



Synthesis and Evaluation of Poly (isobutylene-alt-maleic anhydride)-co-Poly (ethylene glycol) and its Copper Oxide Nanocomposite for Enhancing the Performance of Water-based Drilling Fluids in HPHT Wells

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Abstract

Enormous research work has been performed in order to retain the desired rheological, filtration, and friction properties of water-based drilling fluids at elevated temperature and pressure. In the current work, polyester copolymer (PES) was synthesized by esterification of poly isobutylene maleic anhydride (PIBMA) with poly ethylene glycol (PEG). Copper oxide nanoparticles (CuO-NPs) were added during the copolymerization in different ratios, 0.5, 1, and 2 Wt. %, so that new nanocomposites were obtained. The prepared PES and its nanocomposites were characterized by nuclear magnetic resonance (NMR), X-ray diffraction (XRD), transmission electron microscope (TEM), Fourier infrared spectroscopy (FTIR), and thermal gravimetric analysis (TGA). Moreover, case studies were conducted through analyzing the samples composed of water-based muds (WBM), developed with the copolymer and copolymer/CuO nanocomposites, compared with the blank ones. The results showed great enhancement in rheological, filtration, and friction properties of WBM developed by 3.5 ppb of PES copolymer (PIBMA-PEG) that can withstand high temperature beyond 400^oF. On the other hand, the prepared nanocomposites showed an adverse effect on mud rheology at temperature greater than 300^oF. The results appear a promising development in copolymerization and nanotechnology that plays a vital role to enhance drilling fluids performance at high temperature environment and minimize drilling cost together with the non-productive time (NPT). Considering that the best result is approached by adding 7 ppb PES to NaCl polymer mud that sustain rheological properties especially yield point (YP = 23 lb/100 ft²) accompanied by controlling both filtrate volume and induced friction.

Keywords: Copolymerization; Nanocomposites; Water-based muds; HPHT wells.

1. Introduction

Nowadays, the new frontier of oil and gas industry is to drill deep wells because of the growing demand for oil and gas [1]. The deeper the formation, the higher temperatures and pressures are experienced. HPHT wells are classified according to reservoir pressure and temperature into three categories, including HPHT, extreme HPHT, and ultra HPHT [2]. The HPHT prevails where temperature lies from 300° F to 350° F and pressure from 10,000 Psi - 15,000 Psi, while extreme HPHT develops with temperature between 350° F and 400° F and pressure from 15,000 Psi to 20,000 Psi [3]. Finally, the ultra HPHT condition is known when temperature ascends from 400° to 500° F and pressure is maintained from 20,000 Psi to 30,000 Psi [3, 4]. The major safety concerns associated with drilling HPHT wells are the mechanical equipment's aspects, staff competency and training, drilling and completion fluids, and well

control [5]. These challenges accompanied with high temperature increase the likelihood of encountering extensive non-productive time (NPT) which must be considered while designing the material strength of heavy casing strings, logging while drilling (LWD) and measurement while drilling (MWD) tools, blow out preventer (BOP), and drilling fluid type and properties [6-8].

Primary well control is achieved by providing a sufficient hydrostatic pressure that prevents invasion of formation fluids into the well bore and it is essential to sustain primary well control all times [9]. Secondary control is achieved by selecting the most appropriate BOP equipment which controls the well in case of primary control failure [10]. Drilling fluids play a crucial role to attain a successful drilling operation via several functions including the removal of drilling cuttings from the well, formation pressure

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control, maintaining wellbore stability, and lubricating the drill bit. Accurate knowledge of drilling fluid behavior under the harsh conditions of HPHT is mandatory to maximize operational efficiency. Thus, it is typically restricted to use conventional drilling fluids at HPHT drilling conditions. Rheological and filtration properties of drilling fluids are affected negatively at high temperature environment [11, 12]. The development of HPHT drilling fluid is essential to overcome the drilling challenges in extreme pressure and temperature. The main challenge is to maintain optimum rheological and filtration properties while drilling deep wells with high temperature and pressure [13]. The functional behavior of the fluid depends upon the type of base fluid (oil or water), the solids, chemicals and polymers utilized in the design stage [14]. HPHT fluid loss should be as low as possible to prevent formation damage and stick pipe. Also, HPHT rheology should be stable and predictable to control barite sag, gelation and equivalent circulating density (ECD). Moreover, mud properties should not be changed over time under either static or dynamic conditions, but the properties are slightly dropped after dynamic aging and increased after static aging [15, 16].

In HPHT wells, water-based muds (WBM) and oil-based muds (OBM) are considered to be the most common used drilling fluids [17]. WBM are preferred over OBM that have various disadvantages such as discharge of cuttings, loss of the whole mud and disposal, negative impacts on health like skin allergy and inhalation of fumes, and high initial cost [18]. The advancement in drilling fluid technology, especially for WBM and OBM, is mandatory to qualify them for HPHT purposes [19]. Developing a WBM with steady rheological and fluid loss properties at a temperature above 270^o F is the challenge in HPHT applications. The major objective is to find the most effective ways to improve water-based drilling fluids to be successfully applied in harsh conditions while providing a host of its functions through drilling and constructing HPHT wells [20,21].

Numerous recent studies used nano particles to enhance drilling fluids parameters such as nano aluminum oxide (Al₂O₃), nano titania (TiO₂) and nano iron oxide (Fe₃O₄). It is concluded that when 0.5 to 1.5 gm of aluminum oxide was used with 22.5 gm

of bentonite WBM, thermal stability increased gradually with increasing NPs concentration [22]. Furthermore, Haider experienced the usage of 0.05 gm to 0.5 gm of nano titania in enhancing WBM plastic viscosity (Pv), yield point (Yp), and gel strengths significantly after 16 hours hot rolling at 250 ^oF. The torque also was reduced up to 34% by adding 0.5 gm titania NPs. While adding 0.1 gm TiO₂ nanoparticles, the fluid loss was enhanced significantly whereas 50% reduction in filtration was achieved [23]. It was observed that the nano iron oxide helps to maintain the desired rheological properties of bentonite water-based mud at elevated temperature up to 194^o F [24].

This article presents an approach for the synthesis of new nanocomposites based a new copolymer. This work is novel because studying behavior of the pure copolymer in WBM drilling was not previously addressed. In the present work, a new copolymer was prepared via the copolymerization of commercial polymers, poly (isobutylene maleic anhydride), and poly (ethylene glycol), in order to obtain a polyester copolymer with improved properties. To award further advantages for the prepared copolymer, CuO nanocomposites with different concentration of CuO-NPs were prepared via in-situ polymerization technique. The prepared samples were characterized and evaluated under high temperature conditions.

2. Experimental

2.1. Materials

Poly isobutylene-alt-maleic anhydride (PIBMA) of average M_w ~ 6,000 and 12-200 mesh (85%), poly ethylene glycol (PEG) of M_w ~ 1000, dimethylformamide (DMF) 99.9%, and copper (II) oxide nano particles of particle size <50 nm were purchased from Sigma-Aldrich, (USA). Chemicals used to prepare WBM were provided from Baker Hughes and EMEC; Bentonite, Caustic Soda, Soda ash, Salt, PAC-LV, Chemtrol-X, Xanthan gum, Calcium carbonate fine, Oxygen scavenger, and Barite. All the chemicals consumed in this study were used as received without any further treatment.

2.2. Synthesis of PIBMA-PEG copolymer (PES)

The esterification of PIBMA with PEG could be prepared as follows: in a three-necked flask fitted with a reflux condenser, one mole of PIBMA was dissolved in DMF as a solvent with a concentration of 10 wt. %. Then, one mole of PEG was added and stirred till complete dissolution. P-toluene sulphonic acid (0.5% of total weight) was inserted as catalyst to

the reaction vessel and the whole mixture was refluxed at 266°F under ambient atmospheric pressure. After 3 hrs of a vigorous stirring, a yellowish orange transparent solution was obtained. The DMF was removed from the product by the rotary evaporator and the yellowish viscous polymer was precipitated in distilled water in order to remove the excess solvent. The solid powder of obtained copolymer was collected by filtration and dried at 158°F. After 24 hrs, a pale yellow powder of ethoxylated poly isobutylene-maleated-copolymer was obtained, Scheme (1).

2.3. Synthesis of PES / CuO nanocomposite (C)

The nanocompositing of PES and CuO nanoparticles was performed through in-situ polymerization technique. The typical procedure can be carried out as follows: a certain amount of commercial CuO-NPs was dispersed in DMF by sonication for 1 hour and then one mole of PIBMA was added to the reaction vessel. The whole mixture was left under vigorous stirring for 72 hrs. After that, the whole mixture was transferred to a three-necked flask fitted with a reflux condenser and one mole of PEG in addition to P-toluene sulphonic acid were added and stirred till complete dissolution. The temperature was raised up to 266°F for 3 h under ambient atmosphere. Then, the mixture was transferred to rotary evaporator in order to remove DMF. A reddish green viscous solution was obtained and precipitated in large amount of distilled water then the dispersed solution was filtered out and dried overnight at 158°F. The obtained powder has a greenish yellow color. The previous steps were carried out for three concentrations of CuO- NPs; 0.5 Wt.% (C0.5), 1 Wt.% (C1), and 2 Wt.% (C2).

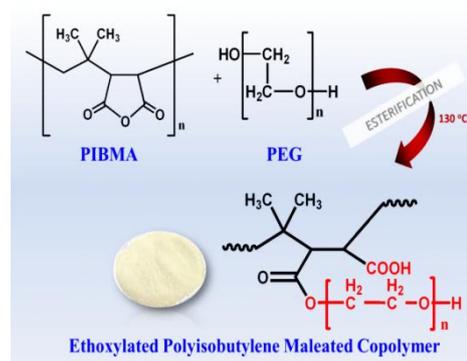
2.4. Synthesis of 90 Pcf WBM (NaCl polymer mud)

This method includes mixing the raw materials in different percentage at 5000 rpm using Hamilton Beach batch mixer at ambient pressure and temperature. The desired WBM was prepared according to the recipe exists, Table (1).

2.5. Techniques

The surface morphology of the purchased CuO- NPs and the prepared nanocomposites was studied using a transmission electron microscope (JEM-1230, JEOL Ltd., Tokyo, Japan) under an acceleration voltage of 80 kV. FTIR spectra for the prepared samples were recorded using Perkin Elmer Fourier Transform Infrared Spectroscopy. The chemical structure of the

prepared polyester was assigned by ¹HNMR. The spectrum was acquired on JEOL-ECA 500 MHz spectrometer in DMSO with tetramethylsilane (TMS) as internal standard at ~300K using 5 mm sample tubes. The X-ray diffraction pattern of the purchased CuO- NPs was determined using a Bruker diffractometer (Bruker D8 advance target). The CuK α -radiation source with a secondly monochromator ($\lambda = 1.5405 \text{ \AA}$) at 40 kV and 40 mA was used and 0.2 min^{-1} was the scanning rate for the phase identification and line broadening profile analysis. The thermal behavior was studied using simultaneous DSC-TGA instrument or SDT Q600 under Nitrogen atmosphere at a heating rate of $10 \text{ }^\circ\text{C}/\text{min}$. A Hamilton Beach mixer was used to mix and shear drilling fluids components with nano composites. Simulation of down-hole conditions and exposing prepared drilling fluids samples to high temperature up to 400°F was achieved using a hot roller oven [25]. A Viscometer (6-speed VG meter) was utilized to calculate plastic viscosity (Pv) and yield point (Yp) by measuring shear stress/shear rate of the drilling fluid [26]. Moreover, shear stress/shear rate relationship and torque was measured by a PVS rheometer at pressure and temperature equal to 1000 psi and 428°F, respectively [27]. Fluid loss volume (filtration) is recorded as a double number of millimeters lost from HPHT filter press which is conducted at 300°F and 500 psi differential pressure [28].



Scheme 1: Synthesis of Polyester Copolymer.

3. Results and discussion

Different characterization results for all materials obtained in this study are discussed. Moreover; the effect of these materials on developing a superior drilling fluid was studied and investigated through laboratory experiments. The testing procedures

included monitoring the rheological and filtration properties at high temperature environment.

3.1. The Concept

As previously reported, poly (isobutylene-succinic anhydride)-co-poly (ethylene glycol) can be applied to the engines oil as a dispersant agent to prevent the agglomeration and precipitation on metallic engine parts that can cause a damage. It was shown that the use of 2 wt.% of the prepared copolymer with lube oil has an excellent dispersion factor (70-90%) for the sludge and solid particles formed during lube oil oxidation compared with lube oil only [29,30]. Researches also showed that nano water based muds (NWBM) prepared by adding the dispersed nano CuO (size ≤ 50 nm) in xanthan aqueous solution to the WBM plays an important role to significantly stabilize electrical conductivity, thermal conductivity, and viscosity of WBM [31]. Therefore, blending of nanoparticles with high thermal stability polymers is expected to change the behavior of WBM.

3.2. Transmission Electron Microscope

The TEM micrographs of CuO-NPs depict quasi spherical particles of average diameter of 25 nm, Fig. 1 A. The inset image was revealed to the electron diffraction which emphasizes the poly crystallinity of CuO-NPs with a little bit large particle size. TEM images of the nanocomposite based copper nanoparticles (1 Wt.%) confirmed better dispersion of

core is the nanoparticles and the shell is the polyester, Fig. 1B.

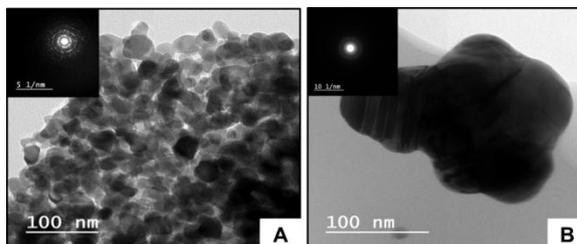


Figure 1: TEM micrographs of [A] commercial CuO-NPs and [B] PES nanocomposite (1 Wt.%). Inset images are electron diffraction.

Unlike the electron diffraction (ED) of CuO-NPs, the ED of PES nanocomposite (inset picture of Fig. 1B) showed high crystallinity along with fine particle in major which might be attributed to the well dispersion of the nanoparticles in polymeric solution for 3 days prior to copolymerization step. This may cause particles size reduction. Also, one can conclude that the polymerization doesn't alter the crystallinity of the nanoparticles. TEM confirmed successful formation of copper oxide based nanocomposites.

3.3. X-ray Diffraction

Fig. 2 shows that the XRD pattern of prepared CuO-NPs clearly exhibits the crystalline nature of this material. The diffraction peaks at $2\theta = 32.62^\circ$, 35.61° , 30.80° , 48.75° , 53.68° and 58.42° were assigned to (110), (002), (111), (202), (020), and (113) of CuO-NPs.

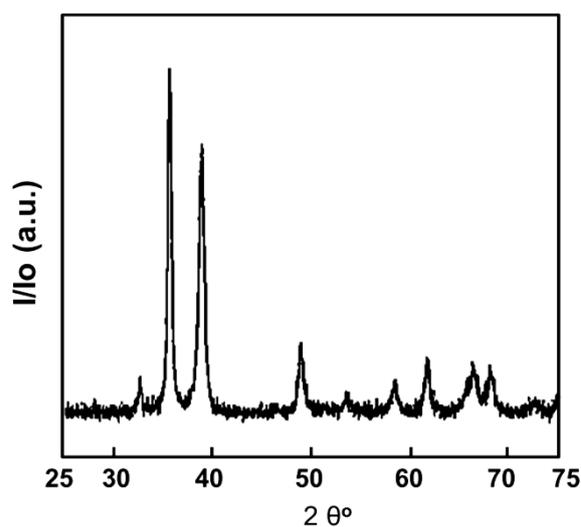


Figure 2: The XRD spectrum of commercial CuO-NPs.

The average crystalline size of CuO-NPs has been estimated from the XRD pattern to be around 25 nm

Product	Concentration (ppb)
Water	0.814
Prehydrated bentonite	5
Caustic Soda	0.5
Soda ash	0.5
Salt (NaCl)	34.98
PAC-LV	3
Chemtrol-X	4
Xanthan gum	1.2
CaCO ₃ Xf	40
Barite	131
Oxygen scavenger	2

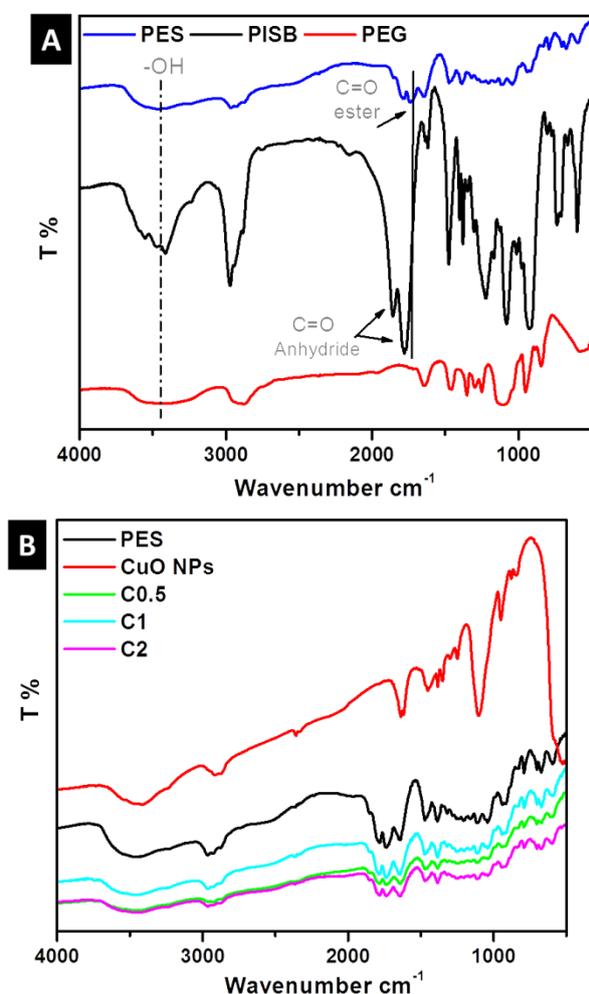
copper oxide nanoparticles inside the polymer matrix. Some images confirmed formation of core shell like structure with enlargement in the particles size as the

which support the TEM. However, it was hard to identify CuO-NPs in the prepared nanocomposites because of the low loading ratio of the nanoparticles in the polymer matrix as well as the limitation of XRD tool to detect the doped materials at concentration less than 5 *Wt.%*.

3.4. Infrared Spectroscopy (FTIR)

FTIR spectra were recorded for the prepared and commercial samples in the range of 400-4000 cm^{-1} (Fig. 3). The reaction of PIBMA with PEG was completed and characterized by FTIR analysis.

Figure 3: FTIR spectra of [A] prepared copolymer and [B] PES nanocomposites.



The spectrum of the product is presented in Fig. 3A. The spectrum shows two characteristic peaks of anhydride groups at 1870 cm^{-1} and 1788 cm^{-1} for PIBMA. The disappearance of these two peaks indicates a ring opening reaction while esterification

process. Moreover, the presence of the broad band at 3450 cm^{-1} and a pronounced peak at 1752 cm^{-1} is representing the OH stretching vibration band and C=O stretching vibration of ester groups, respectively. This confirms the successful formation of the polyester.

Commercial CuO-NPs revealed a strong band at 537 cm^{-1} , which can be attributed to the vibrations of CuO, while the other bands may be reverted to the polymer used as a stabilizer for the nanoparticles, Fig. 3B. The nanocomposites obtained could be also characterized with FTIR to determine the mode of interaction. As shown in Fig. 3B, the characteristic polymer bands were observed at their positions in nanocomposite based CuO nanoparticles. Also, the peaks of CuO are embedded under the polymer bands, which may account to the lower CuO ratio. This makes collecting clear information about the nature of interaction between copper oxide and the prepared polyester difficult. However, the sharpness of the peak at 3440 cm^{-1} was a little bit changed. The peak became broader due to the carboxylic groups in the polyester and the probability to form hydrogen bonding on the surface of CuO.

3.5. Nuclear Magnetic Resonance (NMR)

Polyester was prepared through esterification of commercial PIBMA and PEG in the presence of a catalyst at 266°F in DMF to produce ethoxylated polyisobutylene maleate. The chemical structure of the obtained PES was confirmed by ^1H NMR in DMSO which has a well-known peak at 2.5 ppm. The spectrum of the polyester copolymer obtained is given in Fig. (4). The peaks pronounced at $\sim 5\text{ ppm}$ and $\sim 12.4\text{ ppm}$ might be attributed to -OH protons and -COOH protons in the prepared polyester, respectively. Moreover, the observed peaks at the range from 1 to 2.4 ppm represent methyl and methylene protons in PIBMA. Meanwhile, the appearance of the strong band at 3.5 ppm reveals to methylene protons in PEG. Also, the spectra show the presence of excess DMF, which is the solvent used in the copolymerization reaction, as its characteristics bands are clearly appeared at 2.8 and 8 ppm. It is worth to mention that, it is hard to remove all the amount of solvent from the sample since it is usually accommodated between the polymer chains. Moreover, weak peaks at 7 ppm might be referred to the presence of some catalyst residues. However, ^1H NMR results emphasize the successful

esterification of poly isobutylene-alt-maleic anhydride with polyethylene glycol.

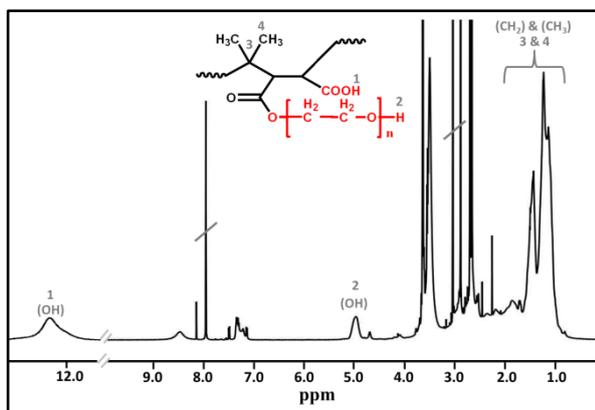


Figure 4: ^1H NMR spectra of the prepared copolymer.

3.6. Thermal gravimetric analysis (TGA)

The thermal stability of the prepared polymer was investigated using TGA technique and the thermogram is shown in Fig. (5). It can be noticed that there is a 3 % weight loss at 244°F due to losing of solvent molecules. The degradation of polymer started at 266°F due to the presence of branching structure and the loss was approximately 10 Wt.% at 446°F then the complete degradation is accomplished at 446°F.

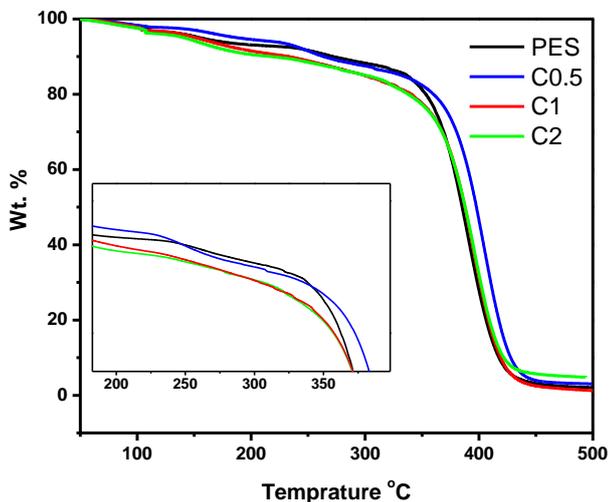


Figure 5: TGA curves of PES and its PES/CuO nanocomposites.

The thermal stability of the prepared nanocomposites based CuO-NPs was also investigated. It was noticed that addition of CuO-NPs to the polyester matrix did not show the expected

enhancement on its thermal stability as 0.5 Wt.% of CuO- NPs has mostly the same thermal behavior of PES. However, results emphasized that increasing CuO percentages in the polymer matrix may not be favorable to increase the thermal stability at higher temperature.

3.7. The influences of the prepared materials on NaCl polymer drilling fluid

3.7.1. The influences of the prepared materials on NaCl polymer drilling fluid using hot roller oven, viscometer, and HPHT filter press at different conditions

The synthesised copolymer and nanocomposites were added to the blank sample of WBM exist in table (1) by 3.5 lb/bbl to form five samples that should be studied. These additives were left to be sheared for 30 minutes at 2500 rpm by the Hamilton Beach mixer. Hot roller oven was used to simulate for down hole conditions. In the first time, the samples were left for 16 hours dynamic aging (25 rpm) at 300°F and 100 Psi (API recommended practice 13B-1). Then, samples were cooled for 30 minutes prior to test the rheology and filtration control properties.

The copolymer PES showed the best rheological and fluid loss properties at a higher temperature as demonstrated in table (2). Furthermore, the rest of additives, 0.5, 1, and 2 Wt.% CuO-NPs, showed adverse effects on both rheology and fluid loss. These results confirm the reliability of thermal stability graphs as the addition of nanoparticles decreases the thermal stability of PES. Shear stresses (θ) at different shear rates (600, 300, 200, 100, 6 & 3) were measured using a viscometer to calculate plastic viscosity (Pv) and yield point (Yp). After that, the two stable samples (Blank & PES) were tested later by a PVS rheometer at 428°F and 1000 psi.

The most thermally stable samples, PES and blank, were newly prepared and tested again with the same procedure at 350°F and 150 Psi using hot roller oven to give the results in Table (3). Table 3 shows the significance in the readings of the rheological properties represented by plastic viscosity and yield point among the samples. Not only the WBM sample fitted with PES gives higher PV, YP and gel strengths at 350°F but also it helps in controlling the fluid loss substantially. The two samples were tested for the last time but after doubling the dose of PES to be 7 ppm using the same

procedure after elevating the temperature and pressure of the cell to be 400°F and 200 psi, respectively.

Table (4) shows that when PES is added to NaCl polymer mud, the thermal stability was enhanced significantly to build a superior fluid. This fluid exhibits high values of YP and PV at 400 °F which makes it the best choice while drilling HPHT wells. The rheological properties were maintained by the addition of PES to WBM. Furthermore, the filtration rate was controlled in the presence of PES. However, at 400°F, the rheological and filtration properties were impaired significantly for the blank sample.

3.7.2. The influences of the prepared materials on NaCl polymer drilling fluid using a PVS rheometer.

The WBM samples that exhibit good thermal stability were taken after hot rolling at 300°F and 100 Psi to be tested using PVS rheometer at more complicated conditions of 428°F and 1000 psi. Table (5) demonstrated the shear stress, viscosity and torque versus various values of shear rates of blank WBM sample.

According to the data acquired from the PVS rheometer for the blank sample, the yield point can be calculated depending on the shear rate values at 300 and 600 rpm. The yield point was calculated using equation (1) to give 7.6 lb/100ft²; a very small value. A failure of the drilling fluid can be indicated by the small values of the yield point which conveys a malfunction in one of its most important function, carrying the cuttings to surface.

$$\text{Shear rate } (\dot{\gamma}) \text{ (sec}^{-1}\text{)} = 1.703 \omega \text{ (rpm)} \{1\}$$

Thus,

Table (2): Influences of different prepared additives on WBM properties at 300°F and 100 psi conditions

Mud properties (WBM)	Blank	PES	C 0.5	C 1	C 2
Mud weight (Pcf)	90	90	80	80	80
θ_{600}	69	98	17	28	24
θ_{300}	44	66	9	16	12
θ_{200}	34	53	6	12	8
θ_{100}	20	35	4	7	4
θ_6	2	7	0	1	0
θ_3	1	5	0	0	0
PV	25	32	8	12	12
YP	19	34	1	4	0
Gel _{10 sec}	1	6	0	0	0
Gel _{10 min}	2	10	0	0	0
HPHT filtrate (ml) at 300°F	50	20	>100	>100	>100
pH	9.5	9.1	7.9	8.4	8

At $\dot{\gamma} = 510$, $\omega = 300$ and at $\dot{\gamma} = 1020$, $\omega = 600$

$$\theta_{300} = 203.4 \text{ dyne/cm}^2 \text{ \& } \theta_{600} = 370.5 \text{ dyne/cm}^2$$

$$\text{Yield point (YP, dyne/cm}^2\text{)} = 2 * 203.4 - 370.5 = 36.3 \text{ dyne/cm}^2$$

$$\text{YP (Pa)} = 36.3 / 10 = 3.63 \text{ Pa}$$

$$\text{YP (lb/100ft}^2\text{)} = 3.63 / 0.4788 = 7.6 \text{ lb/100ft}^2$$

Table (6) shows the effect of PES addition on the rheological properties of WBM after exposing it for two hours at 428°F and 1000 psi by a PVS rheometer. The relations between shear stress and viscosity vs shear rate were illustrated in Fig.10A and Fig.10B, respectively.

According to the shear stress/ shear rate data acquired from the PVS rheometer and illustrated in Fig.10A, the yield point was calculated as described above to be 40.6 lb/100ft². The high value of the yield point proclaims that PES has a significant effect on the thermal stability of WBM. Fig.10B demonstrates a shear thinning behavior of the drilling fluids; as the viscosity was slightly changed at high shear rates. Most drilling fluids exhibit a shear thinning behavior which means viscosity always decreased by increasing shear rates. The torque was measured using the PVS rheometer at 428°F and 1000 psi for two samples, WBM blank and WBM treated with PES. Fig.10C shows the differences in torque percentages between WBM blank and WBM treated with PES and demonstrated that the blank sample exhibited high torque values while adding PES to WBM resulted in a significant reduction in the torque approached 8.1 % at the highest shear rate.

Table (3): Influences of PES on mud rheology and fluid loss at 350°F and 150 psi conditions

Mud properties (WBM)	Blank	PES
Mud weight (Pcf)	90	90
θ_{600}	47	78
θ_{300}	29	49
θ_{200}	18	36
θ_{100}	11	25
θ_6	1	6
θ_3	1	5
Pv	18	29
Yp	11	20
Gel _{10 sec}	1	6
Gel _{10 min}	2	9
HPHT filtrate (ml) at 350°F	> 100	26
pH	9	8.8

Table (4): Influences of PES on mud rheology and fluid loss at 400°F and 200 psi conditions

Mud properties (WBM)	Blank	PES
Mud weight (Pcf)	80	90
θ_{600}	33	79
θ_{300}	19	51
θ_{200}	12	40
θ_{100}	7	31
θ_6	0	6
θ_3	0	5
Pv	14	28
Yp	5	23
Gel _{10 sec}	0	5
Gel _{10 min}	0	8
HPHT filtrate (ml) at 400°F	> 100	28
pH	8.5	8.4

Table (5): The PVS rheometer readings of the WBM blank sample

Viscosity (CP)	Torque %	Shear rate (1/sec)	Shear stress (Dyne/cm ²)
769.3	14.8	84.9	81.5
644.5	14.9	127.5	92.2
550.3	15.1	169.9	99.7
411.0	15.8	212.5	111.0
316.0	16.9	255.0	119.9
260.1	17.2	297.4	128.8
199.5	18.7	339.9	141.1
162.8	18.9	382.4	155.6
111.5	19.3	425.0	169.0
92.7	19.8	467.5	186.2
83.4	20.5	510.0	203.4

76.2	21.3	552.5	225.1
65	22.4	595.0	237.5
61.1	22.9	637.5	249.2
56.5	23.9	680.0	266.8
50.6	24.1	722.5	278.0
49.3	24.4	765.0	290.7
42.9	24.9	807.5	303.9
37	25.2	850.0	315.3
32.5	26.1	892.5	331.4
30.8	26.5	935.0	342.1
27.1	26.9	977.5	356.6
25.2	27.2	1020.0	370.5

Table (6): PVS rheometer readings of WBM sample fitted with PES

Viscosity (CP)	Torque %	Shear rate (1/sec)	Shear stress (dyne/cm ²)
940.6	6.8	84.9	251.7
830.0	6.9	127.5	266.5
750.2	7.1	169.9	277.2
674.4	7.2	212.5	292.0
590.1	7.3	255.0	325.5
485.3	7.6	297.4	344.2
328.0	7.7	339.9	366.0
246.0	8.5	382.4	390.2
203.5	8.7	425.0	418.2
172.4	9.2	467.5	430.5
133.5	9.3	510.0	446.1
90.8	9.9	552.5	465.5
85.9	10.9	595.0	488.2
74.5	11.3	637.5	507.0
74.0	11.6	680.0	533.5
73.6	12.9	722.5	564.4
68.3	13.5	765.0	591.2
66.2	14.9	807.5	611.8
62.7	15.8	850.0	630.7
61.6	17.2	892.5	644.2
61.1	18.4	935.0	662.3
60.0	18.7	977.5	677.1
59.2	19.1	1020.0	697.4

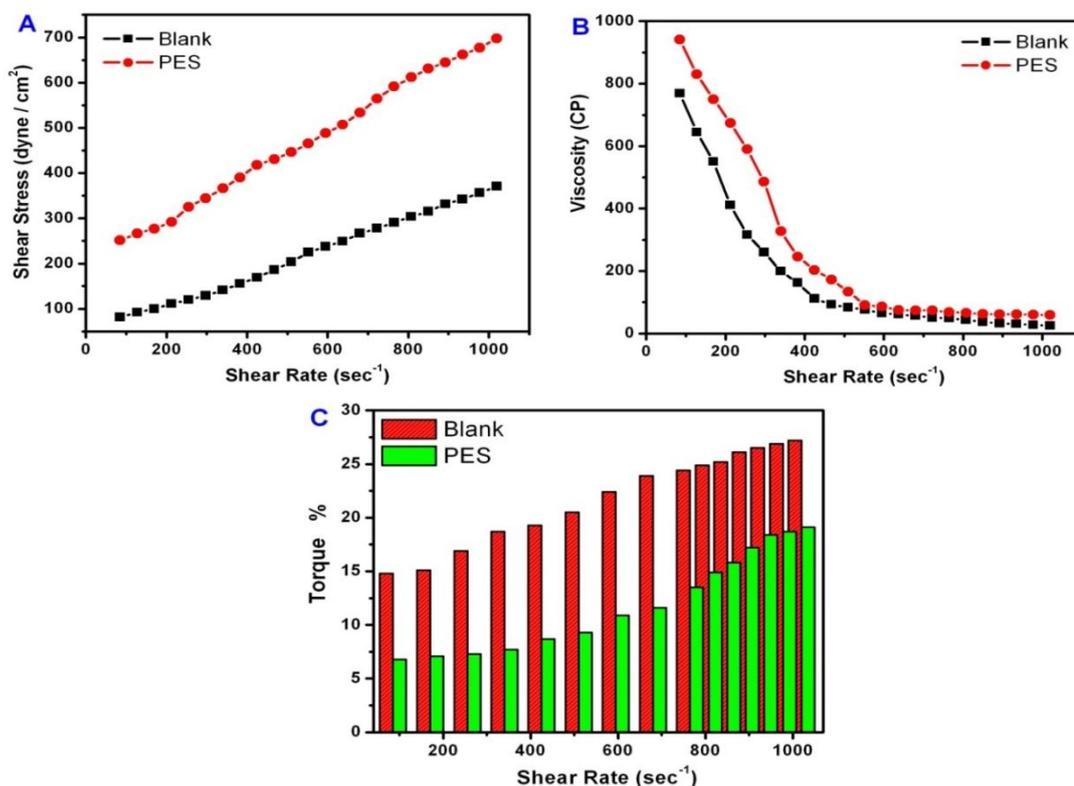


Figure (10): [A] Shear stress vs shear rate of blank and PES WBM samples. [B] Viscosity vs shear rate of blank and PES WBM samples. [C] Torque percentage vs shear rate of blank and PES WBM samples.

4. Conclusions

Novel polyester and its CuO nanocomposites have been prepared via copolymerization and in-situ polymerization approaches, respectively. FTIR, NMR, and TEM confirmed successful preparation of the copolymer and its nanocomposites. TGA emphasized that 0.5 Wt.% of CuO- NPs is the best concentration added to the prepared copolymer. The samples obtained were evaluated under the conditions of HPHT. The results showed the following:

- (i) The yield point of normal WBM was the only stable parameter when it was exposed to a temperature of 300°F.
- (ii) Impairment of gel strengths and fluid losses was exhibited at 300°F for all samples except the one developed by PES.
- (iii) The PES copolymer has a great effect on WBM rheology and filtration properties at a temperature beyond 400°F.
- (iv) The obtained nanocomposites showed adverse influence on WBM.

(v) Adding PES to WBM could reduce torque by 8.1% which could enhance the drilling operation and reduce NPT.

(vi) Copolymerization technology plays a vital role to enhance mainly WBM rheological and filtration properties.

These findings emphasize the feasibility of using the copolymer PES compared to the prepared nanocomposites. Also, it could be assumed that using of the nanoparticles is not favorable all the time in WBM as usually reported. It would have environmental and economic impacts while minimizing usage of the nanomaterials because of the hazardous effect of the nano sized particles.

5. Conflicts of interest

Authors declare there is no conflict of interest.

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7. References

1. Adamson, K., Birch, G., Gao, E., Hand, S., Macdonald, C., Mack, D., & Quadri, A. (1993). High-pressure, high-temperature well construction. *Oil field Review*, 5, pp.15-32.
2. Ghosh, K., Guru, U., and Banik, S., (2013) 'Unlocking the Mystery of Formation Evaluation in the Hostile Conditions of the Krishna- Godavari Basin', *Biennial International Conference & Exposition*, pp.1-5.
3. Trotter, N., Parish, C., (2008) 'New XHPHT Drilling Fluid Used to Successfully Drill Deep Bossier Sands in Central Texas', *American Association Drilling Engineers*, 15, pp.1-6.
4. Debrujin, G., Greenaway, R., Harrison, D., James, S., and Temple, L. (2008) 'High Pressure-High temperature technologies', *Oil Field Review*, 7, pp. 46-60.
5. Crumpton, H., (2018) 'Well Control Surface Equipment', *Well Control for Completions and Interventions*, pp.137-183.
6. Amalu, E. H., Ekere, N. N., & Bhatti, R. S. (2009) 'High temperature electronics: R&D challenges and trends in materials, packaging and interconnection technology', In *2009 2nd International Conference on Adaptive Science & Technology (ICAST)*, pp. 146-153.
7. Shadravan, A., and Amani, M., (2012) 'HPHT 101-What Petroleum Engineers and Geoscientists Should Know About High Pressure High Temperature Wells Environment', 4, pp. 36-60.
8. Craig, B., (2008) 'Materials for Deep Oil and Gas Well', *Powering the Future*, pp. 33-35.
9. Shrivastav, P., (2012), An Integrated Approach towards Well Control for a HPHT Well, *Offshore Technology Conference*, pp.1-6.
10. Bourgoyne Jr, A. T., Millheim, K. K., Chenevert, M. E., & Young Jr, F. S. (1986). 'Applied drilling engineering', Volume 2, pp.42-82.
11. Baird, T., Fields, T., Drummond, R., Mathison, D., Langseth, B., Martin, A., & Silipigno, L. (1993) 'High-pressure, high-temperature well logging, perforating and testing', *Oil field Review*, 5, pp. 15-32.
12. Rajendra, K. W. S. et al., (2010) 'Challenges in Well testing of HPHT Low permeability wells - Case histories', pp. 1-8.
13. Micheal, W., (2000) 'High temperature application of drilling specialties polymers for filtration control', *Drilling Specialties*, pp.1-10.
14. Nasiri, A., Solyemani, M., and Motlagh E., (2012) 'Design of Water-based Drilling Fluids for Obtaining High-Quality Fluid properties during the drilling operation', pp.1-5.
15. Echt, T., & Plank, J. (2019). An improved test protocol for high temperature carrying capacity of drilling fluids exemplified on a sepiolite mud. *Journal of Natural Gas Science and Engineering*, 70, 102964.
16. Bland, R. et al., (2006) 'HP/HT Drilling Fluids Challenges', *Asia Pacific Drilling Technology Conference*, pp. 1-11.
17. Al-arfaj, M., & Al-abdullatif, Z., (2011) 'Preliminary Test Results of Nano-based Drilling Fluids for Oil and Gas Field Application', *SPE*, pp.1-9.
18. Ismail, A. R., Rashid, N. M., Jaafar, M. Z., Sulaiman, W. R. W., & Buang, N. A. (2014) 'Effect of nanomaterial on the rheology of drilling fluids', *Journal of Applied Sciences*, 14, pp.1192.
19. Eghbal, M., and Behzad, S., (2017) 'Hydrophobic silica nanoparticle-stabilized invert emulsion as drilling fluid for deep drilling', *Petroleum Science*, 14, pp.105- 115.
20. Amani, M., Al-Jubouri, M., & Shadravan, A. (2012) 'Comparative study of using oil-based mud versus water-based mud in HPHT fields', *Advances in Petroleum Exploration and Development*, 4, pp.18-27.
21. Xie, B. Q., and Feng, P. (2014) 'Novel Modified Humic Acid as Effective Fluid Loss Agent for Oil Based Drilling Fluid', *Electronic Journal of Geotechnical Engineering*, 19, pp. 4093-4100.
22. Mensah, E., (2016) 'Effect of AL₂O₃ Nanoparticles on the Rheological Properties of Water Based Mud', *International Journal of science and engineering applications*, 5, pp. 7-11.
23. Al-Ogaili, F., and Suripis, N. (2016) 'Evaluation of Nanoparticles in Enhancing Drilling Fluid Properties', *International*

-
- Journal of Scientific & Engineering Research*, 7, 1489-1497.
24. Abdulkadir, M., (2015) 'Effect of Fe₄O₃ Nanoparticles on the Rheological Properties of Water Based Mud', 5, pp. 415-422.
 25. MI Manual, (2001) 'standard procedure for testing drilling fluids', *American Petroleum Institute*, Dallas, Texas, 1st ed.
 26. Schlumberger, (1994), drilling fluid manual, 1st Ed.
 27. Baker H. I., (1995), *Drilling Engineering Workbook*, Houston, TX. 15.
 28. Nur, S., Dody, N., and Rejeki, H. S. (2005) 'Laboratory study of high temperature additive to rheology properties of drilling mud under dynamic conditions', In *Proceeding World Geothermal Congress, Antalya, Turkey*, 24, p. 29.
 29. Nassar, A. M., Ahmed, N. S., Abd El-Aziz, K. I., Abdel Azim, A. A. A., and El-Kafrawy, A. F. (2006). 'Synthesis and evaluation of detergent/dispersant additives from polyisobutylene succinimides', *International Journal of Polymeric Materials*, 55, pp. 703-713.
 30. Brikov, Av., Markin, An., and Sukhoverkhov, Sv., (2015) 'Rheological Properties of Polyethylene Glycols Solutions and Gels', *Industrial Chemistry*, 1, PP.1-5.
 31. Noah, A. Z., El Semary, M. A., Youssef, A. M. and El- Safty, M. A. (2017). Enhancement of Yield point at High pressure High temperature wells by using Polymer nanocomposites based on Zinc oxide& Calcium carbonate nanoparticles. *Egyptian Journal of Petroleum*, 26, 33-40