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Effects of Seawater and Freshwater on Concrete Properties with Varying Sodium Silicate Concentrations at Low Temperature Regime

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ABSTRACT : *Zonal isolation in offshore environments relies on cementitious materials to seal the annular space, preventing fluid migration and ensuring well integrity under challenging conditions. The study investigates the influence of seawater and freshwater on concrete properties when combined with varying concentrations of sodium silicate, focusing on low-temperature effects relevant to marine structures. Key parameters assessed include setting time, free fluid content, and compressive strength. Experiments were conducted under simulated offshore conditions, adhering to ASTM standards, with sodium silicate concentrations of 1%, 2%, and 3%, and temperatures ranging from 80°F to 100°F. Results demonstrate that seawater-mixed cement slurry (concrete) generally achieves higher compressive strength across all sodium silicate concentrations and temperatures compared to freshwater mixtures, with seawater mixtures at 1% sodium silicate showing compressive strengths of 43-68 psi versus 29-58 psi for freshwater. Seawater mixtures also exhibited shorter thickening times, especially at higher temperatures, which may be advantageous for rapid strength development in wellbore cementing. The findings suggest that the ionic composition of seawater, when combined with sodium silicate, enhances the material's rheological and mechanical properties, making it a viable option for offshore cementing operations and marine infrastructure.*

KEYWORDS *Zonal isolation, offshore cementing, seawater, freshwater, sodium silicate, low temperature, compressive strength, setting time, free fluid content, well integrity, marine structures, ASTM standards, rheological properties, wellbore cementing, concrete mix*

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I. INTRODUCTION

Concrete is a ubiquitous construction material extensively used in various industries worldwide, including offshore petroleum engineering, where structures are often subjected to harsh marine environments. The durability and performance of concrete in such settings are influenced by numerous factors, among which the choice of mixing water and the addition of chemical admixtures play significant roles. In marine environments, the availability of seawater as a mixing water source raises questions about its compatibility with concrete properties compared to freshwater. Additionally, the incorporation of additives such as sodium silicate further complicates the interaction dynamics between water, cement, and admixtures, particularly under low-temperature conditions. Research has shown that seawater, with its higher salinity and dissolved mineral content compared to freshwater, can affect the setting time, free fluid content, and compressive strength of concrete. Studies by Smith et al. (2005) and Gupta and El-Tawil (2012) have highlighted the accelerating effect of seawater on the setting time of concrete due to its higher ionic concentration. However, concerns regarding the potential corrosion of reinforcement in seawater-exposed concrete structures have also been raised (Gupta and El-Tawil, 2012). In parallel, the addition of sodium silicate, commonly known as water glass, to concrete mixes has garnered attention for its ability to improve various properties of concrete, including strength, durability, and resistance to chemical attack. The reaction between sodium silicate and cementitious materials leads to the formation of additional calcium silicate hydrate (C-S-H) gel, enhancing the densification of the concrete matrix (Wang et al., 2018). However, the influence of varying sodium silicate concentrations on concrete properties, particularly in combination with seawater or freshwater, remains a topic of active research. Furthermore, the effect of low temperatures on concrete properties cannot be overlooked, especially in offshore environments where structures are exposed to cold seawater. The hydration process of cementitious materials can be significantly slowed down at low temperatures, potentially affecting the setting time, early-age strength development, and durability of concrete (Zhang et al., 2020). Understanding the complex interplay between seawater, freshwater, sodium silicate, and low temperatures is crucial for optimizing concrete mix designs and ensuring the long-term performance of structures in marine environments.

Therefore, this study aims to investigate the effects of seawater and freshwater on concrete properties, with a specific focus on varying sodium silicate concentrations, under low-temperature conditions. By examining the setting time, free fluid content, and compressive strength of concrete mixes, valuable insights can be gained into the performance and durability of concrete in offshore petroleum engineering applications.

II. LITERATURE REVIEW

Seawater, characterized by its higher salinity and dissolved mineral content compared to freshwater, introduces unique solutions to concrete production. Early studies by Neville (1995) and Mehta (1985) established that seawater can accelerate the setting time of concrete due to its higher ionic concentration, promoting the hydration process. This was also affirmed by Vicat test (D.A. Abrams, 1924) and Steinour (1960), who stated that although a significant acceleration is obtained, it is not so pronounced as to cause serious trouble. Ghorab et al (1990) concluded, seawater accelerates the setting time but found it to depend on the type of cement i.e. two cement types were approximately much less affected by the water type. Seawater accelerating effect on setting time was also concluded in reference (Younis et al, 2018). However, this acceleration may lead to reduced workability and increased risk of early-age cracking if not properly managed (Mehta et al., 2014). Conversely, freshwater, being less corrosive and containing fewer dissolved ions, tends to exhibit slower setting times but can offer better long-term durability for concrete structures in certain environments. The use of freshwater is more common in inland construction projects where seawater is not readily available. Regarding long-term compressive strength, Otsuki et al. (2012), after 20 years exposure to tidal environment, found that the kind of mixing water has little influence on the strength. The same effect on long term compressive strength of specimens exposed to marine environment was mentioned by JCI technical committee (Otsuki et al, 2014). The same observation was also reported by Mohammed et al. (Mohammed, 2004). It was mentioned in JCI technical report for concrete under water, even mixed with seawater, steel suffered almost no corrosion after 27 years exposure to a tidal environment. Steinour (1960) also mentioned the same conclusion and found, for other conditions, the type of concrete and the cover depth are important factors. Sodium silicate, commonly known as water glass, is a chemical admixture used in concrete to improve its properties such as strength, durability, and resistance to chemical attack. Research by Bentz et al. (2001) and Justnes (2002) has shown that sodium silicate reacts with calcium hydroxide in cementitious systems, forming additional calcium silicate hydrate (C-S-H) gel, which contributes to densification and increased strength of the concrete matrix. Moreover, the addition of sodium silicate can influence the rheological properties of concrete, affecting its workability and setting time. Studies by Khayat et al. (2015) and Banfill et al. (2001) have demonstrated that higher concentrations of sodium silicate can lead to quicker setting times and reduced free fluid content in concrete mixes, enhancing early-age strength development. The combined effects of seawater and sodium silicate on concrete properties have been investigated by several researchers. For example, studies by Lea (1970) and Malhotra (1981) have shown that the presence of seawater can influence the reactivity of sodium silicate in cementitious systems, potentially altering the hydration kinetics and microstructure of the hardened concrete. Furthermore, the impact of temperature on these interactions cannot be overlooked, especially in offshore environments where low temperatures may slow down the hydration process and affect the performance of concrete. Research by Ferraris et al. (2001) and Juenger et al. (2007) has highlighted the importance of temperature control and insulation techniques to maintain optimal curing conditions for concrete exposed to seawater at low temperatures.

The literature reviewed suggests that the choice between seawater and freshwater, combined with varying sodium silicate concentrations, can significantly influence the setting time, free fluid content, and compressive strength of concrete, particularly under low-temperature conditions. This research tends to unravel the complex interactions between these factors for optimizing concrete mix designs and ensuring the long-term performance of structures in marine environments.

III. EXPERIMENTAL PROCEDURE

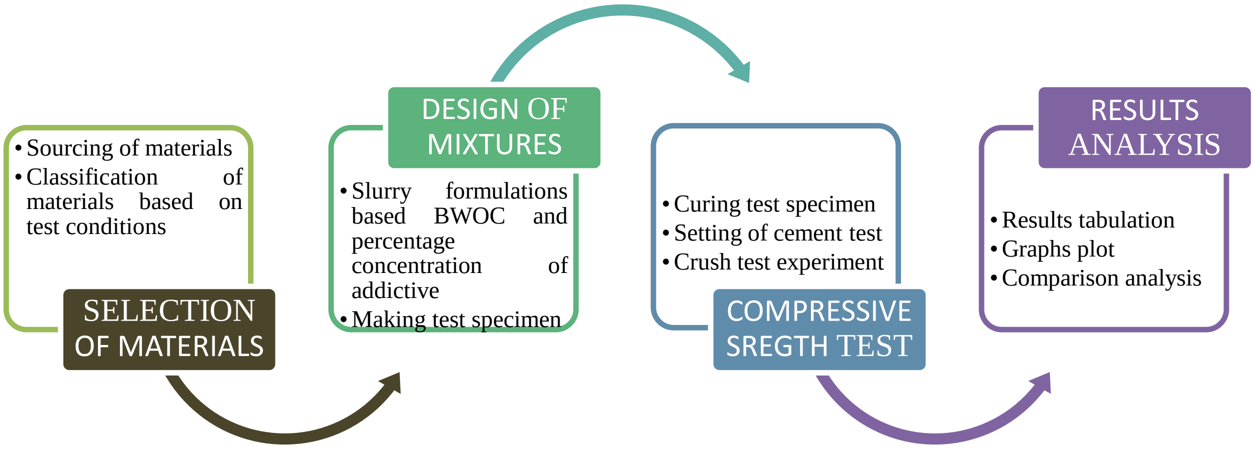

Figure 1: Experimental procedure

IV. TABLE 1: SLURRY COMPOSITION

S/N	Slurry weight	SLURRY MIXTURE	FP-30L (ml)	NA2SiO3 (%)	Na2SiO3 %BWO	Cement (g)	Water (ml)
1	12.ppg	CFM-1	0.77	1	4.34	434.07	459.47
2		CFM-2	0.76	2	8.61	430.42	458.85
3		CFM-3	0.77	3	12.8	426.83	458.25
4		CSM-1	0.74	1	4.18	418.5	464.51
5		CSM-2	0.74	2	8.3	434.07	463.91
6		CSM-3	0.73	3	12.35	411.56	463.33

V. MECHANICAL TESTING

The test carried out on the formulated cement slurry included standard ASTM test to investigate the mechanical properties of the cement, they include:
Table 2:Mechanical properties and method of testing

S/N	MECHANICAL TESTS	MECHANICAL PROPERTISE
1	Cement shrinkage test	Drying Shrinkage
2	Split Tensile Test	Tensile Strength
3	Crush Strength Test	Crush Strength
4	Modulus Of elasticity test	Young's Modulus
5	Bend Test	Flexural strength

Crush strength test also refers to as the compressive strength test will be considered only. Compressive strength test is a mechanical test measuring the maximum amount of compressive load or stress that a material can resist before fracturing.

VI. METHOD

The experimental analysis using a caviar press provides valuable insights into the compressive strength behavior of cement slurry. The results contribute to the broader understanding of concrete material properties and can inform the optimization of mix designs for enhanced structural performance. A specialized caviar press is employed for conducting the compressive strength test. The press applies a controlled force to the specimen, measuring the resistance with the aid of a gauge and providing valuable data on compressive strength. The compressive strength of cement slurry is a critical parameter in determining the structural integrity and durability of concrete. A precisely formulated cement slurry is prepared, part of the cement slurry is poured into a measurable covered cylindrical container (specimen container) to mold specimens for compressive strength testing. The specimen container is inserted inside a water bath set at a constant temperature. This step aims to maintain a consistent curing environment for the cement slurry specimens during a specified duration. Once the slurry is cured, the desired mold is inserted into the cavier press and applicable force is applied. The force applied by the caviar press is carefully controlled to ensure accurate and repeatable measurements. This parameter is crucial in understanding the time-dependent behavior of the cement slurry. The compressive strength of each specimen is measured using the caviar press via the gauge, and the results are recorded for subsequent analysis. Part of the formulated cement slurry is poured in the 250ml cylindrical container for free fluid measurement, whereas during the slurry formulation process, the thickening time was also conducted.

VII. RESULTS AND DISCUSSION

The results of thickening time, and compressive strength test conducted shows the combined effects of seawater, freshwater, calcium chloride and sodium silicate concentration on different cement slurry formulations under low-temperature regimes.

1.1 Lead slurry (12.5ppg) formulation with sodium silicate

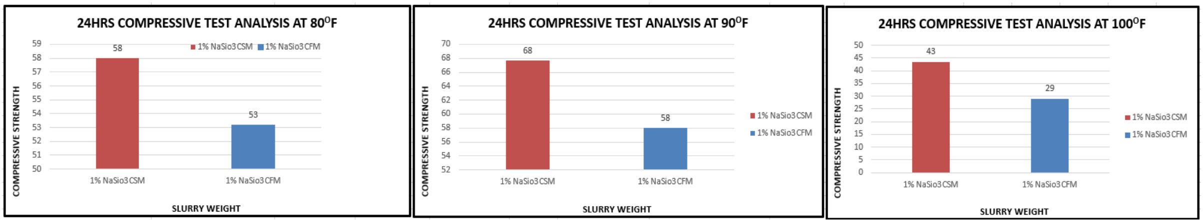

Figure 2: 24hrs compressive test analysis at 1% Na_2SiO_3

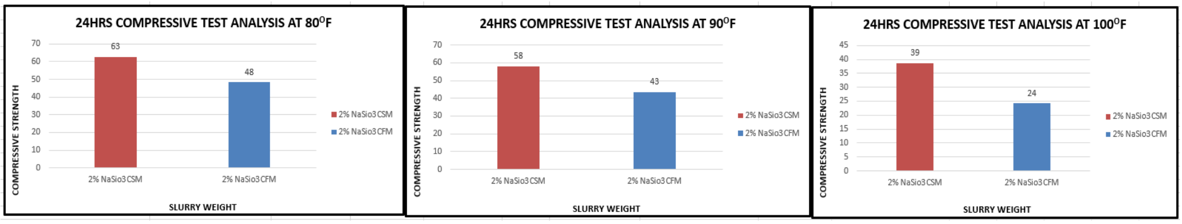

Figure 3: 24hrs compressive test analysis at 2% Na_2SiO_3

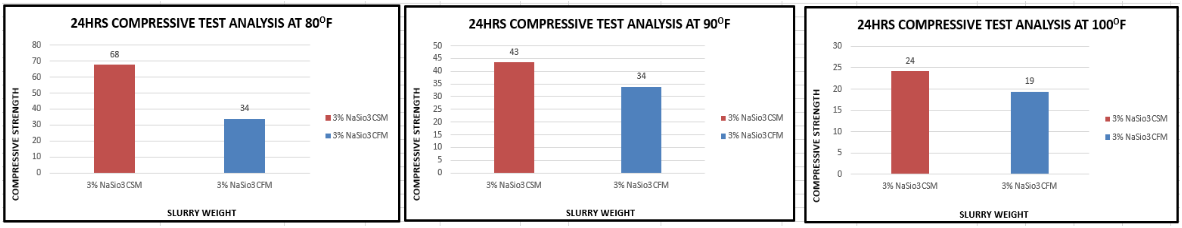

Figure 4: 24hrs compressive test analysis at 3% Na_2SiO_3

Sodium silicate is a chemical extender which can also be used as an accelerator. It can be used to thicken, emulsify, and stabilize a product. The effectiveness depends on the concentration and molecular weight. Low molecular weight may be used at concentration of 1% BWOC or less to accelerate normal density slurries. The application of sodium silicate in cement slurry is a great solution for increasing durability, strength, and resistance against wear and tear as well as providing excellent lost circulation control. Both slurries were induced with powdered sodium silicate, dry blended and slurries formulated. At all concentrations of sodium silicate, cement seawater mixture (CSM) consistently exhibits higher compressive strength compared to CFM. This trend was observed across all temperature conditions tested. For instance, at 1% Na_2SiO_3 concentration, CSM shows compressive strengths ranging from 43Psi to 68Psi, while CFM demonstrates compressive strengths ranging from 29Psi to 58Psi. Similarly, at 2% and 3% Na_2SiO_3 concentrations, CSM consistently outperforms CFM in terms of compressive strength.

It was also observed that at 80^0F, across 1-3% concentration of Na_2Sio_3, the compressive strength increases with increase in the compressive strength of CSM from 58Psi to 68Psi , which signifies at lower temperatures, we might tend to have a better early strength build up with respect to CSM, whereas for CFM the compressive strength decreases from 53Psi to 34Psi as the concentration increases. Same applies at 90-100^0F where the compressive strength reduces vertically with increase in the Na_2Sio_3 concentrations. Based on the results, it was also noticed increase in temperature was directly proportional to general reduction of the compressive strength (horizontally) for both cement formulations. These results suggest that seawater mixture (CSM) tends to produce concrete with higher compressive strength compared to freshwater mixture (CFM), with respect to the concentration of sodium silicate and temperature conditions.

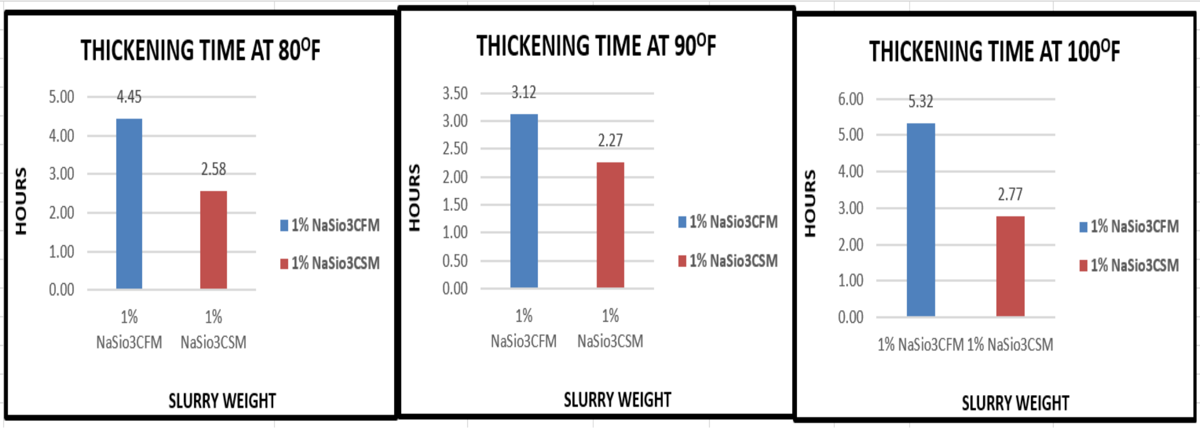

Figure 5: 24hrs thickening time test analysis at 1% Na$_2$SiO$_3$

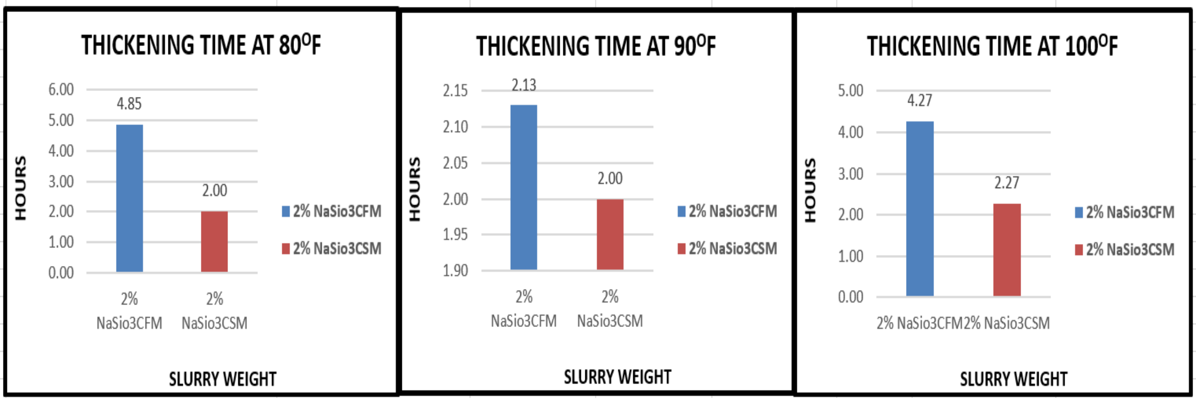

Figure 6: 24hrs free thickening time analysis at 2% Na$_2$SiO$_3$

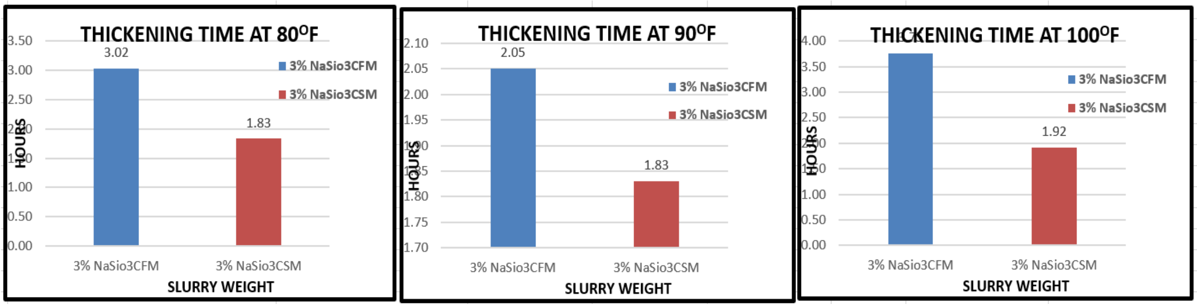

Figure 7: 24hrs thickening time test analysis at 3% Na$_2$SiO$_3$

Detailed analysis of the results shows the effect of temperature on the thickening time of the respective slurries, as temperature and concentration of the slurries increases so does the thickening time reduces. Cement seawater mixture has a better thickening time when compared to the cement freshwater mixture for the given 12.5ppg cement density slurry. At 1% Na$_2$Sio$_3$, the thickening time for a CSM at 80^{0}F, is 3hrs:17mins against CFM at 5hrs:32mins which signifies a 68.5% reduction , the thickening time for a CSM at 90^{0}F, is 2hrs:58mins against CFM at 4hrs:45mins which signifies a 60.1% reduction, and the thickening time for a CSM at 100^{0}F, is 2hrs:27mins against CFM at 3hrs:12mins which signifies a 45.5% reduction. At 2% Na$_2$Sio$_3$ CSM signifies a 50.85% , 53.2 % and, 15.03% reduction in the thickening time required at 80-100^{0}F temperatures respectively.

At 3% Na_2Sio_3 CSM signifies a 105.65%, 35.14 % and, 12% reduction in the thickening time required at 80-100^{0}F temperatures respectively. To further buttress the point of thickening time reduction regarding cement seawater mixture (CSM), as the temperature increases from 80-100^{0}F, and the concentration increases from 1-3% Na_2Sio_3, the thickening time decreases vertically and horizontally respectively. Higher temperatures generally result in shorter thickening times for both CFM and CSM, indicating accelerated setting and hardening of the cement slurries.

VIII. SUMMARY:

This study examines how seawater and freshwater as a mixing fluid, along with varying concentrations of sodium silicate, influences the concrete properties of cement slurries in low-temperature settings (80°F, 90°F, and 100°F). In offshore environments, where freshwater is scarce, seawater is frequently used as an alternative; however, its high salinity and unique ionic composition can impact slurry behavior. Sodium silicate, commonly used as an additive in cement, is known to enhance particle dispersion, reduce water loss, and improve rheological stability under challenging conditions, particularly at low temperatures.

Based on the results, it was noticed increase in temperature was directly proportional to general reduction of the compressive strength (horizontally) for both cement formulations. These results suggest that seawater mixture (CSM) tends to produce concrete with higher compressive strength compared to freshwater mixture (CFM), with respect to concentration of sodium silicate and temperature conditions.

The study also found that increasing sodium silicate concentrations decreased free fluid content in both mixtures, with seawater-based slurries retaining less free fluid overall. These results suggest that seawater, combined with sodium silicate, produces cement slurries with superior rheological performance, offering a viable solution for challenging offshore and low-temperature environments.

CFM consistently demonstrates better retardation properties, allowing for longer thickening times, which could be advantageous in scenarios requiring extended pump times or placement durations. Slurries with shorter thickening times offer advantages such as improved pumping efficiency, enhanced zonal isolation, faster setting and strength development, reduced waiting time, minimized fluid loss, and enhanced cement quality, making CSM as an ideal choice for effective wellbore cementing.

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