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A Novel Bench-Scale Experimental Setup to Evaluate Cement Sealability to Mitigate Gas Migration

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Abstract

Gas leakages from producing and abandoned oil and gas wells are considered a threat to the environment and increase greenhouse gas emissions. They are also a cause of sustained casing pressure and other wellbore integrity problems. Cement integrity in oil and gas wells is crucial to ensure excellent zonal isolation and prevent gas migration into the surface over a long production time. Therefore, cement slurry should be carefully designed and prepared to yield better performance in sealing the annulus between the casing and drilled formations. Cement slurries are primarily evaluated in the laboratory by measuring the static gel strength as an indicator of gas migration. However, the measurements are conducted in a relatively short time, and no gas is involved in the experiments.

This paper introduces a novel experimental setup to evaluate the cement sealability under more actual conditions and over a long time for drilling and plug & abandonment applications to ensure better wellbore integrity. The design is flexible to operate in different scales by changing the pipe dimensions. An experimental plan was developed in this paper, considering the effect of diameter, length, cement additives, temperature, and wait on cement time. Several cement formulations were used in the preliminary study with various concentrations of a new polymeric anti-gas migration additive.

Introduction

Cement in oil and gas wells is introduced to maintain the wellbore integrity throughout the drilling and production operations. It is vital to form good zonal isolation, support and protect the casing, and prevent fluid influx (Murtaza et al. 2016, Tariq et al., 2020). Loss of zonal isolation presents formidable challenges in drilling and production operations. It causes increased casing pressure and wellbore integrity issues (Ahmed et al. 2018). In the long term, gas leakages from producing and abandoned wells are associated with many environmental concerns. Moreover, uncontrolled gas flows may occur at any time during drilling, completion, production, and plug & abandonment, causing severe hazards to the well and environment (Ahmed et al. 2020).

To ensure efficient cementing operation, cement formulation should be designed by selecting the appropriate cement additives to provide excellent properties. Several additives are added to the cement to control its properties, such as accelerators, retarders, rheology modifiers, and fluid loss control additives. Several studies were conducted to improve the cement sealability and prevent gas migration depending on location, depth, downhole conditions, cost, and environmental impact (Ahmed et al. 2020). Silica fume was introduced in the 1980s to improve cement sealability in offshore wells in the North Sea (Coker et al. 1992). The continuous need to develop a gas-tight slurry to stop gas flows pushed the industry towards manufacturing and testing several cement additives such as latex, micro silica, silica fume, fly ash, carbon black, copolymer, and nanomaterials (Bour and East 1988, Calloni et al. 1995, Drecq and Parcevaux 1988, Grinrod et al. 1988, Peyvandi et al. 2017).

In the early times, the industry relied on measuring fluid loss in static conditions to design and evaluate tight-gas slurry. During fluid loss, the space created within the cement column may become a pathway for gas to occupy. Therefore, a good cement slurry should yield a low filtrate volume, less than or equal to 50 mL/30 min (Liska et al. 2019). Sabins et al. (1982) introduced the concept of gas transition time to evaluate the cement sealability. It is the time required to develop critical gel strength to prevent gas flow through the cement column. According to industry practices, 45 min or less gas transition time is the acceptable range for gas-tight cement slurry. Evaluating the porosity and permeability measurements of gelled or set cement is another method to assess cement sealability. The higher the porosity/permeability, the easier for gas to migrate through cement. However, these methods are considered primary indicators for gas migration and do not simulate the actual gas migration process.

Therefore, this study introduces a bench-scale experimental setup to evaluate cement sealability under different temperature and pressure testing conditions. A preliminary study is also conducted to study the performance of a new polymeric additive to mitigate gas migration problems. The experimental setup design, materials, experimental plan, and preliminary results are discussed in the subsequent sections.

Material and Methods

Materials

Various cement slurries were prepared in the laboratory to conduct this study using cement class G. Cement slurries were prepared following the API mixing procedure. Deionized water was used as the base fluid to hydrate the cement. Deionized water was selected to avoid contamination and provide consistent and reliable results. A dispersant was used to prepare homogeneous slurries and achieve good rheological properties. A retarder was also added to delay cement thickening and allow enough time for testing. Both dispersant and retarder are in powder form. Then, a new anti-gas migration additive was added at various concentrations (0 to 6% by weight of cement) to improve the cement sealability. The new chemical is a polymer-based mixture developed by SNF Inc. to prevent gas migration through the cement column. It is a clear to slightly yellow liquid with around 1.1 specific gravity. This additive is added right before the cement. All cement additives were provided by SNF Inc. and mixed in the order shown in Table 1.

Experimental setup description

The primary goal of the experimental setup is to evaluate the cement sealability for both drilling and plug & abandonment applications to mitigate gas migration and channeling through the cement and ensure better wellbore integrity. The pipe setup consists of a vertical pipe where cement slurry is poured and set. It is made of steel and has a 2" diameter and 3 ft length, while a meshed connection is attached to the bottom of the pipe to hold the cement. A heating belt is wrapped around the pipe to heat the system to the testing temperature. A gas cylinder is connected to the pipe to supply the gas to the system and simulate gas migration. Nitrogen is used in the experiments with the flexibility of using other gases such as CO_2 and methane. A regulator and a valve are added to the setup to control the gas pressure. The gas leakages are observed with a high-resolution camera, and the data is recorded over time with a data acquisition (DAQ) system. The experimental setup allows testing over a long period to address the needs of plug & abandonment applications. The design is flexible to test gas migration under a broad range of pressure, temperature, cement formulations, and dimensions. Figure 1 illustrates the experimental setup's schematic, while the experimental parameters used in this work are listed in Table 2.

Experimental plan

The experimental setup operates at different temperatures to study the performance of various cement formulations to help optimize the cementing operations. Since these experiments require higher cement volume than other laboratory techniques, a testing procedure was developed to ensure successful outcomes. A preliminary study should be conducted under the same conditions to evaluate the cement slurry performance using standard lab equipment, such as rheometer and consistometer. The primary objective of this preliminary study is to determine the optimum cement formulation, additives concentration, and additives limitations. Then, the findings will be used to investigate the cement sealability on a bigger scale using the developed experimental setup. For instance, static gel strength (SGS) and gas transition time measured by the consistometer would be a quick indicator of cement sealability. According to industry standards (API STD 65-2), the slurry develops enough solid mass to prevent gas influx when the static gel strength reaches 500 lbf/100ft^2. The shorter it takes to attain this value, the better the sealing performance (Ahmed et al. 2018, Li et al. 2016). Thus, in addition to cement sealability experiments, the experimental plan includes measuring: static gel strength, rheology, consistency, fluid loss, and compressive strength, as illustrated in Figure 2. The standard experimental procedure for these experiments is well explained and documented in the API Recommended Practice 10B-2. Therefore, in the subsequent section, we will discuss the testing procedure of using the novel experimental setup developed for this study.

Cement sealability experiments

Sealability experiments are performed using the following steps:

i. Cement slurry is prepared in the lab with the required volume for each experiment and conditioned following the API standard procedure (API RP 10B-2 2012).
ii. The slurry is poured slowly into the 2-inch pipe to prevent foaming and trapped gas.
iii. Set the heating belt to the desired testing temperature and ensure the gas valve is closed, and connections are not blocked.
iv. Start heating the system until the testing temperature is reached.
v. Switch on the camera and set the pressure regulator at low pressure (<50 psi).
vi. Start the experiment by opening the gas valve and recording the data.
vii. Once everything is okay, start increasing the gas pressure gradually to the desired testing pressure and closely observe the gas flow and time to breakthrough.
viii. Repeat step vii after 2 hrs, 6 hrs, 12 hrs, 18 hrs, and every 24 hrs if the experiment is planned for an extended time.
ix. When the gas flow is detected at the top of the cement column, close the gas valve and wait until the next reading.
x. The recorded data is then analyzed to compare the performance of different cement slurries over time, considering the maximum pressure before the breakthrough, time to breakthrough, and location of gas channels.
xi. A new pipe is used for every experiment.

Preliminary Results

The preliminary study was initially performed to evaluate the developed anti-gas migration additive and determine its optimum concentration that can improve the cement sealability and other cement properties. The new additive was mixed with class G cement in various concentrations, 0 to 6 % by weight of cement (BWOC). The preliminary study starts with measuring the static gel strength, then rheology and consistency. The findings of this study are discussed in the subsequent sections.

Static gel strength (SGS)

The time required to develop the critical gel strength is the primary indicator in evaluating the cement sealability. Initially, gas migration through cement is prevented by hydrostatic cement column. Gas usually propagates through cement during the liquid-to-solid phase transition period (Al-Buraik et al. 1998). Gas transition time is used in the industry to indicate the cement capability to prevent gas migration in formations notorious for gas flow issues. It is the time required to develop an SGS from 100 to 500 lbf/100ft^2. The first SGS (100 lbf/100ft^2) value when the cement slurry starts to lose its ability to transmit hydrostatic pressure, while at the second SGS value (500 lbf/100ft^2), the slurry is capable of stopping gas migration. According to the API standard (RP 10B-6 2010), cement slurry should have a gas transition time of 45 min or less to prevent gas migration.

Figure 3 compares the SGS for the class G cement with different concentrations of the new additive, 0 to 6% BWOC, at 158°F. The base cement slurry started with very low SGS (~0 lbf/100ft^2) and gradually increased after 17 min. SGS reached 100 lbf/100ft^2 after 25 min and developed an SGS of 500 lbf/100ft^2 in around 47 min with a gas transition time of 22 min. The new product improved the cement sealability and developed higher gel strength in a shorter time than the base cement slurry. Increasing the new additive concentrations to 1.89 % BWOC reduced the gas transition time to 18 min, and 500 lbf/100ft^2 SGS was reached in only 30 min, compared to 47 min with the base cement. Adding more than this concentration accelerated the SGS development; however, no further reduction in the gas transition time was observed. Therefore, the new product should be added with a concentration of around 1.89 % BWOC. Adding higher concentrations would add more cost to the cementing operation without further enhancement in the slurry performance.

Slurry rheology

Rheological properties are vital parameters to consider while designing the cement slurry to ensure successful cementing operations. Rheological properties impact the frictional pressure drops, pump pressure, and fluid loss properties. Rheology experiments were performed using Grace M3600 viscometer at atmospheric pressure and two different temperatures (120°F and 158°F). Figure 4 compares the apparent viscosity of the two cement slurries (base cement and with 1.89% BWOC) at various share rates, 5.1-1021 s^{-1}. Both cement slurries exhibited a non-Newtonian shear-thinning behavior, where apparent viscosity decreased as the shear rate increased. At 158°F, the base cement sample showed significantly higher apparent viscosities than at 120°F. Cement slurries tend to harden faster at higher temperatures due to the faster water evaporation and accelerated hydration of cement. Consequently, this thickening effect might be challenging in some cases where the thickening time is insufficient for cement placement (Al-Martini and Nehdi 2007).

In contrast, the new product increased the apparent viscosities of base cement slurry because this additive is a polymer-based chemical. This increase in viscosity would improve the cement suspension and prevent solid settlement. However, the rheological properties of cement slurry should be carefully optimized because the very high viscosity presents other challenges to the cementing operations, such as increased pumping pressure. Moreover, the new additive suppressed the high-temperature impact on cement slurry, and a slight increase in the viscosity was observed at low shear rates (less than 100 s^{-1}). While the apparent viscosity profile at the two testing temperatures perfectly matched at shear rates above 100 s^{-1}, indicating good stability of the cement slurry.

Consistency and thickening time

Consistency and thickening time are crucial properties in designing efficient cement slurry because they significantly impact the cement pumpability and placement. These properties define the time for which the cement slurry can still be pumped. Consistency experiments were performed for the two slurries at 158°F, 2300 psi, and 150 RPM using Grace M7540 consistometer. Figure 5 shows the consistency profile of both cement slurries with time. The base slurry showed consistency of around 5 Bc for 3.5 hrs; then, the consistency increased sharply to reach 70 Bc in 5 hrs. The polymeric additive showed a similar profile with about 10 Bc for 5 hrs; then, the consistency went up to 70 Bc in 40 min. Therefore, the slurry with a 1.89% BWOC polymeric additive can be pumpable up to a slightly longer time (5.67 hrs) than the base cement, allowing more time for cement operations.

Conclusions

A novel experimental setup was introduced in this paper to evaluate the cement sealability of different cement formulations. The experimental setup has a flexible design to test cement slurry under different temperatures, pressures, and pipe dimensions. The experiments can be run for a short and long time to address drilling and plug & abandonment applications. A preliminary study was performed to evaluate a new polymeric additive to prevent gas migration in formations notorious for gas flow issues. Based on this study, the following conclusions can be drawn:

- From the SGS measurements, the new polymeric additive improved the gel strength profile. 1.89% BWOC of the additive significantly reduced the gas transition time to 18 minutes, indicating lower gas migration risks than the base cement slurry.
- The new product increased the apparent viscosity of the base cement slurry with a more stable performance at higher temperatures.
- Both cement slurries showed similar consistency profiles with slightly higher consistency and longer thickening time with the new additive.
- Although the new product improved the cement properties, more research is required to evaluate this additive under a broader temperature and pressure range. A continuation of this study will include testing the new

product in the developed setup and investigating its impact on compressive strength and fluid loss.

Acknowledgments

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Nomenclature

BWOC = *By weight of cement*
DAQ = *Data acquisition*
SGS = *Static gel strength*

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Table 1: Cement formulation used in this study

Additive	Concentration, % (by weight of cement)
Water	44.0
Dispersant	0.2
Retarder	0.05
Anti-gas migration additive	0.0 to 6.0
Cement	-

Table 2: Range of experimental parameters

Parameter	Description
Cement volume	1.8 L
Temperature	65-190°F
Gas pressure	15-2000 psi
Inclination	vertical

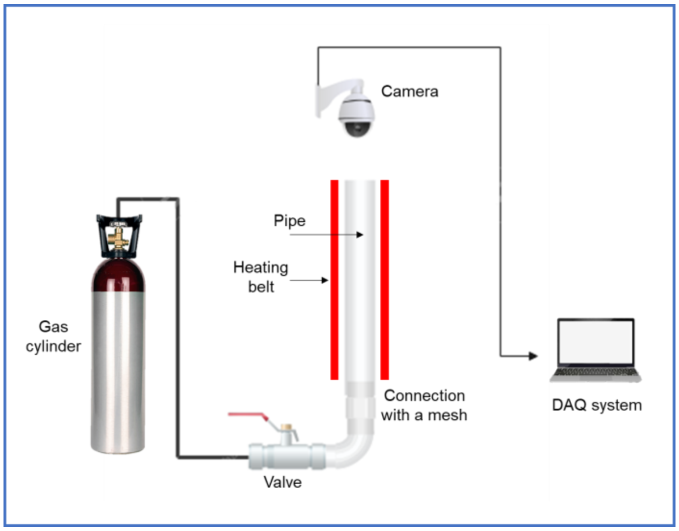

Figure 1 – Experimental setup of cement sealability in the pipe.

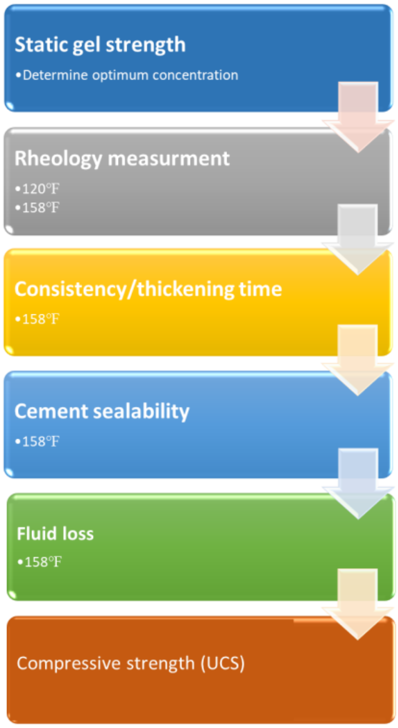

Figure 2 – Proposed experimental plan.

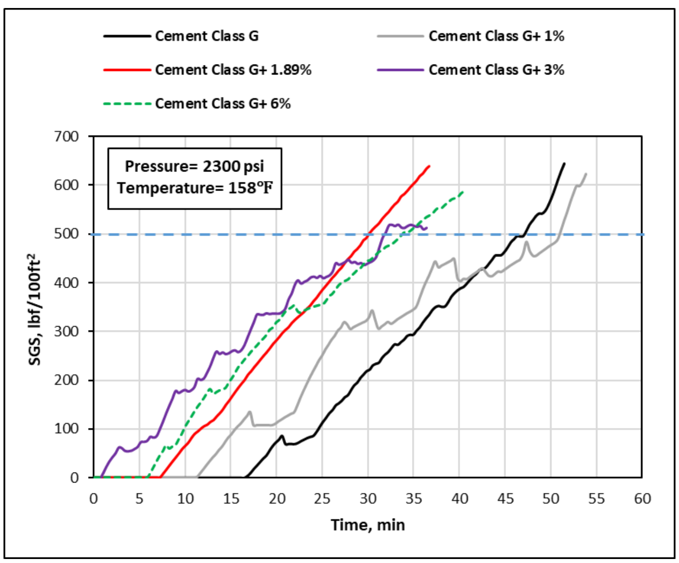

Figure 3 – Static gel strength of different cement formulations.

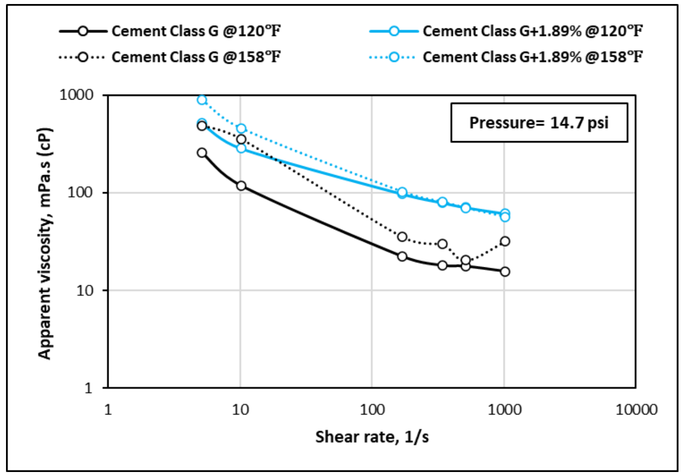

Figure 4 – Slurry apparent viscosity vs. shear rate.

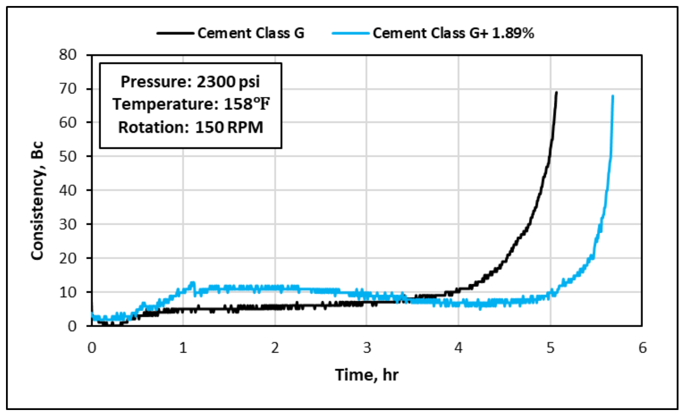

Figure 5 – Consistency of cement formulation at 158°F.