IMPROVING THE RHEOLOGICAL PROPERTIES OF WATER-BASED DRILLING MUDS USING WASTEGLASS POWDER

Article Information

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ABSTRACT

In this study, we examined the rheological characteristics of water-based drilling muds incorporated with waste glass powder of eight different weights (0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, and 4.5 g). The waste glass powder was analysed using FTIR spectroscopy, SEM-EDS, XRD, and particle size analyser, to determine the specific components or compounds present, and the predominate particle size. The analyses showed that the waste glass powder mainly consisted of silicone oxides (SiO2), indicating that it is a pozzolanic material. Moreover, the dimensions of the particles had a substantial impact on the rheological characteristics. In addition, the study assessed the rheological characteristics of the prepared water-based muds by employing a rotational viscometer. This involved measuring the gel strength at 10-second and 10-minute intervals, while keeping the rotational speed constant at 3 rpm. The investigation also recorded the viscosities and yield points at 300 and 600 rpm. Furthermore, the investigation assessed the plastic viscosity, apparent viscosity, gel strength, and yield point for eight distinct amounts of waste glass powder under standard conditions. The plastic viscosity of the mud systems increased from 10 to 31 cP, and the apparent viscosity increased from 20 to 44.5 cP as the weight of the waste glass powder increased from 0to 4.5 g in each of the formulated muds. Correspondingly, the viscosities and yield point at which the gel solidifies rose as the concentration of waste glass powder increased. Utilising waste glass powder to enhance the rheological characteristics of water-based drilling mud has the potential to mitigate the glass waste disposal issues, to the environment, and offer a feasible substitute for commercially accessible additives. This study offers vital insights into the alternative and efficient utilisation of waste glass powder in drilling the conductor and surface interval of a wellbore.

Keywords:Water-based drilling mud, Rheological properties, Waste glass powder.

1. INTRODUCTION

During the drilling of oil and gas wellbores drilling fluids are utilise. Drilling fluids are commonly referred to as drilling mud. Drilling mud fulfils numerous crucial roles throughout the drilling procedure. The drilling operations encompass the penetration of the wellbore's conductor, surface, intermediate, and production intervals. During each of these intervals, the drilling mud serves the purpose of transporting drill cuttings to the surface, ensuring that the wellbore remains free of drill cuttings, to enhance further drilling footage [1a, 2].

There are three types of drilling muds: oil-based drilling mud (OBDM), water-based drilling mud (WBDM), and synthetic-based drilling mud (SBDM). The most prevalent form of drilling mud is water-based drilling mud, consisting mainly of water with other substances. The drilling industry extensively depends onWBDM as a drilling fluid, due to its cost-effectiveness in formulation, wide availability, and environmentally friendly nature. Nevertheless, WBDM has limitations in its ability to efficiently maintain cleanliness in the wellbore, stabilise the wellbore wall, and suspend drill cuttings during tripping [3, 4, 5]. Moreover, as stated by Biwott *et al.*[1b], drilling mud is an essential element in the drilling process, serving a vital purpose in drilling operations. It necessitates meticulous formulation and control to effectively perform its intended tasks in the wellbore. Therefore, when selecting the appropriate mud, issues such as drilling performance, projected wellbore conditions, drill cutting disposals, and personnel safety are taken into consideration [6]. This implies that the drilling contractors must improve the characteristics of the drilling mud, to guarantee the safe, functional, and cost-effective drilling of a wellbore. The key features of drilling mud comprise rheological qualities, pH, mud weight, fluid loss, and thermal stability [1a, 1b]. However, this study examined the rheological characteristics of water-based drilling mud made from waste glass powder.If the rheological properties (plastic viscosity, apparent viscosity, gel strength, and yield stress) decreases considerably, it means that the mud additives are not stable at the conditions down hole [7].

Water-based drilling mud's rheological properties are very important. Inadequate rheological properties can exacerbate hole cleaning problems, worsen wellbore instability, and make it impossible to suspend drill cuttings. On the other hand, excess rheological properties can impede mud circulation, which can cause drilling problems and damage to the formation [3, 4, 5, 8, 9, 10]. The rheological properties of water-based drilling mud are important to think about from an environmental point of view. High-viscosity muds can make fluid spills more likely and make clean-up more difficult, which can have bad effects on the environment [11]. Therefore, it is crucial to carefully select mud additives and manage the rheological properties of drilling mud to minimise environmental risks.There are a variety of mud additives used in designing water-based drilling mud systems to meet their rheological purposes [12]. Environmental preservation is a global concern during the search for these mud additives, and many organisations have received advice to use non-toxic water-based drilling mud additives [13]. Given these considerations, this study suggests incorporating waste glass powder, a non-toxic material, into water-based drilling mud. As a result, this study tends to incorporate waste glass powder into water-based drilling mud to improve its rheological properties.Waste glass powder (WGP), generated from various sources such as bottle recycling has shown compatibility with cementitious materials due to its pozzolanic characteristics [14]. A recent research by Santos *et al*.; Apriantı*et al*. [15, 16] also investigated the effect of WGP on the rheological properties of water-based mud and found it to be a potential material in improving rheological properties. The interaction between WGP and bentonite in water-based mud systems is yet to be fully explored.

Accordingly, Amirhossein *et al*. [17] in a study, enhanced the polymeric properties of water-based drilling fluid using nanoparticles. The study used TiO_2 nanoparticles to improve the rheology of water-based drilling fluid, as well as the electrical and thermal conductivities of the resulting drilling fluids. The test fluids were formulated by the addition of different concentrations of TiO_2 nanoparticles and KCl salt into the base fluid. Consequently, the resultant samples were examined at various temperatures of 19 different shear rates. Furthermore, measurements of TiO_2 and KCl concentrationsrevealed that the viscosities of aqueous TiO_2 dispersed at various temperatures. The study concluded that the TiO_2 nanoparticles had excellent solubility in hot HCl and HF acids. It was found that the viscosity of the base aqueous fluid directly influences the viscosity of the resulting drilling fluid. In this regard, the conducted analysis generated a proposed model.Furthermore, Ismail *et al.*'s [18] study examined the impact of multi-walled carbon nano-tubes (MWCNT) and nanometal oxides on the rheology of water-based drilling fluid. The study found that adding metal oxide and MWCNT significantly improved the rheological properties of the fluid, including yield point, plastic viscosity, and gel strength. The application of nanoparticles in water-based drilling fluid yielded numerous benefits, highlighting the potential of these nanoparticles in improving drilling fluid properties.

Similarly, Elkatatny*et al*. [19] also investigated the effects of nano-clay (bentonite) and nano-silica on the rheological properties of water-based drilling fluids. As a result, the addition of 1 wt% of nanoclayincreased the plastic viscosity by 98%. Likewise, the addition of 1 wt% of nanosilica increased the plastic viscosity value by 140%. In another study, Elkatatny*et al.* (2018) studied the rheological properties of water-based mud for drilling horizontal and multilateral wells. The study, prepared water-based drilling fluid using xanthan gum, starch, KCl, and calcium carbonate.Likewise, Elkatatny*et al.* [20] investigated the effects of bentonite, nanoclay, and nanosilica on the rheological properties of the water-based mud. The study found that adding different amounts of bentonite, nanoclay, and nanosilica affected the rheological properties at different temperatures and pressures. It was found that the optimum concentration of bentonite was 6.66 wt%, resulting in a flat rheology profile for the gel strength, which 7.5 wt% nanosilica showed the optimum performance. However, the nanoclay was not effective in improving the rheological properties of the calcium carbonate based drilling fluid. Thus, the studies of Ismail *et al*.; Elkatatny*et al*.; Elkatatny*et al.*[18, 19, 20] have disclosed that the nanosilica additive showed a more pronounced positive effects on the improvement of the rheological properties of drilling muds.

The existing studies have investigated the effects of various additives, including nanoparticles, on the flow properties of water-based drilling fluids. For instance, studies have assessed the impact of nanoparticles on the flow properties of WBDM, focusing on the methods, results, and observations to draw conclusions about the effects of nanoparticles on the rheological properties of WBDM. However, there remains a knowledge gap concerning the specific effects of waste glass powder on the plastic viscosity of WBDM. As a result, this study aims to address this gap by exploring the potential benefits, limitations, and optimal usage of waste glass powder as an additive in WBDM to enhance its rheological properties.Silica oxide is a major component of glass materials, which silica oxide is one of them.

Silica oxide (SiO_2) is a chemical found in nature, consisting of a silicon atom in its core and two oxygen atoms. It is the primary component of waste glass powder, and in particle form,may have some positive impact on the rheological qualities of water-based drilling mud. Studies have shown that different sizes of SiO_2 particles improves the viscosity and rheological characteristics of drilling mud. This was evidenced by the study of[21], which found out that the inclusion of SiO_2 in water-based mud resulted in notable enhancements in the mud's rheological characteristics, particularly as the mud's concentration increased. Also, Asgari [22] studied the impact of various nanoparticles (NPs) such as SiO_2, CuO, and ZnO on the characteristics of drilling fluid. When examining their effects on rheology and filtration at high and low temperatures. The findings indicated that SiO_2 exhibits a slight tendency to enhance the filtering characteristics of the mud under elevated temperatures and pressures. Therefore, the SiO_2 in waste glass powder may significantly enhances the mud's viscosity and increases drilling density, attributed to the presence of quartz in SiO_2.

Consequently, this study tends to explore the potential of waste glass nanoparticles from waste glass as additive to enhance the rheological properties of WBDM.The aim of this study is to improve the rheological properties of water-based drilling mud by incorporating waste glass powder as additive.This study is targeted to be achieved its aim under the following objectives: to characterize WGP with FTIR spectroscopy, XRD techniques, SEM-EDS, and PSDA; to examine the impacts of different concentrations of WGP on the rheological properties (plastic viscosity, apparent viscosity, yield point, and gel strength) of the WBDM; to optimize the concentration of WGP to achieve the desired improvement in rheological properties of WBDM; to improve the rheological properties of the WBDM with WGP.

Therefore, this study, experimentally focused on how the addition of waste glass powder derived from outdated “Star beer glass bottles”can improve the rheological properties of water-based drilling mud at standard conditions. Hence, the characterization of WGP with Fourier transform infrared (FTIR) spectroscopy, scanning electron microscopy (SEM), X-ray diffraction(XRD), particle size analyser (Malvern). Additionally, the progress of this research is limited due to limited literatures on previous studies for similar area of investigation, budget constraints and availability of equipment unable the analyses of these rheological properties under high temperature and high pressure (HTHP).The importance of studying and improving the rheological properties of water-based drilling mud (WBDM) using waste glass particles as an additive lies in the potential benefits, it can bring to the drilling industry. Drilling mud plays a crucial role in the drilling process by removing cuttings from the wellbore, providing lubrication to the drilling bit, and maintaining pressure control. However, Waste glass powder is a low-cost and abundant material, making it a cost-effective alternative to conventional mud additives in achieving the functions of drilling mud. This potentially reduced the environmental impact of waste glass.

2. MATERIAL AND METHODS

2.1 Materials

A petroleum engineering equipment and materials vendor provided 50 litres of de-ionized water for this study. Additionally, the purchased de-ionised water was sent to the Chemistry Department, Faculty of Sciences, Niger Delta University, Nigeria, for testing, and re-evaluation, which confirmed that the de-ionised water is absolutely free from ions. Likewise, the vendor also provided other chemical reagents such as the defoamer, soda ash, xanthan gum, bentonite, carboxymethyl cellulose (CMC)starch, polyanioniccelluloseregular (PAC-R), potassium hydroxide, potassium chloride, and calcium carbonate. Meanwhile, this study collected waste beer bottles from a waste disposal site around Amassoma city, Bayelsa State, Nigeria. The collected waste glass wereprepared into fine waste glass particles (WGP).The roles of each of the additives (deionised water, defoamer, soda ash, xanthan gum, bentonite, carboxymethyl cellulose (CMC)starch, polyanioniccelluloseregular (PAC-R), potassium hydroxide, potassium chloride, and calcium carbonate).

2.2 Methods

2.2.1 Preparation of the Waste Glass Particles

2.2.1.1 Size Reduction of the materials

The collected waste glass bottleswere broken into fine particles using electronic blender. Subsequently, the waste glass fine particles were sieved by three different sieves (size 90um, 140um, and 150um). The resultant average fine particles size ‘was measured as 200 mesh.

2.2.2 Composition of the Formulated Water-Based Drilling Mud

Table 1 displays the components of the water-based drilling muds (WBDMs) that were utilised to investigate the impact of waste glass particles on the rheological properties. The compositions of the WBDMs shown in Table 1 bear resemblance to those developed, formulated, and utilised in a recent study [23]. Nevertheless, we utilised varying amounts of waste glass particles as a substitute for barite. In addition, the solvent or continuous phase of the WBDM utilised was de-ionized water. The additives employed included defoamer, soda ash, xanthan gum, bentonite, starch, PAC-R, potassium hydroxide, potassium chloride, calcium carbonate, and waste glass nanoparticles.

Table 1: The composition of the investigated water-based mud systems

Sample Label	Independent Variables										
	Deionised Water (ml)	Defoamer (g)	Soda ash (g)	Xanthan gum (g)	Bentonite (g)	Starch (g)	PAC-R (g)	KOH (g)	KCl (g)	$CaCO_3$ (g)	WGP (g)
*WBDMWGP-1	350	1	1	1	2	3	1	1	5	2.5	0
WBDMWGP-2	350	1	1	1	2	3	1	1	5	2.5	1.5
WBDMWGP-3	350	1	1	1	2	3	1	1	5	2.5	2.0
WBDMWGP-4	350	1	1	1	2	3	1	1	5	2.5	2.5
WBDMWGP-5	350	1	1	1	2	3	1	1	5	2.5	3.0
WBDMWGP-6	350	1	1	1	2	3	1	1	5	2.5	3.5
WBDMWGP-7	350	1	1	1	2	3	1	1	5	2.5	4.0
WBDMWGP-8	350	1	1	1	2	3	1	1	5	2.5	4.5

*The control experiment

2.2.3 Characterization of waste glass particles

A sample of the waste glass particles used for the experiment was sent to the Department of Chemical Engineering, Ahmadu Bello University, Zaria, Nigeria, for the characterization (FTIR, XRD, SEM-EDS, and PSD) Analyses. The analytical results were collected, recorded and sent via mail and were used for interpretation as discussed in section 3.

2.2.4 Drilling Mud Preparation

A digital scale was utilized to quantify a portion of the created 150 µm WGP that were produced during the unit operation process. The measured proportions were distributed across eight different quantities: 0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 and 4.5 g. Subsequently, each of these quantities were individually included in eight (8) distinct containers, which were appropriately labelled. Furthermore, each of these containers held 350 ml of de-ionized water, together with specific amounts of defoamer (0.08 g), soda ash (0.5 g), xanthan gum (0.5 g), bentonite (4 g), starch (6 g), PAC-R (1 g), KOH (0.5g), KCl (20 g), and $CaCO_3$ (5 g) as shown in Table 1. In addition, the contents of each of these containers were thoroughly blended using a table-top drilling mud mixer operating at a speed of 60,000 rpm for approximately 300 seconds. The procedure of mixing was repeated seven times, resulting in the formation of a homogeneous WBDM. Subsequently, rheological tests were done on each of the eight (8) formulated water-based drilling muds (WBDMs), to find their rheological properties.

2.2.5 Rheological measurements

It is important to remember that water-based drilling muds are fluids that do not follow Newton's law of viscosity, and their thickness reduces as the rate of deformation increases [24]. The key rheological properties of drilling muds are plastic viscosity, yield point, apparent viscosity, flow behaviour index, and consistency index [25, 26]. Drilling fluids utilise various additives, such as viscosifiers, polymer thinners, and deflocculants, to improve their rheological properties. Nevertheless, this investigation employed a high-speed electronic rotational viscometer (BLS-D6 Model) operating at a rotational speed of 3 revolutions per minute for durations of 10 seconds and 10 minutes in order to ascertain the viscosity of the mud gel. The plastic viscosity, apparent viscosity, and yield point were measured using the high-speed electronic rotational viscometer (Model: BLS-D6). The Bingham plastic fluid model equations (Equations 1, 2, and 3) were employed to compute the specified parameters [27].

$$PV = \theta_{600} - \theta_{300} (cP) \quad [28] \quad \ldots \quad 1$$

$$YP = \theta_{300} - PV = 2 * \theta_{300} - \theta_{600} \left({}^{lb}/_{100 * ft^2} \right) \quad [28] \quad \ldots \quad 2$$

$$AV = \frac{\theta_{600}}{2} (cP) \quad [28] \quad \ldots \quad 3$$

where, θ300 and θ600 are the dial reading at 300 and 600 rpm, respectively. AV represents the apparent viscosity; PV is plastic viscosity; likewise, YP is the yield point.

2.2.6 Experimental Design

The design of experiment (DOE) is an efficient and systemic approach that enables a researcher to study relationship between multiple input variables at different concentrations and levels to achieve the responses. The variation of WGNP in the water-based drilling mud made up of many chemicals is shown in Table1.

3. RESULTS AND DISCUSSION

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3.1 Characterization of Waste Glass Powder

3.1.1 Fourier Transform Infrared (FTIR) Characterisation of Waste-Glass Powder

The Fourier Transform Infrared Spectroscopy (FTIR) analysis was used to study the functional groups present in the waste glass particles. It helped in identifying the chemical bonds and gave understand to the composition of the particles. The FTIR characterisation showed the WGP with different functional groups at several wavelengths with intense peaks at 2020.2, 1982.9, 1408.9, 961.7, and 767.8 cm-1 is shown in Figure 4.

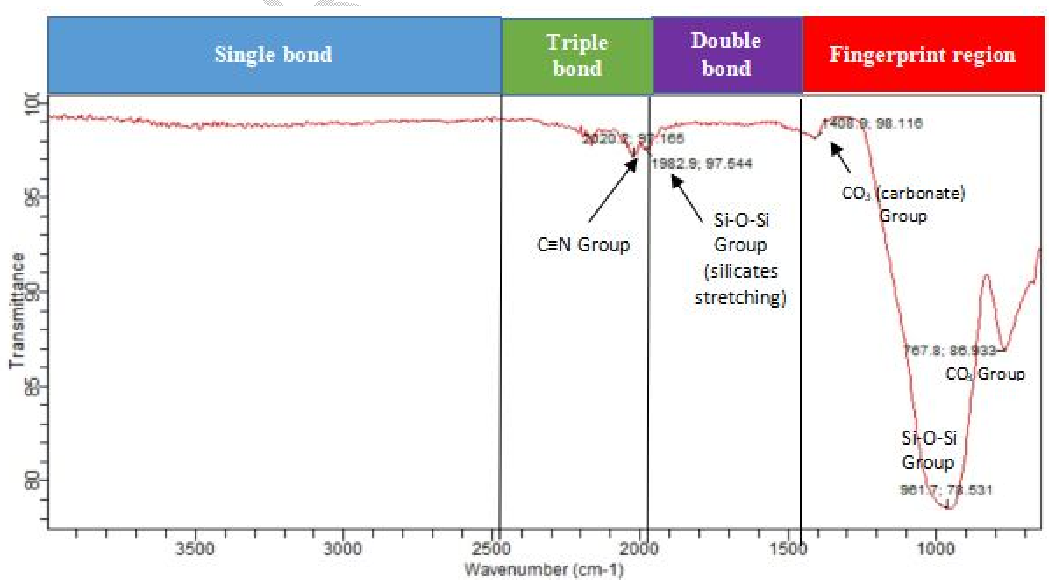


Figure 1: The FTIR Spectrum of WGP

The rheological properties of water-based drilling muds are crucial for their performance in drilling applications. These properties include plastic viscosity, yield point, apparent viscosity, flow behaviour index, and consistency index. The presence of a nitrile (C≡N) group in the triple bond region of methyl cyanoacrylate ($C_5H_5NO_2$) may be due to contaminants present in adhesives or coatings of the glass. The band at 1982.9 cm^{-1} in the double bond region indicates the existence of a low oxide group, possibly iron silicate (FeO_4Si) or aluminium silicate ($3Al_2O_3.2SiO_2$), which affects the friction of the drilling mud. Furthermore, the peaks at 1408.9 cm^{-1} and 767.8cm^{-1} are commonly linked to stretching and bending vibrations, suggesting the presence of a carbonate (CO_3) group. The occurrence of carbonate ions in the waste glass powder may have caused the appearance of these peaks at these specific wavenumbers. Lastly, the peak at 961.7cm^{-1} can be associated with the flexing oscillation of Si-O-Si or Si-O-T (T = tetrahedral cations such as Al and Fe), which are frequently present in silicates such as glass like materials. This peak suggests the existence of silicate structures in the waste glass powder.

Additionally, the presence of calcium (Ca) and carbonate ions (CO_3) in a water-based drilling mud can influence the plastic viscosity. Calcium and carbonate ions in water-based drilling mud can undergo a chemical reaction to form calcium carbonate ($CaCO_3$), which can enhance the viscosity of the drilling mud by forming a colloidal gel structure. This gel structure can result in more resistance to flow, thereby elevating the plastic viscosity of the drilling mud. Similarly, it was also observed that, the presence of calcium carbonate can also impact other rheological parameters of the drilling mud, such as its yield point and gel strength. Also, the presence ofsilicon in the waste glass powder can indirectly influence the plastic viscosity of water-based drilling mud, but its impact may not be as substantial as that of other additives. Silicon helps to improve the stability and rheological characteristics of the drilling mud, which can indirectly affect the plastic viscosity. The findings shows that thepresence of nitrile groups, low oxide groups, carbonate ions, and silicon in the waste glass can all contribute to the improvement of the plastic viscosity of the drilling mud. Therefore, waste glass powder can be used as a viscosifying additive in water-based drilling mud .

3.1.2 X-Ray diffraction of waste glass powder

The x-ray technique was used to obtain the chemical composition, and crystal structure of waste glass powder [29].The results are presented in Figure 2, and Table 2.

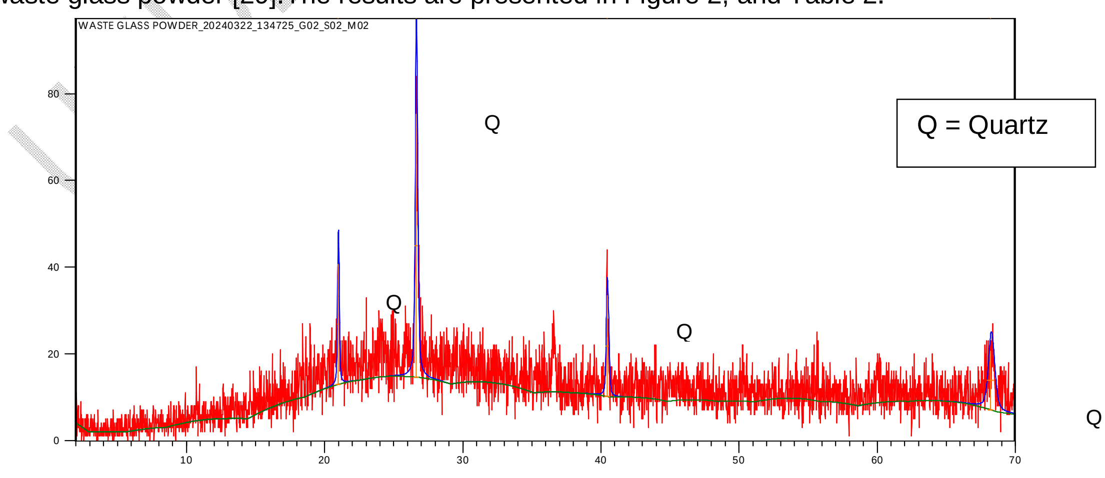


Figure 2: The X-Ray Diffraction(XRD)characterisation of Waste glass powder

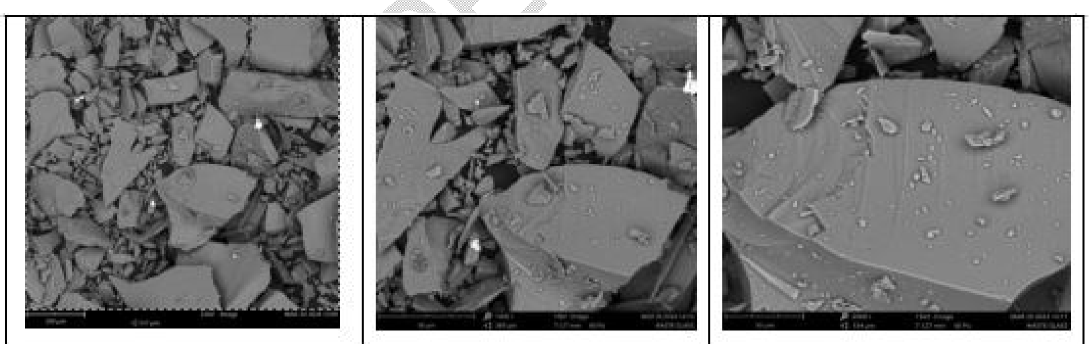
Table 2: The peak location of WGP X-raycharacterization

Pos. [°2Th.]	Height [cts]	FWHM Left [°2Th.]	d-spacing [Å]	Rel. Int. [%]
20.9796	27.67	0.1181	4.23451	45.58
26.6333	60.71	0.1968	3.34707	100.00
40.4475	23.26	0.1574	2.23016	38.31
68.2199	13.51	0.4723	1.37475	22.25

The XRD result show that quartz which is sand, and silicate oxide were the major constituents in the waste glass powder. The physical and chemical aspects of waste glass used in this study are shown in Table 2, while X-ray diffraction (XRD) is given in Figure 2. At 20.9796, 26.6333, and 40.4475 degrees, many amorphous peaks of quartz (Q) in the XRD analysis of WGP showed the major amorphous nature of WGP. The chemical composition of WGP showed that the material may have had pozzolanic potential, which can be attributed to the accumulative chemical composition of SiO_2, Al_2O_3, and Fe_2O_3 exceeding 70%.

3.1.2 SEM-EDS Characterization of the Waste Glass Powder.

SEM is scanning electron microscopic technique used to analyze the chemical compositions and shape of materials. The SEM images of the waste glass powder show that the size of the glass powder particles is about 7.127 mm with sharp edges. The SEM of the waste glass sample show three distinct field of view (FOV), each with a unique length, and characteristics (Plate 1: a, b, & c).



(a) FOV (534 µm), and length (100 µm) | (b) FOV (269 µm), and length (80 µm) | (c) FOV (134 µm), and length (30 µm)

Plate 1: The SEM-EDS of waste glass particles with field of view (FOV) and length

The SEM results of the waste-glass particles show three images with varying Fields of View (FOV), and particle characteristics, providing a comprehensive understanding of the particles' morphology and properties. All three images display particles with a consistent size of 7.127 mm, indicating aggregated or clustered particles, and a surface roughness of 60 Pa, suggesting similar mechanical properties.These properties can significantly impact the rheological properties of water-based drilling mud and drilling operations. Accordingly,larger particles and aggregates sizes can increase the mud's viscosity, affecting its flow behaviour and drilling performance. The rough surface can lead to increased friction and interactions between particles, influencing the mud's rheological properties and drilling efficiency. The shape and structure (i.e. morphology) of particles can affect their suspension **properties** and settling behaviour in the drilling mud. The SEM-EDS analyses disclosed the chemical composition of the WGP in Figure 3 and Table 3.

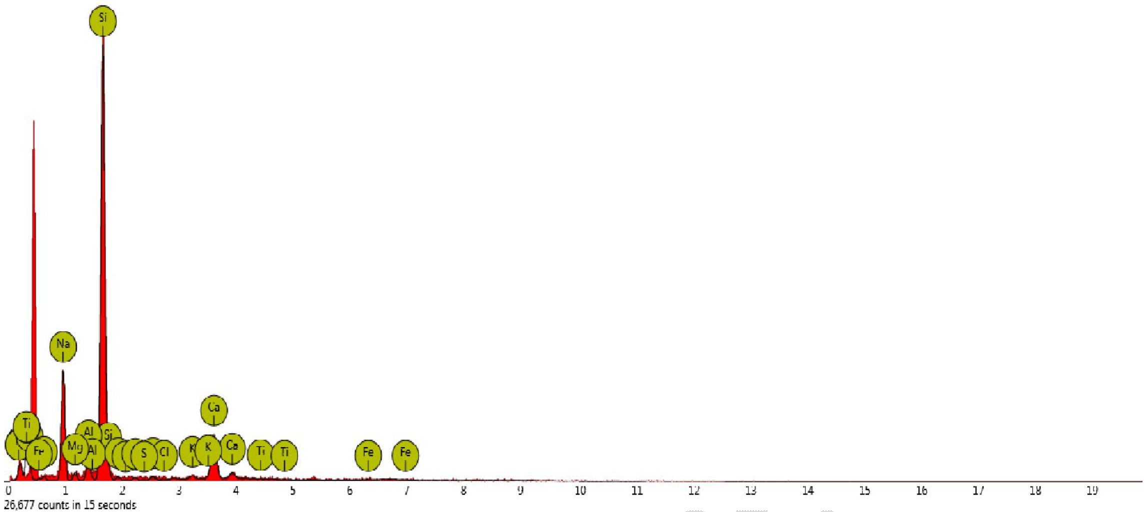


Figure 3: The chemical composition of the WGP by SEM-EDS

Table 3: The **s**canning electron microscopy-energy dispersive spectroscopy of WGP

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
14	Si	Silicon	62.92	61.92
20	Ca	Calcium	10.89	15.29
11	Na	Sodium	18.72	15.08
13	Al	Aluminium	3.26	3.08
12	Mg	Magnesium	1.29	1.10
19	K	Potassium	0.76	1.04
15	P	Phosphorus	0.82	0.89
17	Cl	Chlorine	0.68	0.85
16	S	Sulfur	0.67	0.76
22	Ti	Titanium	0.00	0.00
26	Fe	Iron	0.00	0.00

The result shown in Table 3 shows that silicon (Si) occupied 62. 92 % composition of the waste glass particles, which make it a pozzolanic and serve as viscosity enhancer in the water-based drilling mud. Another most abundant constituent is Na which plays a vital role in controlling the yield point of the drill mud. Based on the SEM-EDS results, the intermediate-sized particles (80 µm x 269 µm) appear to be the most effective for better drilling operations. They offer a balance between carrying capacity, settling behaviour, and lubricity, making them suitable for a wide range of drilling applications. However, the optimal particle size may vary depending on specific drilling conditions and mud formulations.

3.1.3 Particle size distribution analysis of the WGP

Particle size distribution (PSD) analysis is a laboratory test that determines the size range and proportion of different particle sizes within the waste glass particles. The particle size distribution analysis of the waste glass particles provides valuable information about the distribution of particle sizes in the sample. The results in Figure 4 is presented in terms of three peaks representing the size, number percentage, and standard deviation of the particles. Additionally, the results for number, volume, and intensity of the waste glass particles are also provided in Figure 4; while, the particles size distribution analysis of the WGP is shown in Table 4.

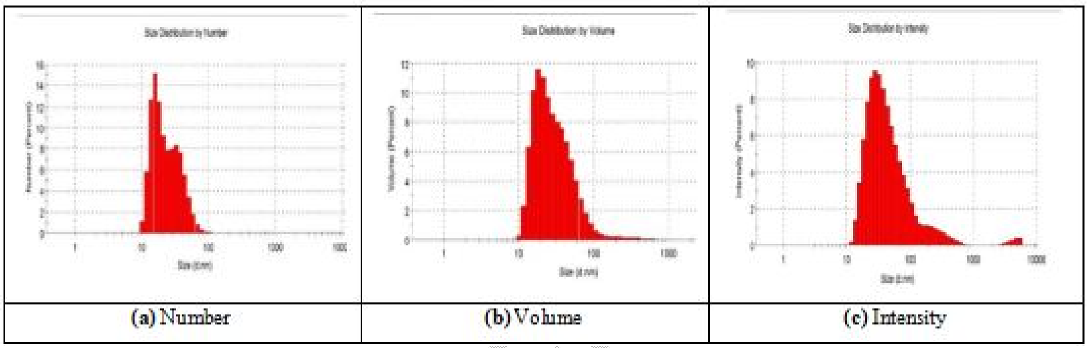


Figure 4: The .particle size distribution of the waste glass particles

Table 4: The Particles size distribution analysis of the WGP

Peaks	Size (d.nm)			Distributions (%)			Standard Deviation (d.nm)		
	Number	Volume	Intensity	Number	Volume	Intensity	Number	Volume	Intensity
1	17.11	35.67	60.78	59.5	99.9	98.4	3.916	42.34	75.14
2	36.46	4987	4436	40.5	0.1	1.6	11.91	896.9	911.1
3	0.00			0.0			0.00		

The size and distribution of the waste glass particles in the investigated water-based drilling mud systems; significantly, impact on the water-based drilling mud rheological properties [30]. Figure 4shows a trimodal distribution, leading to complex interactions between the particles and the surrounding fluid. Smaller particles (Peak 1, 17.11 nm) can increase the viscosity of the water-based drilling mud due to their larger surface area, while larger particles (Peak 2, 36.46 nm) have a lesser impact [30]. The last peak is an artifact, indicating no particles are present at this size (essentially, a "zero" point) which are ultra-fine particles and can reduce sedimentation issues. However, the presence of larger particles (36.46nm) can still lead to some sedimentation over time, potentially affecting water-based drilling mud rheological properties. Furthermore, the presence of different particle sizes can increase yield stress, making it harder to initiate flow, and alter shear-thinning behaviour [30]. For effective drilling operations, smaller particles size in Peak 1 are generally preferred, as they can increase viscosity, improve suspension and hole cleaning, and create a more effective filter cake, reducing fluid loss and torque [30]. However, larger particles in Peak 2 may be beneficial in specific situations, such as improved bridging and sealing properties, and a combination of particle sizes can achieve a balance between desired properties.The exact effects of particle size distribution on rheological properties can be complex and depend on various factors such as particle shape, concentration, and the presence of other additives in the drilling mud [30]. Considering the specific requirements of drilling operations is crucial, as larger particle sizes may be beneficial in certain situations.

3.2 The Rheological Responses

Table 5 show the experimental data collected during the laboratory practicals under atmospheric (Temperature and Pressure)conditions. The data were also collected and recorded with respect to API specification for rheological properties as shown in Table 6.

Table 5: API Recommended values for drilling mud rheological properties

Property 0f the Mud	Recommended Values
Plastic Viscosity, PV (cP)	8-35
yield point, YP ($lb/100ft^2$)	minimum = 5 maximum = YP ≤ 3 X PV
10sec gel strength ($lb/100ft^2$)	2 − 5
10min gel strength ($lb/100ft^2$)	2 − 35

Table 6: The rheological responses of the investigated water-based mud systems

Sample Label	Responses: Gel Strength ($lb/100ft^2$)		Speed (RPM)		PV (cP) = $\theta_{600} - \theta_{300}$	AV (cP) = $\frac{\theta_{600}}{2}$	YP ($lb/100ft^2$) = $\theta_{300} - PV$ = $2 * \theta_{300} - \theta_{600}$
	10_{sec}	10_{min}	θ_{300}	θ_{600}			
*WBDMWGP-1	8	12	30	40	10	20	20
WBDMWGP-2	6	10	26	40	14	20	12
WBDMWGP-3	6	9	50	65	15	32.5	35
WBDMWGP-4	5	8	39	55	16	27.5	23
WBDMWGP-5	8	13	54	75	21	37.5	33
WBDMWGP-6	15	20	65	95	30	47.5	35
WBDMWGP-7	7	12	39	70	31	35	8
WBDMWGP-8	8	14	58	89	31	44.5	27

*The controlled experimental response.

3.2.1 The Plastic Viscosity, and Apparent Viscosity

Plastic viscosity, and apparentviscosity are the basic parameters of the Bingham model. They depict the water-based drilling mud viscosity. Figures5, and 6 displaythe responses of the plastic viscosity, and apparentviscosity, respectively,of the investigated drilling mud systems formulated with different weight proportions of the WGP.

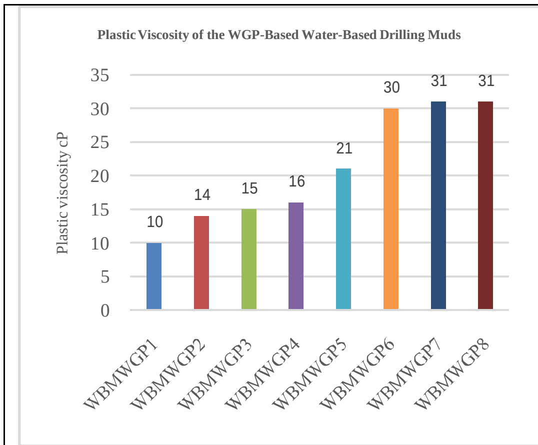


Figure 5: The Plastic Viscosity

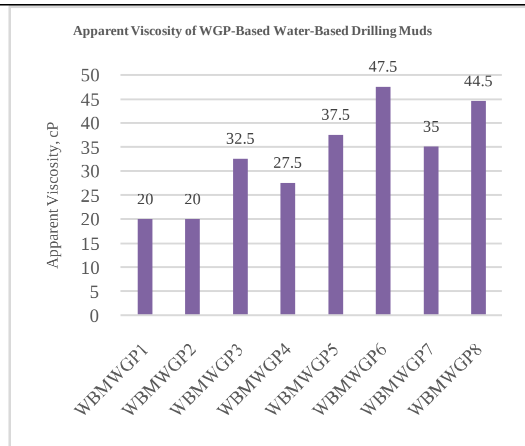


Figure 6: The Apparent Viscosity

The results of Figure 5 show that the recorded plastic viscosity (PV) of WGP-based water-based drilling mud systems are between 10 and 31 cP, which are within the range of the API recommended values (8-35cP) for water-based drilling mud. Also, it was observed that as the proportion of WGP increased in the subsequent WGP-based water-based drilling mud, the plastic viscosity of the drilling mud proportionately increased. This was as a result of the abundant presence of silicon and calcium carbonate in the WGP, with a consistentparticles size of 7.127 mm, indicating aggregated or clustered particles, and a surface roughness of 60 Pa. In addition, the The highest PV value was recorded for WBMWGP7 and WBMWGP8.Whereas, the optimal WGP concentration (3.5 g of WGP per 350 ml of deionised water) in this study was recorded for sample WBMWGP6. Although, the higher the value of PV,the more viscous the mud becomes, which can cause extra load on the circulating pumps. Hence, this value should be kept in optimal range recommended by API to avoid the excess load on the pumps. On the other hand, Figure 6 showed the results of the apparent viscosity (AV) of the WGP-based water-based drilling mud systems. The results of Figure 6 disclosed that the AV remained constant at 20 cP within the control sample (WBMWGP1) of 0 g of WGP, and 1.5 g of WGP (WBMWGP2) respectively. Then, the AV began to fluctuate from 20 to 32.5; then, 32.5 to 27.5; likewise, 27.5 to 37.5; 37.5 to 47.5; 47.5 to 35, and 35 to 44.5 cP for 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, and 4.5 g of WGP, respectively. This was affected by the WGP's high concentration of silicon and calcium carbonate, which had a constant particle size of 7.127 mm, which indicated aggregated or clustered particles, and a surface roughness of 60 Pa.

3.2.2 The Gel Strength, and Yield Point

Figures 7, and 8 present the results of the Gel Strength (GS), and yield point (YP), respectively, for the WGP-based water-based drilling muds.

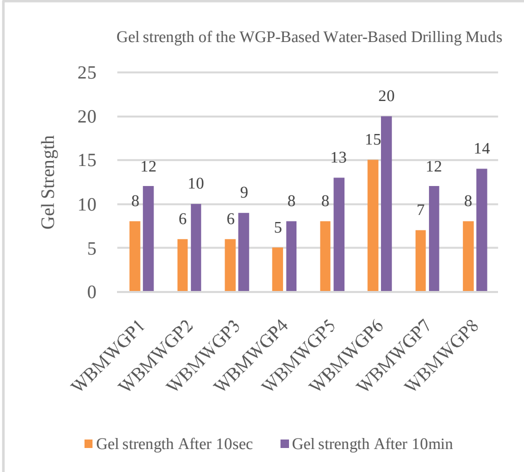


Figure 7: The Gel Strength

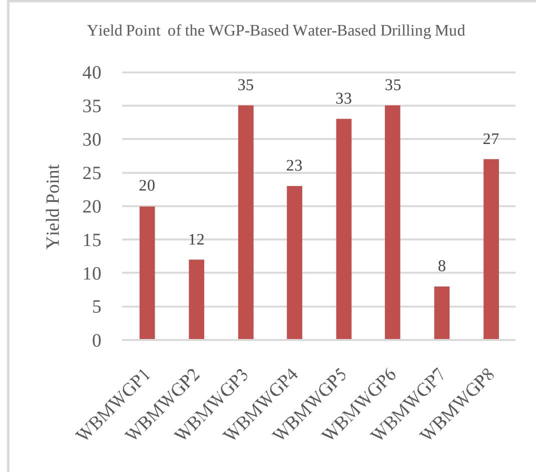


Figure 8: The Yield Point

Figure 7 displays the findings regarding the examined gel strength (GS), whereas Figure 8 illustrates the findings regarding the investigated yield point (YP). Figure 7's GS results indicate that the control sample (WBMWGP1) achieved 8 lb/100 ft^2 at 10 seconds and 12 lb/100 ft2 at 10 minutes. As the dosage of WGP rose from 0 to 2.5 g, specifically from samples of WBMWGP1 to WBMWG4, the GS decreased. Table 5 [1b]. (Biwott et al., 2019) demonstrated that the optimal GS was achieved at 5 and 8 lb/100 ft2 after 10 seconds and 10 minutes, respectively, when the dosage of waste glassparticle (WGP) increased from 0 to 2.5 g in sample WBMWGP4. Figure 7 demonstrated that WGP has the capacity to enhance WBDM's GS strength. Conversely, the YP represents all the elements that contribute to variations in the viscosity of low shear rates. According to the YP, incorporated powdered additives in clay layers have the potential to combine and form a flocculated structure [31]. The tabulated representation of the YP data, computed using Equation 2 in Table 6, demonstrates that the incorporation of WGP modifies the YP of WBDM. The YP showed notable improvements as the concentrations of WGP increased. Nevertheless, as the concentration of WGP reached 4.0 g, the YP dropped from 35 to 8 lb/100 ft^2 compared to the YP at a WGP concentration of 3.5 g. Figure 8 demonstrates that the yield point (YP) of all mud concentrations aligns with the levels recommended by the American Petroleum Institute (API) in sample WBMWG7 (Biwott et al., 2019).The high concentration of silicon and calcium carbonate in the WGP, along with a uniform particle size of 7.127 mm suggesting the existence of aggregated or clustered particles, and a surface roughness of 60 Pa, had a significant impact on this phenomenon.

4. CONCLUSION AND RECOMMENDATION

4.1 Conclusion

In this study, the aim was to improve the rheological properties of water-based drilling mud using waste glass powder. The study conducted experiments on eight different waste glass powder (0 to 4.5g) based water-based drilling muds under standardconditions. The results of the rheological properties (plastic viscosity, apparent viscosity, gel strength, and yield point) were obtained and comparedwith the API recommended standard values, and were found favourable.The characterization analyses of the waste glass powder revealed that it was mainly composed of Silicone oxide (SiO_2) and calcium carbonate. Although, other minor chemical such as Sodium (Na), Calcium (Ca), Aluminium (Al), Magnesium (Mg), potassium, just to mention a few were present. On this background, this study concludes that the presence of $SiO_2$and $CaCO_3$in the waste glass powder enhanced the rheological properties of the water-based drilling muds, and could be used as a viscosifier in water-based drilling muds.This was influenced by the abundance of silicon and calcium carbonate in the WGP, with a consistent particle size of 7.127 mm indicating aggregated or clustered particles and a surface roughness of 60 Pa.. Furthermore, the The highest plastic, and apparent viscosity values wereaveragely identified,and recorded as 30 and 45.7 cP with an optimalWGP concentration (3.5 g of WGP per 350 ml of deionised water). Whereas, the optimal GS was achieved at 5 and 8 lb/100 ft^2 after 10 seconds and 10 minutes, respectively, when the dosage of waste glassparticle (WGP) increased from 0 to 2.5 g. Also, as the concentration of WGP reached 4.0 g, the YP dropped from 35 to 8 lb/100 ft^2 compared to the YP at a WGP concentration of 3.5 g. Therefore, the values of the plastic viscosity, and apparent viscosity increased, as the dosage of WGP increased to a particular magnitude; while, gel strength and yield point values depreciated, as the dosage of WGP increased to a particular magnitude.

4.2 Recommendation

Based on this study findings, that the application of WGP as a viscosifier additive for water-based drilling muds might promote local content expansion, but their introduction into water-based drilling mud should be painstakingly considered. On this premise, this study recommended that waste glass powder be used as a viscosifier to improve the properties of water-based drilling mud. The optimal concentration of waste glass powder was found to be about 3.5g for the plastic viscosity and apparent viscosity, with the largest increase in viscosity occurring between 2.5g and 3.0g. The waste glass powder also increased the gel strength and yield points of the drilling mud at higher concentrations of 2.5, and 3.5g, respectively. However, further investigations could be done to determine the effects of other factors such as high temperature (HT), high pressure (HP), and the addition of other chemicals on the rheological properties of water-based drilling mud.

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