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EFFECT OF BISMUTH FERRITE ($BiFeO_3$) NANOPARTICLES ON RHEOLOGICAL AND MECHANICAL PROPERTIES OF CLASS G OIL WELL CEMENT

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Abstract

Oil well cement plays an important role in drilling operations. Oil well cement restricts fluid movement between the formation and supports the casing. To understand the behavior of cement slurry, we must analyze the rheological and mechanical properties of that slurry. This study investigates the effect of bismuth ferrite ($BiFeO_3$) nanoparticles in API Class G oil well cement (OWC). In this experiment, nanoparticles of $BiFeO_3$ are made in the laboratory using the solution evaporation method (SEM). NPs are dosed at different concentrations of 0.05, 0.1, 0.2 and 0.3% by weight of cement (BWOC) in the laboratory-prepared cement slurries. For all cement slurries, the water-cement (w/c) ratio was maintained at 0.44. The experimental work encompassed the synthesis and characterization of bismuth ferrite NPs, evaluating slurry density, specific gravity, apparent viscosity, plastic viscosity, and yield point. The result of this study reveals that 0.05, 0.2, and 0.3% BWOC concentrations of nanoparticles decreased the plastic viscosity by a maximum of 42%. Apparent viscosity of cement slurries was increased for all concentrations of nanoparticles except 0.3% BWOC and a maximum increment of 5.54% for the 0.2% BWOC. This experiment also provides an increment for the yield point of cement slurries. The yield point was increased by 6.1%, 18.5% and 23.47% compared with the base cement slurry at 0.05, 0.2 and 0.3% BWOC concentrations of nanoparticles respectively. In this study, the density and specific gravity of cement slurry dropped slightly by 4.9% and 2.08% respectively. In the compressive strength test, this NPs showed a great result and there was an increment in compressive strength for all concentrations of nanoparticles. A maximum increment of 80% was obtained at 0.3% BWOC concentration of NPs. This indicates that $BiFeO_3$ nanoparticles can be used as a potential additive in Class G oil well cement (OWC) to enhance its rheological and mechanical properties. However, further tests should be conducted to ascertain its stability under High pressure, High Temperature (HPHT) conditions.

Keywords: Nanoparticles (NPs), Oil well cement (OWC), Rheology, Compressive Strength, XRD.

1. Introduction

The exploration and production of hydrocarbon resources in the oil and gas industry are highly dependent on cementing operations. Cement plays a crucial role in providing well integrity, zonal isolation, and long-term stability for oil and gas wells. However, harsh downhole conditions, such as high pressures, temperatures, and corrosive fluids, pose significant challenges to the performance and durability of cement sheaths [1]. For addressing these challenges, researchers and engineers have been actively seeking innovative approaches to improve the properties and functionality of oil well cement. One promising avenue is the incorporation of nanomaterials into cement matrices, enabling the development of nano-enhanced cement with superior mechanical, thermal, and chemical properties. Among the various nanomaterials, $BiFeO_3$ nanoparticles (NPs) have emerged as a particularly compelling candidate due to their unique physical and chemical characteristics. $BiFeO_3$, a multiferroic compound, possesses remarkable ferroelectric, ferromagnetic, and piezoelectric properties [2]. These properties make it an intriguing candidate for applications in energy, electronics, and catalysis.

API Class G oil well cement, commonly used in oil and gas industry operations, faces numerous challenges related to its mechanical strength, resistance to high temperatures, and chemical stability in corrosive environments. These challenges have motivated the exploration of alternative materials and approaches to improve the properties of Class G oil well cement. $BiFeO_3$ NPs, with their unique properties, offer a novel pathway to address these issues. It is important to note that the development and application of nanoparticle-based oil well cement are still areas of active research and development. The selection and incorporation of nanoparticles must be carefully evaluated to ensure compatibility, performance,

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and long-term stability. Proper testing and validation are necessary to assess the effectiveness and safety of nanoparticle-based oil well cement in real-world well conditions.

This study aims to investigate the effects of $BiFeO_3$ NPs on the rheological and mechanical properties of Class G oil well cement through a comprehensive experimental study, by using the solution evaporation method to synthesize $BiFeO_3$ NPs and the influence of varying nanoparticle concentrations on the cement properties. The results of this study will contribute to the understanding of the potential of $BiFeO_3$ nanoparticles as an additive for improving the properties of Class G oil well cement. The findings will also provide insight into the mechanism of improvement in properties, which can aid in the development of more efficient and effective cementing materials for the oil and gas industry.

2. Materials

Class G Oil well cement, Iron (III) nitrate nonahydrate ($Fe(NO_3)_3·9H_2O$), Tartaric acid ($C_4H_6O_6$), Nitric acid (HNO_3), Distilled water, Bismuth (III) nitrate pentahydrate ($Bi(NO_3)_3·5H_2O$).

3. Experimental Method

3.1 Synthesis of $BiFeO_3$ NPs

In this research study, the synthesis of bismuth ferrite ($BiFeO_3$) nanoparticles was carried out using the solution evaporation method (SEM) as described by [3]. The methodology involved the precise preparation of a transparent solution by combining equimolar concentrations (0.1M) of iron nitrate nonahydrate ($Fe(NO_3)_3.9H_2O$), 2.43 grams of bismuth nitrate pentahydrate ($Bi(NO_3)_3.5H_2O$), and 0.3M tartaric acid ($C_4H_6O_6$) with (65%) diluted 2N nitric acid (HNO_3). The resulting mixture was subjected to controlled heating on a magnetic hot plate stirrer at a temperature of 105°C while maintaining constant stirring at a speed between 1000 revolution per minute (rpm) and 1200 rpm for 2 hours. This heating and stirring process facilitated the evaporation of the entire liquid from the beaker, resulting in the formation of a light green powder. To obtain a fine powder, the synthesized powder was further processed by subjecting it to a temperature of 550°C for 2 hours in a muffle furnace. This thermal treatment transformed the powder into a fine, well-defined form, suitable for subsequent characterization and analysis. By employing this systematic and controlled synthesis methodology, the study successfully obtained bismuth ferrite nanoparticles and characterized their crystal structure and size using X-ray diffraction (XRD) analysis.

3.2 Design of cement slurry

In this study, the preparation of the base cement slurry and the introduction of $BiFeO_3$ nanoparticles were conducted according to [4]. For the base cement slurry, 500 grams of Class G oil well cement was mixed with 220 millilitres of distilled water, resulting in a water-to-cement ratio of 0.44. The mixing process was carried out using a Hamilton Beach mixer at 13,000 rpm for 10 minutes. To create cement slurries with incorporated nanoparticles, varying weights of $BiFeO_3$ nanoparticles (0.05%, 0.1%, 0.2% and 0.3% BWOC) were added to the mixture after 5 minutes of initial mixing. The nanoparticle addition was followed by an additional 5 minutes of mixing. This step allowed for the dispersion and homogenization of the nanoparticles within the cement.

3.3 Rheology Tests

Rheological properties of the cement slurry were measured using a 6-speed rotational viscometer or as known as rheometer. The slurry was poured into the rheometer cup and the cup was placed on the rheometer stage. To determine the plastic viscosity, apparent viscosity and yield point of the cement slurry, the API recommended Practice 10B-2 [4] was followed at room temperature. A rheometer was utilized, and the spindle was programmed to rotate at different speeds, ranging from 3 rpm to 600 rpm. To determine the density and specific gravity of the cement slurry, the mud balance apparatus was suspended from a balance hook, ensuring its stability and accuracy [4]. A representative sample of the cement slurry was then carefully poured into the cup of the mud balance until it reached the brim. Any excess slurry was meticulously removed using a straight edge to achieve a level surface. The weight of the cement slurry in the air was accurately recorded using the mud balance.

3.4 Compressive Strength Test

The compressive strength of Class G cement was measured using standardized destructive testing procedures [5]. Cylindrical specimens with a diameter of 1.5 inches and a height of 1.5 inches, were prepared from cement slurry (Figure:1).

Figure:1 Cylindrical specimens of Class G oil well cement

The specimens were carefully cast and compacted to ensure uniformity and minimize voids. Then the specimens were subjected to a compressive force using a mechanical or hydraulic testing machine. The compressive strength test involved gradually increasing the applied load until failure occurred. Multiple specimens were tested to ensure statistical validity, and the average compressive strength value was reported as the representative value for the cement.

4. Results and discussion

4.1 Characterization of $BiFeO_3$ Nanoparticles

The crystal structure and size of the synthesized Bismuth Ferrite (α-$BiFeO_3$) nanoparticles were investigated through XRD analysis. The XRD pattern displayed in Figure:2 represents the distinct diffraction peaks corresponding to the synthesized $BiFeO_3$ nanoparticles. The characteristic peaks observed at specific 2θ values, approximately 22.22°, 31.58°, 39.09°, 45.35°, 50.83°, 51.30°, 55.94°, 56.59°, 56.61°, 66.5°, 70.71°, and 75.40°, correspond to the crystallographic planes 82.6, 100, 29.5, 40, 29, 14.8, 14, 19.1, 33.2, 11, 7.8, and 9.8, respectively.

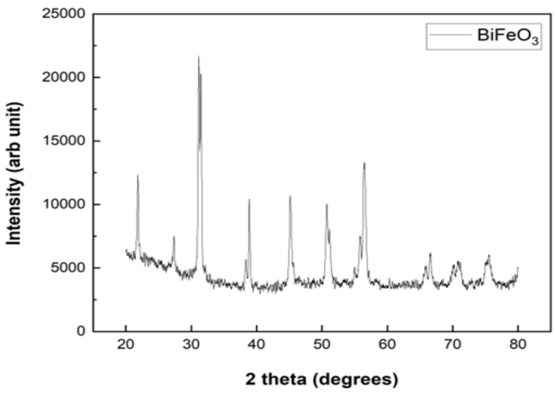

Figure:2 XRD pattern of synthesized $BiFeO_3$ nanoparticles

The sharp and narrow peaks observed in the XRD pattern indicate the highly crystalline nature of the synthesized $BiFeO_3$ nanoparticles. This suggests the achievement of high purity in the synthesized nanoparticles using the employed synthesis method. The presence of well-defined diffraction peaks at the expected positions confirms the formation of the desired α-$BiFeO_3$ crystal structure.

4.2 Effect of $BiFeO_3$ Nanoparticles on Plastic Viscosity of cement slurries

The plastic viscosity of an oil well cement slurry is a measure of its resistance to flow under shear stress. It directly affects the slurry's ability to achieve good displacement and fill the wellbore effectively. The graphical representation of plastic viscosity (cP) vs. $BiFeO_3$ NPs concentration (%BWOC) is shown in Figure:3. For base cement slurry it was found 23 cp as plastic viscosity. Here plastic viscosity was reduced by 6.55%, 11.6%, and 42% at 0.05, 0.2, and 0.3 %BWOC of $BiFeO_3$ NPs concentration respectively.

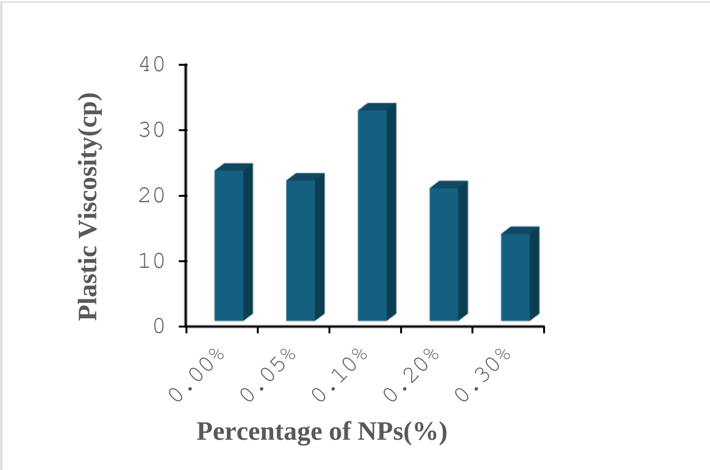

Figure:3 Effect of concentration of $BiFeO_3$ NPs on plastic viscosity of Class G oil well cement slurries.

This indicates that nanoparticles improved the dispersion of cement particles within the slurry. In this study, the increment of plastic viscosity is found at 0.1% BWOC of $BiFeO_3$ NPs concentration by 39.9% compared with the base slurry.

4.3 Effect of $BiFeO_3$ Nanoparticles on Apparent Viscosity of cement slurries

In this study, apparent viscosity was measured with different $BiFeO_3$ NPs concentrations. The graphical representation of apparent viscosity (cP) vs. $BiFeO_3$ NPs concentration (%) BWOC is shown in Figure:4. The apparent viscosity of base cement slurry was about 59.139 cp. The apparent viscosity of cement slurries slightly increased with the addition of bismuth ferrite NPs except for 0.3% BWOC concentration. In 0.3%, apparent viscosity reduced 3.3%. Here, the maximum 5.54% rise of apparent viscosity is found at 0.2% BWOC of $BiFeO_3$ NPs concentration compared with the base cement slurry.

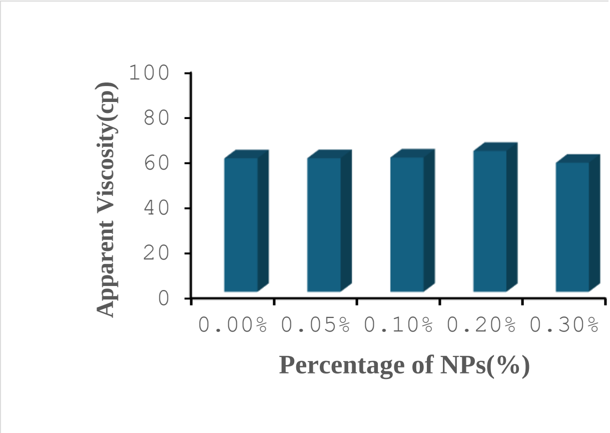

Figure:4 Effect of concentration of $BiFeO_3$ NPs on the apparent viscosity of Class G oil well cement slurries.

4.4 Effect of $BiFeO_3$ Nanoparticles on Yield Point of cement slurries

The yield point is a measure of the minimum shear stress required to initiate flow. It represents the point at which the slurry transitions from a static, solid-like state to a flowing, liquid-like state. The yield point of an oil well cement slurry is significant as it influences pumpability, displacement efficiency, suspension of solid particles, stability, and thixotropic behaviour. Figure:4 shows that increasing NPs concentration can enhance the yield point of oil well cement. It happened because nanoparticles are surface-modified or functionalized to improve their compatibility with the cement matrix. The maximum increment of yield point is 23.5% at 0.3% BWOC of $BiFeO_3$ NPs concentration compared with the base cement slurry. But at the concentration of 0.1% BWOC yield point was reduced by 23% (Figure:5). As most of the concentrations provide the increment of yield point, so we can consider this NPs as a potential additive to enhance the yield point of oil well cement slurry.

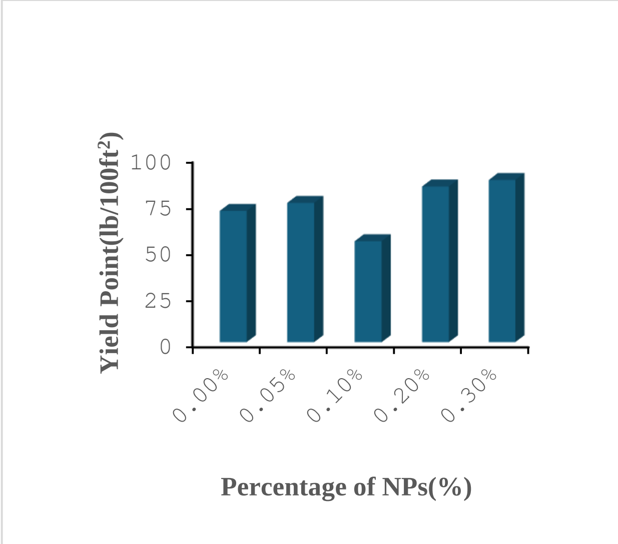

Figure:5 Effect of concentration of $BiFeO_3$ NPs on the yield point of Class G oil well cement slurries.

4.5 Effect of $BiFeO_3$ Nanoparticles on Cement Slurry Density and Specific Gravity

It is observed that density and specific gravity decreased after adding nanoparticles in this study. The base cement slurry had a density of 16.3 lb/gal and specific gravity was 1.92 gm/cm3. The value of specific gravity fluctuated between 1.88 gm/cm3 to 1.89 gm/cm3 after adding nanoparticles into the cement slurry (Figure:6) and the density value oscillated between 15.8 lb/gal to 15.85lb/gal (Figure:7). But as the reduction of both properties is very slight, it will not affect the overall cementing process [6].

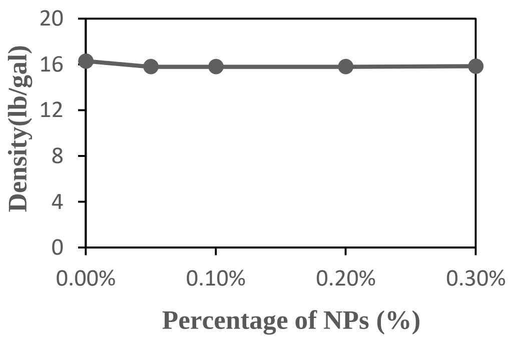

Figure:6 Effect of concentration of $BiFeO_3$ NPs on the yield point of Class G oil well cement slurries.

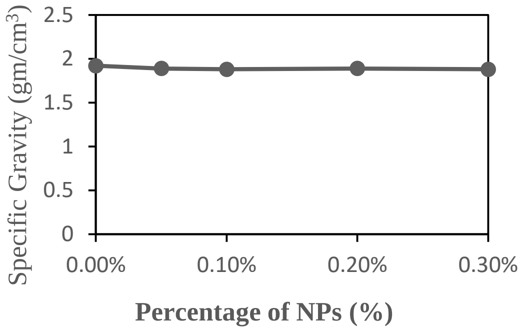

Figure:7 Effect of concentration of $BiFeO_3$ NPs on the yield point of Class G oil well cement slurries.

4.6 Effect of $BiFeO_3$ Nanoparticles on Compressive Strength of cement slurries

In our study, it is observed that an increment in compressive strength after adding NPs in different concentrations to the cement slurry. Figure:8 shows the graphical representation of the increased percentage of compressive strength (%) vs. percentage of NPs (%). We got a maximum 80% increment in compressive strength compared with base slurry after adding 0.3% BWOC concentration of NPs. The numerical value of highest compressive strength was 10.525 MPa or 1526.52 psi which meets the demand. For other concentrations increment in compressive strength was 25%, 40%, 75% after adding 0.05, 0.1, 0.2 % BWOC concentration of NPs respectively. So, we can conclude that this bismuth ferrite ($BiFeO_3$) NPs have the potential to be used as an additive to increase the compressive strength of oil well cement.

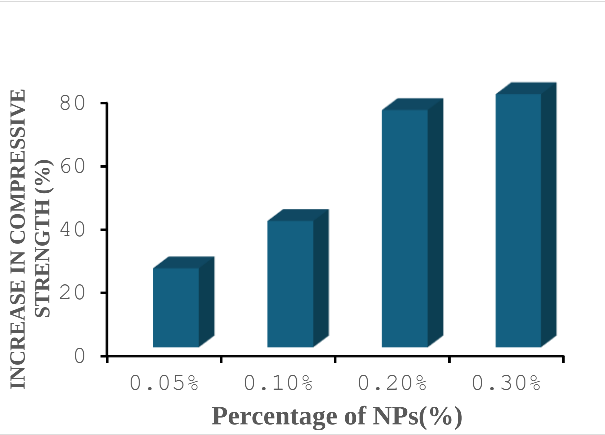

Figure:8 Effect of concentration of $BiFeO_3$ NPs on Compressive Strength of Class G cement slurries

5. Conclusion

In general, the addition of nanoparticles increases the apparent viscosity of cement slurry. For NPs concentrations of 0.05% BWOC, 0.1% BWOC, 0.2% BWOC apparent viscosity increased by 0.048%, 0.61% and 5.54% respectively compared to base cement slurry. The only exception is 0.3% BWOC concentration where apparent viscosity got 3.34% reduction. For NPs concentrations of 0.05% BWOC, 0.2% BWOC, and 0.3% BWOC plastic viscosity decreased by 6.55%, 11.6%, and 42% respectively compared to base cement slurry whereas, NPs concentrations of 0.1% BWOC increased plastic viscosity by 39.9%. Yield stress of cement slurry got increment after the addition of NPs except for the concentration of 0.1% BWOC, where yield stress decreased by 23% compared to base cement slurry. We got the highest increment of yield stress for NPs concentration of 0.3% BWOC and it was 23.47% from the base slurry. In case of density and specific gravity, it has decreased after the addition of nanoparticles for all concentrations compared to base cement slurry.

$BiFeO_3$ nanoparticles are great for increasing the compressive strength of class G oil well cement slurry. Compressive strength increased to a maximum of 80% at 0.3% BWOC concentration of NPs. Besides that, we got 25%, 40% and 75% increments for the 0.05, 0.1 and 0.2% BWOC concentrations of nanoparticles respectively. The experimental results confirmed that the bismuth ferrite nanoparticles can also be used as a potential additive in Class G oil well cement to reduce viscosity and to increase yield stress, and compressive strength which in turn increases the productivity index and save drilling time and cost, but the concentration of NPs must be monitored properly to get the best output.

6. Outcomes

The experimental results confirmed that the bismuth ferrite nanoparticles can also be used as a potential additive in Class G oil well cement to reduce viscosity, increase yield stress, and compressive strength which in turn increases the productivity index and save drilling time and cost, but the concentration of NPs must be monitored properly to get the best output.

7. Limitations

The utilization of bismuth ferrite ($BiFeO_3$) nanoparticles in Class G oil well cement presents certain limitations. Achieving homogeneous dispersion and compatibility of the nanoparticles within the cement matrix can be challenging, as they may tend to agglomerate or settle, leading to uneven distribution and compromised effectiveness. Moreover, the stability of $BiFeO_3$ nanoparticles in extreme downhole conditions, characterized by high temperatures, pressures, and corrosive environments, remains a concern. Interaction between the nanoparticles and the various additives commonly used in oil well cement formulations can further complicate their performance. Additionally, the cost and availability of $BiFeO_3$ nanoparticles at the required scale for industrial applications may pose practical constraints. Furthermore, the long-term performance and durability of $BiFeO_3$ nanoparticles in oil well cement systems warrant further investigation. Consideration of these limitations is crucial in assessing the feasibility and suitability of $BiFeO_3$ nanoparticles as additives in Class G oil well cement.

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