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Formulation and enhancement of the rheological properties of raw bentonite using sodium carbonate and sodium carboxymethyl cellulose

Przygotowanie i poprawa właściwości reologicznych naturalnego bentonitu przy użyciu węglanu sodu i karboksymetylocelulozy sodu

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ABSTRACT: Drilling fluids play a critical role in the exploration and production of oil and gas. Among the various types of drilling fluids, water-based mud has attracted significant attention due to its sustainability and low cost compared to synthetic mud. In Kenya, there is an increasing demand for sustainable drilling fluid compounds, such as bentonite, which is readily available in some parts of the country, for example, Isinya and Amboseli. The main drawback for the beneficiation of Kenyan bentonite include low concentration of smectite, high levels of iron contaminant, and inconsistent composition. Hence, there is a need to enhance local bentonite to improve its performance for effective drilling applications. In this work, we incorporated sodium carbonate (Na_2CO_3) and carboxymethyl cellulose (CMC) as additives to improve the properties of the raw bentonite. The rheological characteristics of both pristine and activated bentonite were investigated using the Rheolab QC rheometer. The findings revealed that the yield point of the Isinya and Amboseli samples increased as a function of the levels of activation reagents (Na_2CO_3 and CMC). It was noted that more than 1.25w% of Na_2CO_3 was required to bring the yield stress closer to the required 15 Pa for drilling application. Additionally, the Isinya bentonite (IS3) provided adequate rheological characteristics for drilling muds after compounding with 2.5w% CMC additive. These results demonstrate the feasibility of using the local bentonite in Kenya for drilling applications. In the future, we will explore the potential of using other additives to further enhance the properties of local bentonite for geothermal power production, with the goal of lowering electricity generation cost and supporting ongoing efforts to provide reliable and affordable energy, as proposed in Kenya Vision 2030 project.

Key words: bentonite, rheological properties, drilling, Sodium Carbonate.

STRESZCZENIE: Płuczki wiertnicze odgrywają kluczową rolę w procesie poszukiwania i wydobycia ropy naftowej i gazu ziemnego. Spośród różnych rodzajów płuczek wiertniczych, dużym powodzeniem cieszą się płuczki na bazie wody, ze względu na ich trwałość i niski koszt w porównaniu do płuczek syntetycznych. W Kenii rośnie zapotrzebowanie na zrównoważone mieszanki płuczek wiertniczych, jak np. bentonit, który jest łatwo dostępny w niektórych rejonach kraju, np. w Isinya czy Amboseli. Głównymi wadami kenijskiego bentonitu są niska zawartość smektytu, wysoki poziom zanieczyszczeń żelazem i niejednolity skład. W związku z tym istnieje potrzeba wzbogacania lokalnego bentonitu w celu poprawy jego wydajności pod względem efektywnego wykorzystania w procesie wiercenia. W niniejszej pracy zastosowano węglan sodu (Na_2CO_3) i karboksymetylocelulozę (CMC) jako dodatki poprawiające właściwości naturalnego bentonitu. Właściwości reologiczne zarówno czystego, jak i zmodyfikowanego bentonitu zostały zbadane za pomocą reometru Rheolab QC. Wyniki wykazały, że granica płynięcia dla próbek z Isinya i Amboseli wzrastała w zależności od poziomu odczynników aktywujących (Na_2CO_3 i karboksymetyloceluloza). Zaobserwowano, że do uzyskania granicy płynięcia zbliżonej do wymaganych 15 Pa dla zastosowań wiertniczych wymagany był dodatek Na_2CO_3 w ilości ponad 1,25w%. Dodatkowo, bentonit Isinya (IS3) wykazywał odpowiednie właściwości reologiczne dla płuczek wiertniczych po dodaniu 2,5% karboksymetylocelulozy. Ponadto bentonit Isinya (IS3) wykazał odpowiednie właściwości reologiczne po dodaniu 2,5% dodatku CMC. Wyniki te wskazują na możliwość wykorzystania lokalnego bentonitu w Kenii do zastosowań wiertniczych. W przyszłości przebadany zostanie potencjał wykorzystania innych dodatków w celu dalszej poprawy właściwości lokalnego bentonitu w aspekcie produkcji energii geotermalnej, jak również obniżenia kosztów wytwarzania energii elektrycznej i wspierania bieżących wysiłków na rzecz zapewnienia niezawodnej i przystępnej cenowo energii, zgodnie z założeniami projektu Kenya Vision 2030.

Słowa kluczowe: bentonit, własności reologiczne, wiercenie, węglan sodu.

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Introduction

Drilling fluids are critical elements in any drilling operation, whether for oil and gas or geothermal applications. According to Chilingarian et al. (1983), drilling fluid contributes between 25–40% of the total drilling cost in many applications and plays multifunctional roles.

There are various categories of drilling fluids based on their composition or base materials, including gas-based, oil-based, water-based (emulsions), and synthetic-based, each requiring different additives to function optimally (Bleier, 1990). Oil-based muds use petroleum products, such as diesel fuel, as the base fluid. Oil-based muds are beneficial for numerous reasons, including enhanced lubricity, improved shale inhibition, superior cleaning power with less viscosity, and the ability to withstand higher temperatures without degrading. This type of muds come in two varieties: pseudo-oil-based muds and inverted emulsion oil muds (Mahmoud et al., 2023). Oil-based drilling muds are known for their superior properties due to their lubricating properties, which provide exceptional fluid loss control and filter cake quality, wellbore stability, low drag and torque, and superior rheological properties (Maiti et al., 2021). Moreover, oil-based drilling muds do not interact with shale, thus minimizing swelling. Water-based muds are the most commonly used drilling fluids, accounting for approximately 80% of all wells drilled worldwide (Caenn et al., 2011). Water-based muds (WBMs) are considered to be most environmentally friendly and least expensive drilling fluids, and they are easier to maintain. However, they are also characterized by a number of limitations, including instability in shale formations leading to swelling, and a lack of suspension properties to enable cutting transportation (Mahmoud et al. 2023).

The main functions of drilling fluids include the formation of an impermeable filter cake, transportation of the cuttings, lubrication and cooling of the drill bit, and cleaning and pressure control of the wellbore (Mahmoud et al., 2023). Other functions include cutting suspension, wellbore stability, support for the bit and drilling assembly, sealing permeable formations, and reduction of formation damage. Hydraulic energy is transferred to tools and bits, ensuring adequate formation evaluation, corrosion inhibition, environmental impact reduction, and simplifying cementing and completion drilling muds. These functions are achieved due to the chemistry that occurs between the drilling fluids and the additives added to enhance properties such as rheology, density, and fluid characteristics. The key rheological properties include plastic viscosity (PV), apparent viscosity, gel strength, and yield point (YP) (Taghdimi et al., 2023).

There is a linear relationship between the rheological characteristics and the carrying capacity of water-based muds. If the fluid has optimal viscosity and yield stress, this will result in a better load-carrying capacity. Therefore, the rheological properties of water-based muds are crucial for ensuring safe and successful drilling operations (Rafieefar et al., 2021).

Bentonite is a commonly clay used clay that provides the required rheological properties, such as viscosity and filtration control, in drilling fluids, particularly in water-based muds (Gamal et al., 2019). Bentonite clay has some fundamental properties that make it suitable for this application. For example, it acts as a natural absorbent when interacting with water, using its positively charged particles to attract the hydroxyl ions present in water molecules through electrostatic attraction (Li et al., 2018). Additionally, bentonite swells when it interacts with water up to about 18 times its original volume (Diman and Wijeyesekera, 2008). For use as a drilling mud, raw bentonite undergoes several chemical and mechanical processes, such as crushing, sieving, and the addition of several elements in order to achieve the desired rheological properties.

Bentonite comprises over 80% montmorillonite from the smectite group and is formed through the alteration of volcanic ash. There are two (2) types of bentonite: calcium bentonite, which has low swelling and water absorption capabilities, and sodium bentonite, which is more abundant and exhibits higher swelling and absorption capabilities, forming a more viscous fluid (Elzea and Murray, 1994; Eisenhour and Brown, 2009). Bentonite is known for its superior physical properties, such as high surface area (SA), small particle size, high viscosity, significant bond strength, exceptional swelling and absorption properties, cation exchange capacity, and high impermeability making it an important mineral for industrial applications. Moreover, it is non-toxic, non-hazardous, and insoluble in water. Commercially, bentonite isused as a sealant indams and landfills, in drilling muds for oil wells, cosmetics, foods, ceramics, paints, iron production, as an adsorbent for wastewater treatment, and in agriculture as a fertilizer additive and soil conditioner (Khan et al., 2017; Zhao et al., 2022).

Selecting the correct drilling fluid is essential, as using an unsuitable fluid can disrupt the whole drilling process in various ways, including by increasing fluid filtration, reducing penetration rates, causing downhole blowout, and leading to stuck pipe incidents (Aftab et al., 2017). To address these challenges, researchers have attempted to develop various additives, from the macro scale to the subatomic (Wei et al., 2022). Khan et al. (2017) observed that the addition of xanthium gum and carboxymethyl cellulose improved the rheological properties of the drilling mud by increasing the plastic viscosity, gel strength, and yield point.

In another study, Zhao and his co-workers (Zhao et al., 2022) investigated the potential of polymers to enhance the rheological properties of calcium bentonite suspensions. They investigated xanthan gum biopolymer, modified vegetable gum, and a salt-tolerant polymer mixture, finding that a 0.35% concentration of the salt-tolerant polymer mixture increased the apparent viscosity (AV) by about 1,500% and raised shear reading values from 0 dia. to 5 dia., thus enhancing viscosity and the cutting-carrying capacity of the calcium bentonite.

Emerging technologies have enabled the development of additives that enhance drilling fluid properties due to their unique chemical, electrical, thermal, mechanical, and hydrodynamic properties (Kafashi et al., 2020). Emerging nanotechnologies have also been employed to improve the rheological properties, filtration loss, and viscosity of water-based drilling muds. Studies indicate nanoparticle (NPs) additives not only improve the rheological properties of water-based drilling mudbut also reduce friction and fluid loss (Halali et al., 2016; Sadeghalvaad et al., 2016; Song et al., 2016a, 2016b; Alvi et al., 2020). For instance, Barry et al. (2015) investigated the effect of iron oxide on water-based bentonite drilling muds and observed higher shear stress values with the addition of NPs compared to the base mud.

This study proposes a novel approach to formulating drilling mud by combining sodium carbonate (Na_2CO_3) and sodium carboxymethyl cellulose ($C_8H_{15}NaO_8$) to enhance the properties of locally sourced water-based bentonite drilling mud for geothermal drilling applications. Subsequently, the rheological properties of the drilling mud and the effects of these additives were investigated using a Rheolab QC rheometer. The novelty of this study lies in the improvement of the rheological properties of the drilling mud by improving the yield stress of the Isinya samples. This modified water-based drilling mud could be highly beneficial in the geothermal industry, as Kenya urgently needs to look for strategies to increase its use of renewable energy sources to meet its energy demands, given the rising costs of petroleum resources and the critical need to combat climate change (Elbarbary et al., 2022). Geothermal energy is clean, virtually inexhaustible, and has limited environmental impact compared to other hydrocarbon sources. In Kenya, total geothermal energy production contributes about 40% of the country's total electricity production.

Study Area

The research was conducted in the Isinya and Amboseli areas. The exact locations where the samples were collected are Isinya (Engirgirr) at 258 379.33 E and 9822 230.65 N, and Amboseli (Kimana) at 310 537.04 E and 9 706 459.66 N. The samples from the Isinya area were taken from an abandoned open pit mine, formerly used for gypsum mining by the Athi River Mining Company for cement production. A digital image of the study area, showing the sampling locations, is presented in Figure 1. The digital image was produced using remote sensing and Geographical Information System (GIS) techniques.

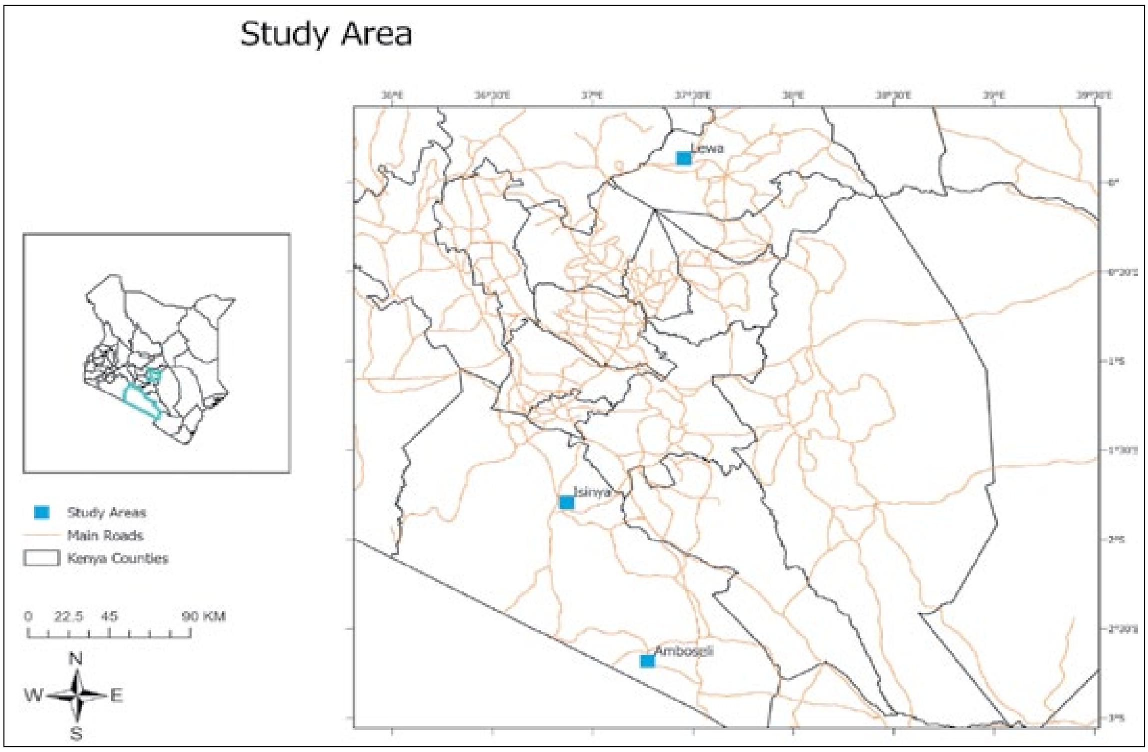

Figure 1. Map of the study area showing the two raw bentonite sampling locations: Isinya and Amboseli

Rysunek 1. Mapa obszaru badań przedstawiająca dwie lokalizacje pobierania próbek naturalnego bentonitu: Isinya i Amboseli

Materials and Methods

Materials

In this study, raw bentonite, a highly absorbent clay mineral that acts as a binding agent, was sourced from two distinct geological sites in Kenya: Isinya (IS) and Amboseli (AM). These locations were selected to investigate potential variations in mineral compositions and characteristics. Since the bentonite from IS was collected from former gypsum mines, careful sampling was conducted at various depths (1–3 meters), randomly spaced within the gangue.

Two chemicals, sodium carbonate (Na_2CO_3) and carboxymethyl cellulose (CMC), were procured from Sigma Aldrich (St. Louis, MO, USA) and were used in their as-received state without additional purification.

Carboxymethyl cellulose is formed by attaching carboxymethyl groups ($CH_2{-}COOH$) to specific hydroxyl groups on cellulose through areaction with sodium monochloroacetate ($ClCH_2{-}COONa$), substituting hydroxyl groups with carboxymethyl groups during synthesis. CMC is categorized into three grades—high, medium, and low viscosity—each used in drilling fluids, while the classification is based on the degree of substitution (Hammad, 2015; Rafieefar et al. 2021).

Pristine and modified bentonite preparation

The clays were dried, crushed using a Retsch pulveriser (RS-200) at 150 rpm for about 15 minutes, and sieved through a 90 μm mesh sieve mounted on a shaker. To ensure sample dryness, the moisture content of the samples was determined through gravimetric analysis by heating samplesto 110°C, after which they were repackaged in zip-sealed plastic bags to prevent moisture re-entry.

The samples were designated as IS1-3 and AM1-3, where the numbers (1–3) denote the collection location/point. Five mud suspensions from each location (IS1-3 and AM1-3) were prepared by dispersing in DI water at concentrations ranging from 10–30w%. These suspensions were mixed using a magnetic stirrer (MR 3001 K) at 400 rpm for about 20 mins and served as controls. The rheological properties of the 30w% clay suspensions were modified by adding either sodium carbonate or carboxymethyl cellulose at varied concentrations, as shown in Figure 2. The rheological behavior of bentonite dispersions is influenced by various factors such as bentonite type, concentration, particle size and shape, electrostatic properties, exchangeable ions, and electrolyte concentration. Notably, the Na^+/Ca^{2+} ratio strongly affects the flow of bentonite dispersions. Sodium-based bentonite offers high swelling properties when mixed with water, making it suitable as a drilling fluid in industries such asoil and gas. In contrast, calcium-based bentonite has lower swelling properties compared to sodium-based

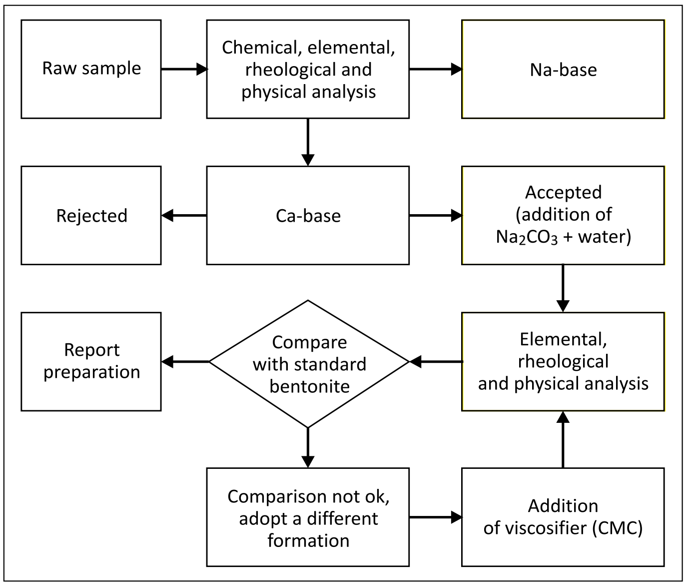

Figure 2. Flowchart illustrating the beneficiation procedure of the raw bentonite with either sodium carbonate or carboxymethyl cellulose (CMC)

Rysunek 2. Schemat blokowy ilustrujący procedurę wzbogacania surowego bentonitu węglanem sodu lub karboksymetylocelulozą

bentonite, and therefore it is commonly used in agriculture as a soil conditioner, in ceramics production, and as a binder, but was not suitable for this research. In choosing the appropriate mixture for this study, the Na^+/Ca^{+2} ratio was crucial. Sodium-based bentonite had Na^+/Ca^{+2} ratios of 3.73 and 1.12, respectively, while a Na^+/Ca^{+2} ratio of 0.81 classifies the bentonite as calcium-based. This work focused on the Ca-based bentonite, which is a non-swelling clay and forms colloids very quickly in water. The samples were heated to accelerate the swelling process and improve the rheological properties.

Rheological Properties

Non-Newtonian fluids are widely used in various industrial and heat transfer applications. Unlike Newtonian fluids, they exhibit a nonlinear relationship between the shear stress and the shear strain at a constant pressure and temperature. As such, they exhibit interesting behaviors such as shear thickening, thinning, and interdependence as shown in Figure 3 (Sochi, 2010; Hammad, 2015; Marum et al., 2020). In operational scenarios, shear thinning tends to limit pressure drop at high flow rates, while yield stress and gel behavior facilitate the transport of solids under static or near-static conditions. Consequently, the formulation of drilling fluids incorporates a shear thinning yield stress characteristic to mitigate pressure drops at elevated fluid flow rates.

According to the American Petroleum Institute (API) Standard 13B, drilling fluids, which are non-Newtonian fluids, are modelled using the Herschel Bulkley model (API 13B-1: 2009-03). According to the Herschel Bulkley model for

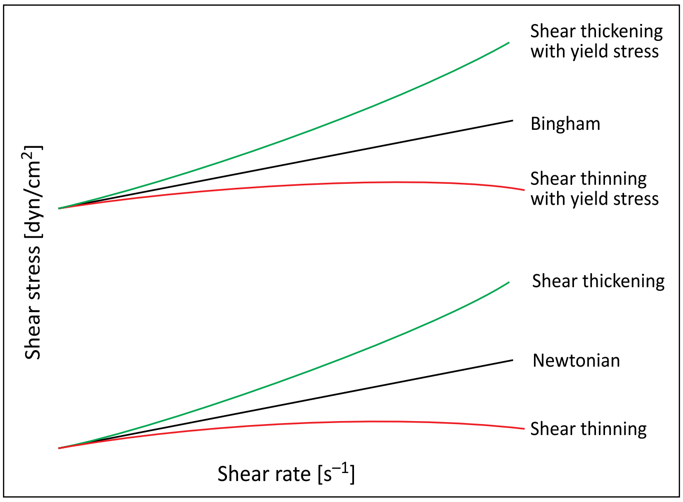

Figure 3. Rheological properties of both Newtonian and non-Newtonian fluids (according to Jankowska et al., 2023)

Rysunek 3. Właściwości reologiczne płynów newtonowskich i nienewtonowskich (według Jankowskiej et al., 2023)

non-Newtonian fluids, the shear stress is related to the shear rate using Equation (1):

$$\tau_0 + k\mu^n = \tau \tag{1}$$

where:
τ_0 – yield stress,
k – consistency index,
μ – shear rate,
n – flow index behavior,
τ – shear stress.

The three values of the indices (τ_0, k, and n) best describes the classification and behavior of various non-Newtonian fluids as shown in Table 1.

Therefore, accurate measurements of such fluids can be crucial from a design and operational perspective. Various methods exist for determining the rheological properties of drilling fluids. Viscometers, particularly vibrating wire rotary types, are commonly used; however, they require power to operate, have operational limitations, and involve complex structures (Zambrano et al., 2016; Fernandes et al., 2019). While viscometers offer several advantages, they measure viscosity only under one flow condition (Vajargah and Van Oort, 2015). Given variable fluid conditions of drilling muds, rheometers are advantageous. Typically, two types of rheometers are used: rotational or shear rheometers, which control the applied shear stress, and extensional rheometers, which apply extensional stress or strain. Of the five types of rotational rheometers—annular flow, linear shear, rotational cylinder, capillary, and cone and plate rheometers—the oil and gas industry commonly uses rotational types to determine the flow characteristics of drilling muds (Vajargah and Van Oort, 2015).

To determine the rheological properties of the drilling fluid, a Rheolab QC rheometer with a dual concentric cylinder configuration was used in this study. The setup replicates the fluid interface and pipe wall dynamics. The rheometer has a rotating bob and a stationary cup, with the sample fluid filling the annular space between them. During operation, the bob rotates at a set speed, generating torque due to the fluids' viscous drag. Experiments were conducted at atmospheric pressure following the American Petroleum Institute (API) Standard recommended practice 13B, and the results were analyzed using Rheoplus software (RP API, 2009). The rotational speed varied between 1–776 rpm, and the temperature and shear rate of the rheometer were configured appropriately.

The rheological properties, including apparent viscosity (AV), plastic viscosity (PV), and yield point (YP), were determined by recording the rheometer readings at θ_{300} and θ_{600} at Fann rotational speeds of 300 rpm and 600 rpm, respectively. Using these readings, the apparent viscosity (AC), plastic viscosity (PV), and yield point (YP) were calculated according to Equations 2–4 (Lam and Jefferis, 2014):

$$\text{AV}\ (CP) = \frac{\theta_{600}}{2} \tag{2}$$

$$\text{PV} = \theta_{600} - \theta_{300} \tag{3}$$

$$\text{YP} = 2\theta_{300} - \theta_{600} \tag{4}$$

where: θ_{300} and θ_{600} signifies represent the viscosity values at 300 and 600 rpm, respectively.

Table 1. Fluid classification according to the API 13B standard (Sedaghat, 2017)

Tabela 1. Klasyfikacja cieczy zgodnie z normą API 13B (Sedaghat, 2017)

S/No.	Name of fluid	Flow index behavior (n)	Yield stress (τ_0)
1.	Shear thinning (pseudoplastic)	$n < 1$	$\tau_0 = 0$
2.	Shear thinning with yield stress	$n < 1$	$\tau_0 > 0$
3.	Newtonian	$n = 1$	$\tau_0 = 0$
4.	Bingham plastic	$n = 1$	$\tau_0 > 0$
5.	Shear thickening (dilatants)	$n > 1$	$\tau_0 = 0$
6.	Shear thickening with yield stress	$n > 1$	$\tau_0 > 0$

Results and Discussion

Figure 4a–i shows the shear stress and viscosity variations against shear rate and rotor speed for the IS1-3 samples. Figure 4a-c shows the Isinya samples exhibited a non-Newtonian behavior at both low and high solid concentrations. Additionally, the samples showed similar shear stress patterns, with the 30w% reaching a maximum shear stress of approximately 18.5 Pa. The behavior of the 30w% samples aligns with the Bingham model as previously reported by Vajargah and van Oort (2015). The effect of shear rate and rotor speed on shear stress and viscosity at different concentrations of the Isinya samples is further illustrated in Figure 4d–f. It was observed that an increase in solid content led to an increase in viscosity. Specifically, the Isinya samples (IS1-3) exhibited a significant viscosity increase at a solid concentration of 30.0w%, which is indicative of pseudoplastic behavior. This phenomenon can lead to a reduction in penetration rate and an increase in differential sticking, resulting in excessive torque and drag (Mahto and Sharma, 2004; Kang et al., 2016). Moreover, at higher bentonite concentrations, the samples tend to form a continuous gel structure rather than individual flocs due to flocculation influenced by Brownian motion (Luckham and Rossi, 1999). This requires modification of the bentonite clay with polymers in order to achieve the desired rheological properties for optimum performance.

The plot of viscosity versus rotor speed at different bentonite concentrations for IS1-3 is shown in Figure 4g–i. A drastic decrease in the viscosity was observed as the rotor speed increased. This behavior indicates that the IS1-3 samples have thixotropic properties. Higher rotor speeds tend to induce microbubbles that are difficult to remove from the formation, creating inhomogeneity. Although lower rotor speeds can prevent air entrapment, they have a negative effect on the shear level and are therefore unsuitable for breaking agglomerates. Consequently, lower viscosities were observed at low suspension concentrations, resulting in lower shear levels, which are not desirable for drilling applications.

Further analysis compared the variation in shear stress versus shear rate, and viscosity versus the shear rate and rotor speed for the 30w% IS1-3 samples, as shown in Figure 5a–d. Rheological properties were examined at 30w% concentration levels due to the formation of continuous gel structure rather than individual flocs under the influence of Brownian motion. The 30w% samples exhibited similar rheological behavior aligning with the Bingham model, with the IS3-30 exhibiting the maximum shear stress and viscosity. This suggests that the Isinya bentonite has a comparable structure or morphology, with minimal differences in shear stress and viscosity. As illustrated in Figure 5d, the viscosity of IS1-3 samples decreased with increasing rotor speed, indicating that optimal viscosities for drilling applications may lie within the 25–30w% range

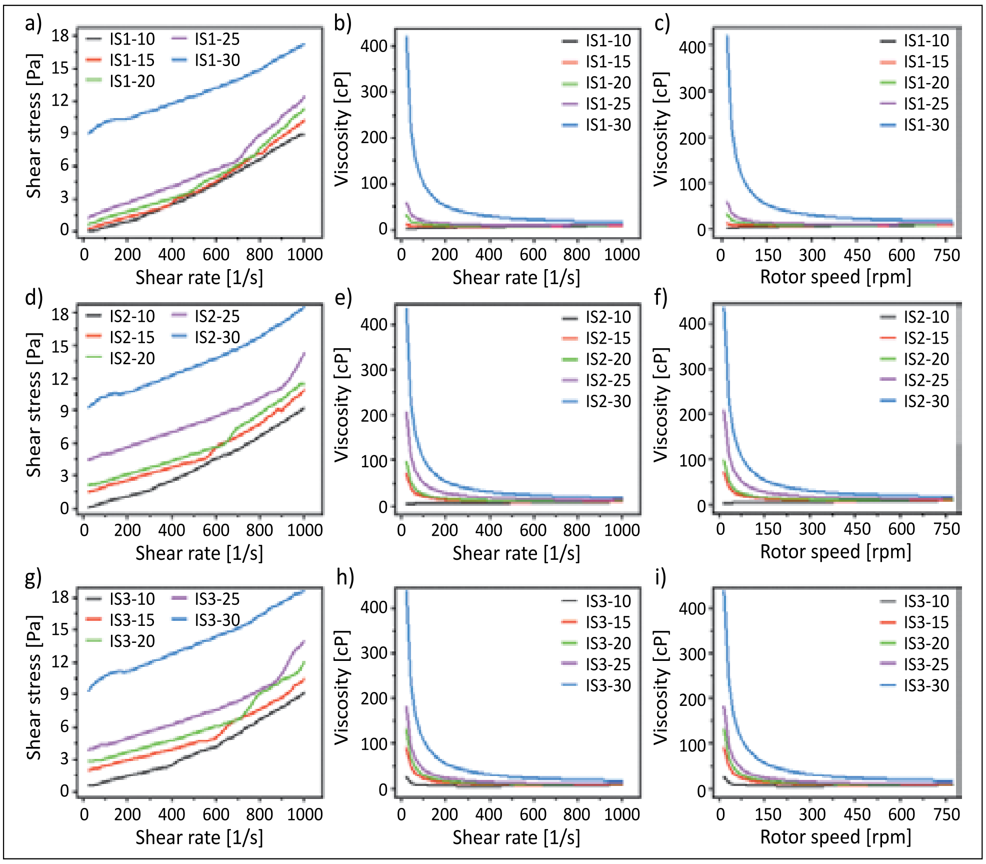

Figure 4. Shear stress versus shear rate (a–c); viscosity versus shear rate (d–f); and viscosity versus the rotor speed (g–i) for IS1-3 samples

Rysunek 4. Naprężenie ścinające w funkcji prędkości ścinania (a–c); lepkość w funkcji prędkości ścinania (d–f) oraz lepkość w funkcji prędkości wirnika (g–i) dla próbek IS1-3

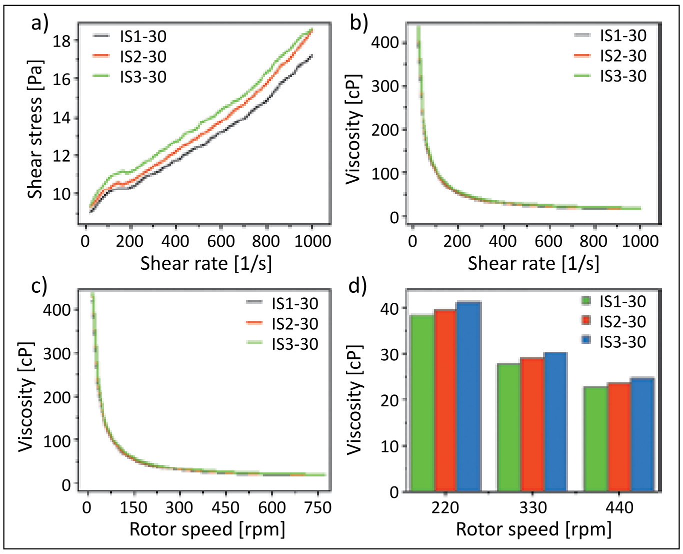

Figure 5. Variation in shear stress (a) and viscosity (b) versus shear stress, and viscosity of 30w% versus the rotor speed (c–d) for IS1-3 suspensions

Rysunek 5. Zmiana naprężenia ścinającego (a) i lepkości (b) w zależności od naprężenia ścinającego oraz lepkości 30w% w zależności od prędkości wirnika (c–d) dla zawiesin IS1-3

for IS1-3 suspensions. However, at the 30w% concentration, desired rheological properties might not be achieved due to excessive torque and drag during drilling, highlighting the need for modification.

The mineralogical composition of the raw Isinya and Amboseli clay suspensions revealed a low smectite concentration along with impurities, limiting their suitability for drilling operations. These clays were similar to Kom Oshim bentonite from Egypt's El-Fayoum province (El-Mahllawy et al., 2013). As shown in Figure 6a, XRD analysis of the Isinya samples revealed high gypsum levels, which reduce the swelling capacity. The illite-montmorillonite mineral present in the samples was identified as an interlayered material composed of two discrete species: one with low interlayer spacing and the other with layers interstratified with montmorillonite. This mineralogical analysis confirmed the dominance of montmorillonite in the Isinya samples, with calcium montmorillonite detected at 3 Å and 5 Å harmonics. Similarly, Figure 6b presents the mineralogical analysis of the Amboseli samples, revealing a low montmorillonite proportion and indicating the presence of smectite group clays in the region. These samples also contained illite, which, when mixed with montmorillonite, forms a non-expanding crystalline mineral. Consequently, without beneficiation, the industrial applications of Isinya and Amboseli clays remain limited. Additionally, the sodium content of these samples was lower than that of Wyoming bentonite, and they contained typical saturated smectite, along with traces of kaolinite, gypsum, calcite, and significant quartz content. The presence of such impurities limits their applicability in geothermal drilling operations, underscoring the need for modification to improve their chemical reactivity and rheological properties (Ngugi, 2012; Shenoy, 2013).

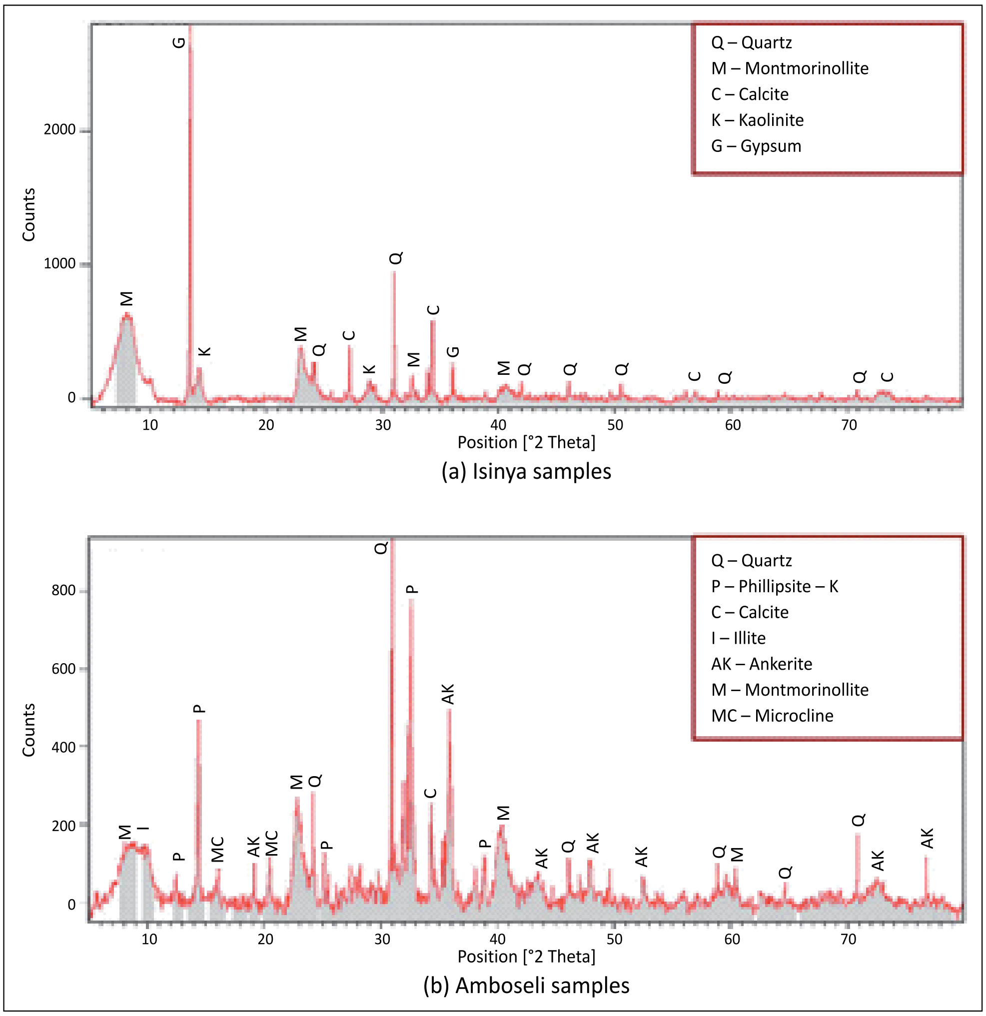

Figure 6. Mineralogical analysis of Isinya (a) and Amboseli (b) bentonite samples

Rysunek 6. Analiza mineralogiczna próbek bentonitu z Isinya (a) i Amboseli (b)

To understand the effect of exchangeable cations (Na^+) with Ca^{2+} ions in the interlayer of bentonites, rheological tests were conducted on Isinya and Amboseli samples activated with Na_2CO_3 and sodium carboxymethyl cellulose (CMC). The American Petroleum Institute

(API) requirements were followed in preparing each activated bentonite suspension, and their apparent viscosity, plastic viscosity, and yield point were evaluated. The IS3 and AM3 samples were activated with varying amounts of Na_2CO_3 (0.50w%, 1.25w% and 2.50w%) according to API-recommended procedures, with results depicted in Figures 7a–i. As shown in Figure 7a–e, a drop in yield stress, viscosity, and yield point was observed in both IS3 and AM3 bentonites as Na_2CO_3 concentration increased. The significant variations in yield stress and viscosity at high concentrations of Na_2CO_3 were associated with the presence of inhomogeneous particles and size distribution. Despite a decrease in yield point for IS3 bentonite (Figure 7e), IS3 demonstrated a significant increase in yield stress at the same Na_2CO_3 content (2.5g) compared to AM3 bentonite, as shown in Figure 7f–g, indicating relatively good rheological properties. The Na_2CO_3-modified IS3 bentonite achieved the highest yield point of 5.8 Pa, while AM3 bentonite had a yield stress of less than 1 Pa. Therefore, IS3 bentonite is preferred for modification due to its relatively higher yield stress, exhibiting promising properties compared to standard commercial clays (15–20 Pa), making it more suitable for drilling applications than AM3 bentonite.

To evaluate the plastic viscosity (PV) of IS3 and AM3 bentonites, viscosity values at 600 rpm and 300 rpm were measured, with the results shown in Figure 7h. A decrease in PV values with increasing Na_2CO_3 concentration was observed for IS3 bentonite, while the AM3 sample displayed an initial decrease followed by an increase in PV, as evident in Figure 7(h). This variation may be due to the unstable flow of particles caused by in homogeneous particle size and distribution. To gain further insights into the rheological properties of the clays, the yield point to plastic viscosity ratio (YP/PV) of the clays was evaluated, as illustrated in Figure 7i. The IS3 bentonite displayed a marked decrease in YP/PV ratio with increased Na_2CO_3 concentration, while AM3 bentonite showed lower and relatively constant YP/PV values. Notably, Na_2CO_3-modified IS3 recorded a better YP/PV value compared to AM3 bentonite, remaining below the maximum required value of 3.0 Pa/cP. The decreaseand disparity in YP/PV values with increased Na_2CO_3 concentration may be attributed to the dispersion behaviors of IS3 and AM3 after the activation. In Ca-bentonite dispersions, Ca^+ ions adsorbed onto two adjacent surfaces do not freely dissociate from the silica surface of the bentonite crystallites. In Na-bentonite dispersions, Na^+ ions adsorbed onto one clay surface pass into the solution upon interaction with water, allowing them to dissociate fromthe clay minerals more readily.

To further enhance the rheological characteristics of IS3 and AM3 bentonites, carboxymethyl cellulose (CMC) was used as a viscosifier. The rheological properties of the 30w% IS3 and AM3 bentonites reactivated with CMC (0.50–2.50g) are shown in Figure 8. In Figure 8a–d, the CMC-modified clays displayed superior variations in the shear stress and viscosity compared to Na_2CO_3-modified clays, confirming the suitability

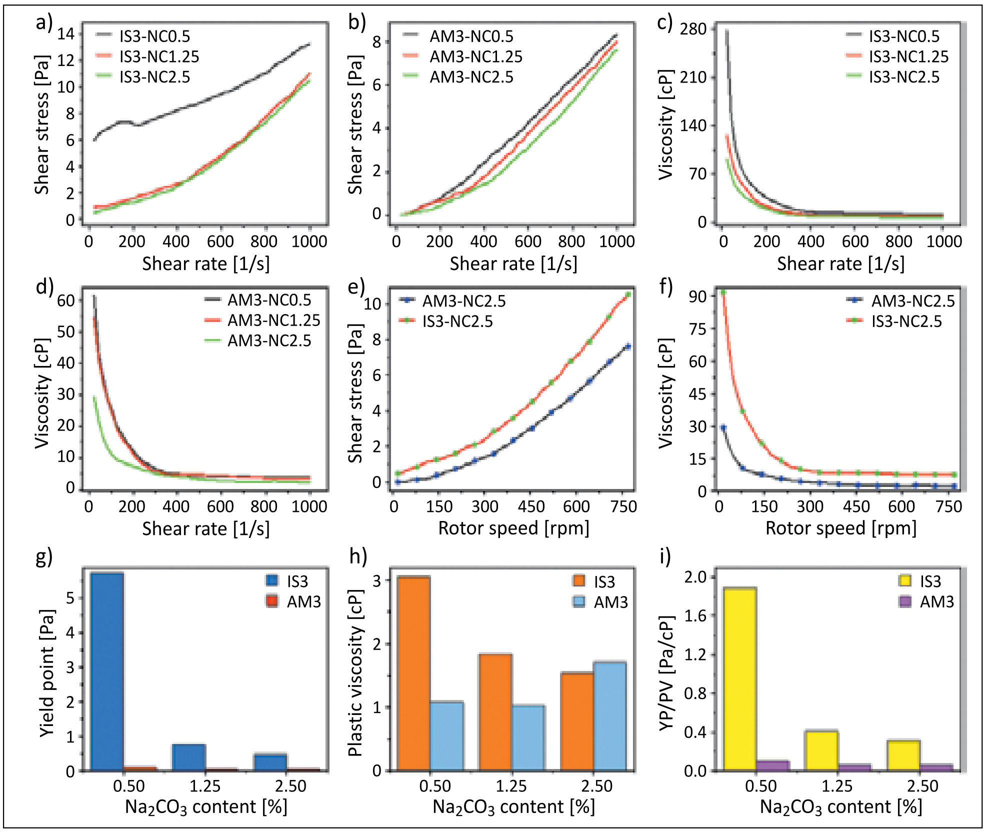

Figure 7. Shear stress and viscosity versus shear ratefor Na_2CO_3 modified IS3 and AM3 bentonites (a–d); yield point variation with Na_2CO_3 (e); comparison of shear stress and viscosity for the high Na_2CO_3 content (2.5g) modified clays (f–g); plastic viscosity and YP/PV variation with Na_2CO_3 content (h–i)

Rysunek 7. Naprężenie ścinające i lepkość w zależności od prędkości ścinania dla bentonitów IS3 i AM3 modyfikowanych Na_2CO_3 (a–d); zmiana granicy płynięcia przy dodaniu Na_2CO_3 (e); porównanie naprężenia ścinającego i lepkości dla modyfikowanych iłów o wysokiej zawartości Na_2CO_3 (2,5 g)(f–g); zmiana lepkości plastycznej i granicy płynięcia/lepkości plastycznej przy dodaniu Na_2CO_3 (h–i) of CMC as a rheological modifier. Although analogous variations to Na_2CO_3 (2.5g) were made for the shear stress and viscosity of the high content CMC (2.5g) modified bentonite, the IS3-CMC2.5 demonstrated excellent characteristics, as depicted in Figure 8(e–f). The high shear stress (16–20 Pa) achieved by the IS3 bentonite is desirable for drilling applications compared to AM3 bentonite.

An increase in the yield point for both IS3 and AM3 bentonites with increasing CMC content was observed, as shown in Figure 9a, with IS3 bentonite reaching the highest yield point of 11.5 Pa compared to AM3 (5.58 Pa), shown in Figure 9b. Additionally, the plastic viscosity of IS3 increased with rising CMC concentration, as illustrated in Figure 9c. Conversely, AM3 bentonite displayed an initial decrease followed by an increase in PV values with rising CMC content, attributed to unstable particle flow. The high YP/PV of IS3 CMC 2.5 suggests a satisfactory lifting capacity for drilling fluids, as it can clear cuttings efficiently and confer a "flat" velocity profile (Chilingarian et al., 1986). Figure 9d further shows the results for the yield point to plastic viscosity ratio for IS3 and AM3 bentonites as a function of the CMC content, revealing a significant increase in YP/PV for IS3 bentonite with a maximum at 2.5g CMC, while AM3 demonstrated a maximum at 1.25g CMC content.

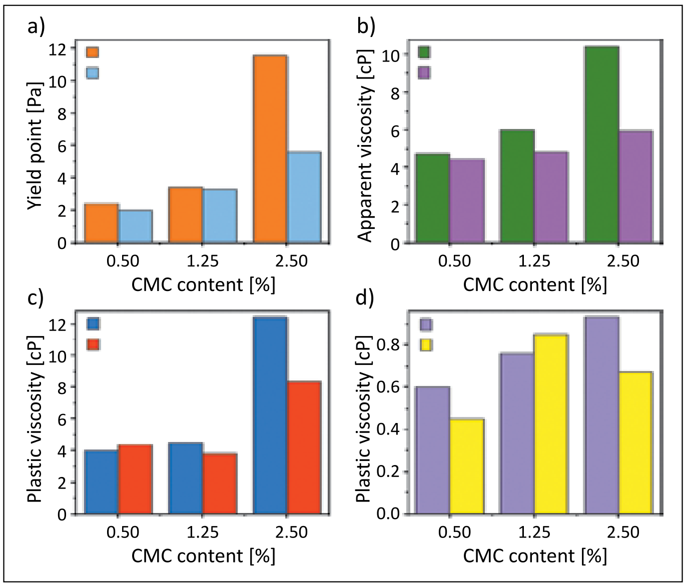

Figure 9. Yield point, apparent viscosity, plastic viscosity, and YP/PV versus CMC content for IS3 and AM3, respectively

Rysunek 9. Granica plastyczności, lepkość pozorna, lepkość plastyczna i YP/PV w zależności od zawartości karboksymetylocelulozy odpowiednio dla IS3 i AM3

Conclusion

Isinya clay was found to have a higher Na content compared to Amboseli clay. After beneficiation with Na_2CO_3 and CMC in varying quantities, the yield point of both Isinya and Amboseli samples increased with rising concentrations of the beneficiation materials. However, none of the samples met the API requirements (70–90% water, 5–15% bentonite, 1–5% polymers, 1–5%, and 1–3% additives including pH, control agents, biocides, and defoamers) when activated with Na_2CO_3 alone, which are 10–20 Pa, 10–12 cP, and 30–50 cP at a shear rate of 102 s^{-1} for YP, PV, and AV, respectively. The rheological properties of IS3 and AM3 bentonite deteriorated withincreased Na_2CO_3 concentration.

Dosages of Na_2CO_3 above 1.25g were necessary to achieve yield stress closer to the required 15 Pa for drilling applications. IS3 bentonite demonstrated the most promising rheological properties needed for drilling mud requirements after treatment with a CMC concentration of 2.50g. Both raw and modified Isinya samples have better drilling properties than Amboseli bentonites.

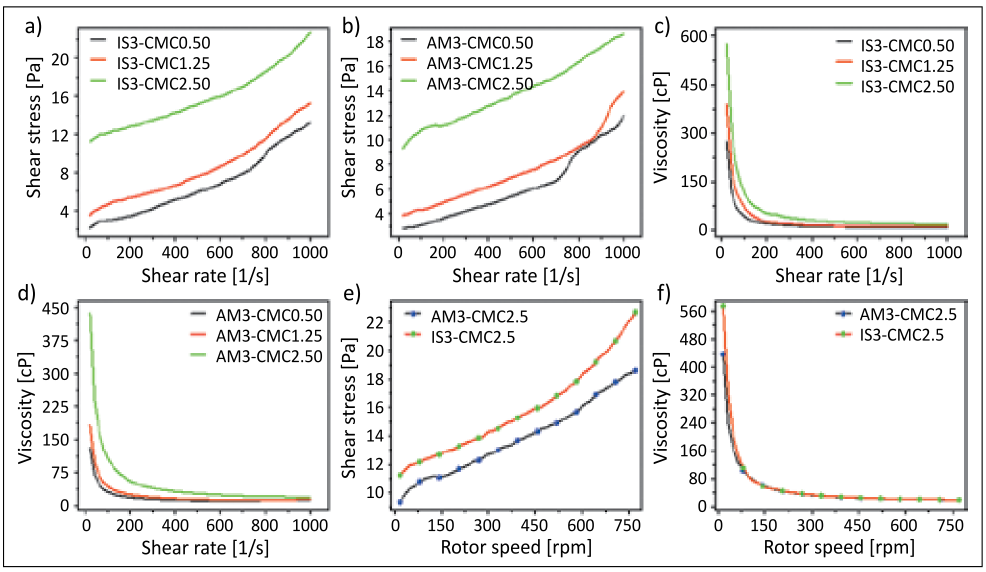

Figure 8. Shear stress and viscosity versus shear rate (a–d), and comparison of shear stress and viscosity against rotor speed (e–f) for the CMC-modified bentonites

Rysunek 8. Naprężenie ścinające i lepkość w zależności od prędkości ścinania (a–d) oraz porównanie naprężenia ścinającego i lepkości w zależności od prędkości wirnika (e–f) dla bentonitów modyfikowanych karboksymetylocelulozą

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