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Investigation of water-based drilling fluid properties modified by nano ZnO-polyacrylamide composite

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ABSTRACT

This study investigates the synthesis and application of a novel ZnO-polyacrylamide nanocomposite as a performance-enhancing additive for water-based drilling fluids. The nanocomposite was successfully synthesized through a modified solution polymerization method, producing uniformly dispersed spherical particles ranging from 35 to 45 nm as confirmed by FESEM analysis. XRD characterization revealed distinctive peaks at 2θ values of 31.7°, 34.4°, 36.2°, 47.5°, and 56.6°, confirming the hexagonal wurtzite structure of ZnO, while FTIR spectroscopy demonstrated effective integration through characteristic absorption bands at 3435 cm^{-1}, 2924 cm^{-1}, and 1656 cm^{-1}. Systematic evaluation of drilling fluid properties showed that incorporation of the nanocomposite at concentrations between 0.1−1.0% (w/v) significantly enhanced performance parameters. The optimal concentration of 0.7 wt% achieved a 43.8% reduction in API fluid loss, decreased filter cake permeability by 62.4%, and maintained rheological stability with viscosity reduction rate of 0.15 cP/°C compared to 0.28 cP/°C for the base fluid. HTHP testing at 150°C and 500 psi demonstrated enhanced thermal stability with 35.5% reduction in filtrate volume. Shale inhibition studies revealed improved performance through both linear swelling tests and recovery measurements, with recovery rates remaining stable even after secondary exposure to fresh water. The research demonstrates that the integration of ZnO nanoparticles within a polyacrylamide matrix creates a synergistic effect that addresses multiple drilling fluid challenges simultaneously, offering potential applications in high-temperature wells and reactive shale formations.

Keywords: Rheological properties; Formation stability; Thermal resistance; Filtration control; Nanostructured materials.

1. INTRODUCTION

Drilling fluids play a pivotal role in the success of oil and gas well drilling operations, serving multiple critical functions including cleaning and transporting drill cuttings, maintaining wellbore stability, lubricating and cooling the drill bit, and controlling formation pressures [1]. Among the various types of drilling fluids, water-based drilling fluids (WBDFs) are the most widely utilized, accounting for approximately 80% of wells drilled globally due to their economic advantages and environmental compatibility compared to oil-based alternatives [2, 3]. However, conventional WBDFs face significant challenges when drilling through complex formations, particularly in high-temperature environments and reactive shale zones [4]. The primary limitations of conventional WBDFs include thermal instability at elevated temperatures, inadequate shale inhibition properties, and suboptimal rheological characteristics [5]. These shortcomings can lead to various drilling complications such as wellbore instability, differential sticking, poor hole cleaning, and formation damage. Traditional polymer additives used to enhance WBDF properties, such as partially hydrolyzed polyacrylamide (PHPA), xanthan gum, and polyanionic cellulose (PAC), often degrade at temperatures above 300°F and exhibit reduced effectiveness in saline environments [6]. This degradation compromises the drilling fluid's ability to maintain desired rheological and filtration properties throughout the drilling operation.

Recent advances in nanotechnology have opened new avenues for enhancing drilling fluid performance through the incorporation of nanoparticles. The exceptional properties of nanomaterials, including their high surface area to volume ratio, enhanced thermal conductivity, and unique mechanical characteristics, make them promising candidates for improving drilling fluid properties [7–9]. Among various metal oxide nanoparticles,

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zinc oxide (ZnO) has garnered particular attention due to its remarkable thermal stability, chemical inertness, and cost-effectiveness [10, 11]. ZnO nanoparticles exhibit excellent heat transfer capabilities and can potentially enhance the temperature resistance of drilling fluids while simultaneously improving their rheological and filtration properties [12]. Polyacrylamide, a widely used polymer in drilling fluids, provides essential functions such as viscosity enhancement, shale inhibition, and filtration control [13, 14]. However, its performance is limited by thermal degradation and salt sensitivity [15, 16]. The development of nanocomposites combining ZnO nanoparticles with polyacrylamide represents an innovative approach to overcoming these limitations [17]. The synergistic interaction between the nanoparticles and polymer matrix can potentially yield superior performance compared to either component alone, offering enhanced thermal stability, improved rheological properties, and better shale inhibition characteristics.

The incorporation of ZnO-polyacrylamide nanocomposite into WBDFs introduces multiple mechanisms for performance enhancement. The nanoparticles can act as thermal stabilizers, preventing polymer degradation at elevated temperatures while simultaneously improving heat transfer within the fluid system [18]. The composite structure may also provide better particle dispersion and stability, reducing aggregation and sedimentation issues commonly associated with nanoparticle additives [19]. Furthermore, the combination of nano-scale particles with polymer chains can potentially create more effective barriers against fluid invasion into shale formations, thereby improving wellbore stability [20, 21]. The application of nanocomposites in drilling fluids represents a shift from traditional single-component additives toward more sophisticated multi-functional materials [22, 23]. This approach allows for the simultaneous enhancement of multiple drilling fluid properties while potentially reducing the overall quantity of additives required. The development of such advanced materials also aligns with industry efforts to improve drilling efficiency and reduce environmental impact through the use of more effective and environmentally compatible additives.

Understanding the behavior and effectiveness of ZnO-polyacrylamide nanocomposite in WBDFs requires comprehensive investigation of its effects on key drilling fluid properties. These properties include rheological parameters such as plastic viscosity, yield point, and gel strength, as well as filtration characteristics and shale inhibition performance. Additionally, the thermal stability and salt tolerance of the modified drilling fluid system must be evaluated to assess its suitability for challenging drilling environments. This research aims to investigate the synthesis and characterization of ZnO-polyacrylamide nanocomposite and evaluate its effectiveness as a drilling fluid additive. The study encompasses detailed analysis of the nanocomposite's impact on WBDF properties, including rheological behavior, filtration characteristics, and shale inhibition performance across various temperatures and concentrations. The findings will contribute to the development of more efficient and stable drilling fluid systems capable of meeting the challenges of modern drilling operations.

2. MATERIALS AND METHODS

2.1. Materials

Zinc chloride ($ZnCl_2$, 98% purity) and acrylamide monomer (C_3H_5NO, 99.9% purity) were obtained from Shanghai Chemical Reagent Co., Ltd. Potassium persulfate ($K_2S_2O_8$, analytical grade) was purchased from Beijing Chemicals Corporation. Commercial-grade bentonite clay was supplied by Tianjin Mining Chemical Company. Additional drilling fluid additives including potassium chloride (KCl, industrial grade), xanthan gum, and polyanionic cellulose (PAC) were procured from Shandong Drilling Materials Co., Ltd. Sodium hydroxide (NaOH, 98% purity) and hydrochloric acid (HCl, 37%) used for pH adjustment.

2.2. Synthesis of ZnO-polyacrylamide composite

The ZnO-polyacrylamide nanocomposite was synthesized using a modified solution polymerization method under controlled conditions. Initially, $ZnCl_2$ solution was prepared by dissolving 5.0 g of $ZnCl_2$ in 200 mL of deionized water under continuous stirring at room temperature. The solution pH was adjusted to 8.5 using 2M NaOH solution, leading to the formation of zinc hydroxide precipitate. The precipitate was aged for 2 hours at 60°C under constant stirring at 300 rpm using a magnetic stirrer. Simultaneously, the polymerization reaction mixture was prepared by dissolving 30 g of acrylamide monomer in 150 mL of deionized water. The solution was purged with nitrogen gas for 30 minutes to remove dissolved oxygen. Potassium persulfate (0.5 g) was dissolved in 20 mL of deionized water and added as an initiator to the acrylamide solution. The aged zinc hydroxide suspension was then gradually introduced into the polymerization mixture while maintaining a nitrogen atmosphere. The polymerization reaction was conducted in a three-neck round-bottom flask equipped with a mechanical stirrer, thermometer, and nitrogen inlet. The reaction temperature was maintained at 70 ± 2°C using a thermostatically controlled oil bath for 4 hours. The resulting product was precipitated using excess acetone, filtered, and washed repeatedly with a methanol-water mixture (70:30 v/v) to remove unreacted monomers and impurities. The purified nanocomposite was dried in a vacuum oven at 60°C for 24 hours and ground into a fine powder using an agate mortar.

2.3. Drilling fluid preparation

The base drilling fluid was prepared by gradually adding 25 g of bentonite to 350 mL of deionized water under high-speed mixing. The mixture was aged for 24 hours to ensure complete hydration of the bentonite. Subsequently, 4% (w/v) KCl, 0.3% (w/v) xanthan gum, and 1.5% (w/v) PAC were added sequentially under constant mixing at 10,000 rpm. The ZnO-polyacrylamide nanocomposite was incorporated into the base drilling fluid at concentrations ranging from 0.1 to 1.0% (w/v). Prior to addition, the nanocomposite was dispersed in 20 mL of deionized water using ultrasonic treatment for 30 minutes. The modified drilling fluids were mixed for an additional 30 minutes to ensure uniform dispersion and aged at room temperature for 16 hours before testing.

2.4. Rheological measurements

Rheological properties were measured using a six-speed rotational viscometer (Model ZNN-D6, Shanghai) at temperatures of 25°C and 80°C. Readings were taken at 600, 300, 200, 100, 6, and 3 rpm. The rheological measurements were conducted across shear rates ranging from 5.1 s^{-1} to 1022 s^{-1}, corresponding to the rotational speeds of 3 to 600 rpm on the ZNN-D6 viscometer. The conversion factors used were 1.7 s^{-1}/rpm for our specific bob and rotor geometry. Plastic viscosity (PV) and yield point (YP) were calculated according to the Bingham plastic model. Initial and 10-minute gel strengths were determined following standard procedures. Filtration characteristics were evaluated using both standard API filter press and high-temperature high-pressure (HTHP) filter press equipment (Model GGS42-2, Qingdao). API filtration tests were conducted at room temperature and 100 psi pressure for 30 minutes. HTHP filtration tests were performed at 150°C and 500 psi differential pressure. Filter cake thickness was measured using a digital caliper after careful removal and drying of the filter cake.

3. RESULTS AND DISCUSSION

3.1. Characterization of ZnO-polyacrylamide composite

The synthesized ZnO-polyacrylamide nanocomposite was characterized through multiple analytical techniques to confirm its structure, composition, and thermal properties. The results demonstrate successful incorporation of ZnO nanoparticles within the polyacrylamide matrix while maintaining the characteristic properties of both components [24]. XRD analysis revealed the crystalline structure of ZnO within the nanocomposite, as shown in Figure 1. The diffraction pattern exhibited distinctive peaks at 2θ values of 31.7°, 34.4°, 36.2°, 47.5°, and 56.6°, corresponding to the (100), (002), (101), (102), and (110) planes of the hexagonal wurtzite structure of ZnO [25]. The sharp and well-defined nature of these peaks indicates high crystallinity of the ZnO phase. The average crystallite size, calculated using the Scherrer equation, was determined to be 38.5 nm. The absence of additional peaks confirms the phase purity of the synthesized material [26].

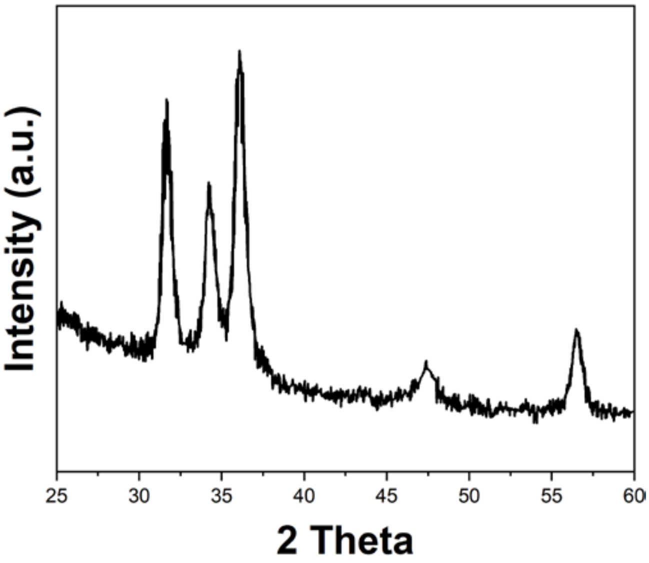

Figure 1: XRD pattern of synthesized ZnO-polyacrylamide nanocomposite.

FTIR spectroscopy provided evidence of successful interaction between ZnO nanoparticles and the polyacrylamide matrix (Figure 2). The spectrum displayed characteristic absorption bands at 3435 cm^{-1} (N-H stretching), 2924 cm^{-1} (C-H stretching), and 1656 cm^{-1} (C=O stretching) associated with the polyacrylamide component [27]. The presence of Zn-O vibrations was confirmed by the absorption band at 465 cm^{-1}. Additionally, new bands observed at 732 cm^{-1} and 696 cm^{-1} indicate the formation of coordination bonds between zinc ions and oxygen atoms of the amide groups, suggesting effective integration of ZnO within the polymer network [28].

Morphological analysis through FESEM revealed the structural characteristics of the nanocomposite at different magnifications (Figure 3). The micrographs demonstrate uniform dispersion of spherical ZnO nanoparticles throughout the polymer matrix, with particle sizes ranging from 35 to 45 nm. The polymer matrix exhibits a continuous network structure with embedded nanoparticles, indicating successful prevention of particle agglomeration [29]. Higher magnification images reveal the surface texture of individual particles and their interface with the polymer matrix, showing good adhesion between the components.

Thermal stability of the nanocomposite was evaluated using TGA, with results presented in Figure 4. The thermogram shows three distinct degradation stages: initial weight loss of 4.2% between 80–190°C due to moisture evaporation, followed by major decomposition of the polyacrylamide chain (42.5% weight loss) between 250–350°C, and final degradation above 350°C [30]. The residual mass at 800°C was 43.3%, corresponding to the ZnO content in the composite.

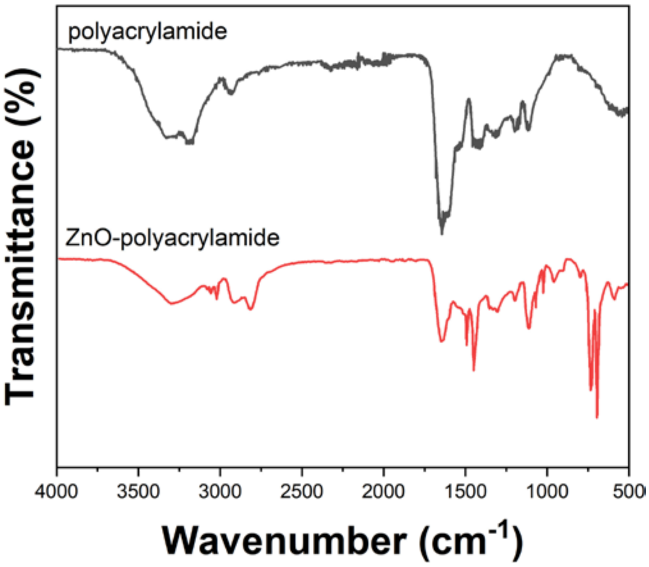

Figure 2: FTIR spectrum of ZnO-polyacrylamide nanocomposite displaying characteristic absorption bands of both components and their interactions.

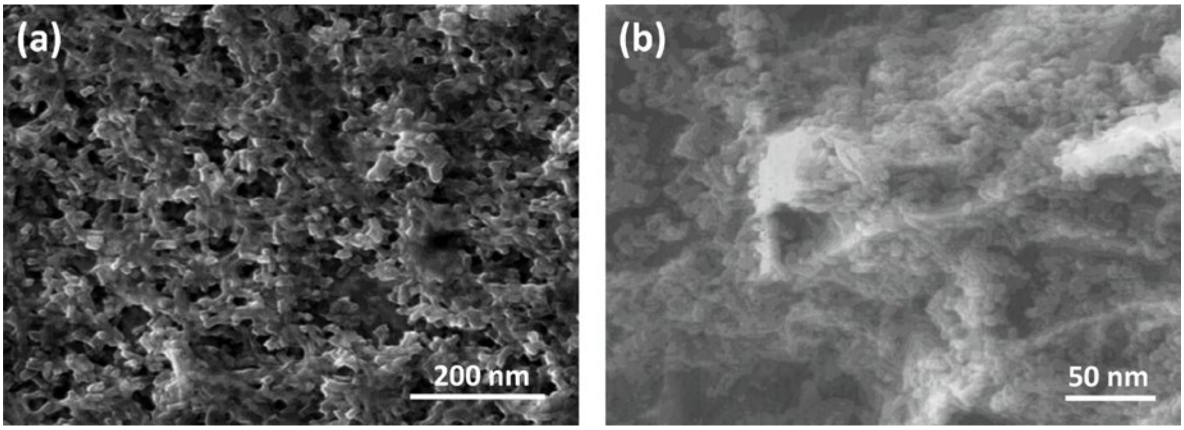

Figure 3: FESEM images of ZnO-polyacrylamide nanocomposite at (a) low and (b) high magnification.

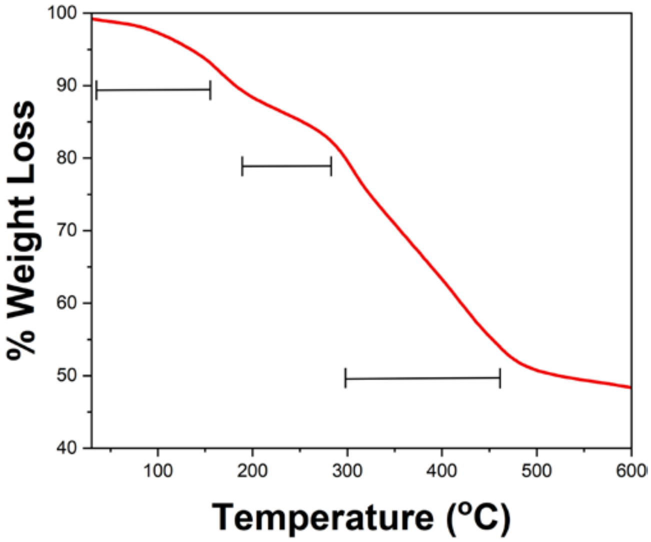

Figure 4: TGA curves comparing thermal degradation behavior of ZnO-polyacrylamide nanocomposite.

3.2. Rheological properties

The incorporation of ZnO-polyacrylamide nanocomposite significantly influenced the rheological behavior of the water-based drilling fluid, with distinct variations observed across different concentrations and temperature conditions. The modifications in rheological parameters demonstrate the complex interactions between the nanocomposite and the base fluid components.

The AV of the drilling fluid showed concentration-dependent behavior at both 25°C and 80°C (Figure 5). At 25°C, the base fluid exhibited an AV of 35 cP, which increased progressively with nanocomposite addition up to 0.7 wt%, reaching 48 cP. Further increases in concentration produced minimal additional effects. At elevated temperature (80°C), though overall viscosity values were lower, the nanocomposite-modified fluids maintained better viscosity stability compared to the base fluid. The enhanced temperature tolerance can be attributed to the thermal stabilizing effect of ZnO nanoparticles within the polymer matrix [31, 32].

PV measurements revealed noteworthy trends in the internal resistance to fluid flow. As shown in Figure 6, the base fluid displayed a PV of 17 cP at 25°C, which initially increased with nanocomposite addition up to 0.5 wt% (reaching 25 cP) before showing a gradual decline at higher concentrations. Table 1 presents the complete PV data across all tested concentrations and temperatures. The initial increase in PV indicates enhanced

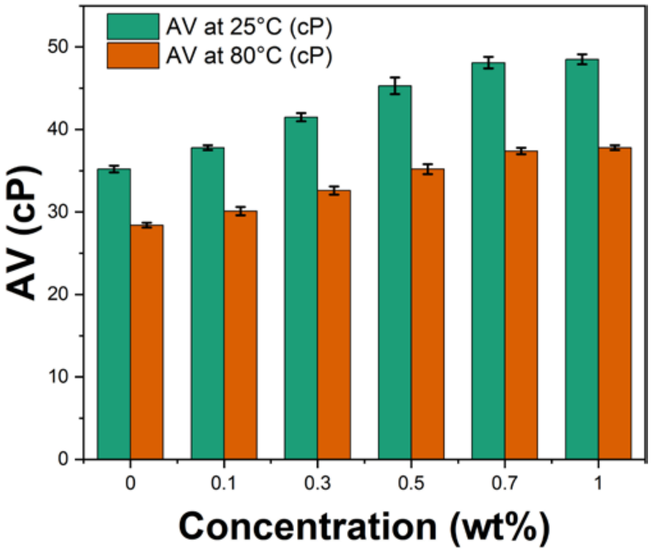

Figure 5: Effect of ZnO-polyacrylamide nanocomposite concentration on apparent viscosity at 25°C and 80°C.

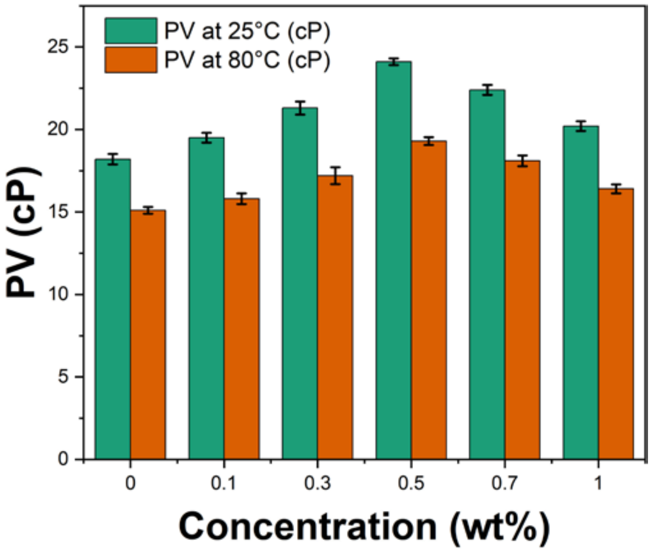

Figure 6: Variation of plastic viscosity with nanocomposite concentration.

Table 1: Plastic viscosity values at various nanocomposite concentrations and temperatures.

CONCENTRATION (wt%)	PV AT 25°C (cP)	PV AT 80°C (cP)
0.0	17	15
0.3	21	18
0.5	25	19
0.7	22	17
1.0	20	16

particle-particle interactions, while the subsequent decrease suggests a possible lubricating effect of the nanocomposite at higher concentrations [33].

YP analysis demonstrated significant enhancement in the fluid's carrying capacity with nanocomposite addition. The base fluid exhibited a YP of 15 lb/100 ft^2 at 25°C, which increased substantially to 28 lb/100 ft^2 at 0.7 wt% nanocomposite concentration (Figure 7). This improvement in YP indicates stronger electrochemical forces between fluid particles, enhancing the suspension stability and cutting-carrying capacity of the drilling fluid [34]. Temperature elevation to 80°C resulted in moderate YP reduction, but the nanocomposite-modified fluids maintained relatively higher YP values compared to the base fluid under similar conditions [35, 36].

The YP/PV ratio, a critical indicator of drilling fluid performance, showed notable improvement with nanocomposite addition. As presented in Table 2, the ratio increased from 0.82 for the base fluid to 1.28 at 0.7 wt% nanocomposite concentration at 25°C. This enhancement suggests improved hole cleaning capability without excessive pump pressure requirements. The relationship between nanocomposite concentration and YP/PV ratio demonstrates a clear optimization point at 0.7 wt%, beyond which minimal additional benefits were observed.

3.3. Filtration characteristics

The incorporation of ZnO-polyacrylamide nanocomposite demonstrated significant influence on the filtration properties of the water-based drilling fluid, affecting both fluid loss volume and filter cake characteristics under various testing conditions.

Standard API filtration tests conducted at room temperature and 100 psi revealed progressive improvement in fluid loss control with increasing nanocomposite concentration. The base fluid exhibited an API fluid loss of 12.8 mL over 30 minutes, while the addition of nanocomposite resulted in systematic reduction of filtrate volume, as shown in Figure 8. At 0.7 wt% nanocomposite concentration, the fluid loss decreased to 7.2 mL, representing a 43.8% reduction. The enhanced filtration control can be attributed to the formation of a more compact and less permeable filter cake due to the presence of nano-sized particles filling interstitial spaces between larger particles [37].

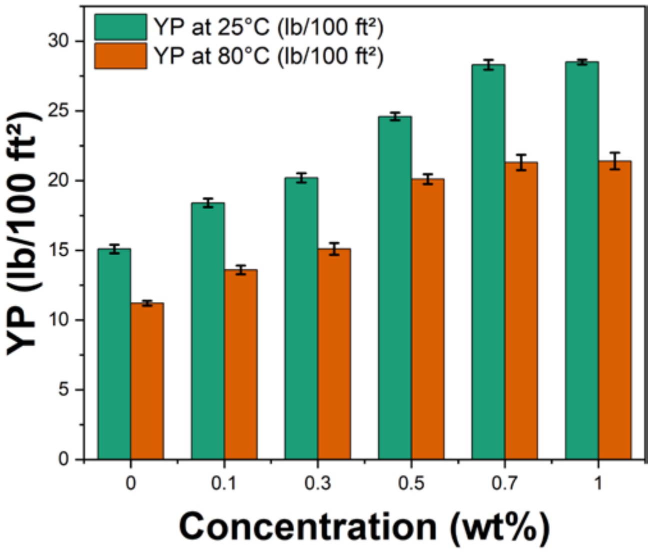

Figure 7: Yield point values as a function of nanocomposite concentration at different temperatures.

Table 2: YP/PV ratio values at different nanocomposite concentrations.

CONCENTRATION (wt%)	YP/PV RATIO (25°C)	YP/PV RATIO (80°C)
0.0	0.82	0.75
0.3	0.95	0.88
0.5	1.15	1.05
0.7	1.28	1.18
1.0	1.25	1.15

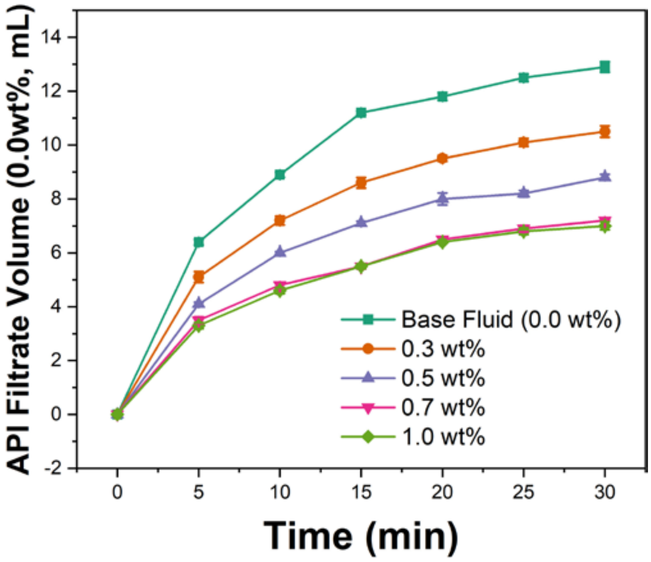

Figure 8: API filtrate volume versus time for drilling fluids containing different concentrations of ZnO-polyacrylamide nanocomposite.

HTHP filtration tests at 150°C and 500 psi provided insights into the performance of the nanocomposite-modified drilling fluid under more challenging conditions. Figure 9 illustrates the HTHP filtrate volume as a function of time for different nanocomposite concentrations. The base fluid showed accelerated filtration at elevated temperature, with a 30-minute filtrate volume of 24.5 mL. Addition of the nanocomposite significantly improved high-temperature filtration control, with 0.7 wt% concentration reducing the HTHP filtrate volume to 15.8 mL, demonstrating the thermal stability of the filtration properties.

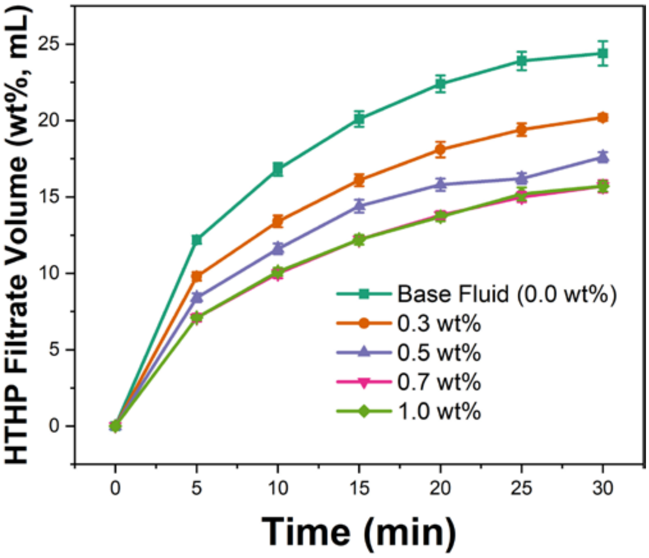

Figure 9: HTHP filtration behavior of drilling fluids at 150°C and 500 psi showing cumulative filtrate volume over 30 minutes.

Table 3: Filter cake properties at different nanocomposite concentrations.

CONCENTRATION (wt%)	API THICKNESS (mm)	HTHP THICKNESS (mm)	PERMEABILITY (μD)
0.0	2.8	3.4	0.85
0.3	2.4	2.9	0.61
0.5	2.1	2.5	0.45
0.7	1.9	2.2	0.32
1.0	1.8	2.1	0.30

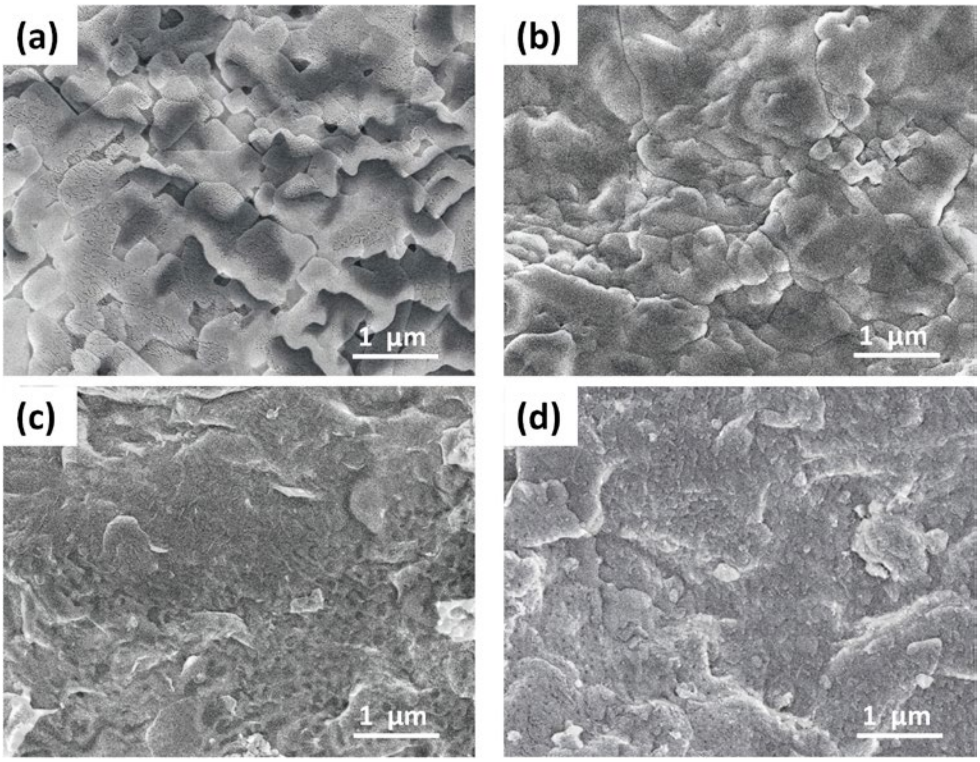

Figure 10: Microscopic images of filter cakes formed by (a) base fluid, (b) 0.3 wt%, (c) 0.7 wt%, and (d) 1.0 wt% nanocomposite-modified drilling fluids.

Filter cake analysis revealed substantial modifications in physical characteristics with nanocomposite addition. As detailed in Table 3, filter cake thickness decreased from 2.8 mm for the base fluid to 1.9 mm at 0.7 wt% nanocomposite concentration under API conditions. More importantly, the permeability of the filter cake, calculated using Darcy's equation, showed a reduction from 0.85 µD to 0.32 µD, indicating formation of a more effective seal against fluid loss.

Microscopic examination of filter cakes (Figure 10) revealed progressive structural modifications with increasing nanocomposite concentration. The base fluid produced relatively loose, poorly consolidated filter cakes, while nanocomposite-modified fluids generated more compact and uniform filter cakes [38]. The improved structure results from the ZnO nanoparticles effectively bridging gaps between larger particles and the polymer component providing additional binding strength [39].

3.4. Temperature effects

The thermal stability of drilling fluids modified with ZnO-polyacrylamide nanocomposite was evaluated through extended aging tests at elevated temperatures. The results demonstrated significant improvements in maintaining rheological and filtration properties compared to the base fluid system.

Aging tests conducted at 150°C for 16 hours revealed superior thermal stability of the nanocomposite-modified fluids. As shown in Figure 11, the base fluid experienced substantial degradation of rheological properties, with apparent viscosity decreasing by 45% after aging. In contrast, drilling fluids containing 0.7 wt% nanocomposite maintained 82% of their initial apparent viscosity under identical conditions. This enhanced thermal stability can be attributed to the protective effect of ZnO nanoparticles on the polymer structure and their role in maintaining the overall fluid system integrity at elevated temperatures [40].

The temperature performance curve (Figure 12) illustrates the relationship between plastic viscosity and temperature for various nanocomposite concentrations. While all formulations showed decreasing viscosity with increasing temperature, the rate of decrease was significantly lower in nanocomposite-modified fluids [41]. At 0.7 wt% concentration, the viscosity reduction rate was 0.15 cP/°C compared to 0.28 cP/°C for the base fluid, indicating improved temperature tolerance.

3.5. Shale inhibition properties

Shale inhibition characteristics were evaluated through linear swelling tests and shale recovery measurements using standardized shale samples. The incorporation of ZnO-polyacrylamide nanocomposite demonstrated marked improvement in shale stabilization properties.

Linear swelling tests conducted over 24 hours revealed significant reduction in shale hydration with nanocomposite addition. Figure 13 shows the swelling curves for different fluid formulations. The base fluid

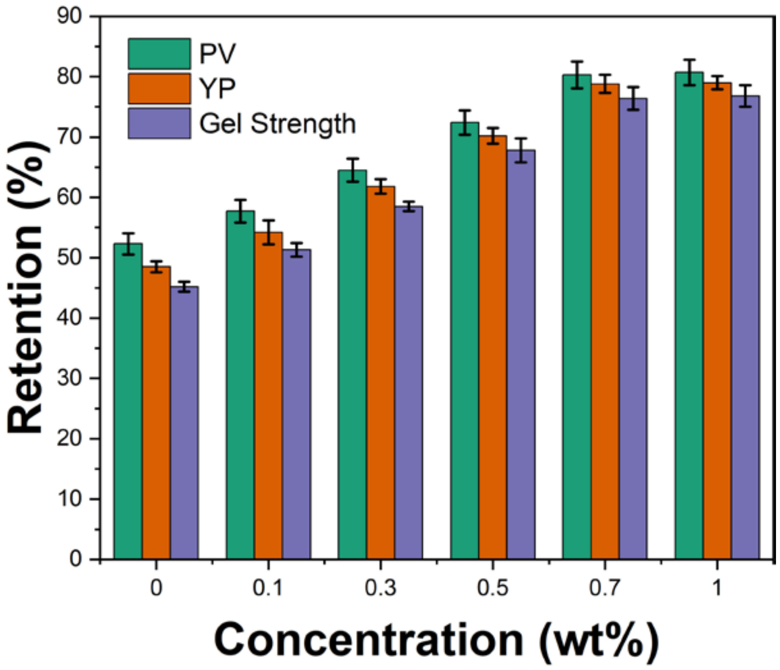

Figure 11: Rheological property retention after aging at 150°C for 16 hours as a function of nanocomposite concentration.

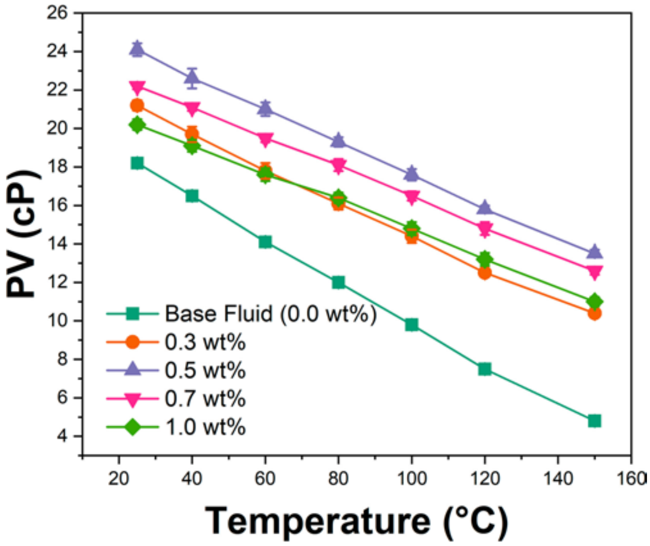

Figure 12: Temperature dependence of plastic viscosity for different drilling fluid formulations.

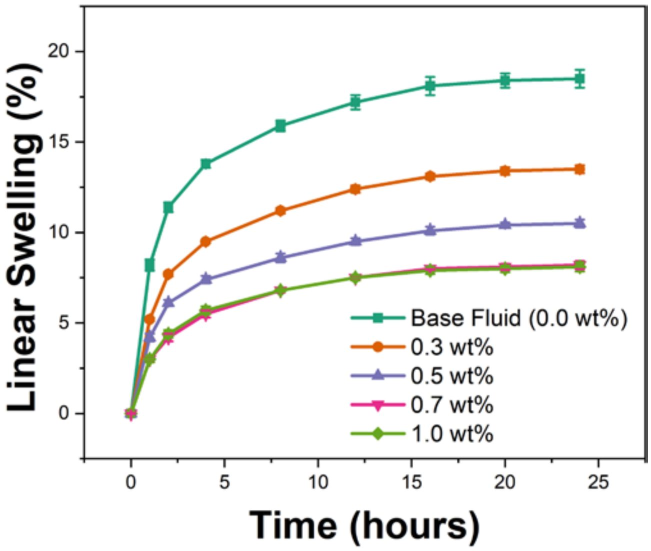

Figure 13: Linear swelling curves of shale samples exposed to various drilling fluid formulations over 24 hours.

resulted in 18.5% linear swelling after 24 hours, while the addition of 0.7 wt% nanocomposite reduced swelling to 8.2%. This enhancement in shale inhibition can be attributed to the synergistic effect of ZnO nanoparticles providing physical barriers against water invasion and the polyacrylamide component contributing to surface modification of clay particles [42].

Shale recovery performance tests (Table 4) further confirmed the improved inhibitive properties of the nanocomposite-modified fluids. The base fluid showed a recovery rate of 75.3%, while fluids containing 0.7 wt% nanocomposite achieved 92.8% recovery. Recovery rates remained stable even after secondary exposure to fresh water, indicating formation of a persistent protective barrier on the shale surface. While the ZnO-polyacrylamide nanocomposite demonstrates promising performance improvements, several challenges need consideration. The synthesis process requires precise control of reaction conditions and high-purity raw materials, potentially increasing production costs compared to conventional additives. Current laboratory-scale synthesis yields approximately 100g per batch, and scaling up to industrial production would require significant process optimization and capital investment in specialized equipment. Additionally, the uniform dispersion of ZnO nanoparticles becomes more challenging in larger batches, potentially affecting product consistency. The estimated material cost is 3-4 times higher than traditional polyacrylamide additives, though this may be partially offset by the reduced quantity needed for equivalent performance. Further research is needed to optimize the synthesis process and reduce production costs while maintaining product quality for industrial-scale applications.

Table 4: Shale recovery performance results.

FLUID SYSTEM	INITIAL RECOVERY (%)	SECONDARY RECOVERY (%)	TOTAL RECOVERY (%)
Base Fluid	75.3	62.4	68.9
0.3 wt% Nanocomposite	83.7	75.6	79.7
0.5 wt% Nanocomposite	88.5	82.3	85.4
0.7 wt% Nanocomposite	92.8	88.5	90.7
1.0 wt% Nanocomposite	93.1	88.9	91.0

4. CONCLUSION

This comprehensive investigation of ZnO-polyacrylamide nanocomposite as a drilling fluid additive has demonstrated significant improvements in water-based drilling fluid properties. The synthesized nanocomposite, with an average ZnO crystallite size of 38.5 nm, exhibited uniform particle dispersion and thermal stability up to 350°C as confirmed by TGA analysis. The incorporation of the nanocomposite at an optimal concentration of 0.7 wt% resulted in substantial enhancements in rheological properties, with apparent viscosity increasing from 35 cP to 48 cP at 25°C, while maintaining 82% of initial viscosity after aging at 150°C for 16 hours. Filtration characteristics showed marked improvement, with API fluid loss reduction from 12.8 mL to 7.2 mL and HTHP filtrate volume decrease from 24.5 mL to 15.8 mL at 150°C and 500 psi. The nanocomposite-modified drilling fluid demonstrated superior filter cake properties, with thickness reduction from 2.8 mm to 1.9 mm and permeability decrease from 0.85 μD to 0.32 μD. Shale inhibition performance was notably enhanced, with linear swelling reduction from 18.5% to 8.2% over 24 hours and improved shale recovery rates from 75.3% to 92.8%. The YP/PV ratio increased from 0.82 to 1.28 at 25°C, indicating enhanced hole cleaning capability without excessive pump pressure requirements. These results demonstrate that the ZnO-polyacrylamide nanocomposite represents a promising multifunctional additive for water-based drilling fluids, offering improved thermal stability, filtration control, and shale inhibition properties suitable for challenging drilling environments. The successful synthesis and application of this nanocomposite opens new possibilities for developing advanced drilling fluid systems that can meet the demands of complex well conditions while maintaining environmental compatibility.

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