

Nano Silica reinforcement to mitigate cement strength retrogression in high-temperature wells

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Abstract

Portland cement undergoes phase changes at temperatures above 200 °F, greatly reducing its compressive strength which is referred to as strength retrogression. It is typically seen in oil well cement sheaths where the temperature gradient is comparatively higher (E.g.- Eagle Ford Shale) or the fields having heavy oil that has received a steam injection. The goal of the current study is to prevent retrogression by evaluating the mechanical behavior of Class H cement slurries containing nano-silica.

A neat Class H cement of 15.5 lbs/gal density was compared to class H cement with nano silica concentrations ranging from 0.1% to 0.5% with a 0.1% increment. For 24, cement was cured at temperatures of 212, 250, and 275 °F. Unconfined compressive strength tests were carried out using a compressive load frame to assess the effect of nano silica on cement sheath strength retrogression.

Introduction

Portland cement is one of the most widely used building materials in the world, valued for its strength, durability, and versatility. It is commonly used in construction applications ranging from buildings, bridges, and highways to tunnels, dams, and offshore platforms. However, cement is susceptible to changes in its physical and chemical properties when exposed to high temperatures, which can compromise its strength and durability.

In oil and gas drilling operations, cement is used to seal the annulus between the casing and the formation. This seal, called the cement sheath, is crucial for ensuring

well integrity, preventing fluid migration between different zones, and providing support for the casing. However, oil well cement sheaths are often exposed to high temperatures and pressures, which can cause the cement to undergo phase changes and lose its strength over time. This phenomenon is known as strength retrogression and is a significant concern for the oil and gas industry.

The causes of strength retrogression are complex and multifaceted. They can include factors such as thermal expansion and contraction, chemical reactions between the cement and the formation fluids, and the presence of microcracks and other defects in the cement sheath. The severity of strength retrogression depends on a variety of factors, such as the temperature gradient across the cement sheath, the duration of exposure to high temperatures, and the chemical composition of the cement.(Arbad et al., 2022)

One approach to mitigating strength retrogression is to add nanoparticles, such as nano-silica, to the cement slurries. Nano-silica is a type of silica with particle sizes in the nanometer range, typically between 5 and 100 nanometers. Nano-silica has a high surface area and reactivity, which can improve the mechanical properties of the cement. Previous studies have shown that adding nano-silica to cement slurries can enhance their strength, reduce their porosity, and increase their durability.

Despite the potential benefits of nano-silica, its effectiveness in preventing strength retrogression in oil well cement sheaths have not been thoroughly studied. The current study aims to fill this gap by evaluating the mechanical behavior of Class H cement slurries containing nano-silica and determining the potential of

nano-silica in preventing strength retrogression at high temperatures. The results of this study can help develop more durable and reliable oil well cementing practices, ultimately improving well integrity and reducing the risk of environmental contamination.

Background of Experimentation

The objective of this study is to evaluate the effect of nano-silica on the prevention of strength retrogression in Class H cement slurries at high temperatures. The experimental design involved the preparation of cement slurries with varying concentrations of nano-silica and curing them at different temperatures to simulate the conditions of oil well cement sheaths. The mechanical behavior of the cured cement was then evaluated using unconfined compressive strength tests.

The cement used in this study was Class H cement, which is commonly used in oil and gas drilling operations due to its high sulfate resistance and low permeability. The cement slurry was prepared by mixing the dry cement powder with deionized water in a blender at a water-to-cement ratio of 0.44. The nano-silica used in this study had a particle size of 20-30 nanometers and was added to the cement slurry at concentrations of 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% by weight of cement. The neat cement slurry without nano-silica served as the control.

The prepared cement slurries were cured at temperatures of 212°F, 250°F, and 275°F for 24 hours. The curing temperature and time were selected to simulate the temperature gradients and durations typically encountered in oil well cement sheaths, such as those found in the Eagle Ford Shale formation or fields that have received steam injection. The curing was performed in a high-pressure, high-temperature curing cell to simulate the downhole conditions.

After curing, the cement samples were tested for unconfined compressive strength using a compressive load frame. The unconfined compressive strength is a measure of the maximum axial stress that the cement can sustain before failing under uniaxial compression. The testing was performed in triplicate for each sample, and the average value was reported as the compressive strength.

The data obtained from the compressive strength

tests were analyzed to determine the effect of nano-silica concentration and curing temperature on the prevention of strength retrogression in Class H cement. The results were compared to the control sample to determine if adding nano-silica to the cement slurry could prevent strength retrogression at high temperatures. Utilizing statistical software, an analysis to determine the significance of the results was conducted (Bergen et al., 2022).

Background of nano silica

Nano-silica, also known as silica nanoparticles or colloidal silica, has been extensively studied for its potential applications in cement and concrete technology. In recent years, the use of nano-silica in oil well cement slurries has gained attention due to its unique properties that can improve the mechanical and chemical properties of the cement sheath. In this section, we will discuss the uses and benefits of using nano-silica in oil well cement.

One of the key benefits of using nano-silica in oil well cement is its ability to enhance the mechanical properties of the cement. Nano-silica is a highly reactive pozzolan that can react with the calcium hydroxide produced during cement hydration to form additional calcium-silicate-hydrate (C-S-H) gel, which is the primary binder in cement. This additional C-S-H gel can fill in the pores and voids in the cement matrix, resulting in a denser and more compact cement structure. This, in turn, leads to an increase in the compressive strength, flexural strength, and toughness of the cement. This is particularly important in oil well cement sheaths, where the cement must withstand high temperature and pressure variations and mechanical stresses caused by drilling and production operations.

Another benefit of using nano-silica in oil well cement is its ability to reduce the permeability of the cement matrix. The addition of nano-silica can help fill in the capillary voids in the cement matrix, resulting in a more impermeable structure. This can help prevent the migration of fluids through the cement sheath, which is important for maintaining well integrity and preventing environmental damage.

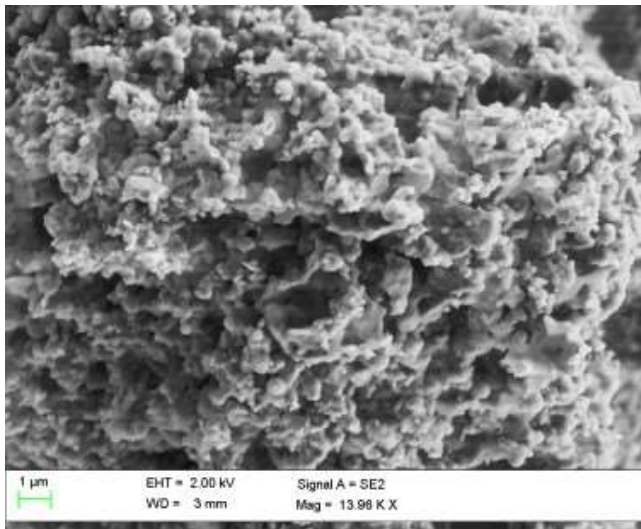


Figure 1- SEM of nano-silica particles

In addition to its mechanical and chemical benefits, nano-silica can also improve the rheological properties of the cement slurry. The addition of nano-silica can help increase the viscosity and yield strength of the cement slurry, which can improve its ability to suspend and transport solids and prevent settling. This is particularly important in oil well cementing operations, where the cement slurry must be pumped through long distances and complex geometries.

Finally, nano-silica has demonstrated excellent thermal stability and chemical resistance, which makes it an ideal additive for use in oil well cement slurries. Nano-silica can withstand high temperatures and harsh chemical environments, which is critical for maintaining the integrity of the cement sheath in challenging downhole conditions (Hussain et al., 2021).

In conclusion, the use of nano-silica in oil well cement slurries has many potential benefits, including improved mechanical properties, reduced permeability, improved rheological properties, and excellent thermal stability and chemical resistance. With further research and development, nano-silica has the potential to revolutionize the oil and gas industry by enabling the development of more reliable and cost-effective cement sheaths for wellbore integrity.

Table 1 – Nano-silica properties (McElroy et al., 2021)

Particle dispersion type	Particle solution appearance	Crystal structure and type	Particle size (nm)	Particle (wt%)	Water (wt%)	Particle purity (%)

Nano-SiO ₂	Translucent liquid	Amorphous	30	25	75	99.9
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Background of experimental facility

Equipment and facilities used at the Texas Tech University Occidental Petroleum Unconventional Research Lab included:

Cement sample preparation (measurements) and placing samples into molds after utilizing the cement blenders

The Model 20 Constant Speed Blender from OFITE was designed to prepare (blend) well cements for testing in accordance with API Specification 10. The properties of well cements are highly dependent on mixing procedures. Furthermore, studies have shown that when constant speed blenders/mixers are used, data from thickening time tests is more reproducible. The right quantity of mix water is carefully weighed and poured into the mixing jar of the blender. The rotational speed is set to 4,000 RPM and allowed to stabilize at that point.

When the “TIMER” button is pressed, the cement is automatically applied to the mix water. The cement can be applied evenly to the water in less than 15 seconds. After 15 seconds, the rotational speed is automatically raised to 12,000 RPM, and the slurry is mixed for an additional 35 seconds. A microprocessor is used to maintain the rotational speed within the API recommendations and is unaffected by changes in line voltage or cement slurry viscosity.



Figure 2- OFITE Constant Speed Blender

Placing molds in the HTHP Curing Chamber at given temperatures in degrees F (212/250/275F) with percentages of nano silica ranging from 0.1% - 0.5% in 0.1% increments

The Model 200 HTHP Curing Chamber is used to prepare well-cement specimens for compressive strength tests. The time required for cement to achieve compressive strength must be calculated so that drilling/production operations can resume as soon as possible.

The aim is to make a slurry that can easily generate compressive strength, thereby reducing the amount of time spent "waiting on cement". Cement specimens are cured in the OFITE HTHP Curing Chambers at the downhole temperatures and pressures.



Figure 3- Cement Molds

- Apply a thin layer of grease to the inner faces of the molds and the contact surfaces of the plates to aid in the removal of the cured cement specimens.
- Prepare the cement slurry in compliance with API Specification 10 Sect. 5.
- Pour the slurry into the prepared molds in a layer half the depth of the mold. After filling all the specimen compartments halfway with slurry, puddle each specimen 25 times with a puddling rod. To avoid segregation, after puddling the first coat, stir the remaining slurry by hand with a puddling rod or spatula. Then, as the first sheet, fill each specimen to overflowing and puddle.
- Using a straight edge, strike off the excess slurry also with the top of the mold after puddling. Specimens in molds that display signs of leakage should be discarded. On top of the mold, place a greased cover layer. A minimum of three specimens should be used for each test determination.



Figure 4- OFITE HPHT Curing chamber

The OFITE CLF-40 Automated Compressive Load Frame was used to test the compressive strength of well cement. The most popular method for determining a cement's compressive strength is to apply a constant force to the sample until it fails. The compressive strength of cement is known as the maximum loading at which it fails. Manually operated hydraulic presses are typically used for testing, and it is extremely difficult to maintain a steady loading rate. Unfortunately, the data generated from this form of testing is often unreliable and highly variable. The CLF-40 improves on the manually operated design by adding a computer-controlled ram capable of maintaining a predetermined loading rate. In contrast to manually operated hydraulic presses, operator inconsistencies are greatly reduced. A cement slurry is prepared and cured in accordance with the API Specification. The cured cement sample is then put on the CLF-40's testing platen. The machine is turned on, a loading rate is chosen, and the test begins. The automatic ram will begin applying a managed increasing load until the cement sample fails.



Figure 5- Compressive Strength Test

Experimental Approach

Figure 6 – Experiment Approach



Tables and Graphics

Table 2 – Cement Sample Compositions

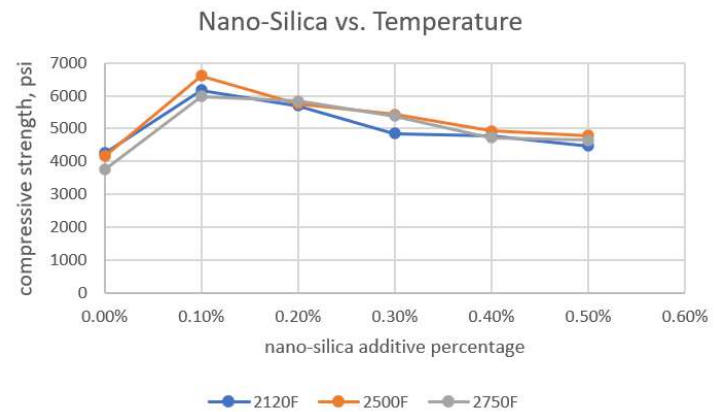
Different Cement Compositions (each tested x3 times under temperatures: 212, 250, 300F)	
Class H Cement (Neat Sample) = 405.54 g + (H ₂ O = 151.57 g)	+ 0 % BWOC SiO ₂ = 0 g
Class H = 405.15 g + (H ₂ O = 150.34 g)	+ 0.1 % BWOC SiO ₂ = 1.62 g
Class H = 404.75 g + (H ₂ O = 149.11 g)	+ 0.2 % BWOC SiO ₂ = 3.23 g
Class H = 404.36 g + (H ₂ O = 147.89 g)	+ 0.3 % BWOC SiO ₂ = 4.85 g
Class H = 403.97 g + (H ₂ O = 146.67 g)	+ 0.4 % BWOC SiO ₂ = 6.46 g
Class H = 403.58 g + (H ₂ O = 145.45 g)	+ 0.5 % BWOC SiO ₂ = 8.07 g

Experimental Results

The information shown in Table 2 and 3 depict our concentrations and results from the nano-silica and cement slurry mixtures of 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% BWOC and cured at 212°F, 250°F, and 275°F for 24 hrs.

Table 3 – Compressive Strength Results (psi)

Cement	212°F	250°F	275°F
Class H	4251	4157	3754
0.1% SiO ₂	6170	6611	5983
0.2% SiO ₂	5690	5755	5835
0.3% SiO ₂	4851	5437	5384
0.4% SiO ₂	4775	4936	4720
0.5% SiO ₂	4481	4787	4641



The Compressive Strength of the samples in Table 3 are in Psi. As the temperature increased, the results clearly demonstrated the strength retrogression in Neat Class H cement and it also depicts that with reinforcement of nano silica in cement, it prevents the strength retrogression, and the compressive strength is increased.

Discussion and Conclusions

In conclusion, the use of nano-silica in 0.1 – 0.2 % slurry mixtures in oil well cement slurries has shown significant potential in preventing the retrogression of Portland cement. Strength retrogression occurs when the cement undergoes phase changes at high temperatures, causing a reduction in compressive strength. By adding nano-silica to the cement slurry in the 0.1-0.2% increments, rather than more, it is possible to improve the mechanical and chemical properties of the cement matrix, resulting in a more durable and robust structure that is less susceptible to strength retrogression.

One of the primary benefits of using nano-silica in oil well cement is its ability to increase the cement's compressive strength. The reactive pozzolanic properties of nano-silica allow it to react with calcium hydroxide produced during cement hydration to form additional calcium-silicate-hydrate (C-S-H) gel. This additional C-S-H gel fills in the pores and voids in the cement matrix (only occurring in 0.1-0.2% mixtures), resulting in a more compact and dense structure. The bonds at a higher

percentage of nano silica lead to bonding within the additives rather than with the cement creating voids in the matrix rather than strengthening it. This, in turn, leads to utilizing nano-silica at the 0.1-0.2% mixtures so that an increase in the cement's compressive strength, which is critical for maintaining wellbore integrity, can occur.

Another benefit of using nano-silica in oil well cement is its ability to reduce the cement's permeability. The addition of nano-silica to the cement slurry can help to fill in the capillary voids in the cement matrix, resulting in a more impermeable structure. This can help to prevent the migration of fluids through the cement sheath, which is essential for maintaining well integrity and preventing environmental damage.

Nano-silica can also improve the rheological properties of the cement slurry, which is important for well cementing operations. The addition of nano-silica can increase the viscosity and yield strength of the cement slurry, improving its ability to suspend and transport solids and preventing settling. This is particularly important in complex geometries and long-distance pumping operations.

Finally, the use of nano-silica in oil well cement slurries has demonstrated excellent thermal stability and chemical resistance. Nano-silica can withstand high temperatures and harsh chemical environments, which is critical for maintaining the integrity of the cement sheath in challenging downhole conditions.

Overall, the use of nano-silica in oil well cement slurries has significant potential in improving the mechanical and chemical properties of the cement matrix, resulting in a more durable and robust structure that is less susceptible to strength retrogression. With further research and development, nano-silica has the potential to revolutionize the oil and gas industry by enabling the development of more reliable and cost-effective cement sheaths for wellbore integrity.

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Nomenclature

HT = High Temperature

C-S-H = calcium-silicate-hydrate

BWOC = by weight of cement

SEM = Scanning electron microscope

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