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A review on the Use of Nano Technology for Enhancing Compressive Strength of Cement in Oil and Gas Industry

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Abstract

This paper provides an extensive analysis to the current state of research on the use of Nano technology in order to improve the cement compressive strength for the well cementing applications in the oil and gas industry. By altering the microstructure and enhancing interfacial bonding between cement particles, nanoparticles have been found to enhance the cement mechanical properties. Various nanomaterials (NM), including graphene oxide, Nano-Silica, Nano-Alumina & Nano-Iron oxide, have been studied for their ability to enhance cement compressive strength.

Furthermore, this review examines the factors that influence the effectiveness of the nanomaterial in oil and gas well cementing, including size, shape, surface area, and dosage. Moreover, the effect of various sizes of the nanomaterials plays an important role in determining the enhancement extend of the cement compressive strength. This review focuses on the impact of different sizes of the nanoparticles on the cement properties including the cement compressive strength. The findings from this review can help to provide insights into the optimal size of the nanoparticles required for effective cementing job in the oil and gas wells.

Introduction

The extraction of hydrocarbons from deep wells through drilling and production has experienced a notable escalation in costs. Each facet of the drilling process is integral and incurs substantial expenses. Consequently, researchers globally are actively pursuing methodologies to diminish the expenditure associated with every drilling operation, thereby striving to optimize the overall cost of well development [1].

In the oil and gas industry, cement plays a pivotal role in the construction of wells. Ensuring appropriate cement design is paramount to safeguarding well integrity and preventing migration from the formation throughout the drilling, completion, and production phases. Furthermore, it serves to prevent the migration of undesirable formation fluids by encasing them with cemented casing. Additionally, cement is utilized in well plugging and abandonment applications, prioritizing both personnel and equipment safety while mitigating environmental impact [2]. To fulfill these objectives, cement must possess specific characteristics, including impermeability to gases and downhole fluids, resilience to mechanical loads, temperature fluctuations, and chemical degradation, thereby ensuring adequate wellbore integrity.

The failure of cement functions can result in significant consequences, encompassing production loss, environmental harm, and safety risks. Over the years, numerous issues concerning cement have been documented. For instance, sustained casing pressure has been observed in numerous wells globally, stemming from gas migration within the annulus. The root cause of this phenomenon often traces back to the gradual deterioration of cement integrity over time, attributable to subpar cementing procedures [3].

Youssef in 2021[4] discovered that over 1100 casing strings in 8000 wells in the Gulf of Mexico experienced sustained casing pressure issues in 1991. According to a report by the Mineral Management Services in 2004, it was revealed that 33% of these sustained casing pressure problems were attributed to inadequate cementing, necessitating costly remedial cement jobs totaling 650 million USD. Furthermore, it was noted that production from 9000 wells was suspended, with many temporarily abandoned due to the aforementioned problem.

Carey [5] conducted tests on the quality of cement within a well subjected to 30 years of exposure to CO_2 in the SACROC Unit, West Texas. A core sample, comprising casing, cement, and shale cap rock, was retrieved from the well. The examination revealed that the retrieved cement retained its capacity to impede significant CO_2 flow, exhibiting air permeability in the tenth of a milli-Darcy range. Nevertheless, evidence of CO_2 diffusion was observed at the interfaces between the cement and shale, as well as the casing.

He observed that a carbonate precipitate layer, ranging from 0.1 to 0.3 cm in thickness, had formed adjacent to the casing. The CO_2 responsible for this deposition may have infiltrated the casing wall or penetrated through corrosion points or threaded sections on the casing. Additionally, evidence of CO_2 diffusion was detected at the interfaces between the cement, shale, and casing.

When a well ceases to be economically viable for production, it undergoes evaluation for retirement, a process known as P&A. Failure in the execution of Plug and Abandonment (P&A) procedures could result in severe consequences, potentially leading to fatalities. Many countries have implemented stringent regulations governing well Plug and Abandonment procedures. In these applications, cement assumes a crucial role, as cement plugs are pumped and left in the wellbore for extended periods. Therefore, the design of the cement plug should ensure long-term wellbore integrity.

The Deepwater Horizon accident and the consequential oil spill in 2010 [6], the industry has undergone significant shifts in its approach to Plug and Abandonment procedures in the Gulf of Mexico in recent years. The well in question was drilled to explore the reservoir and evaluate the presence of hydrocarbons.

The well was subsequently temporarily abandoned to facilitate its utilization for production purposes. The abandonment process adhered to BP policy, employing cemented liners and mechanical plugs to establish barriers against hydrocarbon flow. Following the completion of a negative pressure test, the team inadvertently assumed the test had been successful and proceeded with displacing the mud with seawater. Regrettably, this led to an uncontrolled flow, triggering two explosions and resulting in a fire that claimed the lives of 11 workers and released 5 million barrels of oil. The primary cause of this incident was attributed to a deficient cement sheath, which facilitated gas migration to the surface.

In the wells subjected to post-plugging inspections, Herndon [7] founds evident deficiencies have been noted. Approximately 24 wells in Michigan underwent drilling subsequent to plugging operations, employing cement slurry placement via cement stringers. Out of the 49 plugs examined across 20 wells, it was revealed that eleven plugs had eroded entirely, while six were identified as soft yet containing hard cement streaks. The investigation documented that these occurrences were attributed to gas migration, which compromised the integrity of the cement plugs.

As a result of the aforementioned challenges, countries have implemented stringent regulations to ensure the security of wells throughout the drilling, production, and abandonment phases. Furthermore, researchers are actively engaged in efforts to enhance cement characteristics, aiming to address these issues effectively.

At the meanwhile, for the purpose of the cement operations, the Portland Cement is the most common used product. In order to enhance the hydraulic and mechanical properties of the cements, many additives were added for these purposed as pozzolanic materials. Additionally, a common additive for the oil well cement is the Silica fume, which is a micro sized SiO_2 that fills the spaces between the components of cement which resulted in enhancing the compressive strength of cement.

Over the years, significant research efforts have been devoted to advancing cement properties. These endeavours entail exploring the integration of new materials, alternative binders, and investigating environmentally friendly alternatives to replace conventional cement.

Zahid [8] highlighted that nanotechnology has emerged as one of the solutions to enhance cement characteristics. Nano materials, characterized by structural radii less than 100 nm, are at the forefront of this innovation. Common nano materials include nano Silica, Ferric Oxide, Aluminum Oxide, and Carbon Nano Tubes. He also noted that nanomaterials play a critical role in enhancing the compressive strength of cement through various mechanisms, which will be elaborated upon in detail in the subsequent sections.

Supplementary cementitious materials to enhance cement characteristics

The durability of oil well cement is now regarded as a crucial criterion, underscoring the significance of incorporating pozzolanic materials and supplementary or additional cementitious materials. Replacing a portion of the cement with other materials is advantageous due to the anticipated reduction in equivalent CO_2 emissions and enhancement of durability and strength in the cured cement. Both artificial and natural pozzolanic materials have demonstrated effectiveness, evidenced by their reaction speed and the quantity of liberated lime during the hydration process.

In order to create more environmentally friendly binders, Portland cement clinker is now combined with a number of other cementitious ingredients. Naturally, the local accessibility of the auxiliary ingredients affects the production of such blended cements. These blended cements can be categorised as following: binary, quaternary or ternary blinder. There are few examples for the ternary cement as Silica Fume, Slag or Fly ash.

Fly ashes are divided into two categories in North America which are class F & class C. They could be produced from coal impurities or the burnt lignite produced from the power plant. They are one of the main types of Artificial, it has a direct impact on increasing the cementation of the Portland Cement as they have a grain distribution which is quite close to the Portland Cement.

Silica fume is a densified dry powder and could be used as additive or replacement for the cement. It contains a significant quantity of silica oxide which have a spherical shape and a diameter that is 1/100 that of a cement. The cement could be replaced by 5-10 % of the weight of the cement. As a source of cement strength, silica fume is considered to be pozzolan. The compressive strength of the cement is increased as the silica fume fills the voids in the cement.

The fillers consist of pulverized substances with grain distributions similar to that of cement. They can also serve as substitutes for Portland Cement, with replacement levels of up to 15%. However, they inherently lack binding qualities or, in some cases, may exhibit extremely weak ones. A blended cement incorporating fillers performs satisfactorily in moderate climates and demonstrates compressive strength comparable to that of regular Portland Cement. Nonetheless, in maritime and Nordic regions, careful utilization of this type of cement is necessary. To enhance the strength of cement prepared with such blends in these conditions, it is preferable to reduce the water-to-cement ratio.

Chemical admixtures play a significant role in cement design and are essential for formulating cement compositions. These admixtures have the capability to enhance both the fresh and hardened properties of cement. Viscosity-modifying admixtures, for example, can alter the viscosity of fresh cement, thereby improving the efficiency of cement pumping. Retarders and accelerators, on the other hand, can modify the hydration process of cement. Additionally, admixtures like air-entrainers contribute to enhancing the durability of cement.

However, it's important to note that certain admixtures may have adverse effects on cement design. For instance, some compounds used as water reducers can retard the hydration of cement. In recent years, numerous studies have been conducted to enhance the mechanical properties of cement using various additives or modifications to cement formulations.

Costa [9] in his review investigated the carbon dioxide resistance of three different cement mixes. These mixes incorporated various combinations of dispersant, fluid loss additives, silica flour, and Class G cement. The assessment was conducted at 30, 60, and 90 curing days. Additionally, the study analysed the influence of slurry densities at 1890, 1980, and 2040 Kg/m3 on carbonation resistance under pressure of 2000 Psi and temperature of 70 degrees Celsius.

His findings indicated that samples containing silica flour, dispersant, and fluid loss additives demonstrated the highest levels of carbonation resistance across all three age categories. Furthermore, the sample comprising 20% BWOC of silica flour, 0.5 BWOC % of fluid loss additives, and 0.1 gps dispersant exhibited superior densities and carbonation resistance. Consequently, it was concluded that specimens with higher density exhibited greater resistance to carbon dioxide, albeit at the expense of increased solid content.

Wang in his study [10] introduced a novel cement formulation aimed at reducing heat release from the cement paste during the hydration process, thereby facilitating early strength development at low curing temperatures, particularly for applications in deep-water oil wells. This was accomplished through a combination of 20% ultrafine fly ash, 1% C-S-H seeds, 0.3% Polycarboxylate Superplasticizer, and 1% nano-silica. Wang observed a 28% reduction in heat release after 24 hours of hydration and a 41% increase in compressive strength compared to lightweight deep-water cement formulations.

Bjørge in 2019 [11] explored the changes in the microstructure of Class G cement and contrasted them with samples incorporating 35% BWOC silica flour. The study uncovered that the sample containing 35% BWOC silica flour exhibited increased carbonation at 110 degrees Celsius compared to conventional Class G Portland cement. This outcome was attributed to differences in the permeability characteristics of the cement.

Martín-Del-Rio in his research conducted in 2019 [12] investigated the influence of various types and sizes of fibers on the mechanical properties of Class H Cement. These included low-modulus polypropylene filament fibers with lengths ranging from 19 to 30 mm and diameters of 20-200 µm, mineral fibers, and 7 mm long polyacrylonitrile-based carbon fibers.

The findings revealed that 1-2% of carbon fibers exhibited adequate performance compared to other concentrations. Conversely, 4-7% of mineral fibers resulted in higher compressive and tensile strength. Furthermore, the combination of different types of fibers maintained an acceptable range of permeability at room temperature and pressure.

The results also demonstrated that both carbon and mineral fibers preserved compressive and tensile strength compared to regular cement mixes. However, the presence of polypropylene fibers led to a significant reduction in compressive and tensile strength by 65% and 25%, respectively.

Cheng [13] analysed in his study the impact of using different amounts of cellulose and micro-silica fume light weight cement mechanical properties “Class G cement”. The results indicated that adding cellulose fibers had an impact on the increase of the mechanical strength, however it had a negative impact on the permeability and porosity.

He also found that the use of lignin cellulose fibers led to a shorter lifespan of the cement and this is because of the degradation of fibers in high alkaline environments, which could result in cement degradation. To offset the negative effects of cellulose fibers, the author suggested the inclusion of silica fume, which can act as a filler and exhibit pozzolanic reactivity. The results showed that the mixture containing 8 % cellulose fibers and 15 % silica fume had the ability to enhance the durability and the mechanical properties of the cement.

In a study developed by Guo [14], a new type of retarder which composed of calcium aluminate phosphate cement which is considered to be the most promising system in the acidic environments in regards to the thickening time in the oil well cement. His results showed that the treated sample was effective in avoiding consistency fluctuations but exhibited weak right-angle thickening properties. However, it had a negative impact on compressive strength.

Yang [15] also attempted to mix class G cement, with additives of filtrate reducer and carbonation resistance additive, named ACA which is composed of nano silica, latex, and superfine pitch. The study aimed to find an optimized ACA content and its physical and chemical properties. The mixes were prepared with 8 % BWOC & ACA ratio from 0-5. The permeability and compressive strength were tested by SEM for 30 days exposure to CO_2 in 0.4 M NACL solution under the following conditions: P: 20 MPa & 80 degree Celsius. His results showed that the increase of ACA content, increased the cement compressive strength as it fills the voids in the cement. Moreover, the permeability decreased2 over time by increasing the ACA content over time.

Ahdyda [16] investigated in his study the effect on adding class G fly ash on the cement compressive strength and determining the optimum mix design. He added various ratios of fly ash, sodium hydroxide and sodium silicate. The results showed a decrease in the cement density as the concentration increases. Moreover, the compressive strength increased as the sodium hydroxide increased after 24 H.

Khalifeh [17] explored in his study the feasibility of developing the rock based geopolymers by using the aplite rock for the purposes of the plug and abandonment. He included in his study some materials as micro-silica, aplite, sodium hydroxide, potassium hydroxide and GGBFS. These mixes were prepared by different concentration with maximum 2 wt%.

These mixes were subjected to various tests including triaxial compression test, ultrasonic monitoring, uniaxial compression test and rheological analysis. The rheological analysis indicated that the retarder led to delay in the geopolymer setting time, however it had no impact on the geopolymer mechanical properties. All the mixes gained their strength after 7 days and reaching 3500 Psi under the following conditions: 2000 psi and 90 º C.

Saeed [18] worked to investigate the performance if the fly ash geopolymers in terms of shrinkage, strength and thickening time for the applications of the plug and abandonment with comparing these results for Class H cement under 150 º F, 200 º F for 1,2,3,6,8 and 10 days. He concluded that the Class H cement experienced reduction in size more than the tested sample.

However, to realize the full potential of Nano technology in oil and gas well cementing, a thorough understanding of the underlying mechanisms and factors affecting its effectiveness is necessary. This review provides a comprehensive analysis of the current state of research on the use of nano technology to enhance the compressive strength of cement for oil and gas well cementing applications. The review examines the different types of nano particles studied, the factors influencing their effectiveness, and the impact of varying sizes of nano particles on cement properties. The findings of this review could help to provide insights into the optimal use of nano technology for effective cementing in oil and gas wells.

Nanotechnology

Nano particles can be defined as particles that ranges from 1- 100 nm with a considerable length from 1-1000 nm and diameter from 1-100 nm. The properties of the nano materials depends on their shape and size. Most of the nano materials have high surface area and very low size. Since they have high surface area, they are highly reactive [19]

The nano materials can be prepared using chemical methods or physical methods. In the chemical methods; nanoparticles are synthesized by manipulating the morphological characteristics through modulation of chemical reaction parameters such as reaction temperature, duration, and concentrations of reactants where these methods follow the bottom up approach [19]. In the physical approach, the nano particles are produced by applying radiation energy, pressure or electrical energy to generate the nano particles. The are many physical techniques such as electro-spraying, laser pyrolysis, inert gas condensation or melt mixing .

Nanotechnology in the oil and gas industry

Nano technology gain high attention in the oil and gas industry due to the high significant role the nanotechnology has played in different industry as civil engineering sector and biomedical industry. Many researchers focused on the advantage of the nano material & their significant impact in the oil and gas industry.

A comprehensive review conducted by Akshar Thakkar [20] on the applications of nanomaterials in oil well cementing, with a specific focus on the impact of nano silica. Their study encompassed an extensive analysis of 65 references. Within their review, they highlighted the capacity of nano silica to augment the compressive strength of cement while concurrently reducing its permeability and porosity. Additionally, they elucidated the behavior of nano silica under high temperature conditions.

Their findings revealed a notable increase in thickening time of up to 178% upon lowering the temperature from 90°C to 70°C. However, they observed a further increase in thickening time with higher quantities of nano silica added. They concluded that while lower temperatures during the hydration process extend the setting time of cement, the incorporation of nano silica results in an enhancement of compressive strength, particularly at lower temperatures. Furthermore, their investigation identified an optimal concentration of 1% nano silica, outperforming concentrations of 1.5% and 7%.

In a subsequent study, a comprehensive summary of the influence of common nanoparticles on cement compressive strength, drawing from an analysis of 58 references. Their review concluded that widely utilized nanoparticles such as carbon nanotubes, nano-alumina, nano silica, and nano zinc oxide exert a positive effect on cement compressive strength. Additionally, they reported that each nanoparticle offers unique advantages. For instance, nano-silica reduces fluid loss and inhibits CO_2 propagation, carbon nanotubes enhance blast resistance, nano-clay reduces O_2 permeability, and nano-alumina demonstrates the capability to withstand temperature fluctuations. Moreover, the incorporation of nano silica was found to contribute to an increase in the compressive strength of cement.

It was discovered that cement embedded with nano-silica exhibited superior sealing properties compared to traditional cement. The authors of the review suggested that nano-silica particles ranging from 20 to 30 nm in size would yield better results in terms of compressive strength compared to sizes of 7-10 nm or 60-70 nm. Additionally, they found that under conditions of 50°C temperature and 14.7 MPa pressure, Al_2O_3 and carbon nanotubes enhanced both the compressive and tensile strength of the embedded samples.

Tabish [21], noted that the addition of nano silica enhances both compressive and tensile strength. They observed a direct correlation between the quantity of nano silica and cement compressive strength, attributing this to the accelerated hydration process facilitated by nano silica. Their review concluded that optimal replacement levels typically fall below 5%, as any amount exceeding this threshold tends to yield lower compressive strength.

The applications and mechanism of nanomaterial in cement

Nanomaterials have significantly enhancing the properties of traditional cement. The incorporation of nanomaterials such as nanosilica and nano iron oxides into cement results in improved mechanical strength, durability, and overall performance.

These nanomaterials act as additional nucleation sites, accelerating the hydration process and leading to a denser and more homogeneous cement matrix. Each nano material has its own mechanism in enhancing the cement compressive strength. This section will introduce the effect of few nano materials and their effect on the cement compressive strength. It will also include the working mechanism of these material to enhance the cement mechanical properties.

Nano Silica

Nano silica in cement can be attributed to various mechanisms. firstly, due to its nano-scale size, silica particles function as filler material and occupy gaps within the cement and leading to more compacted and denser strictures for the cement matrix [22]. Figure 1 illustrate different stages or conditions of a material to cement or composite materials. The transition from left to right could represent the process of achieving a more uniform and integrated distribution of additives, enhancing the material properties.

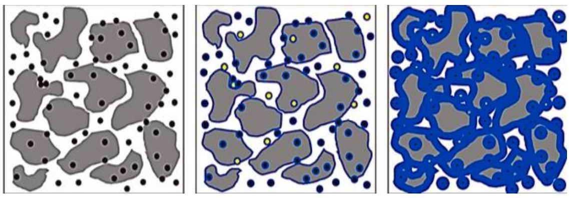

Figure 1 Mechanism of nano-silica on cement hydration process [22].

secondly, the high pozzolanic activity of nano silica materials makes them effective accelerators for cement hydration. I t was observed that blending nano silica into cement grains resulted in the formation of H_2SiO_4, which reacts with Ca2+ to produce excess calcium sulphate. Bahadori and Chithra, and [23] concluded the C-S-H is one the key elements that aid the strength in the hardened cement. Nano silica particles promotes high pozzolanic reactions that increase the consumptions of the $Ca(OH)_2$, which in turn generates additional C–S–H.

Kawshima mixed his experiment Ordinary Portland Cement with tap water and Fly ash [24]. The fly ash particles are round with size ranges of 2-20 microns. Colloidal Nano silica (CNS) were used with average particles size of 10 nm & 20 nm. Two samples were prepared with different CNS sizes (CNS-10: 10 nm, CNS20: 20 nm), different water to cement ratio (0.55, 0.5) with fly ash replacement of 40 % over different time .

He illustrates that the compressive strength of the cement sample containing CNS resulted in enhancing the early strength by 40 % and reaching 60 % enhancement after 7 days of curing. However, the compressive strength decreased after 3 month and was equal to the CNS-20 nm & CNS- 10 nm sample [24]. The findings indicated in the terms of the strength gain, the nano silica oxide did not contribute positively with the fly ash replacement applications.

Haruehansapong focused in his study [25] on the effect of the nano silica particle size on the cement compressive strength. He used various materials in his investigation, including dry silica fume, & Portland Cement Type I and nano silica with different sizes: (AEROSIL 200: 12 nm), (AERO- SIL 90: 20 nm), and (AEROSIL OX 50: 40 nm). Figure 2 represented the results of his experiment where the cement compressive strength was enhanced by 103%, 106 % by replacing the cement by 6 % and 9 respectively.

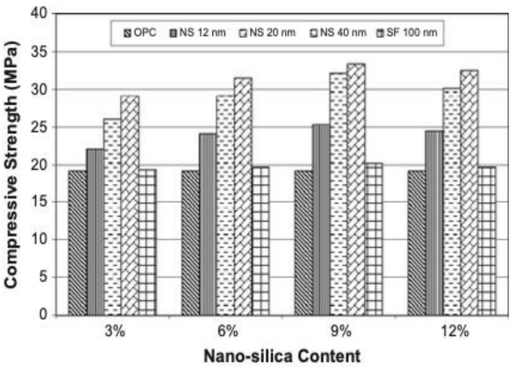

Figure 2 Effect of nano silica on cement compressive strength

Anti carried out his experiment using Colloidal Nano silica with average size of 2-100 nm and six different mixture with different amount of RFA (Rice Husk ASH) [26] , Nano silica and Superplasticizer were prepared as following:

• Sample 1: G0(90% Portland Cement + 0& nano silica, 10% Rice Husk ASH) water: blinder =0.55

• Sample 2:G1.5 (88.5% Portland Cement + 1.5% nano silica + 10% R Rice Husk ASH HA)

water : blinder = 0.55

• Sample 3: (87% Portland Cement +3 % nano silica, 10% Rice Husk ASH) water : blinder =0.55

• Sample 4: (90% Portland Cement +10% Rice Husk ASH) water : blinder =0.35

• Sample 5: (88.5% Portland Cement +1.5 nano silica, 10% Rice Husk ASH) water : blinder =0.35

• Sample 6: (87% Portland Cement +3% nano silica, 10% Rice Husk ASH) water : blinder =0.35.

He noticed that adding the nano silica to the cement paste led to increasing in the compressive strength and it was noticed that as the water to cement ratio decreased, the compressive strength increases after 28 days [27].

Zhang observed the development of compressive strength in cement mortars that incorporate different quantities of NS comparing to Portland Cement with 50 % slag [28]. It was noticed that the original sample experienced lower compressive strength after 91 days, however the compressive strength increased by adding nano silica to the cement.

Also, he in his experiment found that cement sample loaded with 2% nano silica exhibited a 39% and 30% increase in compressive strength after three and seven days, respectively. At 7 days, the cement sample with 2% NS had nearly identical strength to the Portland cement mortar, and surpassed it at 28 and 91 days, however, the nano silica had less effect on the cement after on the 1st day comparing to the slag sample [28].

Chengwen observed that the cement sample containing nano silica oxide solution was slightly lower than that of the original cement, after it was examined for 1 day at the following conditions: 150 º C , 35 MPa. He found that when the concentrations exceeded 8%, cement compressive strength remained stable [29]. To investigate the effect of nano silica oxide solution on the strength retrogression of cement stones at high temperature, the original cement stones, as well as the ones containing 2% and 100% nano silica oxide, were cured for a long period.

He observed that at 25 MPa the compressive strength of the cured cement remained unchanged after 2 days and the compressive strength decreased at 18.07 MPa after 5 days. However, after 28 days, the compressive strength of the original sample slightly drops to 9.62 MPa [30].

Other experiment was conducted by Khalo where he used his experiment Type 2 Portland cement with addition to different concentration of Nano sizes (NS200: 12nm, NS380: 7 nm). He observed that when the water-to-binder was reduced, the NS200 with 0.75% concentration resulted in better compressive strength than NS380 sample. The reason for that is the low water to blinder ratio led to a slower hydration process because less $Ca(OH)_2$ became available to react with nano silica particles [31].

Bai examined the idea of using two type nano-silica with the same size but with different specific surface area (NS-100 : 00 m2/g) and (NS-470 : 470 m2/g). The compressive strength of the cement sample imbedded with nano silica was evaluated after : 1-7-14-21-28 days. Both samples resulted in higher compressive strength when compared with the original sample For NS-100 sample, it was observed that dosage above or below 0.9 wt% resulted in lower compressive strength, however NS-470, it was observed that 0.9 wt% and higher resulted in higher compressive strength [32]

A.Abdalla included in his experiment Ordinary Portland cement type I, nano silica oxide &silica fume,, and tap water [33]. The silica had an SiO_2 content of 91.1% and an average particle size of 7.38 µm. He concluded that as the nano silica oxide concentration increased, the compressive strength of the cement increased comparing to the original sample. Nevertheless, he observed that when the nano silica concentration increased above 7 %, there was no any effect on the cement compressive strength.

It has been observed that higher amounts of nano silica oxide actually decrease the compressive strength of composites rather than improving it, because when the nano silica content increase, it became awkward to disperse the nano particles leading to creating voids leading to forming a lower strength [33]. Moreover, it was noticed that the samples containing 5%, 7% and 9 % of nano silica oxide performed better than the sample containing silica fume and this is because of the higher pozzolanic activity of the nano silica particle.

Sattwar presented in his experiment [34] the compressive of the cement molars which contains Nano-Silica with different sizes of 12, 20, 40 nm and these samples were compared with the cement molar containing silica fume. The experiment showed that the nano silica oxide had a better impact of the compressive strength of the cement sample. The results showed that the Nano-Silica improved the compressive strength of the cement molar.

The cement molars with 40 nm gave higher compressive strength in relation to the other sample. This occurred by replacement the cement with different concentrations of the nano silica (3-6,9,12) %, where the optimum concentration was 9 %. Moreover, it was observed that the increase in the nano silica size had better impact on terms of compressive strength.

Litifi focused in his research [35] the effect of nano silica oxide on the cement compressive strength. Fresh cement was mixed with sand to blinder ratio of 3:1 and water to cement ratio of 0.5. All the samples were prepared by the same ratios with addition of 3 % and 10 % of Nano SiO_2 weight of cement.

Nano Ferric Oxide

Normally and at high temperature, iron reacts with Aluminum and calcium so as to generate tricalcium and alumino ferrit leading to improvement to the hardness and strength of the cement [36]. A.Abdalla examined the addition of iron nanoparticles (Nano Fe_2O_3) in order to enhance cement mechanical properties. He used in his experiment water to cement ratio of 0.38. His study reported the compressive strength of the cement increased by 26 % after 1 day and 42 % after 28 days.

Soltanian mixed cement class E with tap water and adding nano ferric oxide (size: 20-30nm) with different concentrations: 11.81 %, 23.63 %, 35.45% BWOC. Figure 3 shows that by adding nano ferric oxide increased the compressive strength of sample 2,3,4 compared to the base cement [37] . The study showed that by increasing the concentration of nano ferric oxide resulted in the increase of the compressive strength and improvement of the cement microstructure.

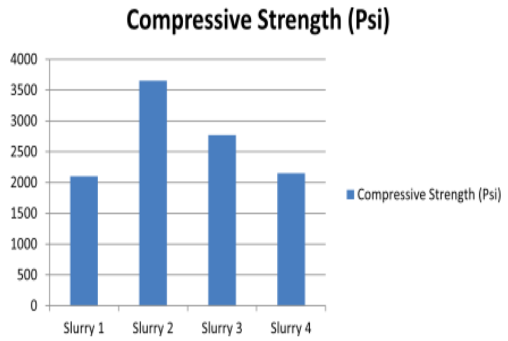

Figure 3 The compressive strength development of 4 samples [37]

Khoshakhlagh used Ordinary Portland Cement with addition to different concentration of Nano Fe_2O_3 (Size: 15nm). The mixtures were prepared using Ordinary Portland Cement but with replacement with nano ferric oxide with different concentration (1%, 2%,3%,4%,5%) and 1% polycarboxylate(water to cement ratio of 0.4%). The results showed an increase of the cement compressive strength [38].

He concluded that the addition of the nano ferric oxide (4.0 % wt replacement) has led to significant increase in the cement compressive strength followed by a slight decrease. However, 5.0% wt replacement resulted in higher increase in the cement compressive strength comparing to the original sample and N1-SCC1, N2-SCC1, N3-SCC. Adding 4 % and higher had a negative effect on the cement as the nano ferric oxide quantity is more than what is required to react during the hydration process [38].

Nazari used Ordinary Portland Cement with addition to Nano Fe_2O_3 (Size: 15nm). Compressive strength of the mixture was determined as per America Standards Explicitly State (ASTM C 39) after 7,28,90 days with water to cement ratio 0.40. The compressive strength development. The study indicates that incorporating nano- Fe_2O_3 particles in concrete results in a significantly higher compressive strength when compared to concrete without such particles [39].

Amin used in his study [39] OPC and mixed with nano-Fe_2O_3 particles (Size: 4-7 nm)prepared from ferrous and ferric solution (concentration: 0.05%, 0.10% and 0.30% by mass of cement). The cement compressive strength was evaluated after 1,3,7,14,28 and 90 days [40].

All the samples demonstrated a rise in the values compressive strength s as the age of hydration increased up to 90 days, suggesting that the hydration process was advancing. Additionally, the presence of Fe3O4 nanoparticles caused two distinct hydration periods that impacted the compressive strength variation. Within the initial 1-14-days period, a rapid rate of hydration occurred, and the inclusion of nano-Fe3O4 contributed to the increased compressive strength values [40]

Abdalla, studied the effect on nano ferric oxide on the compressive and tensile strength of the cement molar. nano ferric oxide was added to the cement past by: 1, 3 and 5 % bwoc. The results showed that samples containing 1, 3, 5% nano ferric oxide improved the cement compressive strength as it reduced the amount and size of $Ca(OH)_2$ which fill the voids and resulted in denser cement [41].

Nano Aluminum Oxide

The inclusion of Aluminum nanooxide in cement results in the filling of voids between cement grains, effectively closing capillary pores. The well-dispersed nanoparticles also accelerate the hydration of the cement slurry, leading to the formation of small crystals and homogeneous clusters in the C-S-H phase [42].

Additionally, the nanoparticles participate in or accelerate pozzolanic reactions, leading to the depletion of chemically unstable $Ca(OH)_2$ portlandite and the production of an additional amount of C-A-S-H phase [42]. Furthermore, the nanoparticles enhance the contact structure in the interface between cement grains, resulting in a stronger bond and a reduction in the occurrence of cracks.

Nano Aluminum oxide is a nano-sized material that is often employed in cement-based materials and is known to have a positive impact on the microstructure, including the pore structure and transition zone This material also increases the modulus of elasticity, improves compressive and bending strength, and enhances the resistance to high and low temperatures [43].

Vipulanandan, studied the influence of adding up to 1% of Nano AL203to smart cement with water to cement ratio of 0.38 %. The study showed that by adding 1 % of Nano AL203 the compressive strength was increased by 14 % after 1 day and 42% after 228 days [44].

Other study investigated the influence of Alumina Nanofibers (ANF) on enhancing the mechanical properties of Class H Cement. Various concentrations of ANF (0.1%, 0.2%, and 0.3% BWOC) were mixed with cement. Results indicated that the addition of ANF led to improved compressive strength, particularly with ANF-1 (0.1% bwoc) showing a significant strength gain of 25.6 MPa compared to the original composite at 17.8 MPa, representing a potential 44% increase in uniaxial compressive strength. This enhancement is crucial given the limited wait time for cement (WOC) setting. The study attributed the strength gain to hydration products formed at high temperatures, with temperature affecting the kinetics and processes of hydration [45].

Meddah used in his study Portland Cement mixed with Aluminum oxide nanoparticles (size of 70–85 nm) was used were added in various amounts as a for the purpose of partial replacement for Portland Cement, with concentration ranging from 1% to 4% with an increase of 1%. A single 10% weight amount of rice husk ash (RHA) that contains more than 86% amorphous silica was used to partially replace Portland cement. The fixed content of 10% RHA were crushed aggregates with nominal maximum sizes of 4.75 mm and 20 mm, respectively [46].

Sample CC represent Portland Cement without any additives following by other samples which contain 10 % rice hush and cement was replacement with different concentration of nano Aluminum oxide ranging from 1 % to 4 %. the cement compressive strength values constructed with a water to cement ratio of 0.41, 10% RHA, and different amounts (from 1% to 4%) of nano Aluminum oxide used to partially replace Portland cement.

Although the data indicate a modest decreases in cement compressive strength at 7 days, mixes with 10% RHA saw measurable strength gains of about 9% at 28 and 90 days compared to the control combination CC. The combination of 3 % nano Aluminum oxide sample (CRH10N3) imposes the highest compressive strength against the four samples with 35 % increase in the compressive strength comparing to the original sample.

Oltulu conducted an experimental study to investigate the individual and combined impacts of nano Aluminum oxide, nano ferric oxide, and nano silica oxide on cement mechanical properties. The findings revealed a significant enhancement in cement mechanical properties after 28 days due to the presence of these nanoparticles. Specifically, the addition of 2.5% nano silica oxide led to a notable 27% improvement in compressive strength.

Furthermore, after a 180-day period, a 1.25% inclusion of Nano- Al_2O_3 resulted in increased compressive strength. Notably, a combination of 0.5% Nano- SiO_2 and 0.5% Nano- Al_2O_3 also demonstrated promising results. These findings underscore the potential of nanoparticle additives in bolstering cement performance, thereby offering valuable insights for optimizing cement formulations for various applications [47].

Nano Graphene Oxide

The inclusion of G, particularly GO, in cement promotes the movement of ions, specifically Ca2+, leading to an improved interaction between the cement surface and the ions. This enhanced interaction fosters the nucleation and growth of C-S-H, ultimately resulting in the acceleration of cement hydration [48]

Chintalapudi examined in his research the effect on Graphene oxide on the compressive strength of the cement. He used in his study various concentrations (0.02%,0.03%,0.04%,0.05%,0.08%) with different water to cement ratio [49]. He noticed by adding 0.03% of GO, there was an increase in the tensile strength of the cement composite, however it decreased the mechanical properties when the dosage of the GO increases. By strong covalent bonds with C-S-H, the nano graphene oxide spread inside the cement matrix and operated as a bridge to promote coherence. By adding low concentrations of GO Nanosheets, you can increase strength by 20–32% and slow down the spread of microcracks.

Mokhtar used in his investigation Six mixtures of cement composites were examined in this experiment. Ordinary Portland Cement was mixed with graphene nano particles in various ratios of 0.01, 0.02, 0.03, 0.04, and 0.05 percent BWOC [50]. Also, Alkhamis studied the addition of the graphene nano particles to the enhance the oil well cement properties. The results of this study demonstrate that introducing graphene nano particles to the cement enhanced the compressive and tensile strengths by 10% and 30%, respectively [51]. The results of the XRD study demonstrated that GNPs were crucial in controlling the microstructure of the hydration products. The graphene nano particles also helped to prevent the growth of tiny fissures in the cement matrix.

Discussion and conclusion

In order to analysis the data provided in the upper section, we will focus on the key findings related to the nano particles mentioned in all the above sections especially their effect on compressive strength, the role of different variables (such as particle size, concentration, and water-to-cement ratio), and the overall trends observed across the different studies.

Bahadori and Chithra observed that nano silica led to high pozzolanic reaction and increasing of C-S-H formation. In Kawashima's Experiment he mixed OPC cement with water and 40 % replacement of fly ash. He also used 20 nm and 30 nm nano silica with different water to cement ratio and he found that the compressive strength increased to around 40 % after 7 days but the long term decreased after 3 months.

Haruehansapong in his study compared different nanao silica sizes with different concentrations when added to ordinary Portland cement. He observed increase in the compressive strength when using up to 9 % nano silica concentration and beyond this concentration, the compressive strength is found not promising. The size of 40 nm also shows the highest compressive strength comparing to the other concentrations, which indicates that the size of the nano particles has a direct effect on the compressive strength of cement.

Anti in his experiment used different concentration of nano silica with fixed 10 % of RHA. He also considered different water to cement ratio. He concluded that the compressive strength of the sample increased when reaching 3 % nano silica in both water to cement ratio concentration and the most significant improvement was observed after 7 days and continued increasing to 28 days. He also found that 0.35 water to cement ratio gives the high performance for the cement.

Bai concluded that the optimal nano silica content for both NS-100 and NS-470 appears to be 0.9%, as this content level consistently yields the highest improvement ratios across all curing periods. NS-470 outperforms NS-100 in terms of strength improvement, with significantly higher improvement ratios observed at all content levels and curing periods. This indicates that NS-470 is more effective in enhancing the compressive strength of cement. Both NS-100 and NS-470 show that 0.9% content is the most effective in improving strength. Content levels below or above 0.9% generally result in lower improvement ratios, indicating the importance of optimizing nano silica concentration.

Litifi also concluded that adding nano silica to the cement mixture significantly enhances compressive strength at all curing times. The 10% nano silica content consistently provides the highest compressive strength, indicating its effectiveness in improving cement performance. While both 3% and 10% nano silica contents improve compressive strength, the 10% content shows superior performance, especially in long-term strength (28 days). Compressive strength increases with curing time for all samples, with the most significant gains observed between 14 and 28 days. The consistent improvement indicates the beneficial role of nano silica in enhancing the hydration process and strengthening the cement matrix.

From the studies mentioned above we found that few researchers use same concentrations but reached different results especially when using two valuables in comparison. Moreover, there is no considerations form temperatures and pressure changes during performing the job or after certain time period when using nano silica. Table 1 represents a summary for the researcher’s efforts on enhancing the cement compressive strength using nano silica by using different nano silica sizes.

Most of the researchers used different concentration of nano iron and the results showed that by increasing in the compressive strength, however only one researcher found that the increase of the concentration of the nano iron led to the decrease in the compressive strength.

Table 1 Researchers efforts in Enhancing Compressive Strength Using Nano-Silica

Author	CS MPA 0%NS	CS MPA %NS	Size nm	Base mateial
Mounir	13	20	3	Portland cement
Min-hong	13	14	2	Portland cement
Shiho	13	14	2	Portland cement
Sattwat	19.16	22	3	Portland cement+ SF
Anto	67	56	3	Portland cement + 10% FA

Nano ferric oxide led to improvement in compressive strength is attributed to the reaction of nano ferric oxide with aluminum and calcium, forming tricalcium aluminoferrite, which enhances the hardness and strength of cement. Nano ferric oxide helps reduce the amount and size of calcium hydroxide ($Ca(OH)_2$), filling voids and improving the microstructure of the cement. The presence of Fe_3O_4 nanoparticles contributes to distinct hydration periods, accelerating the hydration process and leading to higher compressive strength.

A. Abdalla found that the addition of Nano Fe_2O_3 increased compressive strength by 26% after 1 day and 42% after 28 days using a water-to-cement ratio of 0.38. Soltanian's study showed increased compressive strength with concentrations of 11.81%, 23.63%, and 35.45% by weight of cement (BWOC), with higher concentrations yielding better results. Khoshakhlagh's study indicated that 4% nano ferric oxide provided a significant increase in compressive strength, but 5% replacement resulted in even higher strength, though there was a slight decrease after reaching an optimal level. Amin's study found that 0.05%, 0.10%, and 0.30% concentrations led to increased compressive strength over extended curing periods (up to 90 days). Abdalla's study also confirmed improvements in compressive strength with 1%, 3%, and 5% nano ferric oxide

The nano Al_2O_3 played an important role in enhancing the cement compressive strength even by using small concentrations. The Alumina Nanofibers enhanced the compressive strength of the sample however, it was found that by increasing the concentration of Alumina Nanofibers the compressive strength decreased but it was still greater than the basic sample.

The nano GO increased also the compressive strength over time however, by increasing the dosage, it led decrease in the cement compressive strength.

Challenges and future prospect of NMs inclusion in cementing

- Most of the researchers ignored the impact of temperature in the reduction of the compressive strength, however the temperature plays as important role. For example, Under high temperature, Nano-Silica can lead to reduction in the compressive strength in the early curing time so the cement will suffer a strength retrogression.
- The pressure effect on the cement and the change in the differential pressure needs further study.
- The combination of one or two kind of Nano Materials need more investigation.
- The effect of the nano participle on the cement investigation tool (CBL) needs more investigation.

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Conflicts of interest

There are no conflicts to declare.

Nomenclature

Abbreviations

ACA = Nano crystaline SiO_2

BWOC = By weight of cement

CS = Compressive stregnth

FA = Fly ash

GGBFS = Ground Granulated Blast Furnace Slag

NS = Nano Silica

P&A = Plug and Abandanment

RHA = Rice ash hush

SS = Sodium Silicate

SH = Sodum Hydroxide.

SF = Silica Fume

WOC = Wait on cement

References

[1] Smith, J. A. (2020). Cost Optimization in Deep Well Hydrocarbon Extraction. New York, NY: Petroleum Press.

[2] Schlumberger. (2012). The Defining Series: Well Cementing Fundamentals. Retrieved from https://www.slb.com/resource-library/article/defining-cementing.

[3] Vandenbossche, J., & Carey, B. (2014). Cement performance impacts integrity of oil and gas wells.

[4] Yousuf, N. (2021). A comprehensive review on the loss of wellbore integrity due to cement failure and available remedial methods. Journal of Petroleum Science and Engineering, 109123.

[5] Carey, J. W. (2007). Analysis and performance of oil well cement with 30 years of CO2 exposure from the SACROC Unit, West Texas, USA. International Journal of Green House Gas Control.

[6] BP. (2010). Deepwater Horizon Accident Investigation Report. BP.

[7] Herndon, J. (1976). Plugging Wells for Abandonment. Oklohoma: Union Carbide Corporation Nuclear Dicision office of waste Isolation.

[8] Zahid, N. (2022). A Review of Effect of Nano-Materials on Durability of Concrete.

[9] Costa, B. (2021). Analysis of different oil well cement slurry formulations exposed to a CO2-rich environment. Journal of CO2 Utilization , 101636, 13.

[10] Wang, D.-H. (2021). Controlling the early-age hydration heat release of cement paste for deep-water oil well cementing: A new composite designing approach. Construction and Building Materials , 122949, 9.

[11]Bjørge, R. (2019). Carbonation of silica cement of high-temperature well condition. International Journal of Greenhouse Gas Control , 261-268, 8.

[12] Martín-Del-Rio. (2019). Comparing Mechanical Behavior of API H-Class Cement Reinforced with Carbon, Mineral or Polypropylene Fiber Additions. Arabian Journal for Science and Engineering , 6119-6125.

[13] Cheng, X. (2019). A new approach to improve mechanical properties and durability of low-density oil well cement composite reinforced by cellulose fibres in microstructural scale. Construction and Building Materials 177, 499-510.

[14] Guo, S. (2017). The application of a combination of treated AMPS/IA copolymer and borax as the retarder of calcium aluminate phosphate cement. Construction and Building Materials, 142, 51-58.

[15] Yang, Y. (2016). Carbonation resistance cement for CO2 storage and injection wells. Journal of Petroleum Science and Engineering, 146, 883-889.

[16] Ahdyda, M. (2019). Fly ash Class C based Geopolymer for oil well cementing . Journal of Petroleum Science and Engineering , 179, 750-757.

[17] Khalifeh, M. (2015). Cap Rock Restoration in Plug and Abandonment Operations; Possible Utilization of Rock-based Geopolymers for Permanent Zonal Isolation and Well Plugging. International Petroleum Technology Conference.

[18] Saeed, S. (2017). Geopolymer cements: How can you plug and abandon a well with new class of cheap efficient sealing materials. Society of Petroleum Engineers - SPE Oklahoma City Oil and Gas Symposium 2017.

[19] Hornyat, M. J. (2018). Fundamentals of Nanotechnology.

[20] Jafariesfad, N. G. (2018). Cement sheath modification using nanomaterials for long-term zonal isolation of oil wells: Review.

[21]Akshar Thakkar, A. R. (2022). A comprehensive review of the application of nano-silica in oil well cementing. keaipublishing.

[22] Mohammad Tabish, M. M. (2023). Effect of nano-silica on mechanical, microstructural and durability properties of cement-based materials: A review. Journal of Building Engineering.

[23] Bhuvaneshwari. (2012). Role of nano oxide for improving cementitious building materials. Jouranl of Civil Engineering and Scienve., 52-58.

[24]Bahadori. (2012). Reduction of cement consumption by the aid of silica nanoparticles. Civ.Eng.Manag, 18, 416-425

[25] Kawshima, S. (2013). Modification of cement-based materials with nanoparticles. Cement and Concrete Composites, 36, 8-15

[26] Haruehansapong, S. (2014). Effect of the particle size of nanosilica on the compressive strength and the optimum replacement content of cement mortar containing nano-SiO2. Construction and Building Materials , 471-477.

[27] Anti, G. (2022). Mechanical properties and durability of ternary blended cement paste containing rice husk ash and nano silica. Construction and Building, 342, 127732.

[28] Zhang, M.-H. (2012). Use of nano-silica to increase early strength and reduce setting time of concretes with high volumes of slag. Cement & Concrete Composites, 650-662.

[29] Chengwen, W. (2019). Working mechanism of nano-SiO2 sol to alleviate the strength decline of oil well cement under high temperature. Natural Gas Industry, B 6 , 517-523.

[30] Khaloo, A. (2016). Influence of different types of nano-SiO2 particles on properties of high-performance concrete. Construction and Building Materials, 188-201.

[31] Bai, S. (2021). Effect of the specific surface area of nano-silica particle on the properties of cement paste. Power Technology , 392, 680-689.

[32] A.Abdalla, J. (2022). Influence of nanomaterials on the workability and compressive stregnth of cement-based concrete. Materials Today, 65, 2073-2076.

[33] Sattwar, H. (2014). The effect of particles size of nano silica on the compressive stregnth and the optimum replacement content of cement molar containing SI02. Journal of Construction and Building Materials, 50, 471-477.

[34] Litifi, M. (2011). Experimental study of the effect of addition of nano silica on the behaviour of cement mortars. Journal of Procedia Engineering , 900-905.

[35] A.Abdalla. (2015). Iron Nanoparticle Modified Smart Cement for Real Time Monitoring of Ultra Deepwater Oil Well Cementing Applications.

[36] Soltanian, H. (2015). Fe2O3 nanoparticles improve the physical properties of heavy-weight wellbore cements: A laboratory study. Journal of Natural Gas Science and Engineering, 26, 695-501.

[37] Khoshakhlagh, A. (2012). Effects of Fe2O3 Nanoparticles on Water Permeability and Strength Assessments of High Strength Self-Compacting Concrete. JMST , 28, 73-82.

[38] Nazari. (2011). Al2O3 Nanoparticles in Concrete and Different Curing Media. Energy Build, 43, 1480-1488.

[39] Amin, M. (2013). Effect of addition of nano-magnetite on the hydration characteristics of hardened Portland cement and high slag cement pastes. J Thermal Anal Calorim.

[40] Soltanian, H. (2015). Fe2O3 nanoparticles improve the physical properties of heavy-weight wellbore cements: A laboratory study. Journal of Natural Gas Science and Engineering, 26, 695-501.

[41]Amin, M. (2013). Effect of addition of nano-magnetite on the hydration characteristics of hardened Portland cement and high slag cement pastes. J Therm Anal Calorim.

[42] Nazari, A. (2010). Benefits of Fe2O3 nanoparticles in concrete mixing matrix. Journal of American Science.

[43] Li, M. (2015). Mechanical Properties of oil well cement stone reinforced with hybrid fibers of calcium carbonate whisker and carbon fibers . Petroleum Exploration and Development, 104-111, 8.

[44] Vipulanandan. (2015). ron nanoparticle modified smart cement for real time monitoring of ultra deepwater oil well cementing applications. Offshore Technology Conference, onePetro.

[45] McEkroy, P. D. (2020). Permeability and elastic properties assessment of alumina nanofiber (ANF) cementitious composites under simulated wellbore cyclic pressure. Construction and Building Materials, 239, 117867.

[46] M.S. Meddah. (2020). Mechanical and microstructural characterization of rice husk ash and Al2O3 nanoparticles modified cement concrete. Construction and Building Materials, 255.

[47] Silvestre. (2015). Nanotechnology in Cinstruction: toward Stractural Applications.

[48] Meng, S. (2021). The role of graphene/graphene oxide in cement hydration. Nanotechnology Reviews.

[49] Chintalapudi, K. (2020). An intense review on the performance of Graphene oxide and reduced Graphene Pxide in an admixed cement system. Construction and Building Materials, 259, 120598.

[50] M.N. Mokhtar. (2017). Mechanical performance, pore structure and micro-structural characteristics of graphene oxide nano platelets reinforced cement. Construction and Building Materials, 138, 222-229.

[51] Alkhamis, M. (2018). New Cement Formulations Utilizing Graphene Nano Platelets to Improve Cement Properties and Long-Term Reliability in Oil Wells. SPE Kingdon of Saudi Arabia Annual Technical Symposium and Exhibition.