

Nanocarbon-based enhanced squeeze treatment for improved scale management

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Abstract. Oil and gas industry is facing dilemma regarding scale management particularly for offshore production activities in ultra-deep waters under high pressure-high temperature (HPHT) conditions. Scale inhibition squeeze treatment widely employed technique for scale control. However, at HPHT conditions, routine conventional chemistries for scale mitigation are ineffective and unviable. This paper presents promising advantages of employing nanotechnology to enhance conventional scale squeeze treatment. Experimental studies were carried out to examine the potential benefits of using Graphene Oxide (GO) and Carbon nanotubes to increase the adsorption and retention of EDTA scale inhibitor onto reservoir rock in a process coined as 'Nano-carbon Enhanced Squeeze treatment (NCEST)'. This process involves treating the reservoir rock in the near wellbore region with nanomaterials that rendered increased active surface area for scale inhibitor adsorption. Stronger bonding was witnessed between EDTA and reservoir rock which accounts for better retention of EDTA. Test analysis of coreflood experiments were conducted by the aid of FESEM, EDX and UV-visible. Application of the proposed NCEST model was observed to significantly increase adsorption of EDTA on rock core sample treated with GO to achieve maximum scale inhibitor adsorptive capacity of 180mg/g as compared to 51mg/g when treated without nanomaterial.

Keywords: Scale Inhibitor; Squeeze Treatment; Graphene Oxide; Carbon Nanotubes; Organosilane

1. Introduction

The formation of mineral scale associated with production of hydrocarbon has been a major strain in oilfield operations. Scale mass is formed by precipitation due to chemical reactions as ions that are dissolved in produced water react with each other to form an insoluble solid [1]. Relative to the nature of the scale and formation fluid composition, scale deposition can take place within a reservoir which causes formation damage or in the production system where blockage can cause severe operational problems. Solid scale deposition in the producing reservoir matrix can lead to irrevocable and permanent formation damage, eventually cutting-off production by building-up in the near wellbore region by plugging reservoir pore throats and perforations of the production tubing. If not remediated, continuous



scale deposition can narrow-down or even completely choke production tubing and flow lines as shown in figure 1. Pipeline plugging due to scale deposition can result in drastic hike in operational pressure drop thereby reducing well productivity which is economically unwarranted and pose acute safety hazards. Scale formation also gives impetus to corrosion phenomenon. The most common type of scale found in wells is caused by the formation of sulfate and carbonate scales of Calcium and Strontium [2, 3]. Brine is the primary cause of calcite and sulfate scales formation.



Figure 1. Pipeline with constricted diameter due to scale deposition [1]

Scale removal is a common well-intervention operation with a wide range of mechanical, chemical and scale inhibitor treatment options. Scale inhibitor squeeze treatment is the most frequently used and effective scale prevention and mitigation technique [1, 4, 5]. In this technique, about 10% of the commercial inhibitor chemical is pumped downhole (squeezed) at high injection pressures in order to partially adsorb on the reservoir rock followed by 12-24 hours well shut-off for its retention [5]. The adsorbed and retained chemicals on the reservoir rock act as storage. During production, flow of reservoir formation water desorbs and dissolves this stored scale chemical which flows into the production and distribution system to mitigate scale formation process.

Scale inhibitor adsorption and subsequent retention onto the producing formation rock is of paramount importance which determines the effectiveness (success) of squeeze treatment. Squeeze treatment lifetime can be defined as the volume of water produced by a well before the retained inhibitor concentration dwindles below the critical threshold concentration value referred as minimum inhibitor concentration (MIC) or minimum effective dose (MED) [4]. Inhibitor concentration below MIC/MED makes it incapable to prevent scale formation phenomenon.

This conventional squeeze treatment is exorbitant due to high chemical cost and pumping requirements for its injection into the reservoir. Well has to be shut for about 12-24 hours [4] for implementation of this treatment which causes production loss and consequently translates into lesser revenue generation. Significant quantity of scale inhibitor chemical is lost into cracks of reservoir matrix due to high pressure injection and low adsorption. The efficiency of squeeze treatment needs to be improved as it is essential for petroleum industry by enhancing adsorption and long retention of scale inhibitor chemical onto the reservoir rock surface.

1.1. Nanotechnology application for scale inhibition

In light of recent interest in nanotechnology application in oil and gas industry, research efforts are being oriented towards exploring the role of nanomaterials to improve and enhance conventional squeeze treatment process widely applied for scale control. By analyzing the adsorption of conventional squeeze treatment, it can be deduced that lack of availability of suitable active surface for scale inhibitor adsorption is one of the primary reasons for ineffective squeeze treatment with short squeeze lifetimes [4, 5]. Furthermore, weak interactive bonding between the scale inhibitor and the reservoir rock surface is also mainly responsible for premature inhibitor flush-out when water starts to leach out of the reservoir matrix at certain flow rates [4-6].

In order to address the shortcomings of conventional squeeze treatment, injection of highly dispersed GO and CNTs nanomaterials into the reservoir is suggested and investigated as illustrated in figure 2.

A proactive dispersion strategy is utilized to achieve high dispersion of the stated nanomaterials. It is hypothesized that highly dispersed nanomaterial may provide high active surface area for EDTA scale inhibitor adsorption and retention thereby mitigating the negative outcomes of squeeze treatment by enhancing its lifetime.

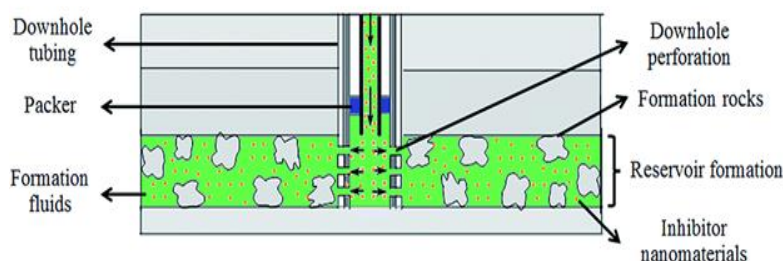


Figure 2. Dispersed nanomaterial injection in downhole region [6]

1.2. MWCNTs and GO nanomaterial

Multiwall carbon nanotubes (MWCNTs) have an elastic modulus of about 1TPa and tensile strength of 100GPa [7], which is over exponentially higher than any industrial fiber. They have high thermal stability and conductivity of $3500 \text{ Wm}^{-1} \text{ K}^{-1}$ at room temperature [8], which can conveniently sustain harsh reservoir conditions. MWCNTs have features of dispersion, deposition and functionalization. They are emerging as a multi-dynamic coating material providing high active surface area for various applications [9]. GO has easy dispersibility in water, organic solvents and different matrixes due to the presence of oxygen functionalities [10, 11]. They can be mixed with ceramic or polymer matrixes to tailor and induce superior mechanical and thermal attributes. They are strong material which can be transformed into paper thin coating films [12]. This structure of CNTs and GO as shown in figure 3 which needs to be explored and hence utilized for wide range of applications.

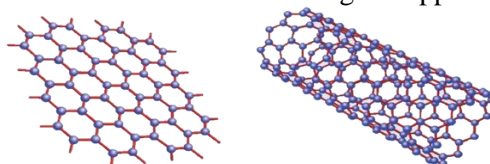


Figure 3. Structure of Graphene (left) and Carbon Nanotubes (right) structure

2. NCEST methodology

The Nano-Carbon Enhanced Squeeze Treatment (NCEST) is a proposed methodology that focuses on enhancing the adsorption of scale inhibitors onto the rock surface to enhance the squeeze treatment lifetimes. This is done by modifying the chemistry of the rock surface using ethyl cellulose as a binder agent. NCEST methodology can be explained in the following steps:

- i. Deposition of a binder on a surface of the core sample.
- ii. Coating nanomaterials to the surface of the core sample to allow adherence between the GO and CNTs nanomaterials and ethyl cellulose by chemical interaction by the aid of core flooding.
- iii. Coating certain concentration of scale inhibitor in the modified core by the aid of core flooding.
- iv. Adsorbed scale inhibitor is gradually leached-out from the core during water production.

This methodology is divided into three experiments namely experiment A, B and C as illustrated in figure 4. Experiment A tests out the feasibility of employing nanomaterials to enhance scale inhibitor squeeze treatment by conducting adsorption test at static condition. Whereas experiment B and C test feasibility of employing nanomaterial in dynamic conditions by the aid of core flood testing.

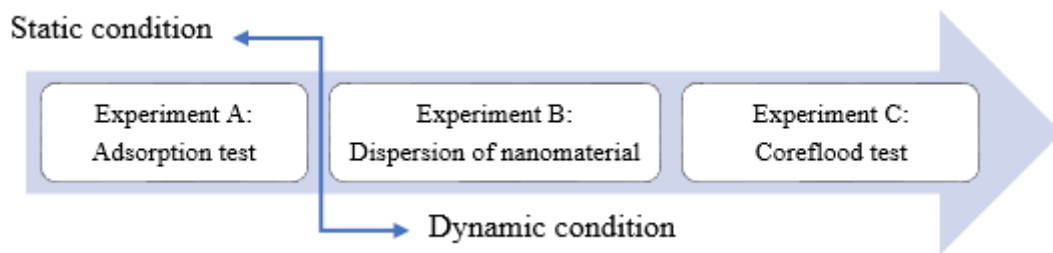


Figure 4. Experimental division of NCEST methodology

3. Materials and methods

Multi-walled carbon nanotubes (MWCNT) were supplied in powder form by Carbon Nano-material Technology Co. Ltd with ~15 nm diameter and ~5 μm length. Reduced Graphene Oxide was procured from Sigma-Aldrich in the form of aqueous dispersed solution stabilized with poly (sodium 4-styrenesulfonate). Calcium chloride dihydrate ($\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$) and ethylene-diamine tetraacetic acid (EDTA) were used as provided from laboratory. Ethyl cellulose and Sodium Dodecyl Sulphate (SDS) surfactant in powder form were supplied by Merck. Probe Sonicator (model: Q-sonica 500) was used to mechanically disperse nanofluid solutions. Ultra-visible (UV-vis) spectrophotometer (model: Agilent Technologies – Cary 60) was used to characterize concentrations of the prepared solutions. Coreflood tests were performed using Vinci-Technologies Bench Top Permeameter system (BPS-350). The porosity and permeability of Berea sand stone core plug was determined by using Vinci-Technologies Poroperm Coval 30 equipment. Scanning Electron Microscope (SEM) (model: Hitachi H-7500) was used for micro-imaging analysis. PVDF Syringe Filter with pore size of 0.45 μm supplied from Ricco Labstore was used to filter the prepared solutions.

3.1. Experiment A: Adsorption test

The first part of this NCEST methodology involves examination of adsorption of scale inhibitor onto the nanomaterials. It is the most fundamental part in this study as it gives indication of improvement in squeeze lifetimes. EDTA scale inhibitor was employed in this treatment. Adsorption tests were conducted both in static and dynamic conditions. For static conditions, the experiment was carried out by simply stirring the nanomaterials with EDTA for 24 hours in ambient temperature and pressure.

3.1.1. Experimental procedure. 300 ml of 0.05 M EDTA in distilled water (DW) was prepared. 4 ml sample of EDTA in DW solution was taken to be used as initial concentration. 300 ml of brine solution was prepared by diluting 1147.8 mg of calcium chloride dihydrate ($\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$) salt in 300 ml DW. 0.05 M EDTA was prepared in the brine solution. 4 ml sample of EDTA in brine solution was taken as initial concentration. 50 ml of 0.05 M EDTA in water/brine solution was then poured into 6 beakers. Desired amount of nanomaterial (refer table 1) was added into each of the beaker and magnetically stirred using magnetic stirrer. After 1 hour, 4 ml of the solution was filtered using 0.45 μm syringe filter for UV-Vis measurement. The solution was then left to be stirred for another 23 hours. After 24 hours, 3 ml of the solution is taken and filtered using syringe filter for UV-Vis measurement.

Table 1. Adsorption test preparation

Sample	Nanomaterials	Weight
A	CNTs	100 mg
B	GO	10 ml
C	CNTs + GO	50 mg CNTs + 5 ml GO

3.2. Experiment B: Dispersion of nanomaterials

Nanoparticles have the tendency of being conveniently agglomerate due to van der Waals forces of attraction which may plug the porous medium. Dispersing the nanomaterial is of critical importance in order to avoid plugging of the wellbore during nanofluid injection. Several dispersing agents such as surfactants have been identified as being principally good at dispersing carbon-based nanomaterials such as GO and CNTs [13], which include N-methyl-2-pyrrolidone (NMP), Sodium Dodecyl Sulphate (SDS), Dimethyl Sulfoxide (DMSO), N,N-dimethylformamide (DMF) etc. Highly dispersed CNTs and GO enables to formulate stabilized nanofluid that can offer high active surface area to chemically bind scale inhibitor chemical for enhanced squeeze treatment along with superior rheological characteristics for its injection into the reservoir.

In order to attain high dispersed of CNT/GO nanofluid, 1000 ml of 2% Sodium Dodecyl Sulphate (SDS) surfactant was prepared by diluting it in distilled water (DW). Three beakers each were filled with 200 ml of the SDS solution. Desired amount of nanomaterial (refer Table 2) was added into the SDS solution followed by putting the beaker in an ultrasonic bath for 2 hours followed by sonication for 5 min for each prepared solution. The solutions were left static under the influence of gravity for 24 hours for any unfunctionalized and undispersed CNTs/GO to precipitate and settle at the bottom of the beakers. Only the upper solution suspension (top half) was used in the next experiments to ensure that the nanomaterials used are well dispersed and eviscerate the possibility of agglomerated nanoparticles.

Table 2. Dispersion test preparation

Beaker	Nanomaterials	Weight
A	CNTs	40 mg
B	GO	4 ml
C	CNTs + GO	20 mg CNTs + 2 ml GO

3.3. Experiment C: Coreflood testing

Coreflood testing was performed to simulate NCEST methodology (refer 2.0) at dynamic conditions by using Vinci-Technologies Bench Top Permeameter system (BPS-350). The CNTs/GO nanofluid was injected into the Berea sandstone core plugs. The length, diameter and weight of the core plugs were measured using Vernier caliper and weighing balance, while their porosity, permeability and pore volume were calculated by Poroperm test using Poroperm Coval 30 equipment.

10 PV of brine solution was prepared by adding 3.812 g/l sodium chloride (NaCl) and 3.826 g/l calcium chloride dihydrate ($\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$) powder in distilled water. 10 PV of 1775 ppm EDTA and DW solution was prepared by adding EDTA salt into distilled water and stirred using magnetic stirrer. The coreflood test was performed at room temperature at the flow rate of 1 ml/min. 10 PV of cellulose was injected into the core followed by shutting it for 1 hour. 10 PV of dispersed nanomaterial solutions were injected into the core shutting it for 24 hours. Then, the core was rinsed with 10 PV of brine solution. 10 PV of EDTA in DW solution was injected into the core and the effluent samples were taken for UV-Vis measurement. The core was again shut for further 24 hours. Post-flushing was performed using DW again UV-Vis measurement of the effluent was performed. Lastly, SEM analysis was conducted on a miniscule piece of the core plug.

3.3.1. Experimental procedure: Baseline core flooding. 10 PV of EDTA and DW solution was injected into the core and effluent sample was taken for UV-Vis measurement. The core was shut for 24 hours to enable the EDTA to adsorb on the rock. The core was afterwards rinsed with 10 PV of brine solution. Background solution (DW) is pumped into the core and effluent samples were taken for UV-Vis measurement. Core sample was analyzed for FESEM micro-imaging.

4. Results and discussion

4.1. Stage 1: Adsorption Test

UV-Vis spectrophotometry is a type of adsorption spectroscopy which operates in ultraviolet-visible region. The concentration of a particular solution is determined by degree of incident light absorbance by the solution which is translated into a concentration value by using Beer-Lambert law. This law states that the absorbance of a solution is directly proportional to the concentration of the absorbing species in the solution and the path length [14]. Concentration of an unknown solution can be calculated by preparing a standard solution with pre-set known concentrations. The standard can range from the lowest to maximum concentrations the sample can achieve. In this experiment, the initial concentration of EDTA in DW/Brine was set at 0.05M [3]. After the adsorption experiment, its concentration is expected to decrease. Hence, the concentrations of standard solutions that were prepared were EDTA in DW/Brine of 0.01M, 0.02M, 0.03M, 0.04M, 0.05M and 0.06M.

Flocculated CNTs are not active in the UV-vis region [15, 16]. Only individual singled-out CNTs absorb in this region. In order to characterize the dispersion and concentration of CNTs in dispersant solution, UV-vis spectroscopy absorbance values were recorded at 200 nm illustrated by UV-vis spectra as shown in figure 5. After the standard solutions were prepared and tested using UV-vis equipment, plot of absorbance vs concentration was drawn as shown in figure 6. The absorbance value must be taken at the same wavelength of 200nm as a control. It is assumed that at this wavelength, the Beer-Lambert law is well-obeyed by CNTs and absorbance is minimally affected by the ambient conditions of CNTs. Plotted graph will validate the assumption of Beer-Lambert law by looking for a straight-line relationship of the data.

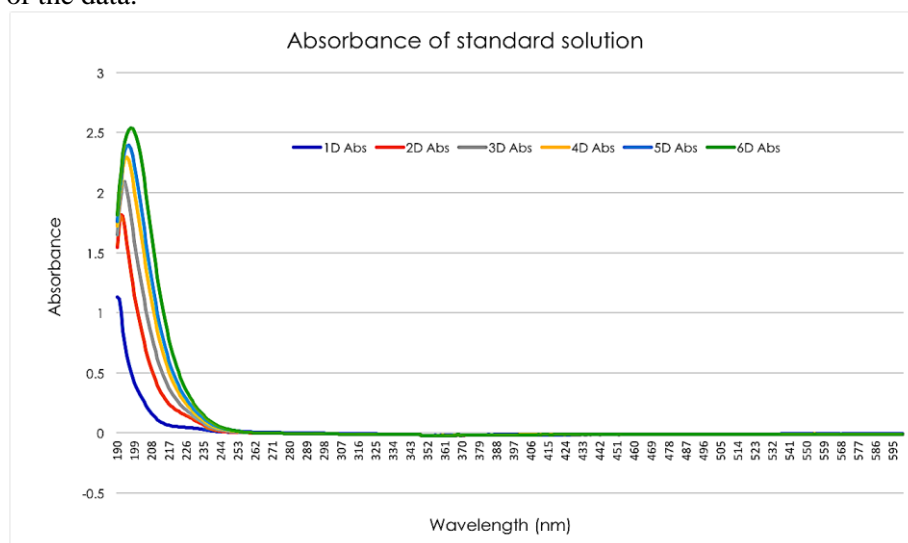


Figure 5. Absorbance spectra of UV-Vis measurement

The line plot shown in figure 6 can be used to determine the concentration of an unknown sample from its absorbance value by interpolation. This is done by drawing a horizontal line from the y-axis at samples' absorbance value until it intersects the best fit line. Then, a vertical line is drawn from that point to the x-axis. The x-value at this point is the concentration of the sample. The second method that can be used to determine the concentration is by simply calculating the value using equation of the straight line of the graph as shown in equation (1).

$$y = 42.451x + 0.0694 \quad (1)$$

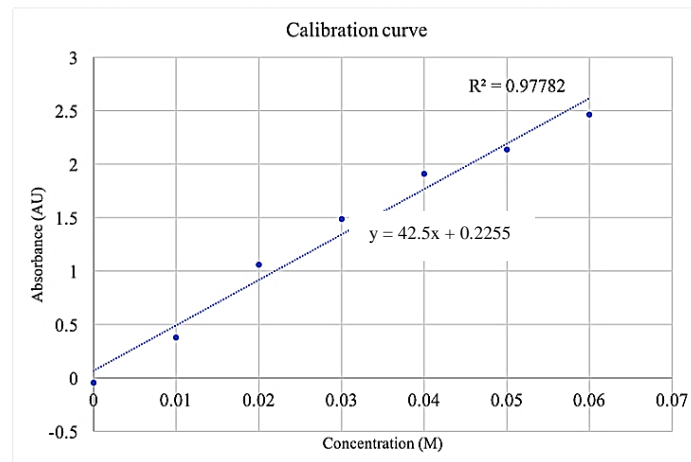


Figure 6. Plot of standard solution

Based on the samples' absorbance values measured by UV-Vis spectrophotometry testing, bar charts of concentration of EDTA in DW/brine against types of nanomaterials were constructed and shown in figure 7 and figure 8.

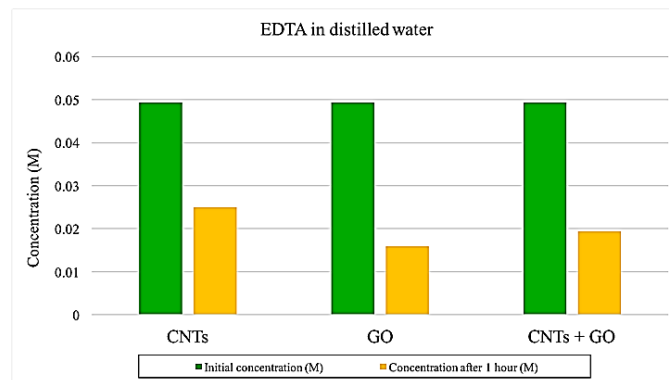


Figure 7. Concentration of EDTA in DW before and after 1 hour of stirring

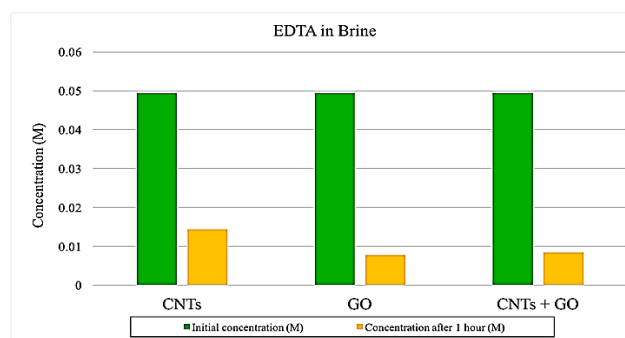


Figure 8. Concentration of EDTA in Brine before and after 1 hour of stirring

The significant difference in concentration value of EDTA before and after the stirring process shows that a significant amount of EDTA scale inhibitor has been adsorbed onto the nanomaterials. Quick adsorption of EDTA on the nanomaterials can also be observed from this experiment as only 1 hour is needed for the EDTA to be effectively adsorbed. From the initial and final concentrations of EDTA in DW/brine for different nanomaterials, the concentration reduction of EDTA in varying nanomaterials was calculated to clearly differentiate which nanomaterials managed to reduce the highest concentration

of EDTA over an hour. Apart from that, the adsorption capacities (q) of the nanomaterials were also calculated using equation (2) as below. Its results are tabulated in table 3.

$$q = \frac{(C_i - C_f) \times V}{W} \quad (2)$$

q = Adsorption capacity (mg/g); C_i = Initial concentration (mg/l); C_f = Final concentration (mg/l);
 V = Volume of adsorbent used (l); W = Weight of the adsorbent (g)

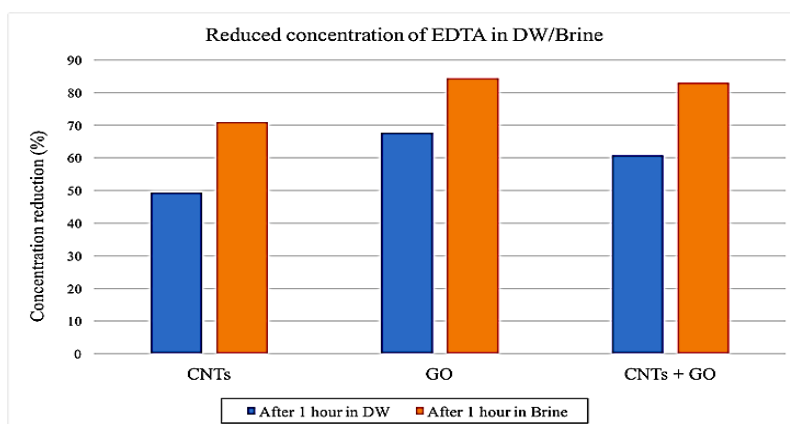


Figure 9. Concentration reduction (%) of EDTA in different nanomaterials and background solution

Table 3. Adsorption capacity of different nanomaterials in varying base solution

Adsorption capacity q (mg/g)	CNTs	GO	CNTs + GO
DW	432.9	594.4	532.8
Brine	621.8	739.4	728.3

Figure 9 and table 3 shows that the best performing nanomaterial to be Graphene Oxide (GO). This can be clearly seen as GO gives the highest reduction in EDTA concentration compared to CNTs and CNTs + GO in both distilled water and brine as the background solutions. This may be due to the structural properties of the GO which are analogous to graphene. Since graphene has a more sheet-like structure when compared with CNTs which are cylindrical nanostructure, graphene particles have lower tendency to agglomerate with each other. On the other hand, CNTs are more prone to agglomeration due to the presence of van der Waals force acting between them. Agglomeration of the CNT nanoparticles reduces its efficiency as an adsorbent as less active surface area is available for adsorption of scale inhibitor. When compared with CNTs, GO provides higher activated surface area rendering more potential to adsorb higher amounts of scale inhibitor required for effective scale squeeze treatments.

Apart from the different nanomaterials, type of background solution used also plays a significant role in enhancing the adsorption of scale inhibitor onto the nanomaterials. In this experiment, two types of background solutions were used which are distilled water and brine. Brine is a solution of calcium chloride dihydrate ($\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$). The purpose of using brine is to investigate the adsorption ability of EDTA scale inhibitor in the presence of calcium ions (Ca^{2+}). From results shown in figure 9, it was observed that the adsorption of EDTA in brine as the background solution is consistently higher than in distilled water. This indicates that the presence of calcium ions plays an important role to bond/adsorb scale inhibitor with the nanomaterial. The calcium ions in the brine solution calcium-functionalize the nanomaterial which conveniently bonds with the negatively charged scale inhibitor molecules as shown in figure 10.

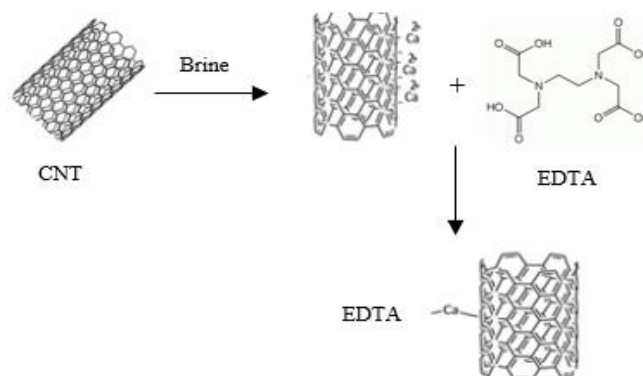


Figure 10. Schematic of EDTA adsorption on CNT in brine solution in the presence of calcium ions. From static adsorption test (Experiment A), it can be concluded that GO is the better nanomaterial to be used as an adsorbent to enhance scale inhibitor adsorption ability. GO was screened and used in the next stage of NCEST methodology which is the dynamic adsorption test.

4.2. Stage 2: Coreflood test

After necessary injection, flooding processes were performed at the flow rate of 1 ml/min. The effluent samples from the coreflood equipment were collected and sent for UV-Vis spectrophotometry measurement. To measure the effectiveness of using nanomaterials to enhance the adsorption of scale inhibitor into the formation rock, the experiment was conducted with two core samples; one with nanomaterial injected and the other without nanomaterial injected (baseline). The results of these two core samples were compared and further analysis were carried out. To analyze the concentration of samples before and after the coreflood run, the process goes through the same flow scheme as in Experiment A. The absorbance value at 200 nm wavelength was taken and interpolated in the calibration curve to reveal its concentration value. After, a graph of concentration against core samples was drawn.

From the results illustrated in figure 11, there is a marked difference in SI concentrations for core sample treated with GO nanomaterial compared to the core sample treated without GO, showing that more adsorption takes place on the core sample that was treated with nanomaterials. This is due to the coating and penetrative potential of GO that provides high surface area platform with active sites for the adsorption of EDTA scale inhibitor on the substrate. Low value of final concentration of EDTA also implies that there is a good retention of EDTA on the formation. The adsorption capacity of EDTA for both cases are calculated and illustrated in figure 12 and table 4.

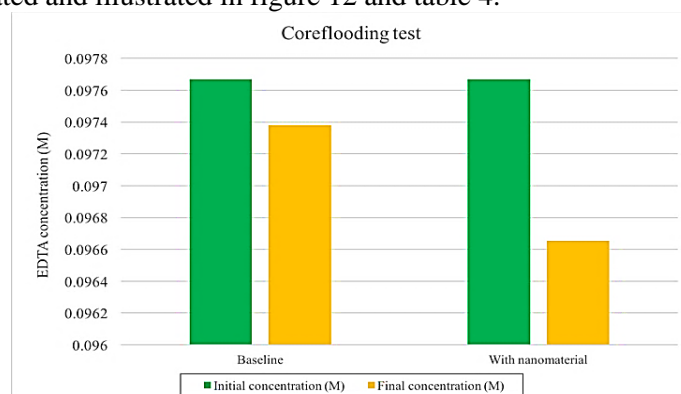


Figure 11. Concentration of EDTA before and after shut in for 24 hours

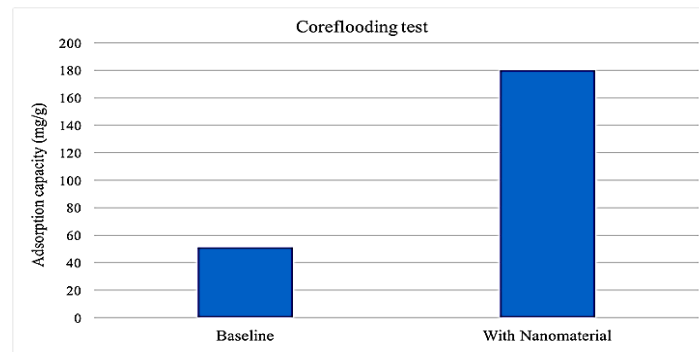


Figure 12. Adsorption capacity of EDTA on core samples

Table 4. Adsorption capacity of EDTA on core samples

Core sample	Adsorption capacity (mg/g)
Baseline	51
With nanomaterials	180

In this dynamic adsorption testing, GO is used as the nanomaterial rendering maximum adsorptive capacity of 180mg/g for EDTA. While in static adsorption testing (Experiment A), the adsorption capacity of EDTA on GO is approximately ~590 mg/g. This is because in dynamic adsorption test, not all of the surface area of GO is in contact with the EDTA. Coreflood test can best simulate the scale squeeze treatment process yielding pragmatic adsorptive capacity estimate value which provides a clear indication of the degree of effectiveness of the treatment.

4.3. Field Emission Scanning Electron Microscopy (FESEM) analysis

After coreflood testing, a small fraction of the core samples was tested for FESEM analysis. This analysis was done to examine the topographical and elemental information of nanoparticles and EDTA on the rock surface at a high magnification. Images in figure 13 depicts the graphene structure on the rock surface, which is clear evidence of nanomaterials attachment on the rock surface. In addition, this FESEM imaging tool has added feature of Energy Dispersive X-ray (EDX) system that analyzes the elemental content on the rock. Results from EDX can be pre-programmed to show the atomic percentage of desired elements as shown in table 5.

Table 5. EDX elemental analysis of core samples

Weight (%)	CORE SAMPLES			
	Baseline (initial)	Baseline (after)	With GO (initial)	With GO (after)
Carbon, C	-3.05	10.83	6.14	49.23
Nitrogen, N	7.78	8.78	2.52	11.3
Oxygen, O	61.3	50.65	63.04	32.59

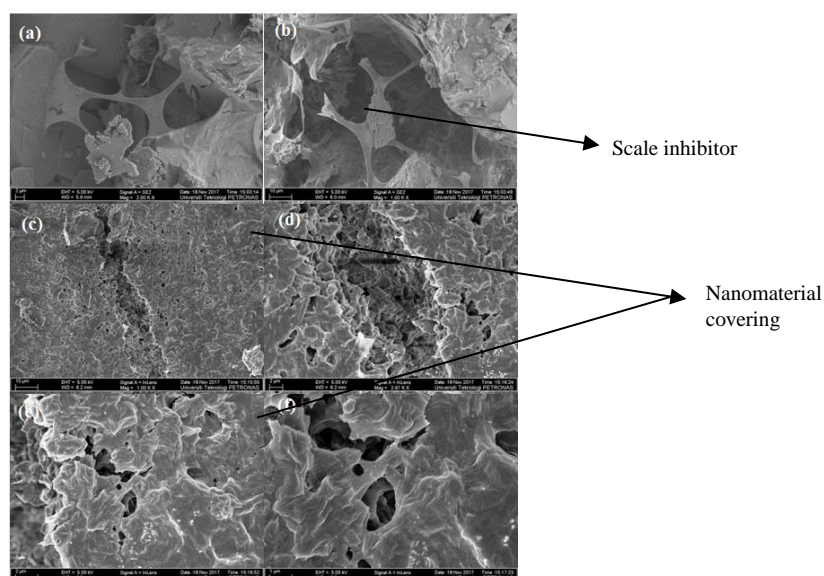


Figure 13. FESEM images of scale inhibitor and graphene particles on rock surface

From the chemical formula of EDTA ($C_{10}H_{16}N_2O_8$), the elements that make up this acid are Carbon, Nitrogen and Oxygen. Given results from the EDX analysis shows that the weight percentage of these three elements exist abundantly after the injection of EDTA on both baseline and with nanomaterials core samples. This indicates that the EDTA scale inhibitor has adsorbed onto the rock formation. However, the increment is higher in core sample that was treated with GO nanomaterial. This further supports the result from coreflood testing, which manifests that the adsorption of EDTA onto rock formation treated with nanomaterials to be higher compared with sample without any nanomaterial adsorbance.

5. Conclusion

The main objective of developing new methodology of optimized nanomaterial namely graphene oxide (GO) and Carbon Nanotubes (CNTs) in expanding scale inhibitor squeeze lifetime was achieved successfully. Based on the outcome from this study, nanomaterials have proven to be effective as an agent to increase and facilitate the adsorption of scale inhibitor onto the rock surface. In this study, the authors managed to investigate the performance of two types of nanomaterials. It was found that GO gives the best performance in enhancing squeeze treatment lifetime due to its structural properties compared CNTs. It was also proven that treating the rock surface with nanomaterials can significantly increase the adsorption rate of EDTA scale inhibitor on the formation rock. Adsorption capacity of EDTA on core sample treated with GO was 180mg/g while the core sample with no nanomaterial treatment was to be only at 51 mg/g.

The results show a promising outcome in optimizing nano-based materials to facilitate better adsorption of scale inhibitor. Further development of this research can include:

- Investigating optimum dispersant concentrations to achieve highest dispersions for different nanomaterials.
- Studying the desorption dynamics of scale inhibitor from nanomaterials to ensure that the scale inhibitor can effectively desorbed back into the produced water providing scale inhibitor chemical concentrations to be above the threshold value.
- Probing rock impairment in terms of reduction of porosity and permeability by injecting rock pretreatment binder agent and nanomaterials.
- Applying NCEST methodology on different types of carbon-based nanomaterials or scale inhibitor chemical as different scale inhibitor may have varying compatibility with nanomaterials.

6. Recommendation

Although the experimented concept was encouraging, there are still several areas in the methodology that needs to be extensively studied and refined. This can be done by performing more experimental work that can simulate environments that are close to the real reservoir conditions. Rock impairment was a primary apprehension and concern. The impact of nanomaterial type, injection velocity and salinity on the permeability and porosity of reservoir rock needs to be further investigated in depth.

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