ACS OMEGA

http://pubs.acs.org/journal/acsodf

Article

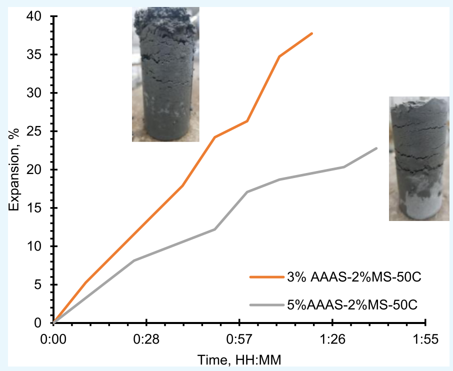
Novel Expandable Cement System for Prevention of Sustained Casing Pressure and Minimization of Lost Circulation

Mobeen Murtaza, Zeeshan Tariq, Muhammad Kalimur Rahman, Muhammad Shahzad Kamal, and Mohamed Mahmoud*

Cite This: *ACS Omega* 2021, 6, 4950−4957

Read Online

ABSTRACT: Sustained casing pressure (SCP) is a common issue in the oil and gas industry. There were several solutions applied to contain it either by mechanical means or by injecting high-performing cement slurries. There are some limitations associated with these solutions such as volume loss, mechanical failures, limited expansion, exact spotting, and material deterioration with time. In this study, a novel expandable cement system contains a novel silicate aqueous alkali alumino silicate (AAAS) and zinc (Zn) metal slurry, and class G cement is introduced as an expandable solution to prevent annulus flow between the casing and formation. The silicate-based admixture reacts with the Zn metal slurry to generate hydrogen gas that results in the expansion of the cement slurry. The reaction and expansion can be controlled by optimizing the quantities of silicate systems and metal slurry. The expansive properties of the silicate system can be utilized to formulate a cement mix for plugging off the annulus flow. Cement slurries with different percentages such as 3, 5, and 8% by weight of water (BWOW) of AAAS silicate and Zn metal slurry were prepared and tested for their expansion. Several laboratory tests such as expansion, consistency, viscosity, and unconfined compressive strength were performed to assess the percentage expansion. The expansion was tested in the plastic tube as well as in expansion molds. The cement slurries were cured at 50 °C temperature in a water bath. It was observed that metal slurry upon reaction with AAAS silicate resulted in cement expansion by several percentages. The cement expansion was reduced by 16% at 8% BWOW concentration of AAAS silicate as compared to the expansion gained at 3% BWOW concentration. Further, the temperature triggers the expansion of cement slurry. The consistency and viscosity were impacted by the addition of AAAS and metal slurry. The application of expandable slurry can help in preventing the annulus flow and eliminating the safety issues associated with SCP. The expansion solution can be applied in loss circulation zones.



1. INTRODUCTION

In an oil well-cementing operation, cement slurry is placed between the formation and casing to provide interzonal isolation that provides integrity to the bore hole.[1,2] Cement slurry shrinks upon setting and breaks the barrier of strong zonal isolation. The weak zonal isolation leads to the channeling of formation fluid and develops sustained casing pressure (SCP) at the surface. Effective zonal isolation can be accomplished with the aid of several high-performance additives that can generate high strength and expansion abilities in the cement slurry to stop the fluid migration. The cement sheath deteriorates and loses its integrity if the gas migration commences and proceeds continuously. A variety of cement additives have been developed to plug the cement cracks and tiny fissures. Most of the plugging materials lose their strength under extreme downhole conditions such as high temperature, high salinity, high differential pressure between formation and the wellbore, and so forth. This challenge can be addressed by developing materials that show better expansion and stability under downhole conditions.

The blockage of pathways around the casing requires expensive materials as additives in the cement. It is an ongoing technical challenge to achieve a tight seal around the casing to block such pathways. The downhole conditions such as water loss, temperature changes, and differential pressure jeopardize the performance of plugging materials. The oil and gas industry has addressed this challenge by developing alternate materials that show better expansion and stability under downhole conditions. Several materials have been developed to combat issues such as material stability, cost, and durability. These

Received: December 9, 2020
Accepted: January 29, 2021
Published: February 10, 2021

solutions have achieved a varying degree of commercial success. In the case of cement, several products have been developed and used in the field to counter the cement shrinkage. For instance, foam is generated using air, surfactant, and water. The foam is blended with the cement to create a foam cement slurry. This approach is commonly used in geotechnical applications such as annular grouts for tunnels, filling of void spaces such as pipes, and replacement of unstable soil under roadways.[3] Further, this approach is used in generating lightweight cement slurries in oil well gas cementing.[4] In addition, CaO and MgO are commonly used as expanders in oil well cementing.[5] Al-Buraik et al. investigated the shallow gas migration to the surface and developed a preventive solution by using GASBLOK additive that created an impermeable filter cake across the gas zone and prevented gas migration to the surface.[6] These expandable materials provide very limited expansion to the cement which is not enough to create a strong bonding of the cement with the casing and formation. So, there is a need for materials which can provide enough expansion to the cement without compromising on its properties.

In the recent years, thermally activated resins have been applied to seal the annulus and prevent the SCP.[7,8] The resin is a solid-free system, and it activates based on temperature. It can be pumped into tiny cracks and fissures to provide sealing. Swelling elastomers have been used in the oil and gas industry in many applications including casing−casing annulus (CCA) and water shutoff.[9] Swelling elastomers swell upon contacting with the formation fluid. They are classified into three categories based on contacting fluid: oil swellable, water swellable, and hybrid. When they come in contact with the formation fluid, the swelling element expands and occupies the empty spaces around it and provides sealing to preclude the migration of the formation fluid. The current challenges are associated with elastomer performance in a sour environment and high temperature. There are several mechanical means utilized to prevent the CCA by isolating the troublesome zones such as application of diverting tool with packer and liner hanger with swellable packers. Both systems provide strong pressure differential sealing in the case of gas migration. The mechanical solutions often face failures during setting at the right place. Expandable tubular fails due to doglegs. Mechanical packers have success rate less than 60%.[10] They also fail if they cannot seal the mother bore liner. Chemical means have less than 50% success rate due to not spotting them at the exact location of water flow, hydrodynamic connectivity, and wrong chemicals.[9] There is a strong need to develop high-performance solutions to counter the SCP.

Over the last few years, the use of sodium silicate has undergone resurgence as a conformance material that is reflected in the increasing number of publications.[11−13] Reviewing the literature, the growth in popularity is being driven by environmental performance, better modeling of gelation kinetics, and recognition of the long-established performance properties associated with silicate-based plugs.[12] Sodium silicate has wide-ranging applications in the oil and gas industry including permeability modification of the reservoir, sealing of microfractures in cement, and lost circulation.[14−17]

The silicate is made to polymerize in three simultaneous processes. The smaller silicate species form higher-order oligomers. The intramolecular condensation of silanol groups lead to the formation of silica particles.[18−20] Individual silica particles aggregate to form a gel structure. As the ratio of surface area to volume decreases due to, for example, larger fractures, vugs, and cavernous zones, it is necessary to build a matrix within the silicate with fillers to avoid loss of volume. Ideally, there should be not only no loss of volume but also a tight seal. In the case of lost circulation, the concern is lack of a tight seal, which may prevent pressure transmission to the fracture tip. The development of an expandable silicate-based system would mark a significant enhancement in performance. The expansion can be achieved by generating gas chemically. It is a well-established method in which aluminum is used as the gas-generating additive. This technique was initially used in structural concrete and later applied in oil well cementing.[21]

The in situ generation of hydrogen in Portland cement served as a starting point for understanding the chemistry, application, and limitations of expandable systems. Metals that are thermodynamically favorable for the generation of hydrogen include aluminum, zinc, and magnesium.[22,23] The metal is processed by melting and atomizing. During the atomizing process, an oxide coating forms on the metal. The oxide layer coating plays a significant role in preventing corrosion and hydrogen generation. To initiate hydrogen, the oxide layer has to be removed to react with silicate. The oxide layer is removed by the alkalinity of the cement slurry, which increases upon hydration of the cement. Further, the gas generation process is controlled by the ratio of SiO_2/Na_2O. (i.e., 1:6 to 4.5:1). For low-ratio silicates, they are quite aggressive in removing the oxide layer over the metal and ignite the gas generation process. The control over the type and amount of alkalinity allows for much more control of the gas generation rate and allows for much longer expansion rates.

This study aims to develop a novel expandable cement system containing a novel silicate aqueous alkali alumino silicate (AAAS), zinc (Zn) metal slurry, and class G cement which is the most commonly used cement type in the cementing of oil and gas wells in the upstream industry. Class G cement is the standard cement type used by oil and gas service companies because of its availability and less cost compared to other types, and it is the type that provides the standard requirements for the casing support and formation isolation in oil and gas wells. The expandable solution could prevent the flow of gas between the annulus of casing and formation. The expandable cement can be used as a lost circulation material for shallow depths without compromising the strength of the cement slurry. In addition, the expandable system can fill washouts and caved portions of the wellbore and provide better zonal isolation. The reaction and expansion were controlled by optimizing the quantities of silicate systems and metal slurry. Cement slurries with different percentages such as 1, 3, and 5% by weight of water (BWOW) of AAAS silicate and Zn metal slurry were prepared and tested for their expansion. To assess the expansivity, several tests such as expansion, consistency, viscosity, and unconfined compressive strength were performed on the expandable cement system.

2. RESULTS AND DISCUSSION

The AAAS and Zn metal slurry in class G cement was tested by analyzing their expansion, consistency, and viscosity at different concentrations of AAAS and conditions.

2.1. Expansion Test Using Plastic Containers. The expansion behaviors of all tested cement slurries are shown in Figures 1−3. In the S-1 cement slurry, when the slurry was poured and immersed in water, it was in the liquid form initially and did not change into any other form like plastic or

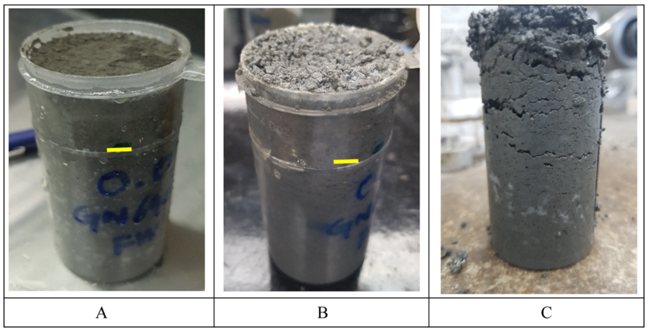


Figure 1. Expansion of slurry S-1 at different intervals (A: initial time, B: 2 h, and C: 24 h).

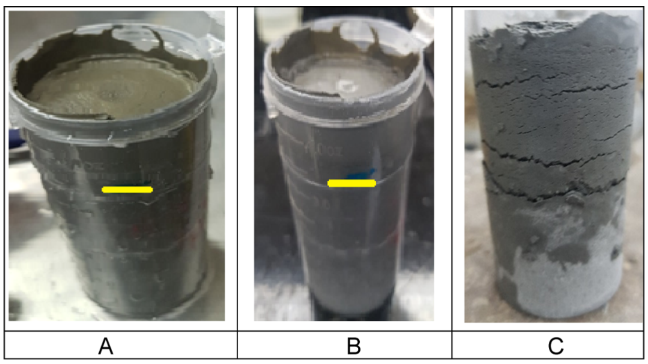


Figure 2. Expansion of slurry S-2 at different intervals (A: initial time, B: 2 h, and C: 24 h).

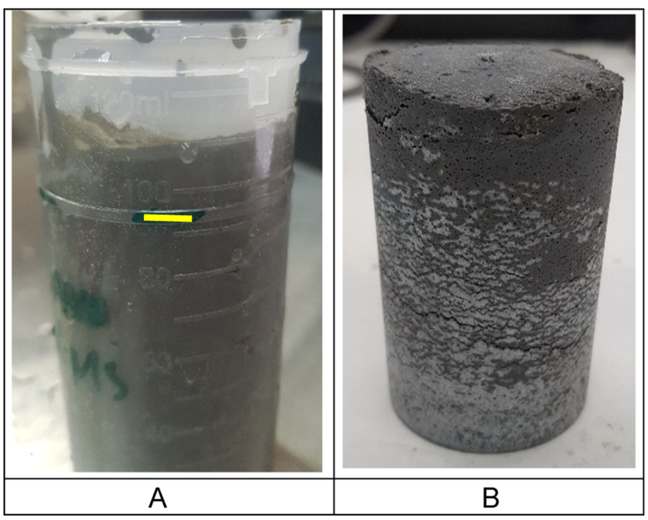


Figure 3. Expansion of slurry S-3 at different intervals (A: 2 h and B: 24 h).

solid form till 2 h. After 2 h of curing, the sample expanded almost 26.6% from its original level; a yellow line as a reference is shown (Figure 1A). At that point, the cement slurry was not hard enough, the finger force could penetrate inside it. After 24 h, a further expansion of about 33% was recorded from the initial level as shown in Figure 1B. The cement was coming out of the test tube, and it was not hard enough. A lot of broken cement pieces accumulated at the top. There were a lot of voids in the sample as shown in Figure 1C. The broken pieces could be dispersed easily.

The S-2 slurry contains high AAAS content (5%) performed initially in a similar manner as S-1 and stayed in liquid form till immersion in water. After 2 hours of curing, the sample expanded almost 11% from its original point, yellow line (Figure 2A). The cement was not hard enough, and the finger force could penetrate it. After 24 h, no further expansion was observed, and the slurry became hard with a lot of voids and cracks occurring due to expansions (Figure 2C). The finger force could not penetrate it.

Similarly, the expansion test was performed on S-3 slurry which contained high AAAS content (8%). After 2 hours of curing, the sample expanded almost 10.6% from its original point, yellow line (Figure 3A). The cement was hard enough as the finger force could not penetrate into the sample. After 24 h, no further expansion was observed. The slurry was hard enough with a few cracks inside the set cement as shown in Figure 3B.

The above experiments indicated that the expansion decreased with an increase in the concentration of AAAS at the same concentration of Zn metal slurry. Further, it was observed that the high content of AAAS provided a more solid structure to the set cement. The cracks and voids were reduced with an increase in the concentration of AAAS as a stable structure was obtained at 8% AAAS as compared to the cracked and fissured 3% AAAS. On the other hand, class G cement slurry prepared at 50% water cement ratio (WCR) resulted in 8% shrinkage from its original point after 24 h of curing at 50 °C temperature as shown in Figure 4. Further, it

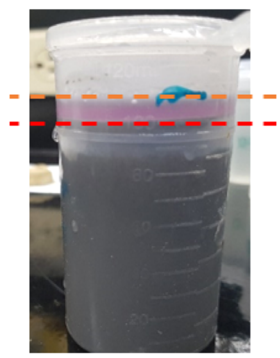


Figure 4. Class G cement shrinkage.

was observed that free water was accumulated at the top surface of the cement. The free water in a class G cement slurry makes it an unsuitable solution to be pumped in lost circulation zones where big voids and vugs exist to be filled in as it does not have expansion capability without an expanding agent. Second, this shrinkage could result in the debonding of cement from the casing and formation, which could result in causing sustainable pressure at the surface. The expandable solution generated with the reaction of AAAS and metal slurry in the presence of class G cement as bridging material could provide a best and reasonable solution for such a problem. In shallow zones where the big vugs exist and lost circulation is difficult to control, the expandable cement system can provide promising results.

2.2. Effect of Temperature on Expansion. For the sake of comparison, the S-1 slurry was studied for temperature sensitivity. The temperature was changed from room temperature to 50 °C. Figure 5 shows the expansion of cement slurry S-1 at various time intervals under room temperature. It was

https://dx.doi.org/10.1021/acsomega.0c05999
ACS Omega 2021, 6, 4950−4957

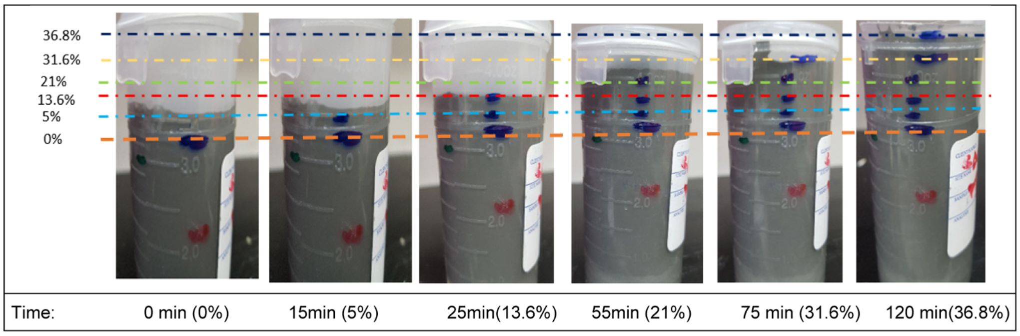


Figure 5. Expansion of S-1 slurry at room conditions at different time intervals.

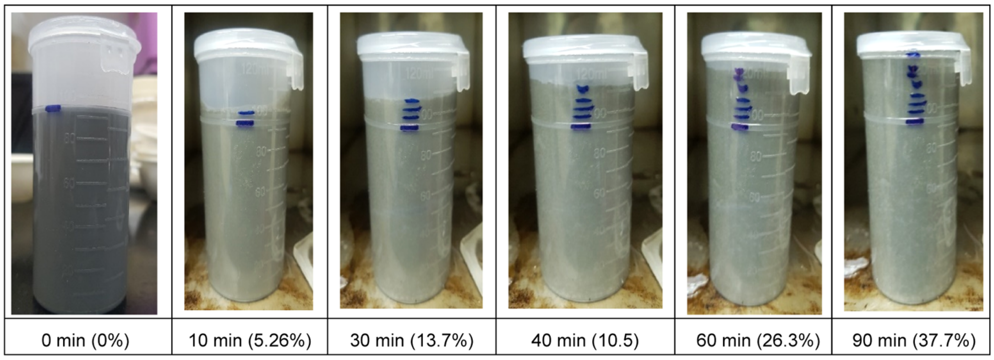


Figure 6. Expansion of S-1 slurry at 50 °C at different time intervals.

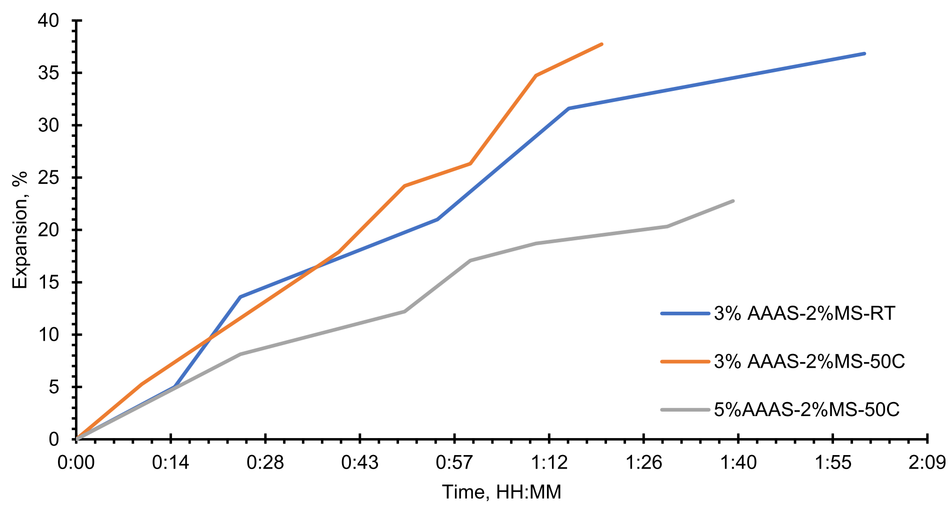


Figure 7. Expansion curves with the time of all tested slurries.

observed that the cement mix expanded by 36.8% from its original point after 2 h of curing.

Similarly, the expansion of S-1 slurry was observed under the temperature influence at various time intervals as shown in Figure 6. In this case, the S-1 slurry after mixing was exposed to 50 °C temperature. It was observed that temperature played a critical role in the expansion and enhanced the expansion rate as well as the total expansion percentage. At 50 °C, the slurry gained 37.7% expansion from the original point within 90 min as compared to 2 h for the test conducted at room conditions. Figure 7 provides the expansion curves of tested slurries with higher and quicker expansion achieved in S-1 at 50 °C. At room conditions, the reaction between Zn and silicate was happening at a slower rate and resulted in a slow expansion rate.

2.3. Expansion Test Using Brass Molds. The expansion of cement slurry containing AAAS and metal slurry was studied using expansion molds. In this test, the expandable cement slurry was cured at 70 °C for 24 h. The expansion of expandable cement slurry was compared with that of class G cement. Table 1 provides the results of the expansion. It was

Table 1. Expansion Test Conducted Using the Expansion Mold at 70 °C

formulation	initial reading (mm)	final reading (mm)	expansion percent (%)
class G cement	11.343	11.370	0.002
5% AAAS + 2% MS + class G	11.185	11.395	0.075

https://dx.doi.org/10.1021/acsomega.0c05999
ACS Omega 2021, 6, 4950−4957

observed that class G provided a negligible change in expansion after 24 h of curing. It resulted in a total expansion of 0.00238%. However, the slurry with AAAS and metal slurry resulted in expansion with prominent change. The expansion was 0.07518% which was quite higher than that of class G cement slurry. Further, it was observed that expandable slurry had a lot of pores on the surface of the cured mold as compared to plain class G cement which did not have pores on its surface as shown in Figure 8. The existence of pores on the surface showed that the expansion happened to the cement slurry in the presence of AAAS and Zn metal slurry.

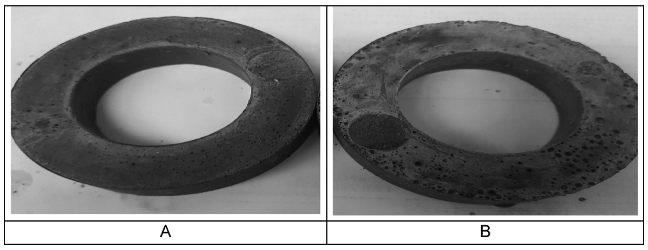


Figure 8. Samples from expansion molds, class G (A) and S-2 (B).

2.4. Consistency and Viscosity. The consistency and viscosity tests were conducted on S-1 slurry. In the consistency test, the S-1 slurry was mixed and loaded in an atmospheric consistometer, and its consistency was measured as shown in Figure 9. The consistency was 1.1 Bc at the start of the test. As the test proceeded, the consistency increased. After 45 min of delay, the cement slurry consistency increased to 40 Bc. This indicates that a high expansion took place in the slurry. The cement slurry reached to the top of the cell after expansion as shown in Figure 10.

2.5. Viscosity Test. The apparent viscosity of S-1 slurry was measured using an atmospheric viscometer. In this test, the cement slurry was stirred at 150 rpm, and a change in viscosity with time was measured. It was observed that the viscosity was rising continuously with time and reached 500 cP after 20 min (see Figure 11). The reaction was quite strong and quick, and as a result, the slurry attained high viscosity in a short span of time. It showed that the cement slurry can be pumped in shallow lost circulation zones. The cement will expand and get a high viscosity in a short time and will prevent further lost circulation. Further, there was a prominent expansion gained, resulting in the cement slurry popping out of the cup.

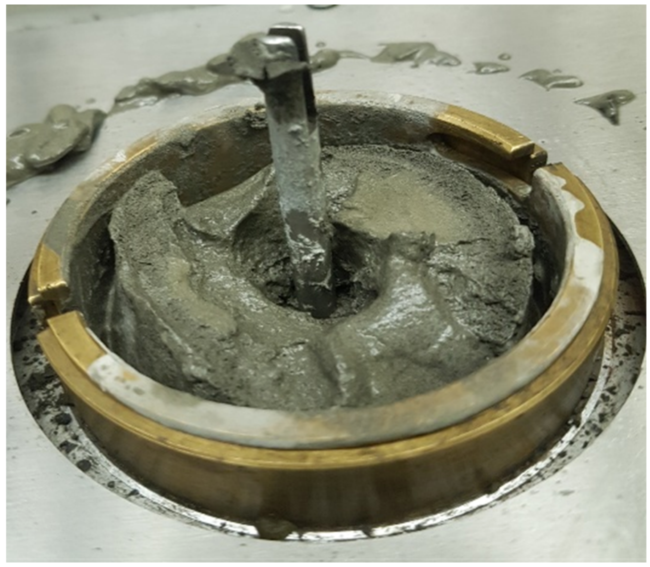


Figure 10. Expansion of S-1.

2.6. Compressive Strength. The compression test was conducted to measure the compressive strength of the expandable cement slurry. The performance of the expandable cement slurry was compared with that of plain class G cement. Both cement slurries were mixed and cured at 50 °C temperature and atmospheric pressure conditions. After aging for 24 h, the samples were crushed to get compressive strength. The average of two readings was reported as the compressive strength (see Table 2).

It was noticed that the expansion of cement slurry did not affect the compressive strength of the class G cement. The compressive strength of both slurries was the same. This indicated that an expandable cement system could be pumped downhole. It provides expansion as well as enough compressive strength against shocks and stresses.

3. APPLICATION IN OTHER FIELDS

As the new slurry system shows promising expansion in oil well cementing, it has potential applications in other fields such as civil and construction. The construction industry requires

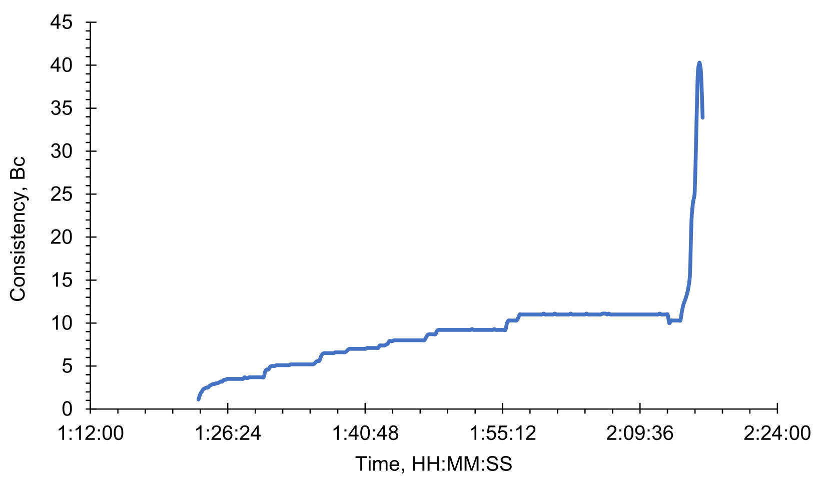


Figure 9. Consistency of S-1.

https://dx.doi.org/10.1021/acsomega.0c05999
ACS Omega 2021, 6, 4950−4957

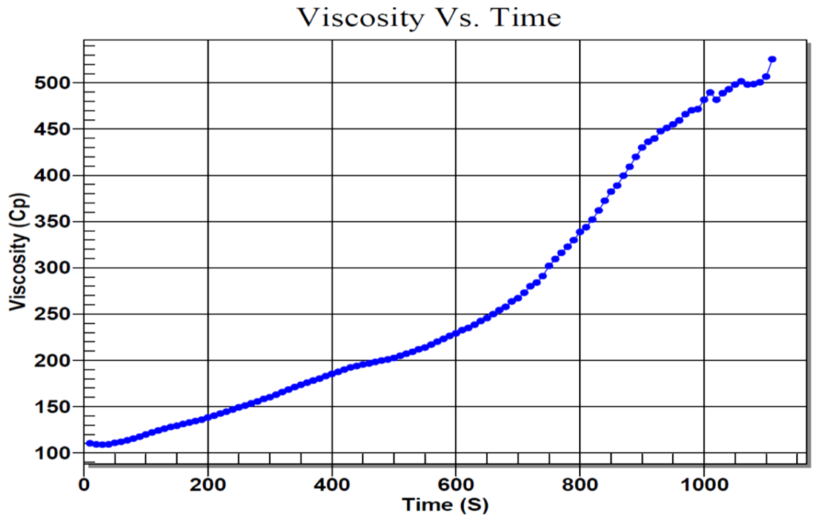


Figure 11. Viscosity trend with a time of S-1.

Table 2. Compressive Strength of Class G Cement and Expandable Cement Slurry (S2)

slurry	composition	compressive strength (psi)	average compressive strength (psi)
class G cement	class G + 50% BWOC water	1927	1869
		1811	
slurry (S2)	class G + 50% BWOC water + 5% BWOW AAAS + 2% BWOW MS	2028	1873
		1718	

quick expandable materials to fill the gaps, fissure, and cracks. The new expandable system can resolve expansion issues and provide enough integrity to the structures. Further, it can be applied in grouting, where a tight sealing material is often required to fill, block, and prevent communication between the isolated sections.

4. CONCLUSIONS

A novel expandable cement system containing a novel AAAS, Zn metal, and plain class G cement is introduced as an expandable solution to prevent annulus flow between the casing and formation and minimize lost circulation. Based on the results and discussions presented in the paper, the following conclusions can be inferred

1. The percentage of AAAS in the cement slurry should be in excess of 8% in order to achieve a lower expansion and increased hardening of the slurry. Cement slurry with 8% AAAS expanded to 10.6% and hardened after 24 h of curing, while the other cement slurries hardened after 24 h. Plain class G cement showed 8% cement shrinkage. Therefore, it cannot be used in lost circulation zones. The expansion of AAAS slurry precludes this and makes it a viable option for the loss of zonal isolation, shrinkage-induced cracking, and consequent gas migration.
2. Temperature enhanced the expansion of cement slurry with AAAS and reached the expansion of 37.1% under 50 °C temperature in 1.5 h, while the same slurry reached the same expansion in 2 h at room temperature.
3. The expansion of AAAS cement slurry did not cause any decrease in the compressive strength and is of the same order as the class G cement slurry.
4. The expandable cement slurry expands by many folds and could be a remedial solution to loss circulation in oil and gas drilling operation.

5. MATERIALS AND METHODS

The expandable cement slurry was formulated using class G cement, AAAS, and zinc (Zn) metal slurry. The properties of AAAS are reported in Table 3. The AAAS silicate is composed of oxides of sodium, silica, and alumina. AAAS was developed by PQ corporation, and it was supplied by Al-Azzaz, Saudi Arabia.

Table 3. Composition of AAAS

compound	Na_2O	SiO_2	Al_2O_3	solids (%)	density (g/mL)
AAAS	16.2	27.9	1.6	45.7	1.60

The Zn metal slurry was utilized to generate hydrogen, and it was supplied by BYK in 50% zinc slurry dispersion (LPR 24178). The cement slurries were prepared by using an adjustable speed, high shear mixer supplied by OFITE, USA as per American Petroleum Institute (API) specifications.[24] Aqueous sodium silicate has a pH range of 11−13.1. The pH of sodium silicate is controlled through the ratio of SiO_2/Na_2O in the range of 1:6−4.5:1.

Eqs 1−4[3] provide the reaction kinetics of Zn and sodium silicate. The reaction of zinc with sodium silicate serves several functions; it improves the durability of the silicate-based plug and serves to insolubilize the zinc. The insolubility of zinc silicate is supported by zinc-rich, silicate coatings which are used in a number of severe environmental conditions where HPHT resistance is required.

$$Zn + 2H_2O \rightarrow Zn(OH)_2 + H_2 \quad (1)$$

$$Zn(OH)_2 + Na_2O{\cdot}xSiO_2 \rightarrow Na_2ZnO_2 + xSiO_2 + H_2O \quad (2)$$

https://dx.doi.org/10.1021/acsomega.0c05999
ACS Omega 2021, 6, 4950−4957

$$Na_2ZnO_2 + xSiO_2 + H_2O \rightarrow ZnNa_2SiO_4{\cdot}H_2O + (x-1)SiO_2 \quad (3)$$

$$2Na_2ZnO_2 + SiO_2 \rightarrow ZnNa_2SiO_4 + 2Na_2O \quad (4)$$

5.1. Slurry Preparation. To prepare the cement slurry, all additives such as AAAS, Zn metal, and water were weighed according to the percentages given in Table 2. The water and AAAS were mixed at 4000 rpm. Cement was added within 15 s while stirring at 4000 rpm. Similarly, the metal slurry was added to a cement slurry while stirring at the same speed. After adding all additives, the cement slurry was mixed at a high speed of 12,000 rpm for 35 s. After mixing, the slurry was poured into the test tube, and the level of the slurry in the test tube was marked. The test tube was immersed in a water bath which was preheated at 50 °C temperature. The test was conducted for 24 h. At the end of 24 h, the set sample was removed, the expansion was calculated, and the outer surface of the sample was inspected visually (Table 4).

Table 4. Expansion Investigation for Different Percentages of AAAS (3, 5, and 8) % BWOW Conducted at 50 °C

material	unit	S-1	S-2	S-3
cement	grams	as required	as required	as required
water	% BWOC	50	50	50
AAAS	% BWOW	3	5	8
metal slurry (LPR 24178)	% BWOW	2	2	2

5.2. Expansion Test Using a Plastic Container. The expansion test was performed on various cement formulations, namely, S-1, S-2, and S-3, that were prepared by different concentrations of AAAS such as 3, 5, and 8% BWOW. The metal slurry concentration was maintained constant at 2% BWOW. The expansion test was performed at 50 °C for 24 h.

Further, the expansion test of the S-1 slurry was compared with another cement slurry prepared at 44% WCR. By conducting this test, the impact of water content can be evaluated on expansion. The expansion test was performed in a plastic container as shown in Figure 12.

Another type of expansion test was performed at 50 °C, and the evolution of expansion was measured with time. In this test, two cement slurry formulations such as S-1 and S-2 were tested.

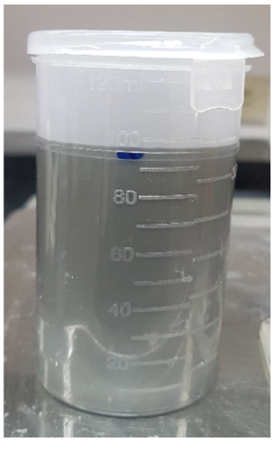


Figure 12. Plastic container for expansion test.

5.3. Expansion Test Using Expansion Molds. The expansion of cement slurry was also conducted using expansion molds supplied by OFITE as per the API standard. The expansion mold is shown in Figure 13. Two cement slurries named S-4 and S-5 with their formulations mentioned in Table 5 were studied. This test was conducted for 24 h under 70 °C temperature.

Figure 13. Expansion mold.

Table 5. Cement Slurries Tested for Expansion Using the Expansion Mold

material	unit	S-4	S-5
cement	grams	as required	as required
water	% BWOC	50	50
AAAS	% BWOW		5
metal slurry (LPR 24178)	% BWOW		1

Cement slurries were mixed as per API RP 10 B2 standard and conditioned in an atmospheric consistometer for 20 min at 50 °C temperature. After the conditioning period was over, the cement slurry was stirred vigorously and poured into the expansion mold. The mold assembly was filled from the large hole on the top of the mold, and the small hole was designed for ventilation while filling the mold. The mold was filled until the slurry seeped through the small hole. After filling the mold, the distance between two steel balls was measured using a Vernier caliper. The mold was placed in the atmospheric curing bath for 24 h. At the end of the curing period, the mold was removed, and the distance between steel balls was measured again using a Vernier caliper.

Similar expansion experiments were performed on the straight class G cement as a reference.

5.4. Consistency Tests. Consistency defines the flowability of the cement slurry. It was measured by using an atmospheric consistometer supplied by GRACE with model number M7210. Consistency was measured in the Bearden consistency unit (Bc), and it was measured while rotating the cement slurry at 150 rpm.

5.5. Viscosity Tests. The viscosity is defined as the resistance to flow. In this part, the effective viscosity of S-1 slurry was measured at 50 °C while rotating the rotor at 150 rpm of an atmospheric viscometer supplied by GRACE (model #3600). The viscosity change with time was measured and reported in this part.

5.6. Compressive Strength Test. To measure the unconfined compressive strength (UCS) of the prepared cement slurries, cube samples of dimensions 2 in. × 2 in. × 2 in. were casted in brass molds. A similar procedure as discussed in Section 2.2 was adopted to cast the cubicle sample. Samples were cured at 50 °C for a period of 24 h. The cube samples were crushed in UCS tests. The UCS machine was provided by

MATEST. The test was conducted on slurry S-2 and plain class G cement as a reference.

AUTHOR INFORMATION

Corresponding Author

Mohamed Mahmoud − *College of Petroleum Engineering & Geosciences, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia;* orcid.org/0000-0002-4395-9567; Email: mmahmoud@kfupm.edu.sa

Authors

Mobeen Murtaza − *College of Petroleum Engineering & Geosciences, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia;* orcid.org/0000-0003-4279-4665

Zeeshan Tariq − *College of Petroleum Engineering & Geosciences, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia*

Muhammad Kalimur Rahman − *Center for Engineering Research, Research Institute, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia*

Muhammad Shahzad Kamal − *College of Petroleum Engineering & Geosciences, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia;* orcid.org/0000-0003-2359-836X

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c05999

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors acknowledged the College of Petroleum Engineering & Geosciences at the King Fahd University of Petroleum & Minerals for providing the laboratory facilities in conducting this research.

NOMENCLATURE

AAAS	aqueous alkali alumino silicate
SCP	sustained casing pressure
CCA	casing−casing annulus
BWOW	by weight of water
WCR	water cement ratio
API	American Petroleum Institute
Bc	Bearden consistency unit
rpm	rotation per minute
PV	plastic viscosity
YP	yield point
AV	apparent viscosity
cP	centipoise
UCS	unconfined compressive strength

REFERENCES

(1) Debruijn, G.; Instructor, P. *Cementing/Zonal Isolation*, 2017, No. May, 2017.

(2) Murtaza, M.; Rahman, M. K.; Samad, A. *Rheological and Microstructural Properties of Saudi Type G Cement Slurry with Silica Flour Used in Saudi Oil Field under HTHP Conditions*, 2013, SPE 168101 Mechanical No. Nelson 1990.

(3) Soucy, K.; Services, M. C.; Cramer, B. *Enhancing Void and Fracture Filling with an Expandable Silicate-Based Grout*; Geo-Edmonton: Alberta, Canada, 2018.

(4) Davies, D. R.; Hartog, J. J.; Cobbett, J. S. Foamed Cement—A Cement with Many Applications. *Society of Petroleum Engineers of AIME*; SPE, 1981.

(5) Ghofrani, R.; Plack, H. CaO-and/or MgO-Swelling Cements: A Key for Providing a Better Annular Sealing?. *SPE/IADC Drilling Conference*, 1993; pp 199−214.

(6) Al-Buraik, K.; Al-Abdulqader, K.; Bsaibes, R. Prevention of Shallow Gas Migration through Cement. *IADC/SPE Asia Pacific Drilling Technology*; APDT, 1998, Sept, 1998.

(7) Al-Ansari, A. A.; Al-Refai, I. M.; Al-Beshri, M. H.; Pino, R. M.; Leon, G. A.; Knudsen, K.; Sanabria, A. E. Thermal Activated Resin to Avoid Pressure Build-up in Casing-Casing Annulus (CCA). *SPE Offshore Europe Conference and Exhibition 2015*, 2015.

(8) Morris, K. A.; Deville, J. P.; Jones, P. Resin-Based Cement Alternatives for Deepwater Well Construction. *SPE Deepwater Drilling and Completions Conference 2012*, 2012, No. June, pp 468−474.

(9) Al-Yami, A. S.; Nasr-El-Din, H. A.; Al-Saleh, S. H.; Al-Humaidi, A. S.; Al-Arfaj, M. K.; Awang, M. Z.; Al-Mohanna, K. S. Lab Investigation of Oil Swelling Elastomers for Smart Well. *Offshore Technology Conference*, 2008.

(10) Al-Yami, A. S.; Nasr-EI-Din, H. A.; Al-Arfaj, M. K.; Al-Saleh, S. H.; Al-Humaidi, A. S.; Awang, M. Z.; Al-Mohanna, K. S. Investigation of Water-Swelling Packers. *Society of Petroleum Engineers—SPE Gas Technology Symposium*, 2008.

(11) Akhlaghi Amiri, H.; Hamouda, A.; Roostaei, A. Sodium Silicate Behavior in Porous Media Applied for In-Depth Profile Modifications. *Energies* **2014**, *7*, 2004.

(12) Fleury, M.; Sissmann, O.; Brosse, E.; Chardin, M. A Silicate Based Process for Plugging the Near Well Bore Formation. *Energy Procedia* **2017**, *114*, 4172.

(13) Lakatos, I.; Lakatos-Szabó, J. Reservoir Conformance Control in Oilfields Using Silicates: State-of-the-Arts and Perspectives. *Proceedings—SPE Annual Technical Conference and Exhibition*, 2012.

(14) Murtaza, M.; Mahmoud, M.; Tariq, Z. Experimental Investigation of a Novel, Efficient, and Sustainable Hybrid Silicate System in Oil and Gas Well Cementing. *Energy Fuels* **2020**, *34*, 7388.

(15) Kaduku, T.; Daramola, M. O.; Obazu, F. O.; Iyuke, S. E. Synthesis of Sodium Silicate from South African Coal Fly Ash and Its Use as an Extender in Oil Well Cement Applications. *J. South. Afr. Inst. Min. Metall.* **2015**, *115*, 1175.

(16) Penberthy, W. L.; Bayless, J. H. Silicate Foam Wellbore Insulation. *J. Pet. Technol.* **1974**, *26*, 583.

(17) Miller, M. L.; Scorsone, J. T.; Whitfill, D. L.; McDonald, M.; Miller, N. The Development of a Geopolymer-Based Pill as an Engineered Solution to Lost Circulation. *Proceedings—SPE Annual Technical Conference and Exhibition*; 2013.

(18) Jackson, M. L. The Colloid Chemistry of Silica and Silicates. *Soil Sci. Soc. Am. J.* **1955**, *19*, 390.

(19) Pinkas, J. Chemistry of Silicates and Aluminosilicates. *Ceram.-Silik.* **2005**, *49*, 287.

(20) Rochow, E. G. Soluble Silicates: Their Properties and Uses (Volume 2). *J. Chem. Educ.* **1953**, *30*, 5.

(21) Carter, L. G.; Waggoner, H. F.; George, C. Expanding Cements for Primary Cementing. *J. Pet. Technol.* **1966**, *18*, 551.

(22) Wang, H. Z.; Leung, D. Y. C.; Leung, M. K. H.; Ni, M. A Review on Hydrogen Production Using Aluminum and Aluminum Alloys. *Renew. Sustain. Energy Rev.* **2009**, *13*, 845.

(23) Crivello, J.-C.; Denys, R. V.; Dornheim, M.; Felderhoff, M.; Grant, D. M.; Huot, J.; Jensen, T. R.; de Jongh, P.; Latroche, M.; Walker, G. S.; Webb, C. J.; Yartys, V. A. Mg-Based Compounds for Hydrogen and Energy Storage. *Appl. Phys. A: Mater. Sci. Process.* **2016**, *122*, 24.

(24) *Recommended Practice for Testing Well Cements*; API Publisher, 2005, No. April 36, API RP 10B-2.