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Review

Properties and Performance of Oil Well Slurry and Cement Sheath Incorporating Nano Silica: A Review

Ahmed Abdulhamid Mahmoud* and Salaheldin Elkatatny*

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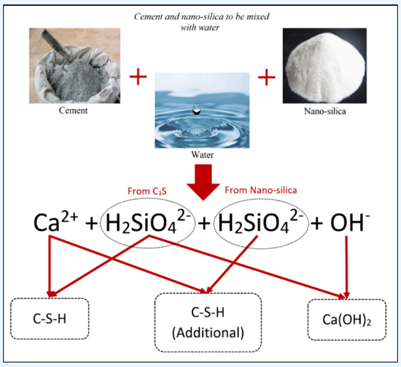
ABSTRACT: The oil well cementing job is the operation in which a cement paste is pumped to fill the annulus behind the casing. Inclusion of nanomaterials in oil well cement results in improving the cement properties. This paper provides a comprehensive overview of incorporating nanosilica into oil well cement, addressing various aspects of the nanosilica manufacturing process, dispersion challenges, the impact on cement hydration and properties, as well as the operational challenges. The addition of nanosilica is found to enhance cement properties such as hydration rate, compressive strength at low temperatures, and resistance to deterioration at high temperatures. However, challenges arise, including increased viscosity and the need for higher water content. Dispersion of nanosilica into cement slurry remains a difficulty, compounded by the high manufacturing cost, limiting its practical application. The paper recommends further research to improve nanosilica dispersion, explore cost-effective raw materials, and overcome operational challenges for broader utilization in oil well cementing.



1. INTRODUCTION

Oil-well cementing is aimed to fill the annular space between the formation exposed to the wellbore and the casing with a cement slurry.[1,2] The cementing process is performed to achieve many purposes such as casing protection and efficient zonal isolation in the wellbore to prevent fluids migration between zones as well as to the surface, which requires a hydraulic seal to be achieved while fluid channels in the cement sheath must be avoided.[3]

Nanomaterials are substances that have been reduced in size to a range of 1−100 nm or possess at least one dimension within this nanoscale range in a three-dimensional space.[4] The introduction of nanotechnology and the use of nanomaterials in oil well cement slurry preparation led to considerable improvement in the cement slurry and cement matrix properties because of the small size, and the unique characteristics possessed by nanoparticles comprise greater surface area per unit volume.[5−10] A comparison of surface area to volume ratio attributed to the different radius size of spherical particles are presented by Amanullah and Al-Tahini.[11]

Nanosilica which is a silica-based material is one of the newly suggested nanomaterials to enhance the cement characteristics and improve its properties and resistance to chemical attack by acidic materials. Figure 1 compares the average size and average surface area of different materials and nanomaterials considered to be a part of the cement system. As indicated in this figure, nanoparticles have very small particles with dimensions between 1 and 100 nm, where nanosilica has a particle size of less than most of the materials considered in cement slurry preparation with a particle size of less than 100 nm, it is also available with sizes of less than 10 nm.[12]

Reduction in particle size of the additives used to prepare the cement slurry from micro to nanoscale is always combined by alteration in conductivity, mechanical properties, chemical reactivity, and optical adsorption. As the size reduced, most of the particle's atoms located on the surface of those particles, which lead to considerable alteration in surface energies and morphologies of the particles.[13−15]

In this review paper, the studies of incorporation of the nanosilica into cement slurry are summarized. The processes of manufacturing nanosilica are reviewed, and dispersion of silica-based chemicals into the cement and hydration of the oil well cement incorporating nanosilica are presented. The effect of the nanosilica materials on the different properties of the oil well cement is reviewed, and the operational challenges encountered upon the incorporation of nanosilica into oil well cement slurry are presented. A summary of the lessons learned and recommendation for future work will be provided based on this review.

2. PROPERTIES OF NANOSILICA MATERIALS

Nanosilica, which is also called silica dust or quartz dust and is commonly known as silicon dioxide (SiO_2) nanoparticles, is

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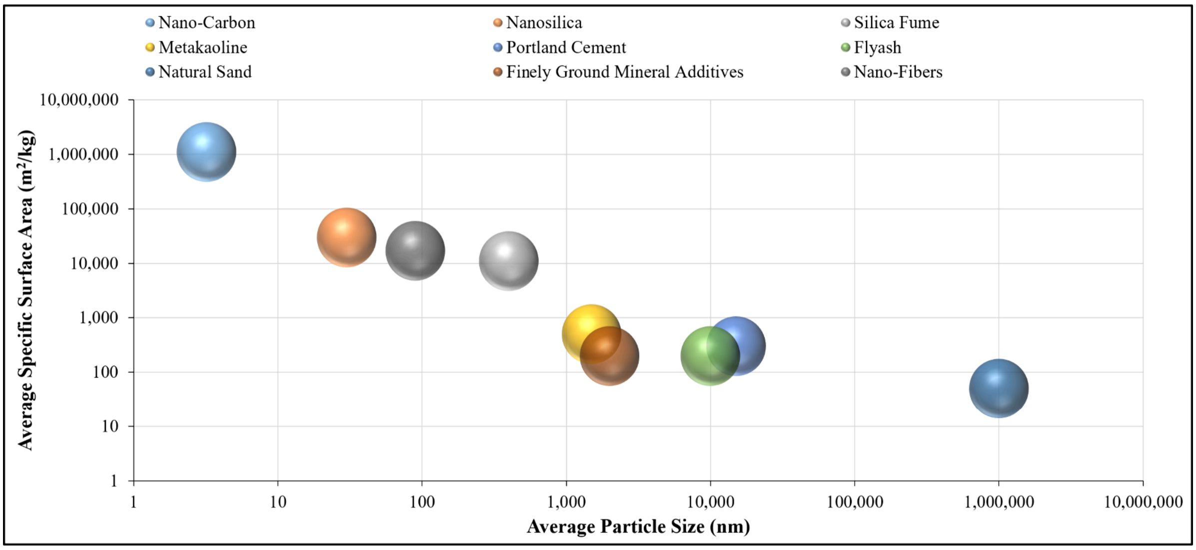

Figure 1. Average surface area and size of the cementitious system particles.

characterized by a very high percentage of SiO_2, greater than 99%.[16] It is a kind of nanomaterial in which silicon and oxygen combine to form a nanoparticle. It is a white powder as shown in Figure 2a. The transmission electron microscope image of the nanosilica is shown in Figure 2b. Nanosilica has the chemical formula of SiO_2, and it is commonly employed in making building blocks in a variety of natural and man-made construction operations.[17,18]

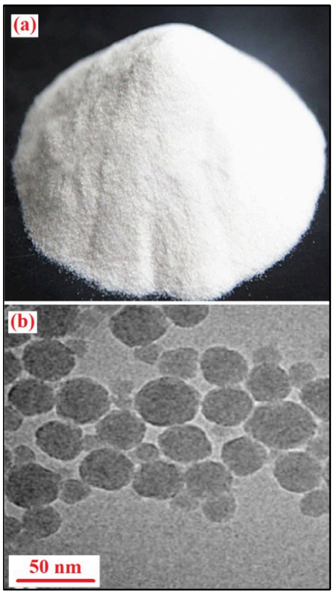

Figure 2. (a) Nanosilica powder and (b) transmission electron microscope image of nanosilica.

According to many experts, the physical and chemical characteristics of nanosilica are well understood. On the other hand, others reported that nanosilica particles have contradictory properties, including the hydrophobic and hydrophilic properties, but both types are nontoxic and inorganic compounds.[19,20]

Nanosilica technology allows for major changes in the chemical, physical, and mechanical behavior of cement at the macro-scale. This is because of the nanoscale dimension of nanosilica-based materials' remarkable characteristics.[17] As shown in Figure 1, the particles size of nanosilica is less than 100 nm. This small size makes the surface area for the silica nanoparticles large; this high surface area is very important to accelerate the reaction of this nanomaterial with cement slurry components, and therefore, it could increase the cement hydration rate, especially at an early time which significantly leads to alteration in the cement properties.[21,22]

The pore-filling effect of nanosilica is another important property that enables this nanomaterial to fill the gaps within the cement matrix, therefore increasing the density, compactness, and strength of the cement body.[16] Nanosilica has lower environmental effects than other types of nanoparticles, and it is considered to be the most environmentally friendly compared to most of the nanomaterials used in the oil industry.[23,24]

3. NANOSILICA MANUFACTURING PROCESSES

The methodologies used to make nanosilica particles could be grouped into two main categories: top-down (physical method) and bottom-up (chemical method).[14,25] The top-down method is based on size reduction strategies which are aimed to reduce the size of the original dimensions of the particles. On the other hand, a typical way for synthesizing nanosilica from a molecular or atomic scale exists and is called the bottom-up method, which involves chemical interactions and processes.[26]

On the basis of the chemical approach of the bottom-up method, which is also called the sol−gel approach, nanosilica could be produced in a variety of ways. At ambient temperatures, one of these ways uses a sol−gel technology (organic or water route). The process starts by adding the preparation components which are generally Na_2SiO_4 and organometallics like tetraethylorthosilicate (TEOS) to a solvent, and then through hydrolysis and condensation, colloidal silica will be formed. Then through aging and pH modification, silica gel will precipitate. This gel will then be dried and calcinated to form the nanosilica powder as explained in Figure 3.

In the sol−gel process, the general reactions of TEOS that generate nanosilica may be illustrated as shown in eqs 1−3.

$$Si(OC_2H_5)_4 + H_2O \xrightarrow[\text{hydrolysis}]{} Si(OC_2H_5)_3OH + C_2H_5OH \qquad (1)$$

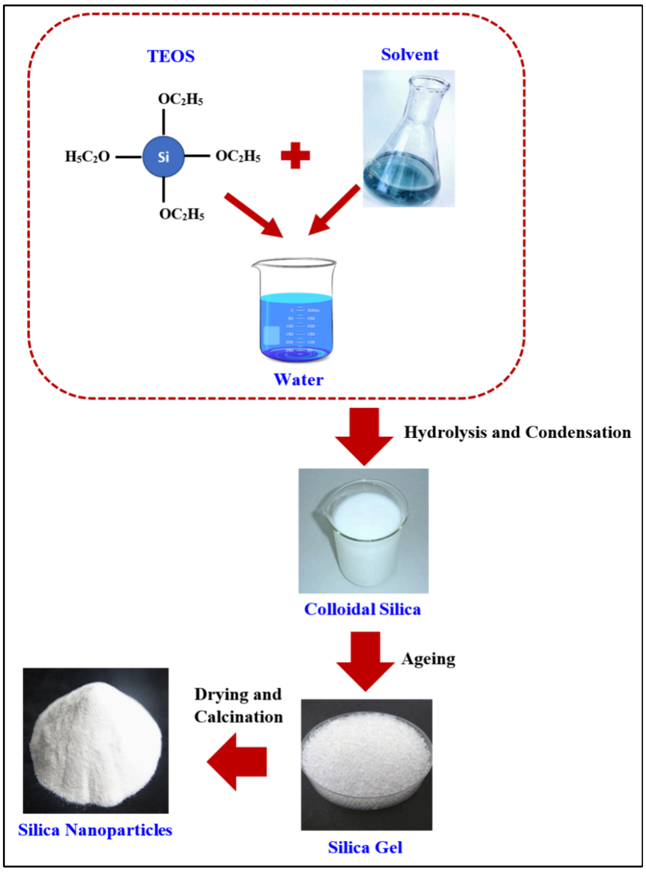

Figure 3. Chemical approach of bottom-up for making nanosilica powder (sol−gel process).

$$\equiv\text{Si—O—H} + \text{H—O—Si}\equiv \xrightarrow{\text{water condensation}} \equiv\text{Si—O—Si}\equiv + H_2O \tag{2}$$

$$\equiv\text{Si—OC}_2\text{—H} + \text{H—O—Si}\equiv \xrightarrow{\text{alcohol condensation}} \equiv\text{Si—O—Si}\equiv + C_2H_5OH \tag{3}$$

Furthermore, according to the reviewed literature, the sol−gel technique is the most widely used method for manufacturing silica nanoparticles because of its capacity to regulate particle size, distribution, and shape by meticulous monitoring of reaction parameters.

In accordance with the latest study findings, a novel low-energy replacement approach for generating nanosilica particles has been discovered. This method involves dissolving olivine, one of the fastest-weathering silicate minerals, in an acidic environment at a low temperature of 50° to 90 °C to produce amorphous nanosilica.[27] Furthermore, Lazaro et al.[27] showed that waste acids like sulfuric acid may be used to create olivine nanosilica (OnS) to reduce the cost of this process. They also showed that OnS has unique properties such as maximum fineness (6−30 nm) and purity, when compared to nanosilica made using the other technologies. However, since OnS is made at a negative pH, this usually leads to formation of nanosilica agglomerations with a large surface area (200−400 m^2/kg), as well as being dominated with (OH) surface groups, which alter its reactivity. As a result, more research into this innovative method of manufacturing nanosilica is advised.

Recently, the production of nanosilica from agricultural wastes was favored, and different agricultural wastes were considered for making the silica nanoparticles. This is because of the presence of a huge amount of silica in these waste materials. As explained by Sarkar et al.,[28] these waste materials could be converted into silica nanoparticles through chemical, thermal, or biological treatments as explained in Figure 4. The description of these different methodologies involved in the production of silica nanoparticles from waste materials was discussed by Sarkar et al.[28]

4. NANOSILICA IN OIL WELL CEMENTING

The addition of nanoscale particles to oil well cement systems can give cement functionality, resulting in a range of novel properties. Several forms of metal oxide nanoparticles, including nanosilica, iron oxide, titanium dioxide, aluminum oxide, copper oxide, zinc peroxide, and a variety of other magnetic nanoparticles, have been utilized as additives in cement to mitigate a variety of common field difficulties.

Because of its unique properties of small particle size, high surface area, and high silica content, nanosilica was used as a complementary additive to improve the different properties of cement. To begin with, silica nanoparticles with nanoscale in size act as a filler, filling the pore spaces within the cement structure, and hence, densify the cement structure and compact it, in addition to its ability to reduce the capillary porosity. Second, the high silica content (>99%) enables nanosilica to have a stronger pozzolanic activity that gives its accelerators functionality.[29,30]

The influence of nanosilica on cement hydration was investigated by Silvestre;[31] according to his findings, mixing nanosilica into cement grains produces H_2SiO_4, which interacts with the present Ca^{2+} to generate more calcium silicate hydrates (C−S−H), as illustrated in Figure 5. These C−S−H gels spread into the water between the cement particles, acting as seeds for a more compacted C−S−H phase to form. As a result, nanosilica particles increase the rate of the pozzolanic reaction.

Furthermore, nanosilica enhances $Ca(OH)_2$ consumption and produces an extra C−S−H gel, which is a vital component for increasing the hardened cement strength.[32] According to other research, the addition of nanosilica to cement slurry reduces the concentration of $Ca(OH)_2$ in the hydration products by converting it to C−S−H gel, and this reaction boosts the cement hardness.[33−35]

5. DISPERSION OF NANOSILICA INTO THE CEMENT SLURRY

Modification of cement composites with nanoparticles allows for not only improved mechanical performance but also increases the cement hydration rate, decreases the free water, and prevents fluid migration through the cement body.[36] In the form of water dispersion, various modifiers, including nano admixtures, are introduced to the dry components of the composite. Therefore, the effective dispersion of the nanomaterials in the cement matrix is a primary property in nanomodification which is important to ensure homogeneous enhancement and modification of the cement slurry and matrix properties.

Because of van der Waals interactions, nanoparticles in water have the propensity to clump together. As a result, obtaining a combination with uniformly dispersed inclusions is one of the most difficult challenges in the preparation of cement nanocomposite.[37] Even though commercial nanoparticles are created with sizes below 100 nm, when applied to cement composites,

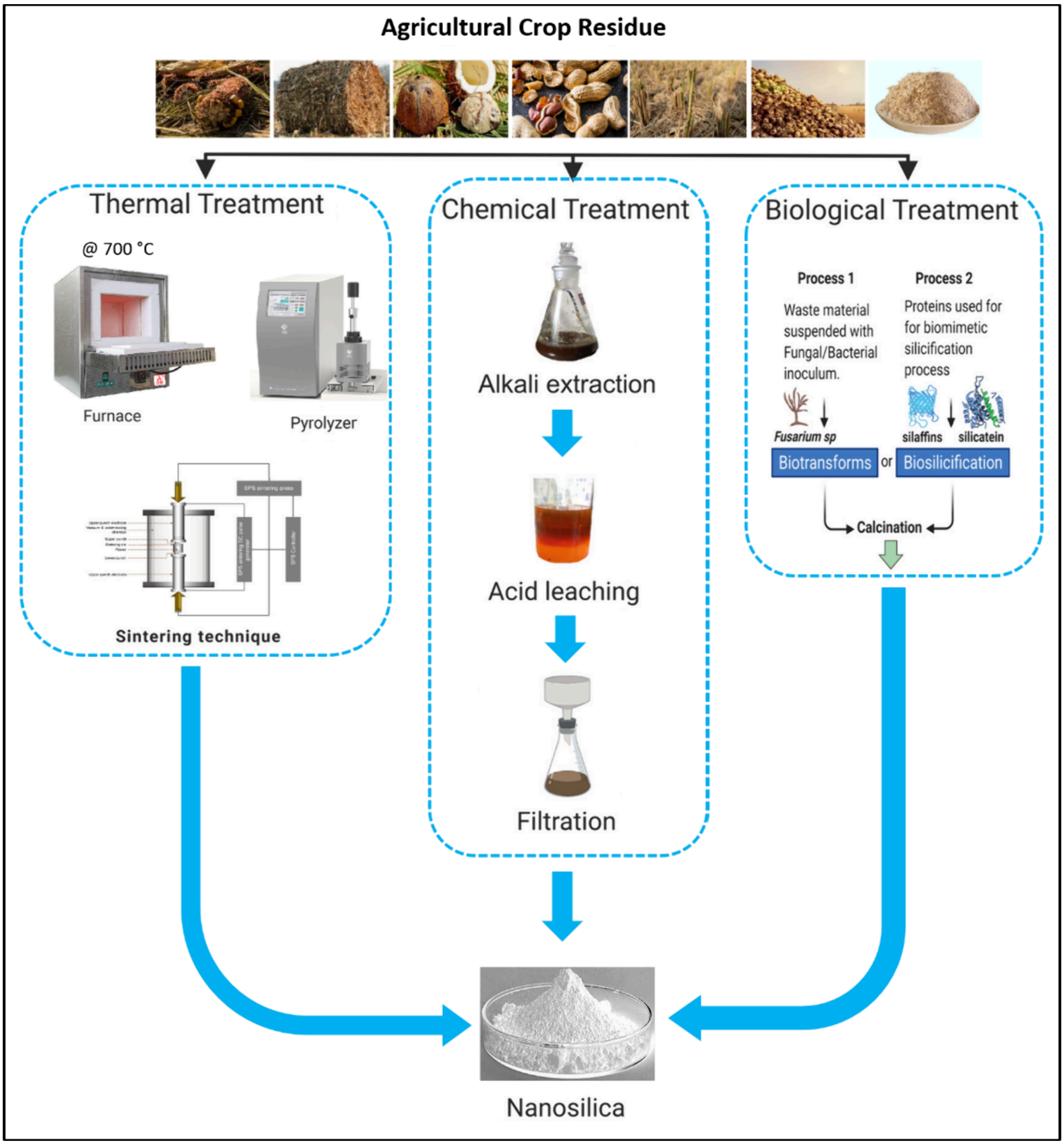

Figure 4. Extraction of the silica nanoparticles from agricultural wastes.

they often form massive agglomerates with sizes ranging from 1 to 10 mm,[38] as explained in Figure 6.

The aggregation of nanoparticles in the cement matrix might result in the formation of weak zones with increased porosity and, hence, a decrease in the composite's mechanical performance.[38] Aside from van der Waals forces, the effect of Ca^{2+} ions, whose concentration is responsible for nanoparticle aggregation, appears to be the important phenomenon here.

The Ca^{2+} bridging effect influences the behavior of nanosilica dispersion in cement paste. As a result, it appears that the ionic composition of cement systems has a considerable impact on the dispersion of nanosilica particles.[39] The stability of SiO_2 nanoparticles is affected by ion concentrations in the pore solution as well as the tendency of nanosilica particles to adsorb, which can lead to agglomeration.[40,41]

To achieve a "perfect" dispersion of nanoparticles, the agglomerates must be broken down into smaller portions, even to the original particle size, with the requisite amount of energy. After breaking the agglomerates, the "broken" parts must be stabilized and prevented from reagglomerating using the appropriate mechanism, such as steric or electrostatic repulsion. Even at a high rate of mixing, the normal mixing of the components is insufficient to provide the optimal dispersion of the nanoparticles in the cement composite. A mix of mechanical procedures and chemical changes is employed to achieve this goal. Depending on the type of nano modifiers and the environment, these approaches are applied independently or together. Mechanical techniques for dispersing nanoparticles in water suspensions and dry binders are frequently employed, including mechanical mixing,[42,43] ultrasonication,[44] and ball grinding.[45]

Superplasticizers are the most often employed modifiers in the industrial manufacturing of cement composites;[46] they are required, for example, to generate high-strength concrete. Superplasticizers are also the most prevalent way of dispersing 0D nanoparticles (those with all three dimensions less than 100

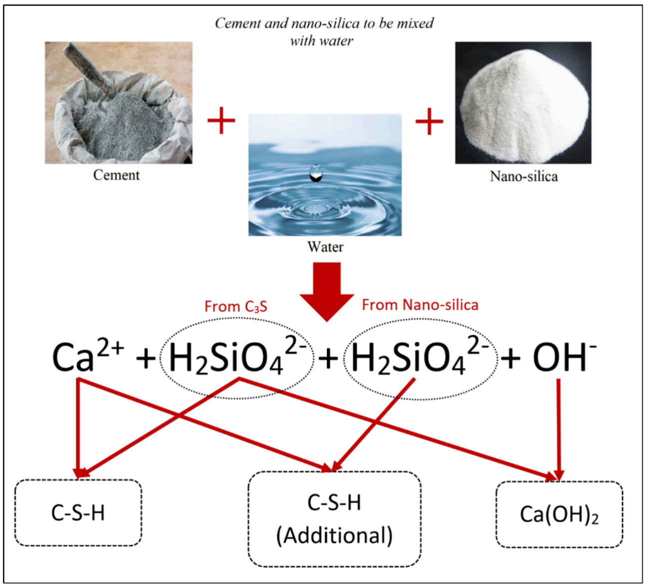

Figure 5. Reaction of nanosilica with cement to produce C−S−H.

nm), such as silica nanoparticles.[47] When these silica nanoparticles are used in cement paste without a superplasticizer, the mixture viscosity increases, and more air bubbles are introduced into the matrix,[48] which is detrimental to the porosity and permeability of the cement structure.

Recently, Batista et al.[49] evaluated the use of nanosilica-coated titanium-oxide particle (nTS) as a secondary additive to the cement slurry, and the authors reported that the nTS exhibited excellent dispersion in water without the need for any dispersive methods.

6. HYDRATION CHARACTERISTIC OF THE OIL-WELL CEMENT CONTAINING NANOSILICA

Hydration is a chemical process in which cement compounds create chemical bonds with water molecules to produce hydrates.[50] Heat is released when the cement is mixed with water, and this heat is referred to as the heat of hydration,[51] which is a result of the exothermic interaction between the cement compounds and water. The faster the hydration reaction in the cement slurry, the less time is needed for the cement to set. At low temperatures, the heat of hydration generation is sluggish while it is quick at high temperatures.

Many studies have examined the impact of nanosilica particles on cement hydration, microstructures, mechanical strength, and other properties. The ability of nanosilica to accelerate cement hydration has been demonstrated in several studies which concluded that the hydration peak was noticeably growing.[52−57] Furthermore, because of its pozzolanic reactivity, these studies claim that nanosilica is an ideal cement hydration accelerator. Its process is primarily linked to nano silica's large specific surface area, which functions as nucleation sites for C−S−H gel precipitation.

Similarly, Chithra et al.[32] and Silvestre[31] observed that adding silica particles to cement grains produces $H_2SiO_4^{2-}$ during the hydration process, and the generated $H_2SiO_4^{2-}$ combines with available Ca^{2+} to generate an excess C−S−H. These C−S−H gels spread in the water between the cement grains, acting as seeds for a more compact C−S−H phase to develop. They also showed that nanosilica enhances the consumption of $Ca(OH)_2$ and results in the creation of an extra C−S−H gel, which is the key component for hardened cement strength. Other researchers also confirmed the finding that the addition of nanosilica lowers the amount of $Ca(OH)_2$ in the hydrated cement by converting it to C−S−H gel, and this transformation boosts the cement strength.[33,34]

According to Mohammed,[58] addition of 1% nanosilica leads to changes in the cement minerology after hydration, where the cement incorporating nanosilica has higher magnesium silicate sulfate and quartz content as confirmed by the XRD analysis.

The cement hydration process is affected by the physical properties of the additive considered to make the cement slurry. Pang et al.[57] performed experiments to evaluate the impact of the size and aspect ratio of silica nanoparticles on the hydration process. They observed that the hydration rate for oil well cement could be increased by incorporation of nanosilica particles, and the rate of hydration is also a function of the particle size and increases with the reduction in the particle size.

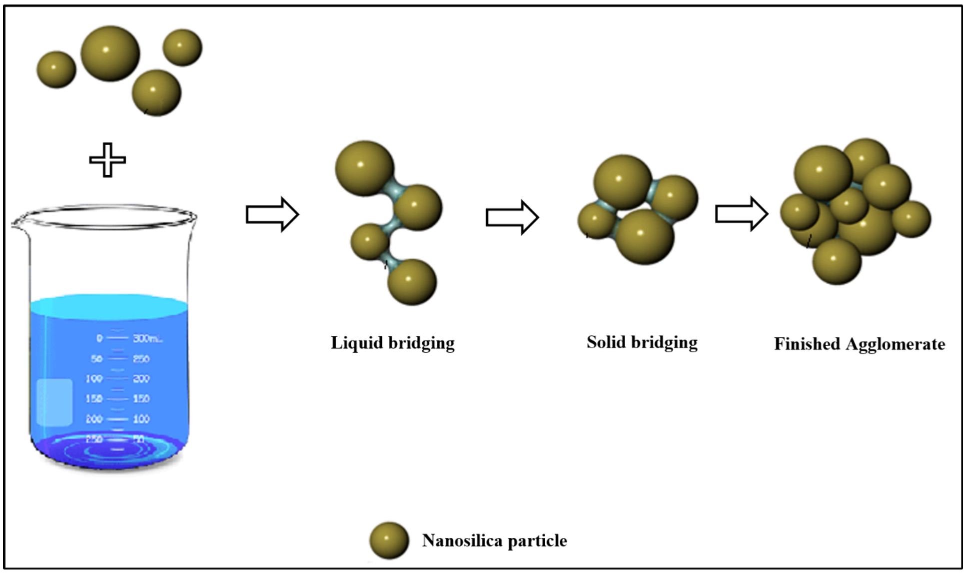

Figure 6. Agglomeration of silica nanoparticles after mixing with water.

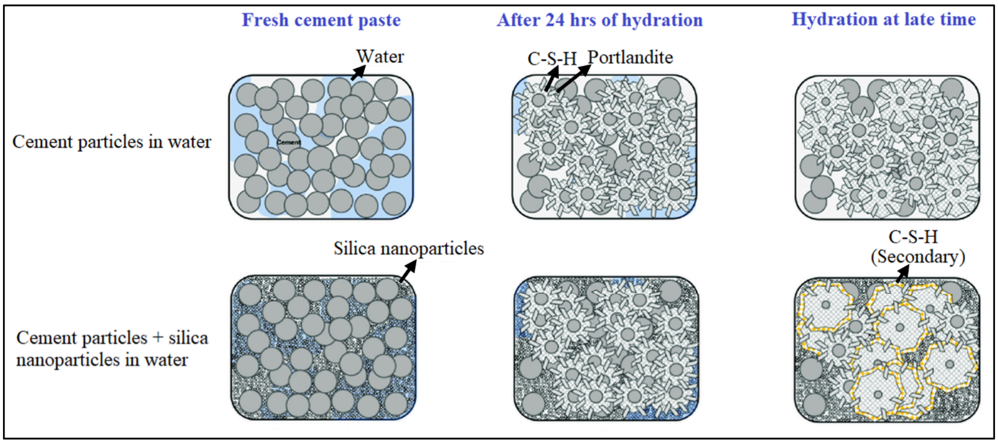

Figure 7. Comparison of the hydration process for the neat cement and the cement slurry incorporating silica nanoparticles.

The best cement hydration accelerators were found to be nanosized silica with particles of 4−6 nm in size.

However, it is still a debatable issue whether the fast hydration of cement in the presence of nanosilica is caused by the pozzolanic activity of the nanosilica or by their high surface activity or both.[52]

Figure 7 compares the hydration process for the neat cement slurry with that incorporating silica nanoparticles. As indicated in this figure, at an early age, the hydrated cement consists of C−S−H and portlandite. While at a later time, for the silica nanoparticles-based cement system some of the portlandite particles are transformed to secondary C−S−H through the pozzolanic reaction,[59] explained by eq 4. This pozzolanic reaction is a secondary chemical reaction between the amorphous silica particles and the portlandite component to form a more stable form of C−S−H.

$$2\text{nano}SiO_2 + 3\text{Ca(OH)}_2 \leftrightarrow 1.5(\text{CaO})(\text{SiO}_2)(\text{H}_2\text{O})_{(3+n)} \quad (4)$$

7. EFFECT OF NANOSILICA ON THE PROPERTIES OF OIL WELL CEMENT

7.1. Rheological Characteristics of the Cement Slurry.

The study of rheological characteristics aims to identify intrinsic fluid properties, particularly the plastic viscosity, yield point, frictional qualities, and gel strength, this is important to determine the flow characteristics of the cement slurry and to discover the correlations between flow rate (shear rate) and pressure gradient (shear stress) that induce fluid movement.[60]

The viscosity of the cement-bound substance is affected by nanotechnology. The viscosity of typical cement is lower, resulting in a more brittle cement bond. On the other hand, nanoenhanced slurries have a greater viscosity, resulting in increased flexural behavior.[61]

Controlling rheological characteristics during well cementing is much more important for improving drilling-fluid displacement in the annulus. The cement paste viscosity should allow for simple annulus penetration and pumpability. The rheology of the cement also influences how well it sticks to the casing and formation.[62] Because of the enormous surface area of nanoparticles, the workability of the cement slurry is generally diminished when they are added. The rheology of the slurry may alter sufficiently to render it unpumpable, depending on the kind and concentration of additional nanomaterial.

The rheological behavior of the cement slurry is affected by many parameters including the water to cement ratio, the cement powder chemical composition, the size and shape of the cement grains, the additives included in the cement slurry, concentration and form of solid particles of the additives, the slurry mixing, and testing procedures.[60] The plastic viscosity and yield stress of the cement slurry normally rise as the fineness and/or particle concentration of the cement and additives increases.[63]

The addition of nanosilica to oil well cement slurry alters rheological properties such as yield point and plastic viscosity. When nanosilica is introduced to the cement slurry for the first time, it has a direct impact on the amount of water necessary for the cement to work. This demonstrates that adding large surface area solid particles increases the demand for more water and chemical additives to make the cement workable. At constant water content, a rise in nanosilica concentration results in tight packing of the particles and a reduction in the free water. As a result, this will lead to increased torque and friction between the particles.[60]

The inclusion of nanosilica also reduces cohesion in the cement slurry, which results in a reduction in flow spread and an increase in plastic viscosity. The spread of the flow is inversely related to the yield stress; the yield stress could greatly enhance as the spread of the flow reduces. The ultrafine nanosilica particles fill vacancies in a cementitious material, enhancing interparticle frictional resistance and densifying the microstructure.[64,65]

The loss in workability seen by many studies is because not all agglomerates act as fillers. Apart from nano silica's strong water absorption, these agglomerates will not only act as fillers but also can absorb free water that was previously a source of fluidity. As a result, whether nanosilica inclusion influences rheological characteristics is essentially governed by whether or not these agglomerates will operate as fillers.[66]

Wang et al.[68] reported that the addition of nanosilica to the cement slurry incorporating 35% silica flour increased the apparent viscosity at a low shear rate while it decreased at the high shear rate, fluidity index was decreased with the addition of nanosilica, and the consistency index did not change significantly.

Another study by Mohammed[58] confirmed that by addition of 1% nanosilica to the cement, significant changes in the cement slurry rheological behavior was observed. The author attributed these changes to the cement minerology alterations caused by addition of the nanosilica which changed the chemical reactions and products during the cement hydration process. According to Mohammed[58] and Vipulanandan and Mohammed,[67] the rheological behavior of the cement slurry incorporating 1% nanosilica could be predicted accurately using Vipulanandan rheological model in eq 5.

$$\tau - \tau_{o2} = \frac{\gamma}{C(NS,\ T) + D(NS,\ T) \times \gamma} \tag{5}$$

where τ represents the shear stress (Pa); τ_{o2} is the yield stress (Pa); C (NS, T) (Pa s)$^{-1}$ and D (NS, T) (Pa^{-1}) denote the model parameters and γ is the shear strain rate (s^{-1}).

7.2. Cement Porosity and Permeability. Formation fluids approaching the wellbore collide with cement, and if channeling exists within the cement body, these fluids could invade the cement matrix through the percent channels and may rise to the surface. As a result, corrective cementing or remedial cementing jobs may be required to fix these channels, which will increase the cementing costs.[69,70]

Various complementary additives are used in the cementing operations to minimize the porosity and permeability of the cement matrix; this can now be done more effectively because of the advancement of nanotechnology. Nanosilica can significantly lower the porosity and permeability of the cement,[71] decreasing the probability of channel development inside the cement body and reducing the possibility of gas migration. Nanosilica interacts with calcium hydroxide crystals, reducing their size and quantity while also making the cement paste denser.[72] The spaces in the C−S−H gel structure are also filled by nanosilica gel, which functions as a nucleus for firmly bonding C−S−H gel particles.[73]

The findings of many previous studies revealed that as the amount of nanosilica in the cement slurry increased, both the porosity and permeability of the cement matrix decreased to some extent. With just 1% nanosilica added to the cement slurry, the porosity was decreased by 15% and the permeability was drastically reduced. When the addition of nanosilica ranges from 0.01% to 0.9%, the porosity and permeability of the cement matrix greatly decreased.[71]

The permeability test performed on cement samples with various nanosilica content; it was discovered that the sample with 0% nanosilica had the highest permeability and that as the percentage of nanosilica in the concrete was increased, the porosity and permeability within the cement decreased.[74]

After attaining the critical threshold, the porosity of the cement increases somewhat. According to Nazari and Riahi,[75] the pore volume of the cement matrix could be reduced as the amount of nanosilica in the cement increases until it reaches a replacement of 4% by weight of cement. Another study showed that with a relatively high nanosilica concentration of greater than 7 wt %, a higher amount of water absorption and apparent porosity were found, as well as unrestricted shrinking and weight loss of the cement matrix.[76]

7.3. Mechanical Strength of the Cement. The compressive strength of the cement is shown to rise as the weight percent of nanosilica increases. However, if the quantity of nanosilica in the cement slurry surpasses a particular threshold, the compressive strength of the cement may suffer. The increase in strength of the cement matrix due to the incorporation of nanosilica could be attributed to two factors: the filling effect of the nanosilica which densifies the cement matrix microstructure and increases its density and the activation effect of the nanosilica to accelerate the pozzolanic reactivity and lead to formation of more calcium silicate hydrates.[68,77−81] The addition of nanosilica to the cement matrix strengthens the connection between the aggregates and the cement matrix.[82,83]

This increase in density caused by incorporation of nanosilica particles can also contribute to improved resistance to fluid migration and better zonal isolation in well cementing applications. Additionally, nano silica has been found to enhance the bonding between the cement and the casing, providing a more robust and reliable wellbore construction.[77−81]

According to Ershadi et al.,[71] the compressive strength of the cement was doubled by adding 1% of nanosilica to the cement slurry; incorporation of more than 1% of nanosilica led to deterioration in the cement compressive strength, whereas for the samples with 1.5% nanosilica, the compressive strength was 7% lower than that of a slurry containing 1% nanosilica.

Nanosilica was shown to be more efficient than silica fume in enhancing compressive strength.[35,84] When 10% nanosilica was combined with dispersion agents, the mechanical strength of cured cement was increased by 26% in 28 days, compared to 15% silica fume in the same curing period.[85] Similarly, it was discovered that adding a little amount of nanosilica (0.25%) to the mix improves mechanical strength. Sobolev et al.[47] reported that a 10% improvement in compressive strength and a 25% increase in flexural strength after 28 days of curing was achieved by incorporating nanosilica into the cement matrix.

Chithra et al.[32] also investigated the influence of colloidal nanosilica with a particle size of 5−40 nm on cement strength. Portland cement was substituted with nanosilica at 0.5, 1, 1.5, 2, 2.5, and 3% by weight of cement to meet the experiment's goal, and the samples were cured for 3, 7, 28, 56, and 90 days. All nanosilica mixes were found to have better mechanical strength than the control specimen.

The relationship between the compressive strength of cement slurry and temperature was investigated, and it was discovered that the slurry's compressive strength is lower at low temperatures. This is because the heat of hydration is low at low temperatures, causing the cement to take a longer time to set and develop compressive strength. Previous studies showed that adding nanosilica to the cement slurry can effectively boost the compressive strength of the cement slurry at low temperatures.[86] Another recent study by Wang et al.[68] confirmed that the use of nanosilica with cement at high-temperature conditions of 150 °C and high pressure of 65 MPa did not lead to an increase in the cement compressive strength.

7.4. Durability of the Cement in the Acidic Environment. Lécolier et al.[87] defined "durability" as the ability of the cement sheath to maintain its initial mechanical integrity (lack of mechanical failure) and low hydraulic conductivity (no increase in porosity and/or connection over time, facilitating the transit of hostile species and/or pollutants). Chemical reactions are the most common cause of changes in the macroscopic characteristics of cement materials.[88] Chemical reactions in cementing materials, on the other hand, may be acceptable if they do not reduce the mechanical strength of the cement sheath or increase its hydraulic conductivity.

The cement matrix experiences a considerable change and deterioration in its mechanical integrity and permeability when exposed to an acidic environment because of the chemical interactions between the cement hydration products and the acidic brine.[89,90]

By measuring the rate of heat evolution, Jo et al.[84] discovered that nanoscale silica acts not only as a filler to enhance

Table 1. Summary of Some of the Previous Studies Evaluated the Incorporation of Silica Nanoparticles into the Cement Slurry

author(s)	research objective	nanosilica concentration	experimental conditions	results
Bayanak et al.[97]	evaluate the effect of nanosilica on flow characteristics of cement slurry and control of gas channeling through the cement body	0, 0.33 and 0.55% for the slurry with a density of 90 pcf and 0 and 0.11% for the slurry with a density of 118 pcf	for a free water test, the pressure is 100 psi and the atmospheric temperature	nanosilica increased the compressive strength of the cement and decreased the fluid migration through the cement
			conditions of other experiments were not specified	nanosilica affected the properties of the lightweight more than the moderate-weight cement slurry
				optimum concentration of nanosilica decreases with the increase in cement slurry density
Pikłowska et al.[98]	evaluate the effect of nanosilica on the cement's compressive strength	0, 0.5, 1, and 5%	samples were cured at 90 °C and 80% for 24 h, then placed in water at 90 °C for 7 days	samples prepared with 1.0% nanosilica showed the highest increase in strength with no significant deterioration of rheological parameters
Pang et al.[57]	use the nanosilica particles as an accelerator to reduce the cement thickening time and to improve the cement hydration process	0, 1, and 2%	atmospheric conditions for two cement slurries with densities of 16.6 and 13 ppg	cement's early hydration rate was increased with the incorporation of nanosilica
				hydration rate increases with the decrease in the nanosilica particle size
				optimum concentration of nanosilica decreases with the increase in cement slurry density
Bayanak et al.[99]	reduce the fluid migration through the cement body using nanoparticles	0, 0.1, 0.2, 0.3, and 0.5% for slurry with a density of 95 and 120 pcf	–	nanosilica does not affect the free water, fluid loss, and thickening time
				fluid migration through the cement was decreased with the addition of nanosilica
Maagi et al.[100]	evaluate the effect of nanoparticles on fluid loss	0, 1, 2, 3, and 4%	70, 80, and 90 °C and gas pressure of 1000 psi	temperature and nanosilica particle dosage considerably alter fluid loss
				optimum concentration of nanosilica to minimize the fluid loss was 3%
Choolaei et al.[86]	evaluate the effect of nanosilica on the physical properties of oil well cement	–	for the free water test, atmospheric pressure and 27 ± 1.7 °C	nanosilica increases the compressive and flexural strength of cement
				there was no free water for samples with nanosilica
			for compressive strength, a pressure of 3000 psi and temperatures of 87.77 and 104.4 °C were considered	thickening time decreased with the addition of nanosilica
Wang et al.[68]	to study the effect of nanosilica particles on cement strength retrogression at high-temperature conditions	0, 1, 2, 4, 6, 8, 10, and 12%	temperature is 150 °C and the pressure of 65 MPa	at high-temperature conditions, nanosilica cannot improve compressive strength, but it can prevent strength retrogression
				apparent viscosity increased at a low shear rate while it decreased at a high shear rate with the incorporation of nanosilica
				fluidity index decreased with the addition of nanosilica
				consistency index did not change significantly
Quercia et al.[17]	evaluate the possibility of using olivine nanosilica as accelerators	0, 0.5, 1, 1.5, 2, and 5%	temperatures of 20, 40, and 60 °C for calorimetric studies	nanosilica could work as an accelerator
				type, source, and surface area of nanosilica material control the hydration rate of cement
Liu et al.[21]	evaluate the effect of using a mixture of nanosilica with graphite oxide to improve the oil well cement properties	0, 0.25, 0.5, 1, 1.5, and 2%	30 °C with 100% relative humidity for 3, 7, and 28 days	hydration process, pozzolanic reaction, and mechanical properties of cement as well as dispersion of nanomaterials into cement were improved by considering the addition of nanosilica with graphite oxide into the cement slurry

microstructure but also as an activator to increase the pozzolanic reaction. The pozzolanic reaction which was explained earlier in eq 4 is a secondary chemical reaction between the amorphous silica particles and the portlandite component which is not stable at acidic conditions to form a more stable form of C−S−H as indicated in eq 4. This reaction could lead to the production of more stable hydration products of the cement which are important to increase the cement stability in an acidic environment.[91−93]

Nanosilica-based cement sheath usually has less calcium leaching, which is attributed to the paste's densification, the pozzolanic transformation of portlandite into C−S−H, and the modification of the internal structure of the C−S−H gel, all of which make the cement paste more stable and strongly bonded.[34]

7.5. Shrinkability of the Cement Matrix. Leakage of the gas into and through the cemented annulus in oil and gas wells can harm the environment and jeopardize well safety. A modest shrinkage of the cement slurry is thought to lessen the danger of gas migration.[94,95]

The chemical composition and dose of the ingredients of a hydrated cement slurry, as well as temperature and pressure, determine whether the slurry shrinks or expands. The volume loss caused by the interaction of cement with water in a hydrated cement is classified into two categories: exterior shrinkage and overall shrinkage. The external shrinkage of cement slurry results in a potential microannulus between the cement and the wellbore, whereas the total shrinkage represents the combined effect of the external shrinkage and the slurry's pore contraction. By boosting slurry production, a cement system's total chemical shrinkage can be minimized.[96]

Experiments confirmed that the chemical shrinkage of cement paste increases as the amount of micro- or nanoscale silica particles increases; nevertheless, nanosilica plays a more active role in early age shrinkage than silica flour which has particles with a larger size than nanosilica. A summary of some of the previous studies performed to evaluate the applicability of using silica nanoparticles is presented in Table 1.

8. OPERATIONAL CHALLENGES OF USING NANOSILICA-BASED CHEMICALS IN OIL WELL CEMENTING AND FUTURE PERSPECTIVES

One of the most difficult aspects of using nanomaterials in oil/gas well cement systems is achieving excellent particle dispersion in the slurry. Nanoparticle aggregation might lead to severe inhomogeneities in materials.[101] It is important to remember that even a well-dispersed slurry might separate under downhole circumstances, therefore, the slurry's stability under the placing situation must also be guaranteed.[69,70]

In accordance with recent studies, the cost of many nanosilica products is greater, limiting the real-field deployment of these potentially useful materials.[102] As a result, future research should focus on creating innovative processes that reduce the cost of raw materials, energy usage, and nanosilica production. Producing nanosilica at a lower cost would allow producers to offer it at a cheaper cost, allowing it to be used in more oilfield applications.

Although there exists the ability to adjust the mechanical, electrical, and chemical characteristics of cement systems, using nanoparticles, on the other hand, may be criticized because of perceived environmental, health, and safety concerns.[103] Potential hazards include respiratory issues due to inhalation of nanosized particles, skin exposure risks, and uncertainties regarding long-term health effects. Implementing comprehensive safety protocols and risk assessments is essential to mitigate these concerns and ensure the responsible use of nanomaterials in the oil and gas industry.

As a result, it is critical to establish explicit handling guidelines and/or preprepare the nanomaterial for safe on-site handling. Furthermore, the use and development of low-cost, renewable, sustainable, and biodegradable nanomaterial may become a future industry requirement to reduce environmental, health, and safety issues.

9. LESSONS LEARNED

In this paper, the studies of incorporation of the nanosilica into cement were summarized. The manufacturing process of nanosilica was reviewed, and dispersion of silica-based chemicals into the cement and hydration of the oil well cement incorporating nanosilica is presented. In addition to that, the effect of the nanosilica materials on the different properties of the oil well cement is reviewed, and the operational challenges of mixing nanosilica material with cement are presented. On the basis of the conducted review, the following points summarize what has been learned: (1) The addition of nanosilica accelerates the cement hydration rate, emphasizing its potential in enhancing early age strength development. (2) Nanosilica influences the water demand for cement functionality, leading to elevated yield point and viscosity in the cement slurry. This effect is attributed to the absorption of the part of the mixwater which was previously contributing to fluidity. (3) Ultrafine nanosilica particles fill gaps in cementitious materials, enhancing frictional resistance and densifying the microstructure, contributing to improved overall strength. (4) Nanosilica enhances compressive strength in low-temperature conditions. However, at high temperatures, it does not improve strength but effectively prevents retrogression. (5) The optimum nanosilica concentration decreases as slurry density increases. The specific type of nanosilica material significantly influences the optimal concentration in the cement mixture. (6) Because of its ability to accelerate the pozzolanic reaction, nanosilica could improve the cement resistance to the acidic environment. (7) Nanosilica plays a more active role in early age shrinkage than silica flour which has particles with a larger size than nanosilica. (8) The viscosity increase in nanosilica-incorporated cement slurry poses operational challenges, potentially rendering the slurry unpumpable. (9) Because of nanoparticle agglomeration, achieving excellent nanosilica dispersion in the cement slurry is challenging. The use of superplasticizers is recommended to increase the dispersion of the nanosilica into the cement slurry. The nanosilica-coated titanium-oxide particle exhibited excellent dispersion in water without the need for any dispersive methods. (10) The limited field application of the nanosilica is because of its high cost, therefore future research should focus on creating innovative processes that reduce the cost of raw materials.

10. RESEARCH GAP AND RECOMMENDATIONS FOR FUTURE RESEARCH

On the basis of the review conducted in this paper, there is a need of more research in certain areas in order to help on reducing the high cost of manufacturing the nanosilica and mitigating the operational challenges of mixing and pumping nanosilica-based cement, these are important to facilitate applicability of using nanosilica with oil well cement at the field scale. Therefore, the following points for future research are recommended: (1) The exploration of a friction reducer capable of reducing nanosilica-based cement slurry viscosity without necessitating an increase in water content is pivotal. This consideration is especially crucial since elevated water content can compromise the integrity of the solidified cement sheath, impacting overall performance. (2) Further research is warranted to identify optimal mixing procedures or additives that enhance the dispersion of nanosilica in water. Achieving excellent dispersion remains a persistent challenge, necessitating a more in-depth investigation into potential solutions. (3) Additionally, the cost associated with nanosilica production poses a significant obstacle to its use in oil well cementing operations. To address this challenge, it is imperative to explore alternatives such as identifying low-cost raw materials for nanosilica production or developing cost-effective manufacturing processes. Resolving the economic barriers to nanosilica application is essential for promoting its practical utilization in the oil and gas industry, warranting continued research efforts in this direction.

AUTHOR INFORMATION

Corresponding Authors

Ahmed Abdulhamid Mahmoud − *College of Petroleum Engineering and Geosciences, King Fahd University of Petroleum & Minerals, 31261 Dhahran, Saudi Arabia*; Email: ahmed.mahmoud@kfupm.edu.sa

Salaheldin Elkatatny − *College of Petroleum Engineering and Geosciences, King Fahd University of Petroleum & Minerals, 31261 Dhahran, Saudi Arabia*; orcid.org/0000-0002-7209-3715; Email: elkatatny@kfupm.edu.sa

Complete contact information is available at:
https://pubs.acs.org/10.1021/acsomega.3c07365

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