Chapter 10
Nanoparticles for Drilling, Cementing, Hydraulic Fracturing, and Well Stimulation Fluids

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10.1 Introduction

The worldwide decrease in oil recovery from available resources, coupled with the increase in energy consumption, has revitalized the curiosity of the oil industry to investigate additional prospects in both conventional and unconventional hydrocarbon formations. During oil production, drilling is one of the essential stages that involves cutting a hole using a drill bit that creates a wellbore for oil and gas recovery. However, the design of the appropriate choice of drilling fluids for particular drilling requirements is an essential aspect for the attainment of drilling processes, especially in unconventional reservoirs. Drilling fluids help by cooling of the drill bit and drill pipe, preventing the formation fluids from entering the wellbore by providing a hydrostatic pressure, transporting drill cuttings to the surface from the wellbore, and suspending drill cuttings in case drilling is paused or in the event of well shutdown [1–3]. Generally, drilling fluids are categorized into three main groups, namely, water-based mud (WBM), oil-based mud (OBM), and synthetic-based mud (SBM). OBM and SBM normally offer better-operating efficiency compared to the WBM. Nevertheless, using OBM and SBM is normally not recommended due to the environmental concerns that they may create [4, 5]. Due to the severity of

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N. N. Nassar et al. (eds.), *Nanoparticles: An Emerging Technology for Oil Production and Processing Applications*, Lecture Notes in Nanoscale Science and Technology, https://doi.org/10.1007/978-3-319-12051-5_10

the wellbore condition especially the harsh reservoir conditions (high pressure and high temperature), normally the rheological properties of these drilling fluids are altered, hence decreasing their efficiency. Moreover, the conventional drilling fluids still face some critical challenges, such as water loss into fractures, drilling fluid leakage into the surrounding formation, and the decrease of fluid density and/or viscosity in the fluid circulation process. This has led to various researchers venturing into the use of different additives that can assist in improving the rheological properties and performance of these drilling fluids. Numerous investigations have been performed on different drilling types over the past years to improve their performance by altering their characteristics with the addition of various agents such as calcium carbonate, soda ashes, and more recently, nanoparticles [6, 7]. Nanoparticles have exceptional behaviors due to their diminutive size and larger surface area-to-volume ratio, hence showing more reactivity with other molecules. Nanoparticles navigate numerous industries, and their type of selection depends on the projected usage. In particular, nanoparticles are increasingly becoming popular in drilling activities, cementing, hydraulic fracturing, well stimulation, etc. [8–11]. Through manipulation of their physical and chemical properties, scientists have generated various nanomaterials with enhanced intrinsic, mechanical, magnetic, thermal, and rheological properties. The impacts of various forms of NPs positively on the characteristics of various types of drilling fluids have been reported by various investigators [12–14]. On the hand cementing is normally performed during the well completion stage where a mixture of cement is used to strengthen and/or stabilize the casing strings and also provide zone isolation between the pipe and the sedimentary formation. Cement consists of organic complex chemical compounds such as calcium silicate, aluminates, and gypsum that are normally added to water generating C-S-H gel as the major hydrate product [15]. The cementing process is essential during oil well construction as the inadequate cementing procedure can result in drastic effects, such as increased costs, well instability, and risks to the environment. During the cement formulation, cement slurry should be designed with the proper materials to resist the temperature, pressure, and depth. Therefore, there is always a gap to create high-performing slurry materials to boost and enhance cementing properties. To improve the mechanical, chemical, and physical properties of cementing slurry downhole, recently different forms of nanoparticles are added to improve its performance, and recent studies will be reviewed in this chapter. Likewise, hydraulic fracturing involves injecting sand, water, and/or other chemicals or other proppants using high pressure into a wellbore to create fractures in the formations through which petroleum and brine can freely flow. Nonetheless, developing new fracturing fluids that can sustain tremendous rheological properties especially at reservoir conditions, as well as reduce the impairment to the reservoir properties, requires more investigation. In recent years, nanotechnology is attracting attention and developing more interest in the aforementioned areas during various stages of oil production [16]. Investigations are in progress, in tackling and improving the challenges of conventional drilling, cementing, and fracking fluids during well stimulation. This chapter, therefore, will highlight some of the recent advances in using nanoparticles during drilling fluid formulation, designing improved well cementing slurries, and hydraulic fracturing and/or well stimulation fluids. Also, future research suggestions and some recommendations will be given to facilitate the evaluation of nanoparticle in the aforementioned applications.

10.2 Types of Drilling Fluids

Drilling mud, or drilling fluids, refers to a highly viscous heavy fluid blend that is employed in oil and gas drilling processes. When drilling a new well, normally a certain form of fluid is required. The key purposes of drilling fluids incorporate lifting the drilled cuttings, providing hydrostatic pressure that can prevent the entry of formation fluids into the wellbore, maintaining its stability, cooling and cleaning the drill bit during drilling, and holding the drill cuttings while drilling is inactive or stopped when the drilling unit is being removed from the hole. There are mainly three types of drilling fluids normally used in the oil and gas industry, namely, water-based muds (WBM), which is either dispersible and non-dispersible; oil-based muds (OBM) or the nonaqueous mud; and synthetic-based mud (SBM), in which a wide range of gases can be used [17]. The selection of particular drilling fluid to be used for a particular well and the additives used normally depends on the type or composition of the rock being drilled, environmental effect, and the cost implications. A standard WBM contains clay, which is typically bentonite, to provide the mud with the appropriate viscosity to transport the cutting from the wellbore to the surface. Also, it may contain minerals such as barite (barium sulfate) which is normally added to stabilize the borehole by increasing the weight of the column. These types of mud are traditionally based on water, either freshwater, distilled water, seawater, or natural occurring brines. In general, WBM are suitable for drilling conventional vertical wells at medium depths and less challenging wells, whereas oil-based muds are appropriate for deeper wells, in directional or horizontal drilling, which requires much more stress on the drilling apparatus [18]. In the shale formations, however, the WBM has some drawbacks as it causes swelling which makes its application feeble in such formations. Moreover, shale swelling can result in more severe destructive challenges such as pipe sticking, wellbore instability, and lost circulation [19, 20]. In contrast, oil-based muds (OBMs) normally require the use of petroleum-refined products such as mineral oil and diesel oil in the fluid formulation. Their limitations are mainly attributed to the environmental impacts that are not friendly to the ecosystem. On the other hand, synthetic-based mud (SBM) are prepared using refined fluid components that are made to more exacting property specifications than traditional petroleum-based oils. These types of drilling fluids were proposed due to the environmental concerns of the OBMs, even though most of the drilling muds are highly regulated in their composition, and in certain environments, some specific combinations may be prohibited from use. Nevertheless, synthetic-based drilling fluids are proven to have numerous high-tech and environmental benefits compared to the WBM and OBM and can reduce the total well costs in many cases. Figure 10.1 shows samples of drilling fluids for (a) WBM and OBM (b).

Fig. 10.1 Photographs of (**a**) water-based mud and (**b**) oil-based mud. Copyright permission was obtained from Zeal Environmental Ltd. (http://www.zealenvironmental.com/)

10.3 Application of Nanoparticles in Drilling Fluids

Selection of a proper drilling fluid depends on the type of the formation and particular drilling job to be accomplished to avoid formation damage and corrosion. To enhance the rheological and filtration properties of various drilling fluids, a variety of additives are proposed based on their mechanical, chemical, and physical properties. Normally, temperature and pressure are some of the limitations that influence the selection of conventional additives such as type, particle size, etc. As thus, nanoparticles are suggested as prospective additives that can enhance the rheological characteristics of drilling fluids [17, 21–23]. In the next section of this chapter, the applicability of nanomaterials in each type of drilling fluid will be reviewed with the existing challenges and limitations explained.

10.4 Effect of Nanoparticle Types and Concentration on the Enhancement of Drilling Fluids

Nanoparticle types and concentration play a critical role in improving the rheological properties of different types of drilling fluids. Therefore, the proper selection of nanoparticle types and optimizing their concentration is imperative. Among the commonly used nanoparticles in improving the performance of drilling fluids include clay nanoparticles, silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), copper oxide (CuO), carbon nanotubes, titanium dioxide (TiO_2), and less costly nanomaterials including calcium carbonate ($CaCO_3$) and fly ash nanoparticles, in the case of unconventional reservoirs [17, 24]. The addition of nanoparticles to drilling fluids can enhance various rheological properties such as elastic stability, plastic viscosity, mechanical filtration, gel strength, and yield point. Some of these properties in regard to drilling fluids will be explained briefly below.

(a) **Plastic Viscosity**

Plastic viscosity (PV) is a Bingham model factor that represents the mud viscosity when extended to infinite shear rate depending on the mathematical model of Bingham

[25]. Normally, for proper drilling operations, mud with relatively high PV is not easily pumped and is not preferred by operators. Nevertheless, mud should have an appropriate density to maintain the hydrostatic pressure that is directly proportional to the mud viscosity. Using mud with lower viscosity can result in the mud with a lower density and lower hydrostatic pressure that can cause blowouts during drilling operations. Therefore, for safer drilling activities, an optimum PV is desirable which can be obtained by considering the mud characteristics and the operational conditions [26]. There are various mechanisms under which nanoparticles improve these properties which depend on the mud and nanoparticle characteristics. Adding nanoparticles to the base mud can increase the friction between the two fluid layers which can result in viscosity increment. Normally, NP properties such as their geometry, heat capacity, density, etc. assist in the adjustment of the drilling fluid properties. Bentonite-WBM and the added NPS link or bond together across several chemical linkages to boost the mud PV properties [27]. This modification, however, depends on the type of nanoparticle used.

(b) **Yield point**

Yield point in drilling fluids is also a Bingham plastic parameter that refers to the stress required by the fluid to start moving. The forces of attraction between the colloidal particles in the drilling mud prevents it from moving until the required stress has been applied. Therefore, a higher yield point value is desirable for faster transportation of drilling cuttings towards the surface [28]. A high yield point is required for proper drill cutting transportation out of the well; however, it should not be too excessive to increase the pump pressure when mud starts flowing [29]. The effects of NPs on yield point of Bentonite-WBMs are shown from some studies, for example in Fig. 10.2. It can be observed that different nanomaterials have different behavior in terms of yield point modification.

(c) **Gel Strength**

Gel strength is also another important behavior of drilling fluids that refers to the measurement of electrochemical forces of attraction within the mud system under

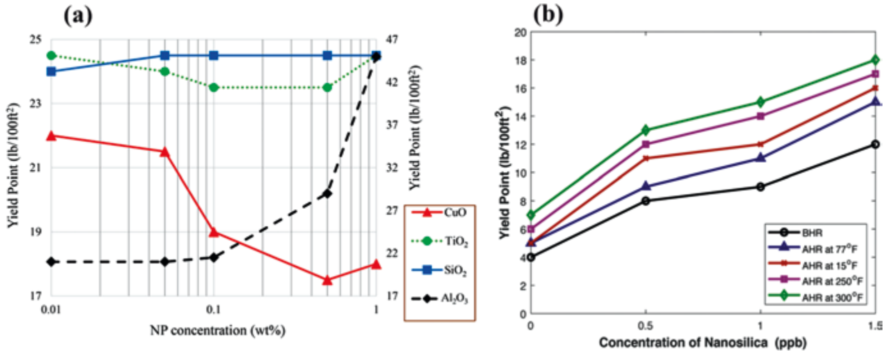

Fig. 10.2 (**a**)Yield point of NPs Bentonite WBM at different concentrations (CuO, TiO2 and SiO2 NPs Bentonite WBM from left Y-axis and Al2O3 NPs Bentonite WBM from right Y-Axis)[30] and (**b**) Yield point of 9 ppg OBM samples at different temperatures [32]. Permissions related to the material excerpted were obtained from Elsevier, and further permission should be directed to Elsevier

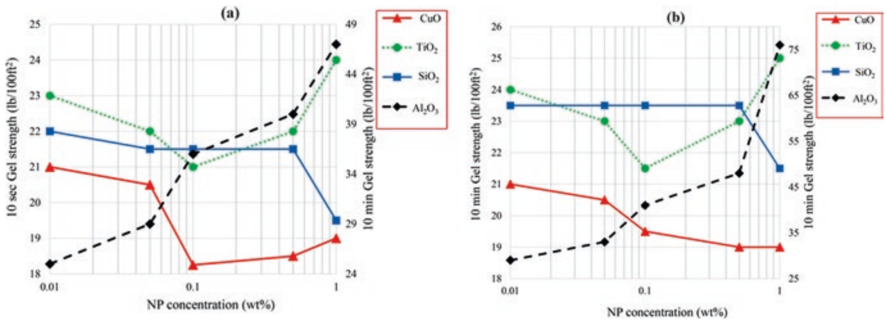

Fig. 10.3 Gel strength of WBM with different NPs quantified in: (**a**) 10 s and (**b**) 10 min [30]. Permissions related to the material excerpted were obtained from Elsevier and further permission should be directed to Elsevier

static conditions. It differs from the yield value because of its time dependence and because it breaks up once the flow is restricted. It also shows the ability of drilling fluids to suspend solids and cuttings. Normally to determine the gel strength, the shear stress is assessed at a lower shear rate after the mud has set. The API procedure for this measurement is normally performed with time frame 10 s to 10 min although measurements between 30 min to 16 h can be performed. It is important to note that a high gel strength is important to prevent several critical drilling challenges. The addition of nanoparticles can therefore improve the gel strength depending on the type, size, concentration, and the measurement time as shown in Fig. 10.3.

(d) **Filtration Loss and Filter Cake Thickness Quality**

The volume of the fluid lost and the thickness of the mud cake are the measurable parameters to quantify this test. High-volume fluid loses during drilling activities are not desirable since they may result in lower hydrostatic pressure and cause formation damage and wellbore instability [31]. Furthermore, filter cake quality assessment and stiffness must be evaluated. The filter mud cake quality is another important parameter that should be addressed during drilling activities. The quality and thickness of the mud cake represent the amount of filter loss that may occur in drilling operations. Therefore, to have proper wellbore stability and prevent fluid loss, it is always appropriate to add some additives to drilling fluids to reduce the filter loss. Adding nanoparticles, depending on the type and concentration, is one of the appropriate ways that has been evidenced to prevent fluid loss by improving the mud cake quality, as seen in Fig. 10.4.

Asaba et al. [33] investigated the impact of nanoparticle concentration and types, namely, aluminum oxide, copper oxide, and magnesium oxide, on the rheological characteristics and the filtration physical properties of WBM fluid at room temperature and higher temperature of 50°C. The authors found out that plastic viscosity of the drilling mud could be decreased by 50% when NPs were used. Also, the yield point for the mud could be enhanced by 84%, 121%, and 231% by adding 0.5%vol

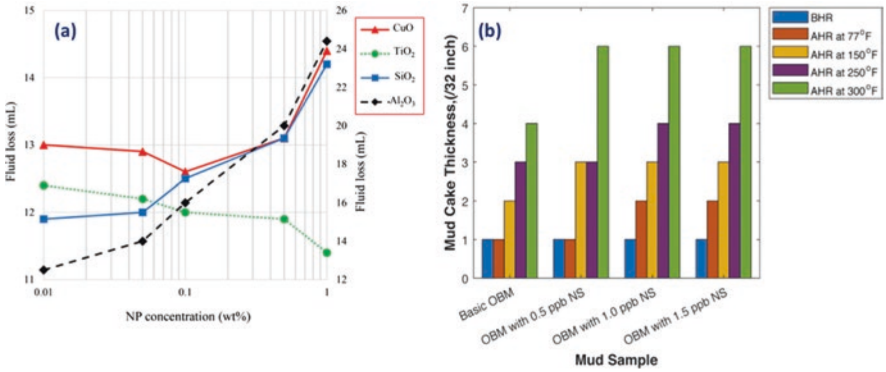

Fig. 10.4 (**a**) WBM fluid loss of different nanoparticles at different concentrations and (**b**) API mud cake thickness in the presence of nanosilica at various concentrations [30, 32]. Permissions related to the material excerpted were obtained from Elsevier, and further permission should be directed to Elsevier

copper oxide, aluminum oxide, and magnesium oxide, respectively. As well, the gel strength improved up to 95% with a fluid loss decrease of 30%. However, they noted that the filtration characteristics were negatively affected by the higher pressure and higher temperature of the formation. The authors noted that increasing the concentration of these nanoparticles had no significant effect on the WBM rheological characteristics. They concluded that the rheological properties, of WBM, can be improved with nanoparticles that can result in proper hole cleaning. In contrast, Yingpei et al. [34] noted a significant increment in the rheological properties and the plugging performance of WBM by increasing the concentration of Fe_3O_4 nanoparticles that were modified with poly(acrylic acid). From their findings, increasing the nanoparticle concentration from 0.05 up to 0.1 wt% resulted in the decrease of the consistency coefficient (K) of the Fe_3O_4/PAA nanoparticles/WBM concentration of the WBM. Using 0.1 wt% nanoparticles was found to perform best as a filtration additive in WBM. Bayat et al. [30] investigated the role of four hydrophilic nanoparticles, aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), silicon dioxide (SiO_2), and copper oxide (CuO). These NPs were added to the formulated bentonite drilling fluids at concentrations of 0.01, 0.05, 0.1, and 1 wt%. Their study showed that the Al_2O_3 NPs could enhance the mud filtration up to 80% but destroy the mud cake quality compared to the based mud. However, the amount of mud filtration had a decreasing trend when SiO_2, TiO_2, and CuO NPs were used especially with mass fractions lower than 0.5 wt%. Moreover, in comparison with the base mud, other properties such as the gel strength and rheological properties were similarly enhanced in the presence of these NPs. Generally, it was deduced that the addition of the NPS at lower concentrations less than 0.5 wt% to the WBM can enhance its rheological and filtration properties. Some of the measured properties using the different nanoparticles (SiO_2, TiO_2 and CuO NPs) are depicted in Fig. 10.5.

The rheological performance of both WBM and OBM at higher temperature was enhanced by adding different nanosilica in the range of 0.5 ppb–1.5 ppb. In their

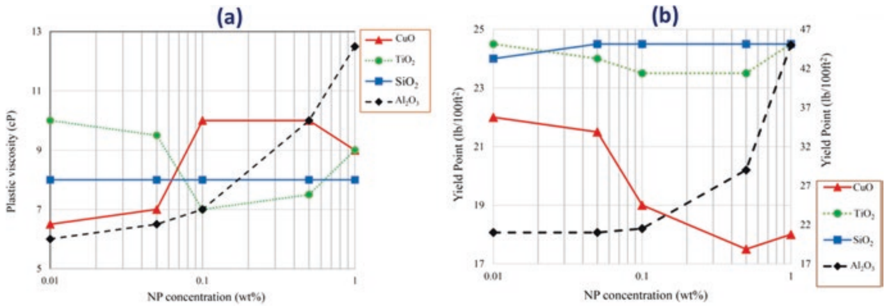

Fig. 10.5 WBM plastic viscosity (**a**) and yield point (**b**) Relative CoF reduction of OBM samples with and without nanosilica [30]. Permissions related to the material excerpted were obtained from Elsevier, and further permission should be directed to Elsevier

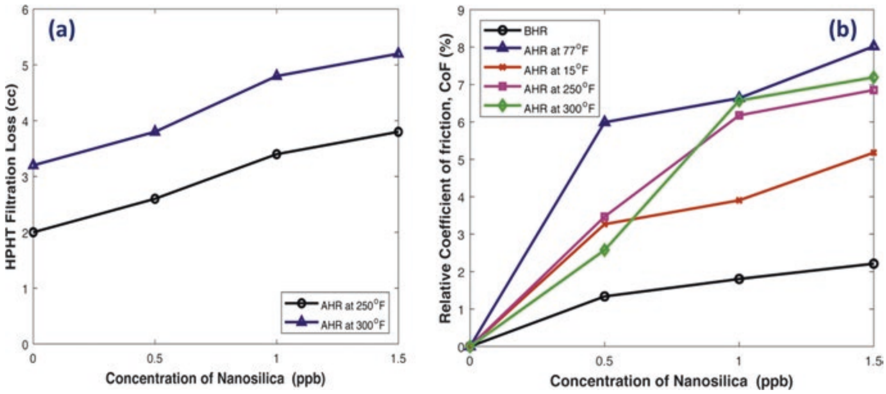

Fig. 10.6 Enhancement of filtration loss properties (**a**) and(**b**) relative coefficient of friction (CoF) reduction of OBM samples with and without nanosilica [32]. Permissions related to the material excerpted were obtained from Elsevier, and further permission should be directed to Elsevier

study, the authors measured various fluid rheological properties, including mud lubricity, electrical stability, and filtration measurements at HPHT, and later rheological models were obtained. Compared to the basic mud, it was found that adding 0.5 ppb nanosilica can improve almost all the tested properties of WBM and OBM [32]. It is always appropriate to optimize the nanoparticles because a higher concentration of nanoparticles used in drilling fluids can increase and alter the friction coefficient of the particles, changing the fluid lubricity which can impact the hole cleaning efficiency [35]. Some of the measured properties in the presence of nanosilica at different temperature are shown in Figs. 10.6, 10.7, and 10.8.

Pitchayut et al. [36] demonstrated that ZnO and copper oxide (CuO) nanoparticles at the concentration in the range of 0.1 to 1 wt% improved the rheological and thermal conductivity of a bentonite-based xanthan gum drilling fluids by up to 38% at elevated temperatures with ZnO therefore improving performance compared to CuO. This improved thermal conductivity can help the drilling fluid to cool more

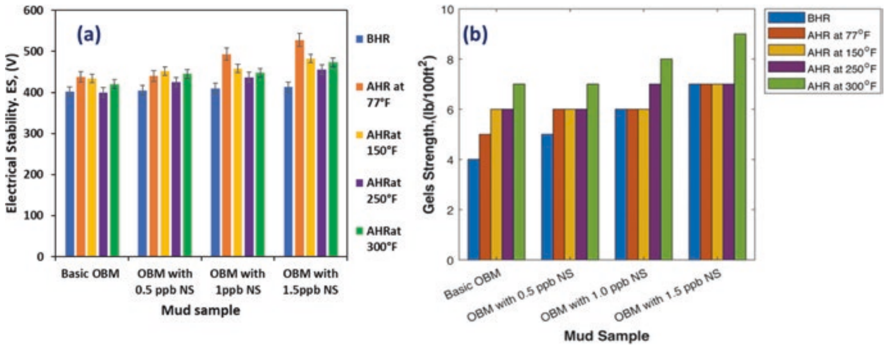

Fig. 10.7 Improving the electrical stability (**a**) and the gel strength (**b**) for oil-based mud using nanoparticles at different concentrations and different temperatures [32]. Permissions related to the material excerpted were obtained from Elsevier, and further permission should be directed to Elsevier

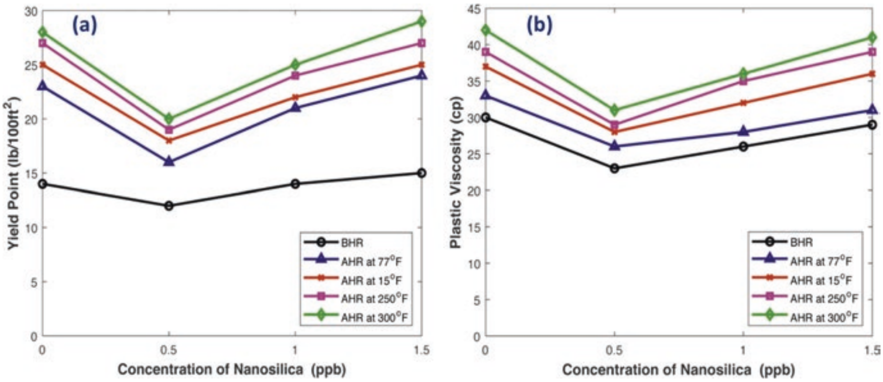

Fig. 10.8 Impact of nanosilica on yield point (**a**) and plastic viscosity (**b**) of drilling mud at different concentrations and temperatures [32]. Permissions related to the material excerpted were obtained from Elsevier, and further permission should be directed to Elsevier

rapidly as it circulates from the wellbore to the surface during the drilling operation. Still, the filtration tests conducted at a higher temperature (100°C and 500 psi) indicated a significant filtration loss reduction (30.2%) with 0.8 wt % CuO in comparison to 18.8% ZnO for the similar concentration. Moreover, there was a significant mud thickness reduction in contrast to the base fluid when these nanoparticles were used. Their findings revealed the capability of using these nanoparticles to improve the properties of WBMs and their possibility to be utilized as filtration loss additives. Another challenge of drilling fluids that have been remediated by the use of nanoparticles is sagging of drilling fluid. Sagging of drilling fluids results in density variation of the mud and, hence, wellbore instability and well control challenges. Wagle et al. [37] showed that nanoparticles can be used to prepare sag-resistant drilling fluids by stabilizing invert-emulsion drilling fluids. Their results proved that using 6–16 lbm/bbl of nanoparticles in organoclay-free invert-emulsion drilling fluid can minimize the emulsion separation and, hence, reduce sag at temperatures up to 250°F. Nanoparticles have also been utilized as additives to improve the fluid loss from drilling fluids. Vryzas et al. [38] found that using iron oxide (Fe_2O_3) NPs enhanced the fluid loss properties in WBM drilling fluids. Adding 0.5 wt% Fe_2O_3 nanoparticles, the fluid loss could be reduced by 42.5% in comparison with the base mud. Zakaria et al. [39] reported that 70% more improvement in fluid loss could be achieved when 2 wt% of NPs were added to OBM drilling fluids with the similar objective of reducing the fluid loss. Furthermore, in shale formations, wellbore stability is reduced when water from drilling fluids invades shale. In another study, there was a reduction by a factor of 5–50 for the permeability of Atoka shale formation by adding 5–22-nm silica nanoparticles, which are understood to penetrate deep into the shale and prevent water invasion; moreover, the water infiltration into the Atoka formation also decreased by 98% compared to seawater by adding nanoparticles [40]. Additional studies to summarize the role of nanoparticles for drilling fluid properties enhancement are shown in Table 10.1.

Table 10.1 Summary of some recent studies performed using different nanoparticles and different types of drilling fluids

Study properties	Mud type	Type of nanoparticle used	Deduction from the study	Reference
Filtrate volume, lubricity, yield point	WBM	Glass beads, multiwall carbon nanotube (MWCNT), silica nanoparticles	MWCNT were found to be better additives for WBM compared to silica NPs and glass beads. Filtrate volume was reduced; mud cake thickness and yield point were all improved due to the addition of MWCNT.	[41]
Mechanical filtration, fluid loss, and viscosity	WBM	Boron nitride (BN) and iron trioxide (Fe_2O_3)	Addition of 0.0095 wt% BN and Fe_2O_3 reduced the mechanical coefficient by 37%, and 43%, respectively. BN did not show any impact on filter loss. There was viscosity enhancement with both nanoparticles.	[35]
Rheological properties Electrical conductivity Thermal conductivity Shale recovery	WBM	TiO_2	TiO_2 altered the electrical and thermal conductivity of drilling fluids. TiO_2 increased the shale recovery, and thermal resistance was improved by 25% and reduced the filtration volumes up to 27%.	[42]
Plastic viscosity, yield point	WBM	ZnO, montmorillonite, and palygoskite	Addition of 50 nm resulted in more stabilized rheological mud characteristics at HPHT conditions.	[43]

(continued)

Table 10.1 (continued)

Study properties	Mud type	Type of nanoparticle used	Deduction from the study	Reference
Yield point gel strength Plastic viscosity	OBM	Silica and nanoclay	Using 2.0 wt% of nanoclay alone or mixed with 1 wt% silica nanoparticles improved the PV and the gel strength of OBM.	[29]
Plastic viscosity	OBM	SiO_2	Addition of 20 nm nanosilica at 2.0 vol% in OBM increased the PV at room conditions and maintained a stabilized rheological profile at HPHT conditions.	[44]
Yield point Gel strength Plastic viscosity	WBM	Cellulose nanoparticles	Addition of 0.5 wt% cellulose nanoparticles in WBM improved the rheological properties at a higher temperature in the range from 20 to 80°C.	[45]
Viscosity	OBM	Nanographite	Addition of nanographite within OBMs improved the fluid PV at ambient condition.	[46]
Plastic viscosity Yield point Gel strength	WBM	SiO_2	Addition of 1.0 wt% of SiO_2 to WBM at all conditions improved all the tested parameters.	[47]
Yield point Plastic viscosity	WBM	SiO_2 Fe_2O_3	Nanosilica (SiO_2) and ferric oxide (Fe_2O_3) NPs were applied in a WBM. Addition of 0.5 wt% of ferric oxide enhanced the fluid rheological characteristics, while SiO_2 at the same mass fraction showed reverse impacts on the measured rheological properties. Fluid having Fe_2O_3 NPs exhibited more stabilized properties at the measured conditions.	[48]

10.5 Application of Nanoparticles in Cementing Activities

One of the most crucial processes during well completion is cementing whose role is to provide zone seclusion between the pipe and the formation. Oil industries are venturing into materials with higher performance to reduce the costs associated with the repair and reduce losses due to cementing failure. A universal overview of the well cementing procedure is shown in Fig. 10.9. The major causes of cement failure can include cement contraction, partial cement placement, casing centralization, diversion of the cement slurry to the nearby formation, inadequate cement formation, micro-annuli in cement, mechanical or thermal stress, rusting/corrosion of the casing string, etc. As thus, similar to drilling operations, efforts are focused on developing and applying nanomaterials at the nanoscale with superior characteristics to offer ways to acquire significant variations in physical, chemical, and mechanical properties to improve numerous practical issues by enhancing

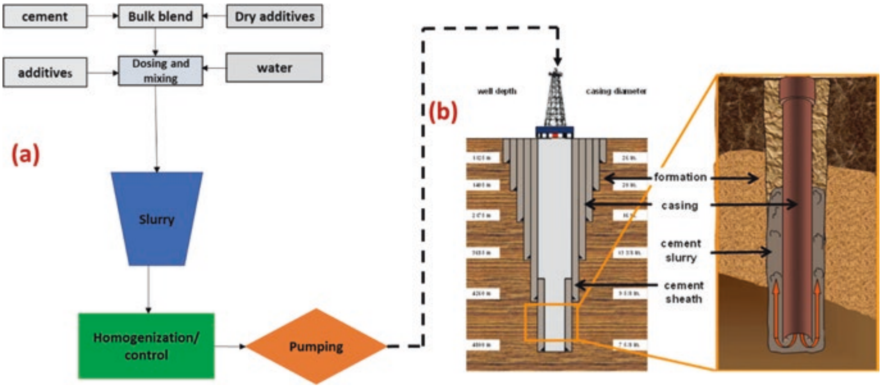

Fig. 10.9 Well cementing process, modified from [54, 55] after permission

mechanical strength and water penetration resistance; accelerating hydration reaction, controlling calcium leaching, density, setting time, heat and electrical conductivity, and filtration; providing self-cleaning properties and viscosity; and reducing the porosity and permeability; etc. Various nanoparticles [15, 49–53] have been evidenced to enhance various cement properties such as impacting toughness, improving the durability, dry shrinkage capacity enhancement and permeability resistance to water, strength, providing self-compacting, etc.

Several researchers have concluded that the addition of nanoparticles to cement can mechanically reinforce cementitious materials because nanoparticles have a high surface area-to-volume ratio that enhances the chemical reactions and are small enough that when dispersed in the slurry, they can occupy the small pores between cement grains, forming thicker concrete and reducing the porosity and permeability. Also, well-distributed nanoparticles act as crystallization centers, quickening cement hydration due to the chemical reactions generated by nanoparticles. Nanoparticles that are highly reactive speed up the pozzolanic reaction (CH + SH-C–S–H) and also react with calcium hydroxide (Ca(OH), forming an additional quantity of C–S–H gel. Similarly, nanoparticles boost the crystallization of small-sized crystals ($Ca(OH)_2$, AF silicate hydrate (C–S–H). Furthermore, adding nanoparticles results in better bonding between aggregates and the cement paste since it enhances the aggregates contact zonal structure [52].

The ability of nanoparticles to enhance the selected cement properties was studied on a laboratory scale, using a colloidal solution of silica (nano-SiO_2), alumina (nano-Al_2O_3) and ternary systems containing calcium oxide, and aluminum (CaO-SiO_2-Al_2O_3). The experiments were conducted through the incorporation of the nanosilica and ternary system in cement slurries. The results indicate the possibility of using nanosilica in cement systems, because the mechanical properties of the systems, such as compressive strength, were improved to almost 90% with concentrations of 0.5 wt% nanosilica. On the other hand, the ternary system introduced qualitative cementitious properties when reacting with water at atmospheric conditions [15]. In another study, multiwalled carbon nanotubes (MWCNTs) were found to enhance the cement properties that included toughness and durability, dry shrinkage capacity, and permeability resistance. Moreover, adding a lower concentration of

Table 10.2 A summary of nanoparticle application during cementing activities

References	Nanoparticle type	Experimental conditions	Deductions
[59]	0.5–1 wt% aluminum oxide	Ambient conditions 25°C	Improved the compressive strength Improved electrical resistivity up to 30%
[60]	Iron oxide	Temperature 25–85°C, pressure 345–465Pa	Improved the compressive strength Improved the setting properties
[61]	MWCNT	Ambient conditions	Improved the setting time
[62]	Silicon dioxide	Low-temperature 15°C and ambient pressure	Enhanced the compressive strength Accelerated the setting time
[63]	Silicon dioxide	Ambient conditions	Improved the mechanical properties
[64]	Iron oxide (0.5 wt%) Silicon dioxide (0.25 wt%)	Ambient conditions	Improved mechanical properties Improved sensing properties
[65]	Nano-synthetic graphite (0.5 wt%)	Ambient conditions	Improving the early compressive strength development
[66]	2 wt% magnesium oxide	Temperature and 40°C and ambient pressure	Improved the setting time Reduced chemical shrinkage
[67]	Aluminum oxide 1.5 wt %	Temperature and 40°F and ambient pressure	Increased tensile strength by 141% Improved mechanical properties
[68]	Graphene nanoplatelets (GNP)	Ambient conditions	Improved mechanical properties up to 30% Reduced chemical shrinkage
[69]	1–2 wt% aluminum oxide	90°C 200 MPa (30,000 psi)	Improving mechanical properties Improved rapid setting with high strength

carbon fibers and carbon nanotubes (CNT) in ultra-range of 0.025–0.05 wt% was found to enhance the electromechanical properties of cement [56, 57]. It has been evidenced that through enhancement of these cement electromechanical and physical properties, it is suitable to apply such cement to offshore oil and gas formations where the cement operations are performed in deeper water bodies. Other applications of nanoparticles in cementing operations have been extensively reported elsewhere [52, 58]. In summary, nanotechnology application for the oil and gas production mainly in upstream processes is expected to result in more advanced materials to enhance the cement properties. This can help to lower the cost and also prevent disastrous wellbore failure. The use of nanomaterials ranging from metal, metal oxides, and carbon nanomaterials can be part of the future additive formulation for cement slurries. Table 10.2 shows a summary of some other studies for enhancing cement properties with nanoparticles and the deductions from such findings.

10.6 Application of Nanoparticles in Well Stimulation and Hydraulic Fracturing

Hydraulic fracturing also known as hydrofracking is a wellbore stimulation technique that involves creating fractures in geological formations using pressurized fluids. During this process, fracking fluids, typically water containing sands and ceramic particles or other suspended proppants with the support of thickening additives, are injected using higher pressure into a wellbore, creating cracks in the deep-rock formations through which natural hydrocarbons and brine flow easily from the reservoir to the wellbore. Hydraulic fracturing stimulation is normally necessary to produce oil from tight reservoir formations with the permeability less than 1 mD; a typical hydrofracking structure is shown in Fig. 10.10.

Before pumping proppant fluids, pad fluids with no proppants are pumped to the formation to open the fractures [70]. Normally, hydrofracturing fluids are used to break down underground formations where oil and gas are trapped. Also, these fracking fluids act as carriers for proppant in the fractures. When the pressure is released, the fracture is kept open due to the pressure, and once released, the proppants are packed inside the fracs to maintain a highly conductive flow of hydrocarbons and prevent the closing of the fractures [71]. Synthetic polymers, biopolymers, foams, viscoelastic surfactant (VES) fluids, and slick water are some of the applied fracturing fluids, with each having different properties that are beneficial under certain conditions [72]. Nowadays, their preparations are well-designed, and of recent, small-sized particles may be added in the nanometer size range. Factors such as reservoir temperature, permeability, and mineralogy define the fluid selection process. For example, temperatures more than 177°C generally warrant synthetic polymers over biopolymers [16]. Water-based fluids are regularly substituted with

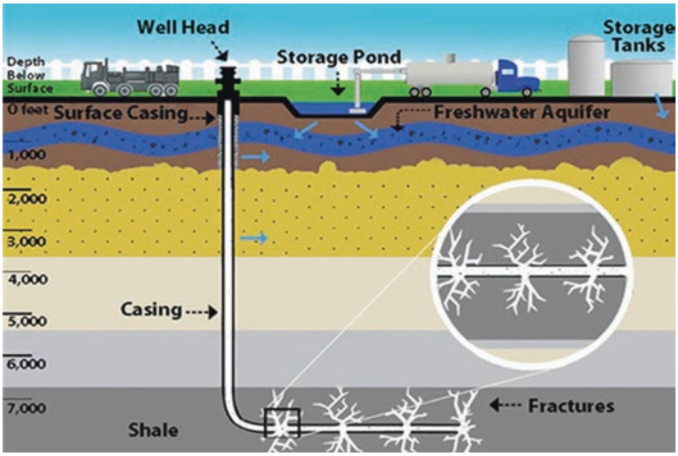

Fig. 10.10 A graphic representation of formation showing hydraulic fracturing operation for the conventional and unconventional formation. Copyright permission was obtained from Oklahoma State University Extension (https://extension.okstate.edu/)

foams, hydrocarbon-based fluids, or alcohol-based fluids in water-responsive formations. In the formations with high leak-off rates, VES-based fluids are normally applied to reduce the damage that could occur if polymer-based fluids are used [16]. Over time, hydraulic fracturing chemicals have been proposed to provide significant performance, improved cleaning of the created fractures, and good control over the hydraulic fracturing operations. Notwithstanding their ability, however, VES-based fluids were found to experience high leak-off rates in moderate-permeability reservoirs less than 200 mD. Because their viscosity at temperature higher than 104°C diminishes significantly, these types of fluids were found ineffective for formations with higher temperatures [73]. Pressure-dependency behavior of borate-crosslinked gels is another problem, where the viscosity was found to decrease significantly under high pressures. Additionally, it is difficult to formulate a fluid that can maintain the fluid viscosity for a given period in high-temperature reservoirs (>176°C). Synthetic polymers (such as acrylamide-based polymers) are frequently employed and have been reported to be used at high concentrations. The high-concentration constraints are necessitated by the need to design a stable viscosity that can withstand high-temperature conditions. Moreover, high polymer loading raises the potential of formation damage caused by the fluid residue. These challenges, which can be addressed by nanotechnology, have a major impact on hydraulic fracturing applications. Nanoparticles have addressed certain technological limitations of fracturing fluids. Low-cost tunable nanoparticles such as nanosilica, carbon nanotubes, nano-sensor, nano-proppants, and polyelectrolyte complex nanoparticles have been used as additives for fracking fluids [16]. For instance, the operating temperature threshold of VES-based fluids was enhanced by adding zinc oxide (ZnO) and magnesium oxide (MgO) nanoparticles from 93 to 121°C [73]. The borate-crosslinked gels were found to maintain their viscosity at higher pressures up to 20,000 psi when boronic acid-functionalized nanolatex silica particles were used as crosslinkers. Moreover, under these high pressures, conventional borate crosslinkers indicated more than 80% reduction in viscosity. Furthermore, the rheological properties of VES combined with polymer fluids were improved by using nanoparticles. Nanoparticles have also been used in the well stimulation of carbonate reservoirs. Nickel nanoparticles were investigated for their ability to generate carbonic acid in situ to improve the performance of hydrochloric acid (HCl)-based acidizing fluids. The nanoparticles were first dispersed in water and then dispersed to formulate the solution. After that, HCl was injected into the carbonate reservoir, generating CO_2 as a result of the HCl reacting with the carbonate reservoir. The generated gas reacted with nickel nanoparticles forming carbonic acid, which enhanced the dissolution of carbonate rocks [74, 75]. For deep sensing of petroleum reservoirs, silver nanowires and tin and bismuth nanoparticles were applied at reservoir temperature and pressure data; this probably is the first phase towards deeper reservoir sensing in the oil field [76]. According to Reza [77], silica and polyelectrolyte complex (PEC) nanoparticles can prevent fluid loss during hydraulic fracturing in low-permeability cores in the range of 10^{-5}–10^{-4} mD, 0.01–0.1 mD, and 1–40 mD. The authors found out that these nanoparticles, when mixed with 2% KCl, can significantly reduce the fluid loss volume for the cores with lower

Table 10.3 Some of the selected nanoparticles used to improve the rheological properties of hydraulic fracturing fluids

References	Nanoparticle type	Improved characteristics
[79]	Silicon dioxide	Reduced permeability damage Reduced adsorption capacity
[80]	Silicon dioxide-hydrophobic NPs (0.5–1.5 wt%)	Improved the permeability of the fractures Formation of microencapsulated acid
[81]	Magnesium oxide Zinc oxide	Improved the rheological properties of fracturing fluid
[82]	Silicon dioxide	Improved the performance of CO_2 foam as hydrofracking fluid at 121°C

permeabilities below 0.1 mD. It was later evidenced that PEC nanoparticles could reduce the fluid loss to zero when utilized with 2% KCl on tight cores, whereas silica nanoparticles revealed slight fluid loss volumes. Generally, both nanoparticle solutions indicated a significant fluid loss control capacity when low permeability and tight cores were used. Furthermore, fluid loss control capability coupled with nanoparticles of specific characteristics of the nanoparticles improved the fracture conductivity by reducing the fluid loss volume caused through formation of thinner filter cakes on the rock surface. This is ascribed to the formation of 3-D network super-micellar structures which supported the development of a low-permeability continuous and integrated reinforced filter cake that obstructed fluid flow [78]. This resulted in the formation of clear fractures with higher fracture conductivity that could produce higher hydrocarbon volumes (Table 10.3).

10.7 Field Applications of Nanoparticles in Drilling, Cementing, and Hydraulic Fracking

Based on the reviewed studies, no major field trials have been reported for nanoparticle application for drilling, cementing, or hydraulic fracturing. Most of the reported studies show nanoparticle applications in these operations at laboratory and development scales. However, some commercial products available from nanomaterials for hydraulic fracturing application were discussed elsewhere [83], as shown in Table 10.4.

10.8 Conclusion

This book chapter focused on highlighting the application of nanoparticles in the areas such as drilling fluids, cementing, hydraulic fracturing, and/or well stimulation. Based on the published literature, nanoparticles are showing promising results based on their performance and efficiency. The obtained findings can be ascribed to

Table 10.4 Commercial products designed from nanomaterials and the reported field applications

Materials	Type of applications	Commercialization	Field	Applications	Reference
OIL perm TM FMMs	Fluid mobility modifier (FMMs)	Halliburton incorporated	Wood ford shale play in Oklahoma	Oil production increased after 30 days for treatment	[83]
Controlled electrolytic metallics (CEM) material(IN-Tallic disintegrating frac balls)	Downhole completion tools	Baker Hughes Incorporated	USA tight formations (Bakken, Niobrara, Marcellus, Utica, Haynesville, Granite Wash, Woodford, Wolfberry, Bone Springs, and Eagle Ford)	Ball-activated sleeve system for multi-stage fracturing of shale gas reservoirs.	[83]
ConFINE fixing agent	Formation fines control additives and clay stabilizers	Baker Hughes Incorporated	The deep-water Gulf of Mexico	For controlling sand and fine migration	[83]
Nano-proppants FracBlack HT™	Nano-proppants	Sun Drilling Technologies	China, South America, and Europe	Applied in traditional and coal bed methane projects (China) Applied as gravel pack material (South America) Applied for recovery of hydrocarbons in both shale and coal bed methane projects (Europe)	[83]

the idiosyncratic properties of nanoparticles. Despite their higher potential, nanoparticles still have challenges such as scale-up for field application due to their economics feasibility and the HSE aspects. This chapter further confirms a number of points. Silica-based nanoparticles continue to be the most investigated nanoparticles used in the improvement of different applications in the oil and gas industry, specifically for the reviewed segments. Generally, most of the nanoparticles that have been used previously depending on their concentrations, sizes and types, for the various applications, have improved the rheological, filtration and mechanical, thermal stability properties for drilling, cement, and hydraulic fracturing fluids. Specifically, for cementing, the setting time and the mechanical properties were significantly improved using different nanoparticles. Improving the fluid properties may depend on the size, nanoparticle type, shape, nanoparticle concentration, and the operating pressure and temperature of the reservoir. For hydraulic fracturing/ well stimulation, given their small particle size and surface area-to-volume ratio, higher hardness and elasticity, and high closure stress resistance, nanoparticles such as fly ash, nanosilica, and carbon nanotubes have been successfully used as effective nano-proppants and have been used to enhance the fracture conductivity and oil recovery. Lastly, it is paramount to investigate the impact of various factors such as nanoparticle type, nanoparticle surface wettability, size reservoir pH properties, salinity on stability, and agglomeration at downhole conditions for better optimization and improved effectiveness.

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