). *The Wellbore Cement Additive, Gilsonite, a Solution to Leaky Gas Wells*.
- Dusseault, M. B., Gray, M. N., & Nawrocki, P. A. (2000). Why Oilwells Leak: Cement Behavior and Long-Term Consequences. International Oil and Gas Conference and Exhibition in China,
- Eilers, L. H., & Nelson, E. B. (1979). Effect Of Silica Particle Size On Degradation Of Silica Stabilized Portland Cement. SPE Oilfield and Geothermal Chemistry Symposium,
- Erik B Nelson, D. G. (2006). *Well Cementing* (2nd ed.). Schlumberger.
- Feng, H., Lv, L., Pang, Y., Wang, Z., Gao, D., & Zhang, Z. (2020). Experimental study on the effects of the fiber and nano-Fe₂O₃ on the properties of the magnesium potassium phosphate cement composites. *Journal of Materials Research and Technology*, 9(6), 14307-14320. <https://doi.org/https://doi.org/10.1016/j.jmrt.2020.10.030>
- Fink, J. (2015). *Petroleum Engineer's Guide to Oil Field Chemicals and Fluids*. Gulf Professional Publishing.
- Fjær, E., Holt, R. M., Horsrud, P., & Raaen, A. M. (2008). *Petroleum Related Rock Mechanics*. Elsevier Science. <https://books.google.com/books?id=l6CfasFxbhYC>

- Gollakota, A. R., Volli, V., & Shu, C.-M. (2019). Progressive utilisation prospects of coal fly ash: A review. *Science of The Total Environment*, 672, 951-989.
- Goodwin, K. J., & Crook, R. J. (1992). Cement Sheath Stress Failure. *SPE Drilling Engineering*, 7(04), 291-296. <https://doi.org/10.2118/20453-pa>
- Guohua, W., zhengmao, C., Jiyu, X., & Keli, Y. (2012). Study on the Effect of Non-Uniformity Load and Casing Eccentricity on the Casing Strength. *Energy Procedia*, 14, 285-291. <https://doi.org/https://doi.org/10.1016/j.egypro.2011.12.931>
- Gutteridge, W. A., & Dalziel, J. A. (1990). Filler cement: The effect of the secondary component on the hydration of Portland cement: Part I. A fine non-hydraulic filler. *Cement and Concrete Research*, 20(5), 778-782. [https://doi.org/https://doi.org/10.1016/0008-8846\(90\)90011-L](https://doi.org/https://doi.org/10.1016/0008-8846(90)90011-L)
- H, B. A. (2015). *Experimental Investigation of Shear Bond Strength and Microstructure of Fly Ash Geopolymer Cement for Oil and Gas Industry* University of Louisiana at Lafayette]. University of Louisiana at Lafayette, Lafayette, Louisiana.
- H., R. (2001). *Well Engineering and Construction*. Entrac Consulting.
- Hannah Ritchie, L. R.-G., Edouard Mathieu, Marcel Gerber, Esteban Ortiz-Ospina, Joe Hasell and Max Roser. (2023). *Population Growth* <https://ourworldindata.org/population-growth>
- Hole, H. (2008). *Cementing*. Norwegian Oil Industry Association.
- Ichim, A.-C. (2017). Experimental determination of oilfield cement properties and their influence on well integrity.
- Ichim, A. (2015). Effect of Cement Thermal Properties on Heat Transfer in HP/HT Wells. *Bachelor Thesis, Clausthal University of Technology, Clausthal-Zellerfeld, Germany*.
- Institute, A. P. (2010). Isolating Potential Flow Zones During Well Construction. In *API Standard 65-2*. 1220 L Street, N.W., Washington, D.C. 20005: API Publishing.
- Jadhav, R., Palla, V., Datta, A., & Dumbre, M. (2017). *Effect of Casing Coating Materials on Shear-Bond Strength*. <https://doi.org/10.2118/186441-MS>
- Kabir, I. I., Sorrell, C. C., Mada, M. R., Cholake, S. T., & Bandyopadhyay, S. (2016). General model for comparative tensile mechanical properties of composites fabricated from fly ash and virgin/recycled high-density polyethylene. *Polymer Engineering & Science*, 56(10), 1096-1108. <https://doi.org/https://doi.org/10.1002/pen.24342>
- Kar, K. K., Lahiri, S., Ahamad, L., Ahankari, S., & Anandhan, S. (2022). *Handbook of Fly Ash Download 11-11-21*.
- Karakosta, E., Lagkaditi, L., ElHardalo, S., Biotaki, A., Kelessidis, V. C., Fardis, M., & Papavassiliou, G. (2015). Pore structure evolution and strength development of G-type elastic oil well cement. A combined 1H NMR and ultrasonic study. *Cement and Concrete Research*, 72, 90-97. <https://doi.org/https://doi.org/10.1016/j.cemconres.2015.02.018>
- Karim, M., Chowdhury, F., Zabeed, H., & Rahman, M. S. (2018). Effect of elevated temperatures on compressive strength and microstructure of cement paste containing palm oil clinker powder. *Construction and Building Materials*, 183, 376-383. <https://doi.org/10.1016/j.conbuildmat.2018.06.147>

- Keating, J., Hannant, D. J., & Hibbert, A. P. (1989). Correlation between cube strength, ultrasonic pulse velocity and volume change for oil well cement slurries. *Cement and Concrete Research*, 19(5), 715-726. [https://doi.org/https://doi.org/10.1016/0008-8846\(89\)90042-2](https://doi.org/https://doi.org/10.1016/0008-8846(89)90042-2)
- Kerunwa, A., Obibuike, J., Duru, U., & Ekwueme, S. (2021). The Effects of Fluid Rheology and Drillstring Eccentricity on Drilling Hydraulics. *Open Journal of Yangtze Oil and Gas*, 06, 129-145. <https://doi.org/10.4236/ojogas.2021.64012>
- Kettl, F. C., Edwards, M. G., & Covington, R. L. (1993). Practical Horizontal Cementing Today. Middle East Oil Show,
- King, G. E., & King, D. E. (2013). Environmental Risk Arising From Well-Construction Failure—Differences Between Barrier and Well Failure, and Estimates of Failure Frequency Across Common Well Types, Locations, and Well Age. *SPE Production & Operations*, 28(04), 323-344. <https://doi.org/10.2118/166142-pa>
- Kiran, R., Teodoriu, C., Dadmohammadi, Y., Nygaard, R., Wood, D., Mokhtari, M., & Salehi, S. (2017). Identification and evaluation of well integrity and causes of failure of well integrity barriers (A review). *Journal of Natural Gas Science and Engineering*, 45, 511-526. <https://doi.org/https://doi.org/10.1016/j.jngse.2017.05.009>
- Kök, B. V., Yilmaz, M., & Guler, M. (2011). Evaluation of high temperature performance of SBS+Gilsonite modified binder. *Fuel*, 90(10), 3093-3099. <https://doi.org/https://doi.org/10.1016/j.fuel.2011.05.021>
- Lambrescu, I., Abid, K., & Teodoriu, C. (2024). Cement-Formation Debonding Due to Temperature Variation in Geothermal Wells: An Intensive Numerical Simulation Assessment. *Energies*, 17(19), 4953. <https://www.mdpi.com/1996-1073/17/19/4953>
- Lambrescu, I., & Teodoriu, C. (2022). Experimental and Numerical Investigations of Cement Bonding Properties at Elevated Temperatures—The Effect of Sample Cooling. *Materials*, 15(14), 4955. <https://www.mdpi.com/1996-1944/15/14/4955>
- Larry W. Lake, R. F. M., Kenneth E. Arnold. (2006). *Petroleum Engineering Handbook*. Society of Petroleum Engineers.
- Lee, C. Y., Lee, H. K., & Lee, K. M. (2003). Strength and microstructural characteristics of chemically activated fly ash–cement systems. *Cement and Concrete Research*, 33(3), 425-431. [https://doi.org/https://doi.org/10.1016/S0008-8846\(02\)00973-0](https://doi.org/https://doi.org/10.1016/S0008-8846(02)00973-0)
- Li, L., Zhang, Y., Hubler, M. H., & Xi, Y. (2022). Experimental study on nanoparticle injection by using a lab-scale wellbore system. *Cement and Concrete Composites*, 127, 104409. <https://doi.org/https://doi.org/10.1016/j.cemconcomp.2022.104409>
- Li, Z., Liu, H., Guo, X., Ou, H., & Gu, T. (2016). Contamination of cement slurries with oil based mud and its components in cementing operations. *Journal of Natural Gas Science and Engineering*, 29, 160-168. <https://doi.org/https://doi.org/10.1016/j.jngse.2016.01.003>
- Luke, K. (2004). Phase studies of pozzolanic stabilized calcium silicate hydrates at 180 °C. *Cement and Concrete Research*, 34(9), 1725-1732. <https://doi.org/https://doi.org/10.1016/j.cemconres.2004.05.021>

- Luke, K., Hall, C., Jones, T., Barnes, P., Turillas, X., & Lewis, A. (1995). New Techniques for Monitoring Cement Hydration Under Simulated Well Conditions. SPE International Symposium on Oilfield Chemistry,
- M. R. Islam, A. B. C., M. M. Khan (2011). *The Greening of Petroleum Operations: The Science of Sustainable Energy Production*. John Wiley & Sons.
- Maagi, M. T., Lupyana, S. D., & Jun, G. (2020). Nanotechnology in the petroleum industry: Focus on the use of nanosilica in oil-well cementing applications - A review. *Journal of Petroleum Science and Engineering*, 193, 107397. <https://doi.org/https://doi.org/10.1016/j.petrol.2020.107397>
- Mahmoud, A. A., & Elkatatny, S. (2024). Properties and Performance of Oil Well Slurry and Cement Sheath Incorporating Nano Silica: A Review. *ACS Omega*, 9(8), 8654-8665. <https://doi.org/10.1021/acsomega.3c07365>
- Matsunaga, T., Kim, J. K., Hardcastle, S., & Rohatgi, P. K. (2002). Crystallinity and selected properties of fly ash particles. *Materials Science and Engineering: A*, 325(1), 333-343. [https://doi.org/https://doi.org/10.1016/S0921-5093\(01\)01466-6](https://doi.org/https://doi.org/10.1016/S0921-5093(01)01466-6)
- Mehta, P. K., & Monteiro, P. J. M. (2014). *Concrete: Microstructure, Properties, and Materials* (4th Edition ed.). McGraw-Hill Education. <https://www.accessengineeringlibrary.com/content/book/9780071797870>
- Michael S. Mamlouk, J. P. Z. (2011). *Materials for Civil and Construction Engineers*. Pearson Education, Inc.
- Mindess, S. (2008). *Developments in the Formulation and Reinforcement of Concrete*. Woodhead Publishing.
- Morgan, B. E., & Dumbauld, G. K. (1952). Use of Activated Charcoal in Cement To Combat Effects of Contamination by Drilling Muds. *Journal of Petroleum Technology*, 4(09), 225-232. <https://doi.org/10.2118/952225-g>
- Murtaza, M., Mahmoud, M., Elkatatny, S., Al-Majed, A., Chen, W., & Jamaluddin, A. (2019). *Experimental Investigation of the Impact of Modified Nano Clay on the Rheology of Oil Well Cement Slurry*. <https://doi.org/10.2523/IPTC-19456-MS>
- Nelson, E. B. (1990). *Well Cementing*. Elsevier Science.
- Neville, A. M. (2011). *Properties of Concrete*. Pearson. <https://books.google.com/books?id=mmygngEACAAJ>
- Niu, Y., Cheng, H., Wu, S., Sun, J., & Wang, J. (2022). Rheological properties of cemented paste backfill and the construction of a prediction model. *Case Studies in Construction Materials*, 16, e01140. <https://doi.org/https://doi.org/10.1016/j.cscm.2022.e01140>
- Onaizi, A. M., Amran, M., Tang, W., Betoush, N., Alhassan, M., Rashid, R. S. M., Yasin, M. F., Bayagoob, K. H., & Onaizi, S. A. (2024). Radiation-shielding concrete: A review of materials, performance, and the impact of radiation on concrete properties. *Journal of Building Engineering*, 97, 110800. <https://doi.org/https://doi.org/10.1016/j.jobbe.2024.110800>

- Peterson, B. (1963). *Bond of cement compositions for cementing wells* 6th World Petroleum Congress, Frankfurt am Main, Germany.
- Poon, C. S., Kou, S. C., Lam, L., & Lin, Z. S. (2001). Activation of fly ash/cement systems using calcium sulfate anhydrite (CaSO₄). *Cement and Concrete Research*, 31(6), 873-881. [https://doi.org/https://doi.org/10.1016/S0008-8846\(01\)00478-1](https://doi.org/https://doi.org/10.1016/S0008-8846(01)00478-1)
- POWERS, T. C. (1958). Structure and Physical Properties of Hardened Portland Cement Paste. *Journal of the American Ceramic Society*, 41(1), 1-6. <https://doi.org/https://doi.org/10.1111/j.1151-2916.1958.tb13494.x>
- R, M. (2012). Well integrity in offshore drilling. *Marine Technology Society Journal*, 46(4), 24-26.
- Radenti, G., & Ghiringhelli, L. (1972). Cementing materials for geothermal wells. *Geothermics*, 1(3), 119-123. [https://doi.org/https://doi.org/10.1016/0375-6505\(72\)90037-5](https://doi.org/https://doi.org/10.1016/0375-6505(72)90037-5)
- Raha. (2016). *Gilsonite is a Critical Component in Cementing Oil well*. Retrieved 10/15/2024 from <https://rahaoil.com/gilsonite-cementing-oil>
- Rashad, A. M. (2015). An exploratory study on high-volume fly ash concrete incorporating silica fume subjected to thermal loads. *Journal of Cleaner Production*, 87, 735-744. <https://doi.org/https://doi.org/10.1016/j.jclepro.2014.09.018>
- Renpu, W. (2011). *Advanced Well Completion Engineering*. Gulf Professional Publishing.
- Rincon, F., Abid, K., Arbad, N., & Teodoriu, C. (2022). A comprehensive analysis of class H cement Unconfined Compressive Strength using cubical and cylindrical samples. *Journal of Petroleum Science and Engineering*, 215, 110692. <https://doi.org/https://doi.org/10.1016/j.petrol.2022.110692>
- Rod, K. A., Fernandez, C. A., Koech, P. K., Dai, G., Correa, M., Huerta, N., Burton, S., Miller, Q. R. S., & Resch, C. T. (2020). Self-repairing polymer-modified cements for high temperature geothermal and fossil energy applications. *Geothermics*, 85, 101790. <https://doi.org/https://doi.org/10.1016/j.geothermics.2019.101790>
- Romanowski, N., Ichim, A., & Teodoriu, C. (2018). Investigations on Oilwell Cement Strength Response to Ultrasonic Measurements in the Presence of Additives1. *Journal of Energy Resources Technology*, 140(7). <https://doi.org/10.1115/1.4039316>
- Romero, M., Devers, D., & Teodoriu, C. (2023). Observations of Thermal Cracking Propagation in Geopolymer Curing. 48th Workshop on Geothermal Reservoir Engineering. Stanford, California. SGP-TR-224,
- Salehabadi, M., Jin, M., Yang, J., Ahmed, R., & Tohidi, B. (2010). *The Effect of Casing Eccentricity on the Casing Stability Analysis of a Wellbore Drilled in Gas Hydrate Bearing Sediments*. <https://doi.org/10.2523/131236-MS>
- Salehi, S., Khattak, M. J., Ali, N., & Rizvi, H. R. (2016). Development of Geopolymer-based Cement Slurries with Enhanced Thickening Time, Compressive and Shear Bond Strength and Durability. IADC/SPE Drilling Conference and Exhibition,
- Salehi, S., Khattak, M. J., Bwala, A. H., & S, F. K. (2017). Characterization, morphology and shear bond strength analysis of geopolymers: Implications for oil and gas well cementing

- applications. *Journal of Natural Gas Science and Engineering*, 38, 323-332. <https://doi.org/https://doi.org/10.1016/j.jngse.2016.12.042>
- Sandl, E., Cahill, A. G., Welch, L., & Beckie, R. (2021). Characterizing oil and gas wells with fugitive gas migration through Bayesian multilevel logistic regression. *Science of The Total Environment*, 769, 144678. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.144678>
- Saunders, C. D., & Walker, W. A. (1954). Strength Of Oil Well Cements And Additives Under High Temperature Well Conditions. Fall Meeting of the Petroleum Branch of AIME, Schlumberger. (2024). *Oilfield Glossary*. <https://glossary.slb.com/en/terms/c/casing>
- Scott J B, B. R. L. (1966). *Coated casing - A technique for improved cement bonding* Drilling and Production Practice, New York, New York, U.S.A.
- Scrivener, K. L., Füllmann, T., Gallucci, E., Walenta, G., & Bermejo, E. (2004). Quantitative study of Portland cement hydration by X-ray diffraction/Rietveld analysis and independent methods. *Cement and Concrete Research*, 34(9), 1541-1547. <https://doi.org/https://doi.org/10.1016/j.cemconres.2004.04.014>
- Shadbad, K., Foroughi-Asl, A., Talatahari, S., & Mohasseb, S. (2022). The Effects of Nanoparticle Additives on Thermophysical Properties of Concrete Mixtures. *Open Journal of Civil Engineering*, 12, 587-614. <https://doi.org/10.4236/ojce.2022.124033>
- Shadravan, A., & Amani, M. (2012). HPHT 101-What Petroleum Engineers and Geoscientists Should Know About High Pressure High Temperature Wells Environment. *Energy Science and Technology*, 4, 36-60.
- Shadravan, A., Narvaez, G., Alegria, A., Carman, P., Perez, C., & Erger, R. (2015). *Engineering the Mud-Spacer-Cement Rheological Hierarchy Improves Wellbore Integrity*. <https://doi.org/10.2118/173534-MS>
- Slagle KA, C. G. (1958). *Gilsonite -A Unique Additive for Oil-well Cements*.
- Smith, D. K. (1990). *Cementing*. H.L. Doherty Memorial Fund of AIME, Society of Petroleum Engineers. <https://books.google.com/books?id=RBzIDAEACAAJ>
- Souza, G., Nogueira, F., Schwantes-Cezario, N., Toralles, B., & Sandoval, G. (2016). Incorporation of micro and nanoparticles of silica in cementitious composites. 6, 2-11.
- T, H., & Ramaswamy, A. (2017). A review on fly ash characteristics- Towards promoting high volume utilization in developing sustainable concrete. *Journal of Cleaner Production*, 147. <https://doi.org/10.1016/j.jclepro.2017.01.114>
- Tabatabaei, M., Dahi Taleghani, A., & Alem, N. (2020). Measurement of mixed mode interfacial strengths with cementitious materials. *Engineering Fracture Mechanics*, 223, 106739. <https://doi.org/https://doi.org/10.1016/j.engfracmech.2019.106739>
- Taylor Boden, B. T. T. (2012). *Gilsonite Veins of the Uinta Basin, Utah*. In *Special Study 141 Utah Geological Survey*. Utah: Natural Resources Map & Bookstore.
- Taylor, H. F. W. (1997). *Cement Chemistry*. Emerald Publishing Limited. <https://books.google.com/books?id=1BOETtwi7mMC>
- Teodoriu, C., Ugwu, I., & Schubert, J. (2010). Estimation of Casing-Cement-Formation Interaction using a new Analytical Model. <https://doi.org/10.2118/131335-MS>

- Teodoriu, C., Yi, M. C., Ichim, A., & Salehi, S. (2018a). A novel view of cement failure with application to geothermal well construction.
- Teodoriu, C., Yi, M. C., Ichim, A., & Salehi, S. (2018b). A novel view of cement failure with application to geothermal well construction. Proceedings of the 43rd Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA,
- The U.S. Energy Information Administration, t. s. a. a. (2023). *The Distribution of U.S. Oil and Natural Gas Wells by Production Rate with data through 2022*.
- Thiercelin, M. J., Dargaud, B., Baret, J. F., & Rodriquez, W. J. (1998). Cement design based on cement mechanical response. *SPE Drilling and Completion*, 13, Medium: X; Size: pp. 266-273. <https://doi.org/10.2118/52890-pa>
- Trudel, E., Bizhani, M., Zare, M., & Frigaard, I. A. (2019). Plug and abandonment practices and trends: A British Columbia perspective. *Journal of Petroleum Science and Engineering*, 183, 106417. <https://doi.org/https://doi.org/10.1016/j.petrol.2019.106417>
- Valizadeh Kiamahalleh, M., Alishah, A., Yousefi, F., Hojjati Astani, S., Gholampour, A., & Valizadeh Kiamahalleh, M. (2020). Iron oxide nanoparticle incorporated cement mortar composite: correlation between physico-chemical and physico-mechanical properties [10.1039/D0MA00295J]. *Materials Advances*, 1(6), 1835-1840. <https://doi.org/10.1039/D0MA00295J>
- Vu, M., Sulem, J., & Laudet, J.-B. (2012). Effect of the curing temperature on the creep of a hardened cement paste. *Cement and Concrete Research*, 42, 1233–1241. <https://doi.org/10.1016/j.cemconres.2012.05.015>
- Wang, L., Du, G., He, X., Wei, Z., Xu, Y., Li, S., & Liu, X. (2023). The Influence of Iron Tailings Powder on the Properties on the Performances of Cement Concrete with Machine-Made Sand. *Coatings*, 13(5), 946. <https://doi.org/https://doi.org/10.3390/coatings13050946>
- Wang, W.-C. (2017). Compressive strength and thermal conductivity of concrete with nanoclay under Various High-Temperatures. *Construction and Building Materials*, 147, 305-311. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2017.04.141>
- William, B., V, D., & Radnojcic, M. (2019). *Nature's solution to wellbore gas-leakage: Gilsonite* 53rd U.S. Rock Mechanics/Geomechanics Symposium,
- Wilson, D. C., Eustes, A. W., & Fleckenstein, W. W. (2018). Lab Testing Cement-Steel Bonding at Shallow Temperature and Pressure Conditions. SPE Western Regional Meeting,
- Wu B, A. E., Tian W, Dao B and Yan S. (2020). Sealant technologies for remediating cement-related oil and gas well leakage - a state-of-the-art literature review.
- Wu, Y., Patel, H., & Salehi, S. (2020). Thermal Considerations of Cement Integrity in Geothermal Wells.
- Xie, L., Chaudhary, S., & Chen, Z. (2015). Analysis of the Effect of Eccentricity on Displacement of Non-Newtonian Fluids with a Hybrid Method. SPE Annual Technical Conference and Exhibition,

- Xing, J., Gao, L., Zhang, Z., & Luo, N. (2024). Application of cement-based materials as engineered barriers in geological disposal facilities. *Alexandria Engineering Journal*, 107, 468-479. <https://doi.org/https://doi.org/10.1016/j.aej.2024.07.090>
- Zhao, X., Guan, Z., Xu, M., Shi, Y., Liao, H., & Sun, J. (2015). The Influence of Casing-Sand Adhesion on Cementing Bond Strength. *PLOS ONE*, 10(6), e0130892. <https://doi.org/10.1371/journal.pone.0130892>
- Zhe, Z., & Yuxiu, A. (2018). Nanotechnology For Oil and Gas Industry – an Overview of Recent Progress. *Nanotechnology Reviews*, 7. <https://doi.org/10.1515/ntrev-2018-0061>