

ENC-2022-0718

THE ROLE OF PRESSURE ON THE YIELD STRESS AND DYNAMIC MODULI FOR AN INVERTED EMULSION DRILLING FLUID

Géssica Palaoro^a
palaorogessica@gmail.com

Jonathan F. Galdino^a
jonathangrag@gmail.com

Diogo E.V. Andrade^b
diogo.andrade@ufrgs.br

Admilson T. Franco^a
admilson@utfpr.br

^aFederal University of Technology - Paraná – UTFPR, Department of Mechanical Engineering – DAMEC, Postgraduate Program in Mechanical and Materials Engineering – PPGEM, Research Center for Rheology and Non-Newtonian Fluids – CERNN, 81280-340, R. Deputado Heitor Alencar Furtado, 5000 - Bloco N - Ecoville, Curitiba, PR, Brazil.

^bFederal University of Rio Grande do Sul (UFRGS) and Rheology and Non-Newtonian Flow Laboratory – ReoSul, 90046-902, R. Sarmiento Leite, 425, Prédio 1107 – Centro, Porto Alegre, RS, Brazil.

Abstract. *Oil and gas exploration and production in deep and ultra-deep wells, located in high pressure and high-temperature zones (HP/HT), is increasing considerably to meet global energy demand. Exploration in HP/HT zones present several challenges to the performance of drilling fluids for well control. The rheological characterization of drilling fluids has been extensively investigated through experiments at atmospheric pressure; however, there are many open questions under high-pressure conditions. The objective of this work is to perform a rheological characterization of invert emulsion drilling fluid with measurements performed under a wide pressure range. The sample is an inverted emulsion using an olefin base oil with an internal phase of sodium chloride brine, with a 60/40 oil to water ratio. Other drilling fluid components are primary and secondary emulsifiers, lime, organophilic clay, and barite. The measurements were performed on the Anton Paar MCR 502 controlled shear stress rotational rheometer coupled to a pressure cell system that allows applying pressures up to 1000 bar. The pressure supply unit consists of an upstream hand pump that pressurizes the internal oil with a pressure range of up to 700 bar, a spindle pump for applying pressures up to 1000 bar, and a separator unit responsible for transferring the pressure from the oil to the sample. The results show that the impact of the pressure is more relevant in the solid-like than in the liquid-like regime. The yield stress and the dynamic modulus tend to increase under pressure. We can anticipate that, interestingly, the higher the applied pressure, the greater the deformation that the fluid withstands in the solid-like regime. The authors are not aware of a similar discussion having been reported previously in the open literature. These findings bring essential information for the engineers in the oil and gas field since one of the main concerns at high-pressure conditions must be the drilling fluid behavior in the solid-like regime.*

Keywords: *inverted emulsion, drilling fluid, high-pressure, rheology, yield point*

1. INTRODUCTION

The current exploration and production of oil and gas reside in deep and ultra-deep wells, located in high-pressure (greater than 690 bar) and high-temperature zones (greater than 150 °C), as known as HPHT wells (Henaut et al., 2020). The extreme conditions in HPHT wells require an appropriate selection of the drilling fluid since most of the problems faced in the drilling procedure are directly or indirectly related to the fluid formulation used during the process (Zamora et al., 2013).

Drilling fluids are classified into two main categories: water-based or oil-based drilling fluids. Although the drawbacks of the high cost and the possible environmental impact of irregular fluid rejection, oil-based drilling fluids are usually used for HPHT wells. This choice is based not only on the possibility of controlling the fluid rheological properties but also due the better thermal stability, lubricity, filtration control for long periods, and reduction on shale instability when compared to the water-based drilling fluid (Ibeh, 2007; Xu et al., 2014; Zhuang et al., 2018).

Drilling fluids are elastoviscoplastic thixotropic materials. In other words, at rest, these materials restructure over time and present a solid viscoelastic behavior when submitted to low strains, presenting a predominantly viscous behavior when submitted to stress higher than a critical stress, named yield stress (Zamora e Growcock, 2010; Bui et al., 2012; Fernandes et al., 2016).

Besides the influence of the shear history on the material behavior, the rheological properties of drilling fluids also depend on both temperature and pressure experienced by the fluid. The influence of the shear history and the rheological behavior of drilling fluids were extensively studied in the literature (Dzuy and Boger, 1985; Coussot et al., 2004; Fernandes et al., 2017a; Whittle and Dickinson, 1998; Choi and Rogers, 2020; Oliveira and Hilliou, 2020). The primary efforts were focused on determining a constitutive equation that represents the rheological behavior of drilling fluids on different applications (Maxey, 2007; Pivnicka et al., 2015; Andrade et al., 2016; Skadsem and Leulseged, 2018; Stokes and Telford, 2004). The main conclusions are that the rheological behavior of the material (such as the gel strength and its time-dependency) was affected by its composition, experimental protocol, and aging time (Rodrigues et al., 2020; Zhuang et al., 2016; Zhuang et al., 2018; Zhuang et al., 2019; Ansari et al., 2021; Bahrainian et al., 2018; Vryzas and Kelessidis, 2017; Bjørkevoll et al., 2003; Gautam and Guria, 2020a). It is worth noting that most of these analyses were conducted at atmospheric pressure and temperature around 25 °C.

In the last six decades, much effort has been applied to understand the effects of pressure and temperature on the rheological properties of drilling fluids (Hermoso et al., 2014a, 2014b, 2015, 2017, Rossi et al., 1999, Amani, 2012; Amani and Al-Jubouri, 2012, Long et al., 2021, Lucky and Johnson, 2018). In general, one can conclude that the apparent viscosity increases with the pressure but decreases with temperature increases. Many authors observed that the apparent viscosity of drilling fluids was affected by changing the temperature regardless of the pressure experienced by the fluid. On the other hand, the role of the pressure is almost negligible up to a certain critical pressure, which varies for each drilling fluid (Alderman et al., 1988; Herzhaft et al., 2001; Gandelman et al., 2007; Gokdemir et al., 2017). The increase in pressure and/or temperature experienced by the drilling fluid must provide chemical, physical, and electrochemical reactions in the material (Zhuang et al., 2019).

One crucial role of the drilling fluids is avoiding cuttings to precipitate over the drill bit during some stoppage on the drilling process (Balhoff et al., 2011; Gautam e Guria, 2020b). These materials develop a structured state at rest to fulfill this requirement, presenting a solid-like behavior when submitted to stresses lower than the yield stress. In order to break up this gel-like structure and reach the liquid-like regime, pumping pressures higher than the usual are usually required to resume circulation, which can be a complex technical problem since this pressure may overcome the formation fracture pressure and damage the borehole walls. The process of breaking up the material structure is usually referred to as solid-liquid transition (Coussot et al., 2006) since the material behaves as a solid for stress below the yield stress and as a liquid when this critical stress is surpassed. The accurate determination of the behavior of the drilling fluids in this solid-like behavior is essential for further understand the solid-liquid transition and, consequently, for better choosing the strategies during the drilling process. In this scenario, the comprehension of the effects of pressure and temperature not only on the viscosity but also on the viscoelastic properties and solid-like structure of the drilling fluid is essential for the oil and gas industry (Maxey, 2009).

Although considerable analyzes have been developed to understand the influence of high-pressures and high-temperatures on the apparent viscosity of drilling fluids, the role of these variables on the behavior of the material in the solid-like regime is still an open question. As far as we are concerned, the only attempts to study the effect of the pressure on the solid-like behavior of drilling fluids were developed by Maxey (2009) and Patel et al. (2019). In both works, the authors focused only on the influence of the frequency applied on the oscillatory test in the linear viscoelastic region for fluids with different compositions submitted to high pressures. Having in mind the importance of understanding the material behavior in the solid-like regime and the solid-liquid transition, in the current work, we investigated the influence of the pressure experienced by an oil-based drilling fluid on its rheological characteristics such as dynamic moduli (G' and G'') and material yield stress. We anticipate that besides increasing the storage modulus and the material yield stress, the yield strain also increased with the pressure. In other words, it seems that the higher the applied pressure the greater is the deformation that the material withstands before reaching the transition from the solid-like to the liquid-like behavior.

2. EXPERIMENTAL METHODOLOGY

A synthetic drilling fluid kindly provided by Petrobras was selected for the experimental study. The sample is an inverted emulsion using an olefin base oil with an internal phase of sodium chloride brine, with a 60/40 oil to water ratio. Other drilling fluid components are primary and secondary emulsifiers, lime, organophilic clay, and barite.

The measurements were performed on the Anton Paar MCR 502 controlled shear stress rotational rheometer equipped with a pressure cell system that allows applying pressures up to 1000 bar.

One of the major issues in performing rheometric measurements at high pressures is the accuracy of the measured results, especially at low shear stresses and shear rates. The sensitivity of the systems is reduced due to the torque transmission that is carried out magnetically. The results reliability was assured by performing identical protocols at atmospheric pressure using the standard configuration rheometer and the pressure cell system coupled with the rheometer.

Thus, it is possible to compare both results and determine the range of shear stress and shear rate in which we can adequately analyze the fluid using the pressure cell apparatus.

Considering that the primary goal of the current work is to analyze the effects of pressure on the structure of the drilling fluid, all tests were performed at a constant temperature of 25 °C. Rheological tests were conducted at five different pressures: atmospheric pressure, 70, 270, 500 and 800 bar. Before any test, whether in the standard configuration rheometer or with the pressure cell system, the drilling fluid sample was homogenized for 10 minutes on the Hamilton Beach mixer.

For tests performed with the standard configuration of the rheometer, the sample was pre-sheared for 10 minutes at 500 s⁻¹ and then left under a zero-shear stress condition for 10 minutes resting time, in which the gel development process took place. After the pre-test, the sample was submitted to different protocols: (i) measurement of the equilibrium viscosity curve in which plateaus of shear rate were applied until the steady-state shear stress determination; (ii) stress amplitude oscillatory sweep from 10⁻³ to 100 Pa and 1 Hz; (iii) stress ramp from 10⁻² to 100 Pa for 5 minutes. For the tests performed in the rheometer coupled with the pressure cell system, the same protocol performed in the rheometer with standard configuration was followed; the only difference is that in this system, the sample is pumped into the measuring device up to the desired pressure.

3. RESULTS AND DISCUSSION

The influence of pressure on the rheological behavior of the drilling fluid was analyzed in three regions: the liquid-like regime, the solid-like regime, and the solid-liquid transition. First, we analyze the liquid regime. In other words, the influence of the pressure on the apparent viscosity of the material. Fig. 1 presents the material equilibrium viscosity curve under different applied pressures. In these experiments, each shear rate was imposed for enough time (minimum of 10 min) until the material reached the steady-state for each condition. First, it is worth mentioning that the difference between the results obtained for the viscosity curve using the standard configuration (blue star) and the pressure cell (red triangle) is neglected at atmospheric pressure. We performed a single-factor statistical analysis of variance (ANOVA) with a significance level of 95% to assess the existence of any statistically significant differences between the tests performed with the usual configuration and with the pressure cell configuration at atmospheric pressure and at 25°C. The ANOVA results are shown in the Appendix. We observed that there are no statistically significant differences between the results obtained with the usual configuration and with the pressure cell configuration.

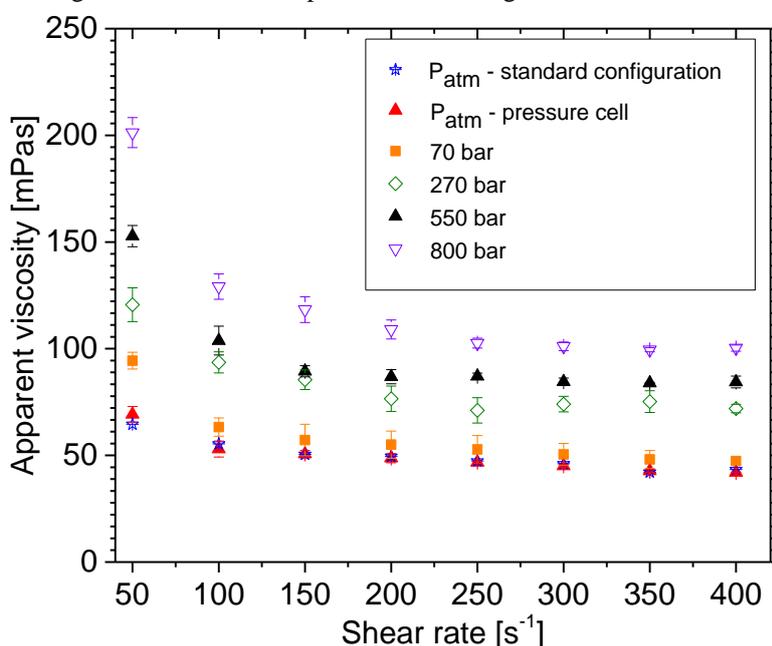


Fig. 1. Viscosity curves as a function of shear rate at 25 °C for atmospheric pressure, 70, 270, 550 and 800 bar. The experiments were repeated twice with different samples and the error bars were determined using a Student's t distribution with a 95.4% confidence interval as proposed by Oehlert (2010).

Interestingly, it seems that as observed elsewhere (Herzhaft et al., 2001; Ibeh, 2007; Xu et al., 2013; Gokdemir et al., 2017), the effects of pressure on the viscosity are negligible up to a certain pressure level for the drilling fluid analyzed in this work. It appears that the pressure effect on the particles and droplets interactions is not enough to change the macroscopic viscosity measurement up to this value. In the current work, we observed that this pressure is between 70 and 270 bar, as shown in Fig. 1, in which, except for the lowest applied shear rate, the 70 bar pressure did not affect the fluid viscosity. It is interesting to point out that a similar range of pressure was suggested by Gokdemir et al. (2017) for

another type of oil-based drilling fluid. From the pressure of 270 bar onwards, the higher the imposed pressure, the higher the viscosity (see Fig.1). The pressure effects are most noticeable at lower shear rates; for example, the apparent viscosity measured at 50 s^{-1} increased almost three times compared with the experiment performed at atmospheric and 800 bar-case. On the other hand, this increment was around two times for 400 s^{-1} in this same comparison. Many researchers also observed with different oil-based drilling fluids that the apparent viscosity doubled or even fourfold when the pressure increased to values between 500 to 1000 bar, regardless of the temperature (Herzhaft et al., 2001; Gandelman et al., 2007; Torsvik et al., 2015). As previously analyzed in the literature in HTHP conditions, these results show that the pressure can play a significant role in determining the operational condition since the viscosity of the drilling fluid can be much affected by the level of the well pressure during the drilling operation.

In order to verify how the pressure can modify the behavior of this drilling fluid in the solid-like regime, oscillatory stress amplitude sweep tests were performed after the pre-shear of 500 s^{-1} and the resting time of 10 minutes (see Fig. 2). This protocol analyzed the storage (G') and dissipation (G'') moduli as functions of the measured strain amplitude at $25 \text{ }^\circ\text{C}$ and different pressures applied to the sample. Three main regions can be observed in this analysis (Hyun et al., 2011):

1. The linear regime at small shear amplitudes (called SAOS – Small Amplitude Oscillatory Shear) in which the material properties are independent of the applied stress amplitude;
2. The MAOS (Medium Amplitude Oscillatory Shear) region in which some nonlinearities are observed on the measurements;
3. Finally, the material reaches the LAOS (Large Amplitude Oscillatory Shear) region, in which the nonlinearities are evident in the measurements.

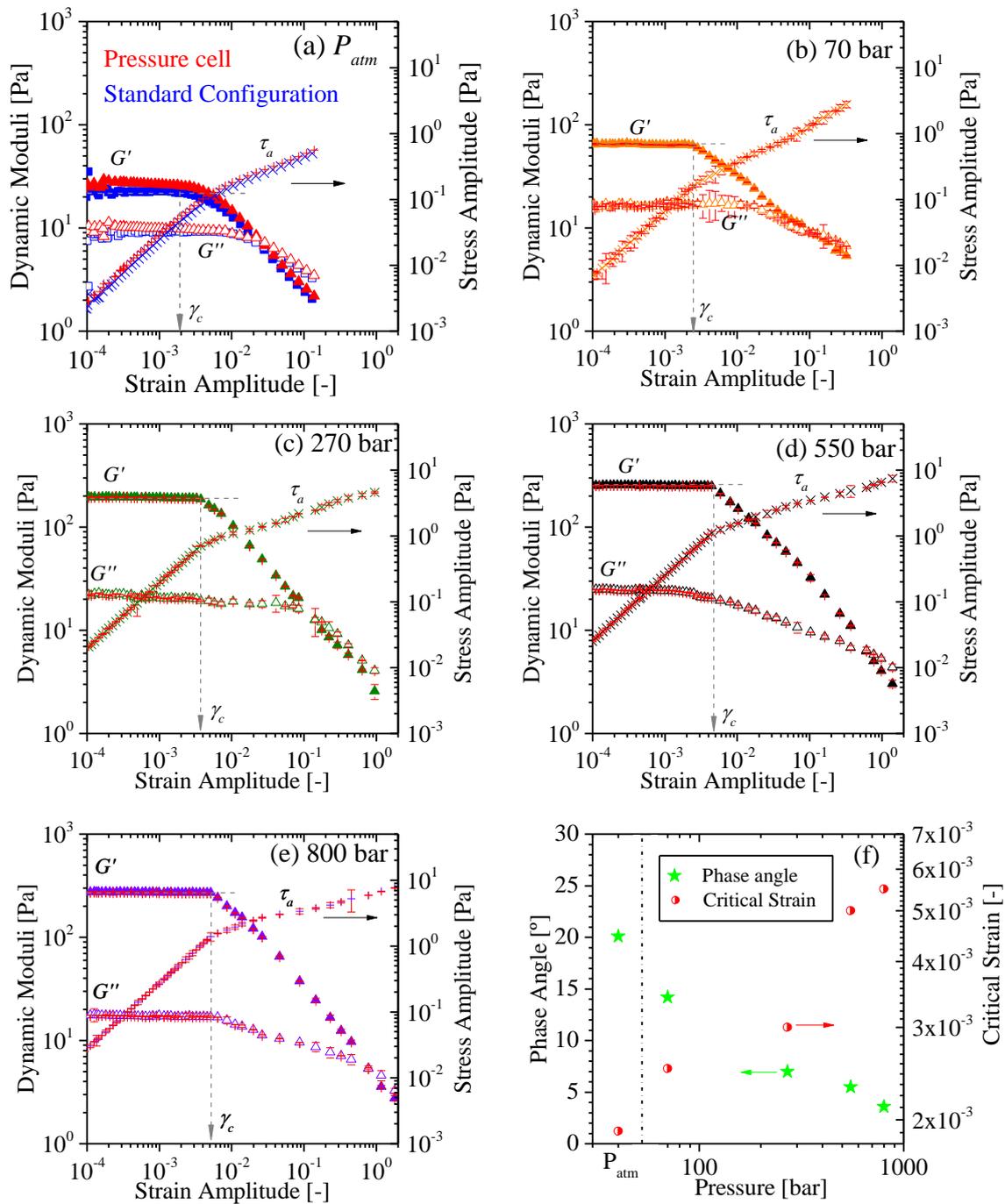


Fig. 2. Oscillatory stress sweep tests performed at different configurations at 1 Hz after pre-shearing the sample for 10 minutes at 500 s^{-1} and then left it under a zero-shear stress condition for 10 minutes. The experiments were repeated twice with the same sample and the error bars were determined using a Student's t distribution with a 95.4% confidence interval as proposed by Oehlert (2010). Figures (a) to (e) present G' , G'' , and the stress amplitude as a function of the strain amplitude of each experiment. Figure (a) presents the comparison between the measurements performed using the standard rheometer configuration (red curves) and with the pressure cell installed in the rheometer (blue curves), both at atmospheric pressure. Figures (b) to (e) show the results at different pressures applied on the sample, and figure (f) shows a compilation of the essential characteristics measured at different pressures. Experiments were performed at $25 \text{ }^\circ\text{C}$.

In order to analyze the reliability of the oscillatory measurements using the pressure cell configuration, the comparison between the results obtained with the standard configuration rheometer (blue symbols) and the pressure cell configuration (red symbols) are presented in Fig. 2a. The figure presents the dynamic moduli (G' and G'') on the y-axis and the stress amplitude on the auxiliary y-axis as a function of the strain amplitude. One can see that the pressure cell results very well represent the main features of the curves. Some points on the curves are important on the analysis, the values of G' and G'' in the linear viscoelastic regime and mainly the comparison between both moduli that can be analyzed by the phase angle shift [$\delta = \text{atan}(G''/G')$] presented as a function of the pressure in Fig. 2f. The phase angle value can be understood as the analysis of the predominance of the elastic behavior over the viscous behavior in the SAOS regime. For an elastic solid $\delta = 0^\circ$ and a viscous fluid $\delta = 90^\circ$ (Macosko, 1994). In addition to these characteristics on the SAOS regime, one can analyze the linear-to-nonlinear viscoelastic transition, the point at which the stress starts to imposed plastic irreversible deformations in the material microstructure (Fernandes et al., 2017a). In this work, the linear-to-nonlinear viscoelastic transition strain is called a critical strain, γ_c , as shown by the gray arrow in Fig. 2a. It is important to keep in mind that although one usually shows the G' and G'' in MAOS and LAOS regime (calculated using the phase angle, the stress and strain amplitudes) and defines the yielding point in the $G'-G''$ crossover; this analysis must be carried on with caution since by definition the dynamic moduli can just be determined appropriately in the SAOS regime (Hyun et al., 2011). The yielding behavior is further analyzed later in Fig. 1, in which a stress ramp is applied in the material, and in Fig. 2, in which the values of $G'-G''$ crossover stress are analyzed. Comparing the main features in Fig. 2a one can state that the pressure cell configuration can reliably reproduce the material's behavior in the stress amplitude oscillatory sweep. This configuration was employed to perform the experiments in the other pressures applied to the drilling fluid (Fig. 2b-e).

Analyzing the influence of pressure applied on the oscillatory stress amplitude sweep (Fig. 2b-e), one can see that the greater the pressure applied, the greater the dynamic moduli, but the increment is higher for G' than G'' . Just as a comparison, the storage modulus increased one order of magnitude (from ~ 20 Pa to ~ 200 Pa), while the increment in the loss modulus was from ~ 10 Pa to ~ 20 Pa when the pressure increased from the atmospheric pressure (Fig. 2a) to 800 bar (Fig 2e). The predominance of the elastic behavior over the viscous behavior as the pressure increases can be compared by the phase angle measured in the SAOS regime (Fig. 2f), i.e., the higher the applied pressure, the lower the phase angle.

As further discussed in Fig. 4, it is important to anticipate that the higher the G' , the higher the material gel strength. With this information in mind, the most interesting result in the oscillatory measurement (Fig. 2) is that, although the material gel strength increased with the pressure, the critical strain also increased. The increment in the pressure experienced by the fluid makes it possible to reach even greater deformations within the linear viscoelastic range of the material. This linear-to-nonlinear deformation, γ_c , is presented by the gray arrow in Fig. 2a-e, and the comparison between all the cases is summarized in Fig. 2f.

In order to further analyze the material solid-liquid transition, unidirectional shear stress ramps were imposed on the material. In this protocol, below the yield stress the material behaves as a solid, whose strain is limited to low values. At a certain point, one can see that the strain starts to increase with the applied stress rapidly; this transition can be understood as the material yield point (Venkatesan et al., 2003; Andrade e Coussot, 2019; N'gouamba et al., 2020). Fig. 3 shows the shear strain as a function of the applied stress for this protocol performed under different pressures after the same pre-shearing and aging time used in the previous analysis. First, it is essential to compare the results obtained with the standard configuration and the pressure cell. In this stress ramp, one can see that the results obtained using the pressure cell configuration reproduces quite well all the main features of the curve measured with the standard configuration. In these experiments, the yielding point was determined using the interception of two power laws lines fitted below and above the yielding region; for example, as presented by the dashed line, the yield stress and strain are around 7.5 Pa and 4.2 Pa, respectively, for the 800 bar-case. Interestingly, as the pressure experienced by the fluid increases, not only the material yield stress increases, but also one can note the increase of the material yield strain (see Fig. 5c, which summarizes the influence of the pressure on the yield stress and yield strain obtained from Fig. 3).

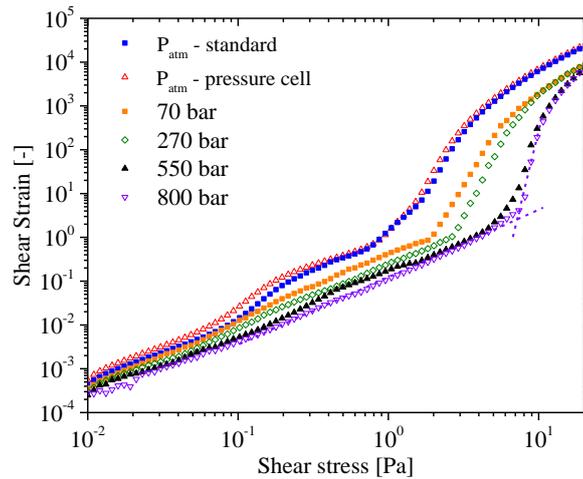


Fig. 3. Shear strain as a function of shear stress for a ramp of stress performed at different pressures applied on the sample at 25 °C after 10 minutes of pre-shearing at 500 s⁻¹ and 10 minutes of aging time. The dashed lines are presented in order to demonstrate the procedure used to determine the yielding point.

As previously discussed (Fernandes et al., 2016), in which the influence of the aging time on the rheological behavior of oil-based drilling fluid was analyzed, the storage modulus and the material yield stress can be somehow correlated. Although representing different fluid characteristics (G' represents the material elasticity and the yield stress the minimum stress required to break up the material), Fig. 4a shows that both rheological parameters can also be correlated in our analyses. For the range of pressures analyzed in the current work, the higher the G' , the higher the material gel strength. Much experimental time can be saved with this information in mind since it is possible to perform oscillatory measurements in the linear viscoelastic region, varying other parameters (such as the pressure applied to the fluid) without performing yielding tests in all the analyses.

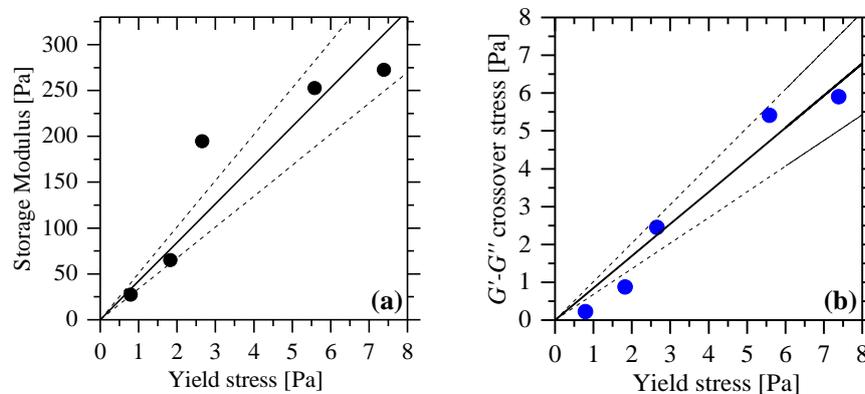


Fig.4 (a) Storage modulus in the linear viscoelastic region and (b) $G'-G''$ crossover stress, both function of the yield stress. The continuous lines represent a linear relationship between the two properties analyzed with the dashed lines +/- 20% reference.

Other interesting comparisons can be observed in Fig. 4b, which presents $G'-G''$ crossover stress obtained from Fig. 2 due to the yield stress obtained from Fig. 3. As previously discussed, although it is a standard procedure to use the $G'-G''$ crossover stress as a value to measure the material gel strength, it is not indicated to use this crossover point as the material yielding point confidently. The main reasons for this caution are that the dynamic moduli can be precisely calculated only in the LAOS region, and also the shear history imposed during the MAOS and LAOS regime is too complex and can affect the break-up point in some materials (Andrade e Coussot, 2019). Although all these caveats, it is interesting to note that, for this material and these specific ranges of the analyzed parameters, one can see a correlation between the $G'-G''$ crossover stress and the material yield stress as presented in Fig. 4b. At least, we can state that the higher the $G'-G''$ crossover stress, the higher the material gel strength. For practical purposes, one can perform only oscillatory stress sweep measurements to determine the elastic modulus and the magnitude of the material gel strength without the requirement of performing other procedures to determine the yield stress.

The results of the main rheological parameters as a function of the applied pressure are summarized in Fig. 5. Curiously, it seems that the effect of the pressure is more evident in the solid-like regime (see G' in the SAOS region in Fig. 5b and yield stress in Fig. 5c) than in the liquid-like regime (see viscosity in Fig. 5a). As discussed above, pressure

in the liquid-like regime is more impacting at low shear rates, but even for 50 s^{-1} the viscosity increased just three times compared with results at atmospheric pressure and 800 bar. Meanwhile, both G' and yield stress increased one order of magnitude at this same comparison.

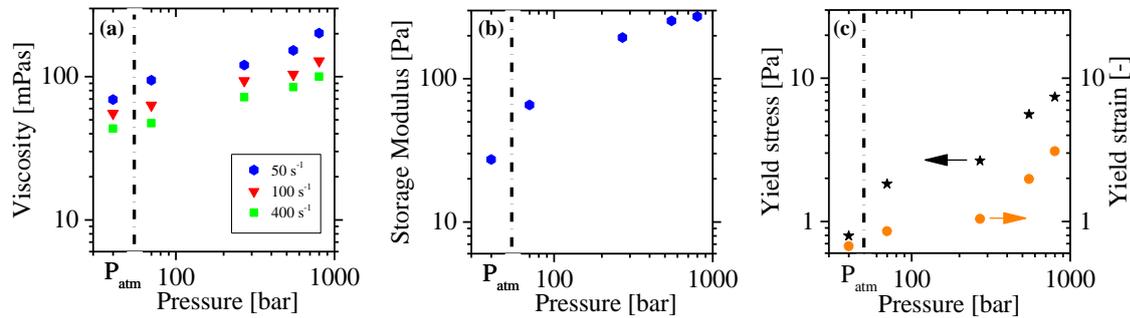


Fig. 5. Influence of the applied pressure on the main rheological drilling fluid parameters: (a) Viscosity at 50, 100, and 400 s^{-1} , results obtained from Fig. 1; (b) Storage modulus at the linear viscoelastic region, results obtained from Fig. 2; (c) Yield stress and yield strain, results obtained from Fig. 3.

Another essential point to be addressed is that it seems the concept that the pressure affects the material only above a critical value is valid only for the liquid-regime, in which the material viscosity is not much affected for the case of 70 bar applied pressure. On the other hand, for the solid-regime, the rheological characteristics are affected even for the lowest pressure imposed on the fluid (70 bar) compared with the results obtained at atmospheric pressure (see G' and the yield stress in Fig. 5). These findings bring essential information for the engineers in the oil and gas field since it seems that one of the main concerns at high-pressure conditions may be the material gel strength. In other words, under these conditions, it can be challenging to break up the material's structure and to resume the flow.

Finally, one can see that the same characteristics observed in the linear-to-nonlinear strain (Fig. 2f) are also noted in the material yield strain (Fig. 5c). The higher the applied pressure, the greater is the required deformation to reach the yield point. As previously analyzed by other researchers (Hiller, 1963; Combs and Whitemire, 1968; Briscoe et al., 1994; Hermoso et al., 2014; Hermoso et al., 2015; Maxey, 2009), it seems that the effect of the pressure on the rheological properties of the inverted emulsion oil-based drilling fluid can be explained by the compression of the dispersed oil phase. The pressure seems to decrease the size of the emulsion droplets, affecting the interactions between the drops and the stiffness of the microstructure, presenting changes macroscopically in the material's mechanical response.

4. CONCLUSIONS

The current work investigated the effects on the rheological behavior of an oil-based drilling fluid submitted to different levels of pressure. The results were obtained employing a pressure cell coupled with a rotational rheometer. We observed that pressure drastically affects the rheological behavior of the drilling fluid, with the impact of pressure being more relevant in the solid than in the liquid regime. The main conclusions can be summarized as:

- The drilling fluid viscosity is roughly independent of the pressure up to a critical value. Above this critical pressure, the viscosity increased with the pressure experienced by the fluid;
- The higher the pressure applied to the fluid, the higher the storage modulus and the lower the phase angle in the linear viscoelastic region;
- The yield stress increased with the pressure applied to the material;
- Interestingly, the critical strain in which the material leaves the linear viscoelastic region and the yield strain increased with the pressure applied to the fluid;
- The pressure's influence is more impacting the solid regime than in the liquid regime since, in the analyzed range (from atmospheric pressure up to 800 bar), the viscosity increased around three times while the storage modulus and the yield stress increased one order of magnitude.

5. ACKNOWLEDGEMENTS

The authors acknowledge the financial support of PETROBRAS S/A (TC 0050.0070318.11.9), CNPq (Process: 487091/2013-2), CAPES, FINEP, PRH-ANP/MCT (PRH-ANP/MCTI no. 21), and PFRH/PETROBRAS (6000.0067933.11.4 and 6000.0082166.13.4).

6. REFERENCES

- Alderman NJ, Gavignet A, Guillot D, Maitland GC ,1988. High-temperature, high-pressure rheology of water-based muds. SPE Annu Tech Conf Exhib Houston, Texas.
- Amani M ,2012. The rheological properties of oil-based mud under high pressure and high temperature conditions. *Advances in Petroleum Exploration and Development* 3:21–30.
- Amani M, Al-jubouri MJ ,2012. An experimental investigation of the effects of ultra high pressures and temperatures on the rheological properties of water-based drilling fluids. Int Conf Heal Saf Environ Oil Gas Explor Prod Perth, Aust.
- Andrade DEV, Coussot P ,2019. Brittle solid collapse to simple liquid for a waxy suspension. *Soft Matter* 15:8766–8777.
- Andrade DEV, Fernandes RR, Santos TGM, Ceccon EV, da Cruz ACB, Franco AT, Negrão COR ,2016. Curve-fitting equation for prediction of the start-up stress overshoot of an oil-based drilling fluid. *Journal of Petroleum Science and Engineering* 146:902–908.
- Ansari M, Turney DE, Morris J, Banerjee S ,2021. Investigations of rheology and a link to microstructure of oil-based drilling fluids. *Journal of Petroleum Science and Engineering* 196:108031.
- Bahrainian SS, Nabati A, Hajidavalloo E ,2018. Improved rheological model of oil-based drilling fluid for south- western Iranian oilfields. *Journal of Petroleum Science and Technology* 8:53–71.
- Balhoff MT, Lake LW, Bommer PM, Lewis RE, Weber MJ, Calderin JM ,2011. Rheological and yield stress measurements of non-Newtonian fluids using a marsh funnel. *Journal of Petroleum Science and Engineering* 77:393–402.
- Bjørkevoll K, Rolv R, Bjarne A, Helga G, Antonino M ,2003. Transient gel breaking model for critical wells applications with field data verification. *SPE/IADC Drilling Conference held in Amsterdam, The Netherlands* 1–8.
- Briscoe B, Luckham P, Ren S ,1994. The properties of drilling muds at high pressures and high temperatures. *Philosophical Transactions: Physical Sciences and Engineering* 348:179–207.
- Bui B, Saasen A, Maxey J, Ozbayoglu ME, Miska SZ, Yu M, Takach NE ,2012. Viscoelastic properties of drilling fluids. *Annual Transactions of the Nordic Rheology Society* 20:33–47.
- Choi J, Rogers SA ,2020. Optimal conditions for pre-shearing thixotropic or aging soft materials. *Rheologica Acta* 59:921–934.
- Combs GD, Whitmire LD ,1960. Capillary viscometer simulates bottom-hole conditions. *Oil Gas Journal* 108–113.
- Coussot P, Bertrand F, Herzhaft B ,2004. Rheological behavior of drilling muds, characterization using MRI visualization. *Oil and Gas Science and Technology* 59:23–29.
- Coussot P, Tabuteau H, Chateau X, Tocquer L, Ovarlez G ,2006. Aging and solid or liquid behavior in pastes. *Journal of Rheology* 50:975–994.
- Dzuy NQ, Boger D V. ,1985. Direct yield stress measurement with the vane method. *Journal of Rheology* 29:335–347.
- Fernandes RR, Andrade DEV, Franco AT, Negrão CO. ,2017a. The yielding and the linear-to-nonlinear viscoelastic transition of an elastoviscoplastic material. *Journal of Rheology* 61:893–903.
- Fernandes RR, Andrade DEV, Franco AT, Negrão COR ,2016. Correlation between the gel-liquid transition stress and the storage modulus of an oil-based drilling fluid. *Journal of Non-Newtonian Fluid Mechanics* 231:6–10.
- Fernandes RR, Andrade DEV, Franco AT, Negrão COR ,2017b. Influence of pre-shearing on rheometric measurements of an oil-based drilling fluid. *Rheologica Acta* 56:743–752.
- Gandelman RA, Leal RAF, Gonçalves JT, Aragão AFL, Lomba RF, Martins AL ,2007. Study on gelation and freezing phenomena of synthetic drilling fluids in ultradeepwater environments. SPE/IADC Drill Conf held Amsterdam, Netherlands.
- Gautam S, Guria C ,2020a. An accurate determination of the shear rate for high-yield-stress drilling fluids using concentric cylinder Fann 35 viscometer data. *SPE Journal* 25:2984–3001.
- Gautam S, Guria C ,2020b. Optimal synthesis, characterization, and performance evaluation of high-pressure high-temperature polymer-based drilling fluid: The effect of viscoelasticity on cutting transport, filtration loss, and lubricity. *SPE Journal* 25:1333–1350.
- Gokdemir MG., Erkeköl S., Dogan HA. ,2017. Investigation of high pressure effect on drilling fluid rheology. 36th Int Conf Ocean Offshore Arct Eng.
- Henaut I, Pasquier D, Rovinetti S, Espagne B, Werner B, Myrseth V, Saasen A, Gadala-Maria F, Acrivos A, Vryzas Z,

- Kelessidis VC, Nalbantian L, Zaspalis V, Gerogiorgis DI, Wubulikasimu Y, De Souza Mendes PR, de Oliveira VAV, Hilliou L, Pivnicka S, et al ,2020. Thixotropic elasto-viscoplastic model for structured fluids. *Oil and Gas Science and Technology* 59:917–930.
- Hermoso J, Martinez-Boza F, Gallegos C ,2015. Influence of aqueous phase volume fraction, organoclay concentration and pressure on invert-emulsion oil muds rheology. *Journal of Industrial and Engineering Chemistry* 22:341–349.
- Hermoso J, Martinez-Boza F, Gallegos C ,2014a. Influence of viscosity modifier nature and concentration on the viscous flow behaviour of oil-based drilling fluids at high pressure. *Applied Clay Science* 87:14–21.
- Hermoso J, Martínez-Boza F, Gallegos C ,2014b. Combined effect of pressure and temperature on the viscous behaviour of all-oil drilling fluids. *Oil & Gas Science and Technology – Revue d'IFP Energies nouvelles* 69:1283–1296.
- Hermoso J, Martínez-Boza FJ, Gallegos C ,2017. Organoclay influence on high pressure-high temperature volumetric properties of oil-based drilling fluids. *Journal of Petroleum Science and Engineering* 151:13–23.
- Herzhaft B, Peysson Y, Isambourg P, Delepouille A, Toure A ,2001. Rheological properties of drilling muds in deep offshore conditions. SPE/IADC Drill Conf held Amsterdam, Netherlands.
- Hiller KH ,1963. Rheological measurements on clay suspensions and drilling fluids at high temperatures and pressures. *Journal of Petroleum Technology* 15:779–788.
- Hyun K, Wilhelm M, Klein CO, Cho KS, Nam JG, Ahn KH, Lee SJ, Ewoldt RH, McKinley GH ,2011. A review of nonlinear oscillatory shear tests: Analysis and application of large amplitude oscillatory shear (LAOS). *Progress in Polymer Science* 36:1697–1753.
- Ibeh C ,2007. Investigation on the effects of ultra-high pressure and temperature on the rheological properties of oil-based drilling fluids. Ph.D Thesis. Texas A&M University, Texas, USA.
- Long H, Chen W, Tan D, Yang L, Zhang S, Wang S ,2021. Development of a high temperature and high pressure oil-based drilling fluid emulsion stability tester. *Open Journal of Yangtze Oil and Gas* 06:25–35.
- Lucky APA, Johnson FA ,2018. Investigation of the effect of Yttrium Oxide nanoparticle on the rheological properties of water based mud under high pressure high temperature (HPHT) environment. *International Journal of Mechanical Engineering and Technology* 9:545–559.
- Macosko CW ,1994. *Rheology principles, measurements and applications*, First Edition.
- Maxey J ,2007. Thixotropy and yield stress behavior in drilling fluids.
- Maxey J ,2009. Non-aqueous fluid rheology at elevated temperature and pressure.
- Mendes PR de S ,2011. Thixotropic elasto-viscoplastic model for structured fluids. *Soft Matter* 7:2471–2483.
- N'gouamba E, Goyon J, Tocquer L, Oerther T, Coussot P ,2020. Yielding, thixotropy, and strain stiffening of aqueous carbon black suspensions. *Journal of Rheology* 64:955–968.
- Negrão COR, Franco AT, Rocha LLV ,2011. A weakly compressible flow model for the restart of thixotropic drilling fluids. *Journal of Non-Newtonian Fluid Mechanics* 166:1369–1381.
- Oliveira VAV de, Hilliou L ,2020. Structure-rheological properties relationships in model drilling fluids formulated in aqueous solutions of carrageenan with varying chemical structures. *Journal of the Taiwan Institute of Chemical Engineers* 111:312–319.
- Patel HA, Santra A, Thaemlitz CJ ,2019. Exceptional flat rheology using a synthetic organic-inorganic hybrid in oil-based muds under high pressure and high temperature. SPE/IADC Drill Int Conf Exhib held Hague, Netherlands.
- Pivnicka S, Nguyen TC, Al-Safran E, Saasen A ,2015. Pressure gradient prediction of time-dependent drilling fluids and the effect of acceleration. *Journal of Petroleum Science and Engineering* 135:246–252.
- Rodrigues RK, Martins S de FC, Naccache MF, de Souza Mendes PR ,2020. Rheological modifiers in drilling fluids. *Journal of Non-Newtonian Fluid Mechanics* 286:104397.
- Rossi S, Luckham PF, Zhu S, Briscoe BJ ,1999. High-pressure/high-temperature rheology of Na⁺-montmorillonite clay suspensions. SPE Int Symp Oilf Chem held Houston, Texas. doi: 10.2118/50725-MS
- Skadsem HJ, Leulseged A, Cayeux E ,2019. Measurement of drilling fluid rheology and modeling of thixotropic behavior. *Applied Rheology* 29:1–11.
- Stokes JR, Telford JH ,2004. Measuring the yield behaviour of structured fluids. *Journal of Non-Newtonian Fluid Mechanics* 124:137–146.
- Torsvik A, Myrseth V, Linga H ,2015. Drilling fluid rheology at challenging drilling conditions - an experimental study using a 1000 bar pressure cell. *Annual Transactions of the Nordic Rheology Society* 23:13–20.

- Vajargah AK, van Oort E ,2015. Determination of drilling fluid rheology under downhole conditions by using real-time distributed pressure data. *Journal of Natural Gas Science and Engineering* 24:400–411.
- Venkatesan R, Östlund JA, Chawla H, Wattana P, Nydén M, Fogler HS ,2003. The effect of asphaltenes on the gelation of waxy oils. *Energy and Fuels* 17:1630–1640.
- Vryzas Z, Kelessidis VC ,2017. Nano-based drilling fluids: A review. *Energies* 10:1–33.
- Whittle M, Dickinson E ,1998. Large deformation rheological behaviour of a model particle gel. *Journal of the Chemical Society - Faraday Transactions* 94:2453–2462.
- Xu L, Chuan S, Xu MB, Zhao L, Wen SC, Liu WH, Xu J, You FC, Gong C ,2014. Experimental investigations into the performance of a flat-rheology water-based drilling fluid. *SPE Journal* 19:69–77.
- Xu L, Zhao L, Xu MB, Xu J, Wang X ,2013. Lab investigations into high temperature high pressure rheology of water-based drilling fluid. *Applied Mechanics and Materials* 418:191–195.
- Zamora M, Growcock F ,2010. The top 10 myths, misconceptions and mysteries in rheology and hydraulics. Fluids Conf. Exhib. Houston, Texas
- Zamora M, Roy S, Slater K, Troncoso J ,2013. Study on the volumetric behavior of base oils, brines, and drilling fluids under extreme temperatures and pressures. *SPE Drilling & Completion* 28:278–288.
- Zhuang G, Jiang W, Zhang Z ,2019. Organic modifiers of organo-montmorillonite in oil system under high temperatures: desorption or degradation?. *Industrial and Engineering Chemistry Research* 58:2644–2653.
- Zhuang G, Zhang Z, Peng S, Gao J, Jaber M ,2018a. Enhancing the rheological properties and thermal stability of oil-based drilling fluids by synergetic use of organo-montmorillonite and organo-sepiolite. *Applied Clay Science* 161:505–512.
- Zhuang G, Zhang Z, Sun J, Liao L ,2016. The structure and rheology of organo-montmorillonite in oil-based system aged under different temperatures. *Applied Clay Science* 124–125:21–30.
- Zhuang G, Zhang Z, Yang H, Tan J ,2018b. Structures and rheological properties of organo-sepiolite in oil-based drilling fluids. *Applied Clay Science* 154:43–51.

7. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.

Appendix — ANOVA

We performed a single-factor statistical analysis of variance (ANOVA) with a significance level of 95% to assess any statistically significant differences between the tests performed with the standard configuration and with the pressure cell configuration at atmospheric pressure and at 25°C. The ANOVA results are shown in the Tables 2, 3, and 4 presented below.

We observed that the F parameters for all tested comparisons are lower than the critical F, indicating no statistically significant differences between the results obtained with the standard configuration and with the pressure cell configuration.

Table 1. ANOVA one factor to analyze significant differences in the viscosity curve performed on the rheometer with the standard configuration and with the pressure cell configuration.

Source of variation	SQ	gl	MQ	F	p-value	Fcrit
Between groups	6.70×10^{-2}	1	6.70×10^{-2}	1×10^{-3}	0.975	4.60
Within the groups	903.47	14	64.53			
Total	903.54	15				

Table 2. ANOVA one factor to analyze significant differences in the stress amplitude oscillatory sweep tests performed on the rheometer with the standard configuration and with the pressure cell configuration.

Source of variation	SQ	gl	MQ	F	p-value	Fcrit
Between groups	268.49	1	268.49	3.45	6.70×10^{-2}	3.97
Within the groups	5913.99	76	77.82			
Total	6182.48	77				

Table 3. ANOVA one factor to analyze significant differences in the stress ramp tests performed on the rheometer with the standard configuration and with the pressure cell configuration.

Source of variation	SQ	gl	MQ	F	p-value	Fcrit
Between groups	1.44×10^{-4}	1	1.44×10^{-4}	1.53×10^{-4}	0.990	3.93
Within the groups	5913.99	108	0.938			
Total	6182.48	109				