

RHEOLOGICAL PROPERTIES STUDY OF FRACTURING FLUIDS USING LOCAL SANDS

R. Akkal^{1*}, M. Khodja²

¹Laboratoire de G_enie Minier, Ecole Nationale Polytechnique, Departement de Génie Minier, 10 Avenue Hassen Badi BP 182 el harrach Alger, Algeria.

²Sonatrach/Division Technologies et Innovation, Avenue du 1er Novembre, 35000 Boumerdès

Received: 21 October 2019/ Accepted: 19 December 2019 / Published online: 01 January 2020

ABSTRACT

A method of extracting natural gas from shale rock formations is hydraulic fracturing. The nearly water-based fracking fluid consists of cross-linking agents, mineral salts, pH-adjusting agents, and other components to control rheological behaviour. The fracturing fluid is pumped deep into a well at high pressure to crack the shale layer in order to access the natural gas. Once the fractures are formed, proppants, usually crystalline silica, keep them open, filling in the cracks created to allow the proper flow of hydrocarbons. This research explores the rheological properties of XLFC-1B polymer (gel-forming) and a borate complex (crosslinker XLW-56) as additives solutions, existing components used in hydraulic fracturing using local sands, including aeolian and quarries sands. Tests have shown that liquids exhibit viscoelastic behavior that allows them to hold the proppants and place them in fractures. It must also be established that these fluids ' minimal stress allows the liquid to flow.

Keywords: Aeolian sand; rheological properties; fracturing fluids; yield value.

Author Correspondence, e-mail: rezki.akkal@g.enp.edu.dz

doi: <http://dx.doi.org/10.4314/jfas.v12i1S.12>



1. INTRODUCTION

Hydraulic fracturing is a well stimulation process used to optimize the extraction of underground resources. This technique is based on injecting fracture fluids into reservoir formations to create fractures that force the subsoil to open more [1–3]. The main functions of a fracture fluid are to open the fracture and transport the supporting agent along the fracture. The optimal fracture fluid should : be able to transport the supporting agent to the fracture, be compatible with the reservoir rock and the fluids contained in these formations, generate sufficient pressure drop along the fracture to create a wide fracture, minimize friction losses during injection [4,5], be formulated with additive chemicals approved by local environmental regulations and have controlled resistance to a low viscosity fluid for cleaning after treatment [6–9]. Such fracturing fluids are generally made up of additives widely used as regulators in fracturing fluids for maintaining the optimal pH, bactericides (reducing gel degradation), breakers (reducing viscosity, breaking polymer bonds or reducing polymer molecule weight), clay stabilizers (preventing clay swelling and/or (destabilization),friction reducers, temperature stabilizers, surfactants (interfacial tension reduction), return regulators for supporting agents, non-emulsifying agents (emulsion separation between liquid and formation) and transport activators for supportingagents. While choosing suitable additives for the formulation of a fracture liquid, care should be taken to use relatively harmless chemical compositions to effectively eliminate or reduce potential environmental exposure [10–13].Gel treatments were often applied to improve conformance and reduce water or gas channeling in reservoirs [14–18]. Liquid gelant solution usually flowed [16] into a reservoir through porous rock and cracks during the installation of traditional lubric treatments. Chemical reactions (i.e., gelation) caused an immobile gel to form after the blocking agent was placed. In comparison, the time required to inject large volumes (e.g. 10,000 to 37,000 bbls) of gel usually exceeded the gelation time by a factor of 100 for the most effective procedures in naturally fractured reservoirs [15–17]. There is a need to decide how much gel should be administered in a given application and where a broken reservoir distributes the gel. Such parameters are critically dependent on the gels properties in fractures. Therefore research programs are applied to classify these properties and describe the gel position in broken structures. To maximize fracturing operations that increase porosity in the underground layers around the well, under

low shear conditions, the fracturing fluid's viscosity must be sufficiently high to enable the supporting proppant to be suspended and transported to the smallest cracks in the fractured rock. Fracturing fluid rheology play a vital role the hydraulic fracturing layout, i.e. the geometry prediction and the magnitude of the fracture produced. To obtain an ideal fluid, a good understanding and characterization of fracture fluids are necessary. However, a failure to select a good fracturing fluid will have a negative impact on reservoir production [19–23]. In the present work, we will characterize the rheological properties of certain fracturing fluids formulated in the laboratory under different temperature conditions and the water type of used in the different formulations and more particularly can an Algerian natural sand act as a supporting agent during hydraulic fracturing and what would be its impact on the fracturing fluid ?

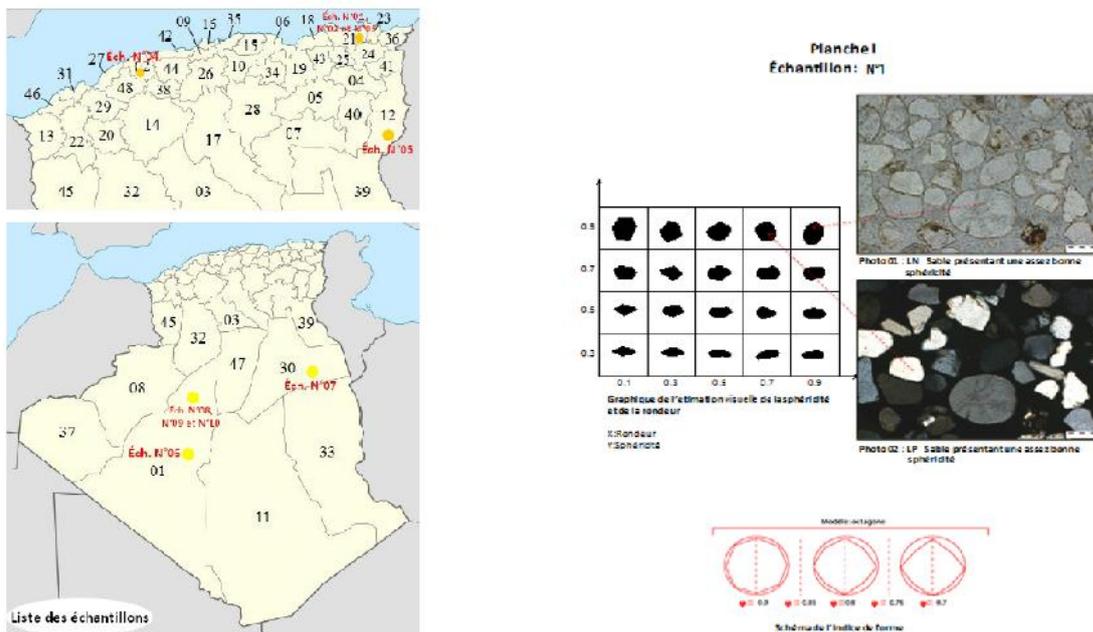
2. MATERIALS AND METHODS

2.1. Solution preparation

In this section, fracture fluids are prepared using an XLFC-1B polymer (gel-forming) and a borate complex (crosslinker XLW-56) as additives provided by SONATRACH Company. The continuous phase is composed of Albian and distilled water, while the two additives are to be fixed at 0.9% and 0.5% respectively. The polymer and borate were gradually added under magnetic agitation with 100 ml of water. After stirring, a sample was left at rest at ambient temperature while the other two fluids are heated in an oven at 50°C and 80°C respectively for 11 hours. The rheological measurements were carried out with rheometer AR 2000 under different conditions.

2.2 The used sand

In order to formulate a fracturing fluid that meets the oil company's requirements, the main mission was to select the sand sample that will represent the best supporting or promoting agent when formulating the hydraulic fracturing fluid. To this end, a number of sand samples were delivered to us, half of which are from quarries and the other half are Aeolian sands. For all these samples, sphericity and roundness, two essential factors in the selection of a fracturing fluid, are examined under a microscope in order to more precisely identify the shape of the grain. The most visible particles show a particular correspondence to one of the shapes classified according to the Krumbien/Sloss graph (Figure 1), and from therefore, the value of sphericity is estimated at 0.9 and the value of roundness varies between 0.7 and 0.9. This indicates the good roundness and sphericity of the grains. The shape index allows you to choose the geometric size closest to the general appearance of the particle. This index expresses the ratio between the projected area of the particle and that of the circle built from the exo-diameter, i.e. from the largest F ret diameter. In our case, the shape index is of the



Octagon type.

Fig.1. a) Localisation of different quarries and Aeolian sands and b) the elements for estimating the roundness and sphericity of sample

3. RESULTS AND DISCUSSION

3.1. Viscosity

Viscosity tests were carried out to analyze formulated fluids' shear behaviour. On the Figure 2, the viscosity as a function of shear rate is presented for the three Albian water-based formulations at ambient temperature and at 50°C and 80°C respectively. It should be noted that the viscosity of these fluids decreases as the shear rate increases, showing rheo-fluidifying behaviour. This phenomenon is in fact due to the nature of the networks system formed between the particles that constitute the fracturing fluid [24–26]. While all three liquids display rheo-fluidic behaviour, viscosity results differ significantly. At low shear rates, the sample A50 °C has a viscosity significantly higher than fluids prepared at 80 °C (A80°C) and ambient (ATamb) temperatures respectively with a relatively low slope reflecting behaviour close to that of the Newtonian fluids. For high shear rate values, viscosity drops rapidly for the A50 °C fluid showing non-Newtonian behavior, while the other two samples (A80 °C and ATamb) form a Newtonian plateau (Figure 6.1).

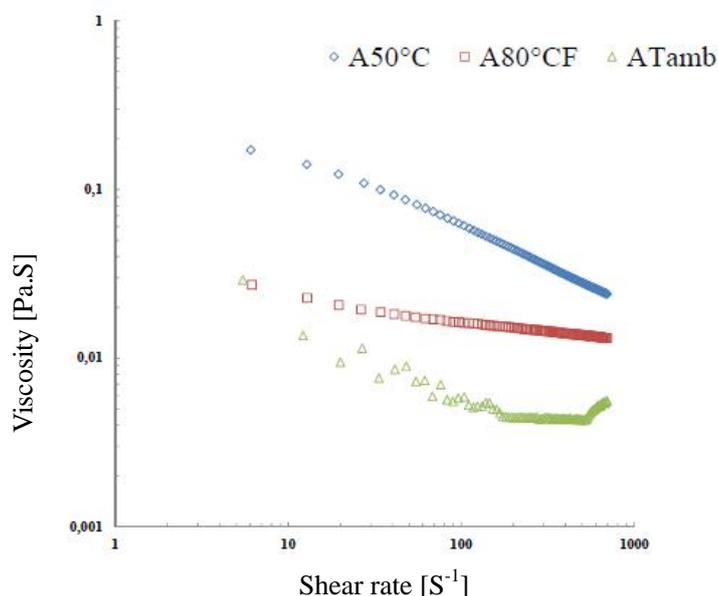


Fig.6.1. Viscosity evolution as a function of shear rate for the distilled water sample at 80 °C, 50 °C and ambient temperature respectively

3.2 The shear strain

Another parameter that seems important in rheological tests is the study of stress as a function of shear rate. These tests give us an idea of the shear rate at which gel deformation occurs and allow us to understand the change in the fracture solutions behaviour under the effect of shear stress. These fluids show non-Newtonian behaviour as shown in on the Figure 6.2, describing the non-linearity between the applied stress and the shear rate. Through Figure 6.2, the applied stress appears to be insensitive to the applied shear rate. When the shear rate increases with a rate of $100(\text{S}^{-1})$, the stress increases with 10 Pa. This is explained by the fact that the pressure gradient required to break the gel structure is insensitive to the injection rate of the fracturing fluid [27–29].

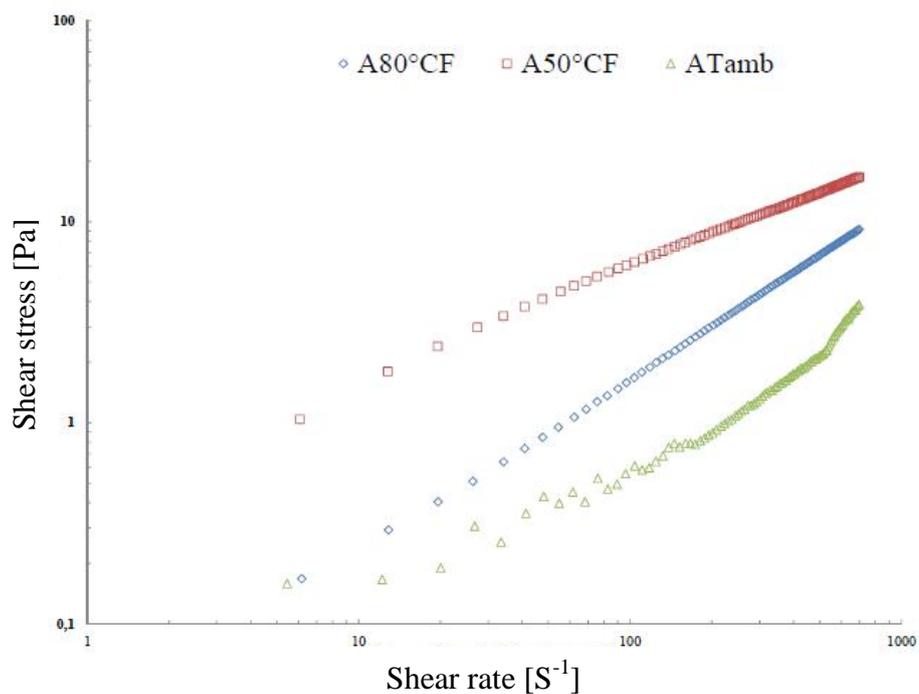


Fig.6.2. Stress evolution as a function of shear rate for the distilled water sample at 80 °C, 50 °C and room temperature

3.3 The yield stress

During fracturing fluid injection into a low-permeability reservoir, it is necessary to apply pressure to make the fluid flow. This means that the fracturing fluid has a threshold stress fluid characteristic. As shown on the Figures 6.3 and 6.4, the shear stress increases as the strain increases. However, the relationship between these two parameters is simulated by a power law model with a regression coefficient around 99 ($R=99$). This model shows a non-linear relationship (equation 1) between the applied stress and the obtained strain. Where σ is the stress applied in Pa, K is the consistency coefficient and n represents the flow index. The latter is less than 1 ($n < 1$) for all formulated samples indicating the ideal elastic behavior [30,31]. According to Figure 6.3, it should also be noted that the higher the temperature, the greater the yield stress, up to a maximum and then decreases as the temperature increases. This is explained by the fact that for temperatures below the maximum temperature, the fracturing fluid component form a stable network showing non-Newtonian behavior [32,33]. However, at temperatures above the maximum temperature, the network formed by these component is destroyed and the fluid thus becomes almost Newtonian [34,35]. The maximum temperature is not achieved at 80 °C for liquids formulated with distilled water (Figure 6.4), so it may be appropriate to further increase the temperature to achieve the limit. The pressure gradient required for gel extrusion is inversely proportional to the square of the fracture size according to the equation 6.2, where w : is the size of the effective fracture opening during extrusion : Can this pressure then be predicted ?. According to the obtained results for the different Albian water-based formulations, the yield stresses obtained are 1.05, 0.2 and 0.07 Pa for samples A50°C, A80°C and ATamb respectively. Using the equation 6.2, the obtained pressure gradients for an opening fracture of 0.1 cm are 2.1 Pa, 0.4 Pa and 0.07 Pa respectively [27,28]. While for distilled water formulations, the yield stresses obtained are 1.1, 0.11 and 0.10 Pa for samples ED50°C, ED80oC and EDTamb respectively. According to the equation 6.2, the pressure gradients obtained for a fracture with an opening of 0.1 cm are 2.2 Pa, 0.44 Pa and 0.40 Pa, respectively. Compared to formulations based on water type (Albian and distillated water), it is concluded that distilled water formulations need relatively high yield stress to flow.

$$\tau = K \dot{\gamma}^n \quad (1)$$

$$\frac{dp}{dl} = \frac{0.02\tau}{w^2} \quad (2)$$

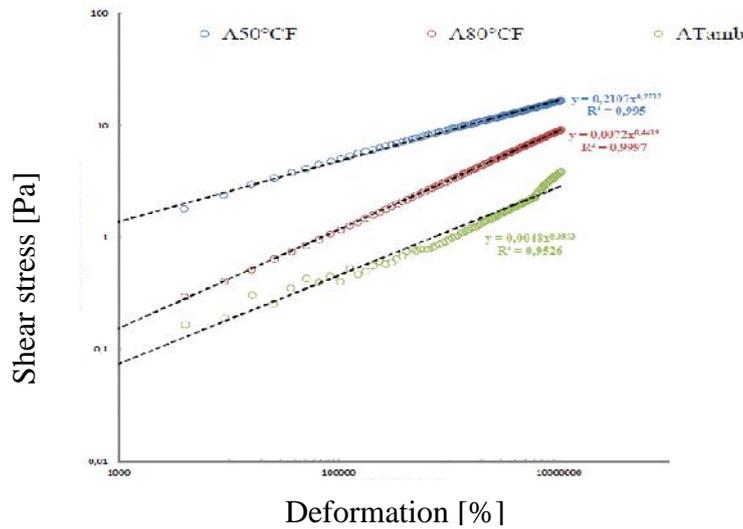


Fig.6.3. Evolution de la contrainte de cisaillement en fonction de la déformation pour l'échantillon à base d'eau albiennaise à 80 °C, à 50 °C et à température ambiante

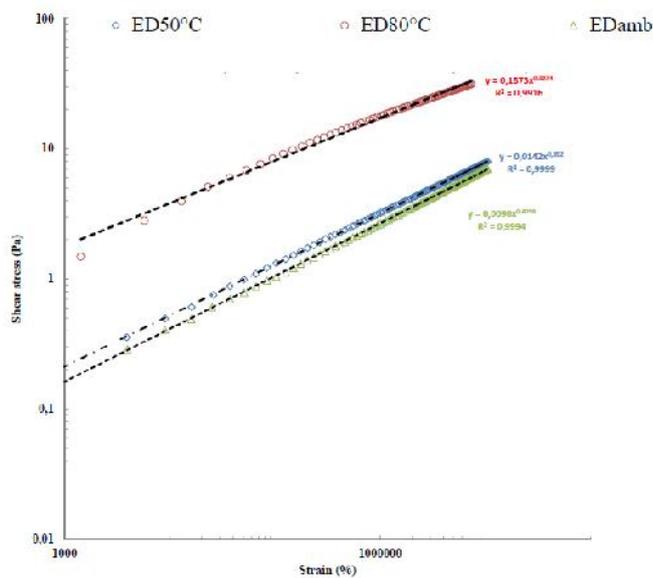
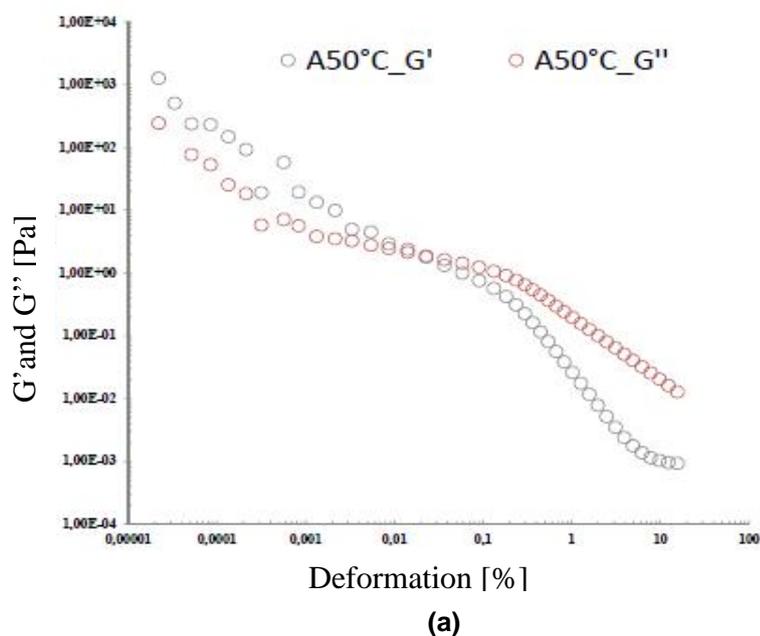
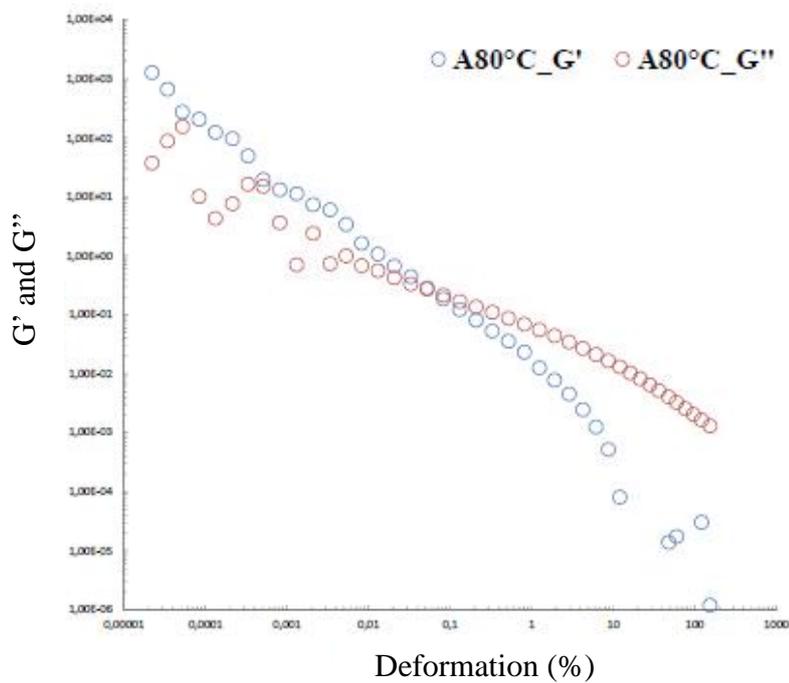


Fig.6.4. Evolution de la contrainte de cisaillement en fonction de la déformation pour l'échantillon à base d'eau distillée à 80 °C, à 50 °C et à température ambiante

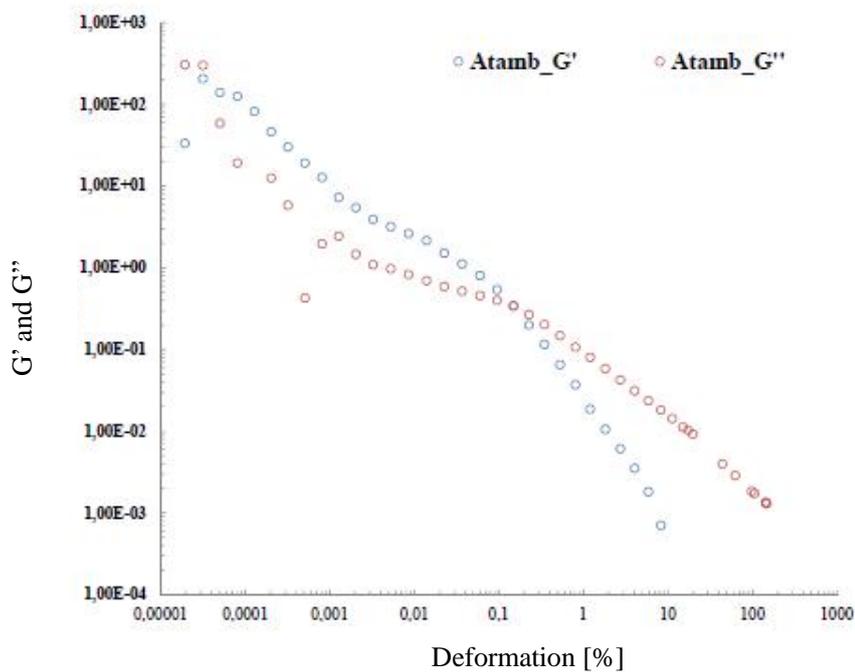
3.4 Visco-elasticity tests

Many important questions occur when a gel is extruded through a fracture. How far can this gel be stretched or deformed before it breaks? Does the gel elasticity dominate over its viscous nature? How do the gel properties vary with composition, temperature and deformation rate? We answer these questions by plotting the elasticity modulus (G') and viscosity (G'') according to the given stresses as shown on the figures 6.5a, 6.5b and 6.5c. It should be noted that for low stresses $< 10^{-3}(\%)$, the fracturing fluids formulated at ambient temperature, 50°C and 80°C respectively, the elasticity modulus (G') with a blue circle, is 1 Pa. When this stress is increased to $10^{-1}(\%)$, G' gradually decreases creating a low plateau indicating that in this range G' is almost constant. This shows that the fluid behaves according to Hooke's law. For stress values $> 0.1\text{Pa}$, G' decreases rapidly explaining an irreversible gel deformation see figure 6.5a. For deformations $< 0.1\%$, the elastic nature is dominant ($G' > G''$). The G' and G'' intersection point is the limit value, i.e. the peak stress at which the liquid is irreversibly deformed. The viscous type is dominant, for deformation values $> 0.1\%$ ($G'' > G'$), which implies that the formed liquids refer to the viscoelastic fluids [36–38].





(b)



(c)

Fig.6.5. Elastic modulus (G') and viscous modulus (G'') as a function of deformation for Albanian water-based fluids for samples (a) heated at 50 °C (A50 °C), (b) heated at 80 °C (A80 °C) and (c) at ambient temperature (ATamb)

3.5. G' et G'' as function of the angular frequency

To investigate the variation of elastic (G') and viscous (G'') modulus as a function of the angular oscillation frequency, these two parameters are plotted as a function of the angular frequency, Figure 6.6. It should be noted that with increasing angular velocity, the elastic modulus (G') increases continuously, showing that G'' is a prevalent description of a viscous fluid for small angular frequencies, while G' is predominant for frequencies greater than 10 S^{-1} , and the fluid has an elastic character [21,39]. The structures of these formulations characterized by G'' and G' have a viscoelastic response characteristic of gel-like materials, depending on the intensity and explaining how intra-molecular interactions in these gels are improved [40,41]. There is a crossover point between the two modules whose corresponding frequency is called the relaxation rate ($\omega_{G'} = \omega_{G''}$). The relaxation time indicates the elasticity of these fluids. Thus, the relaxation time can be used as an index for the number and strength of temporary crosslinking junctions. When the system expands rapidly, a support agent suspended in the fluid can sediment more quickly [42,43].

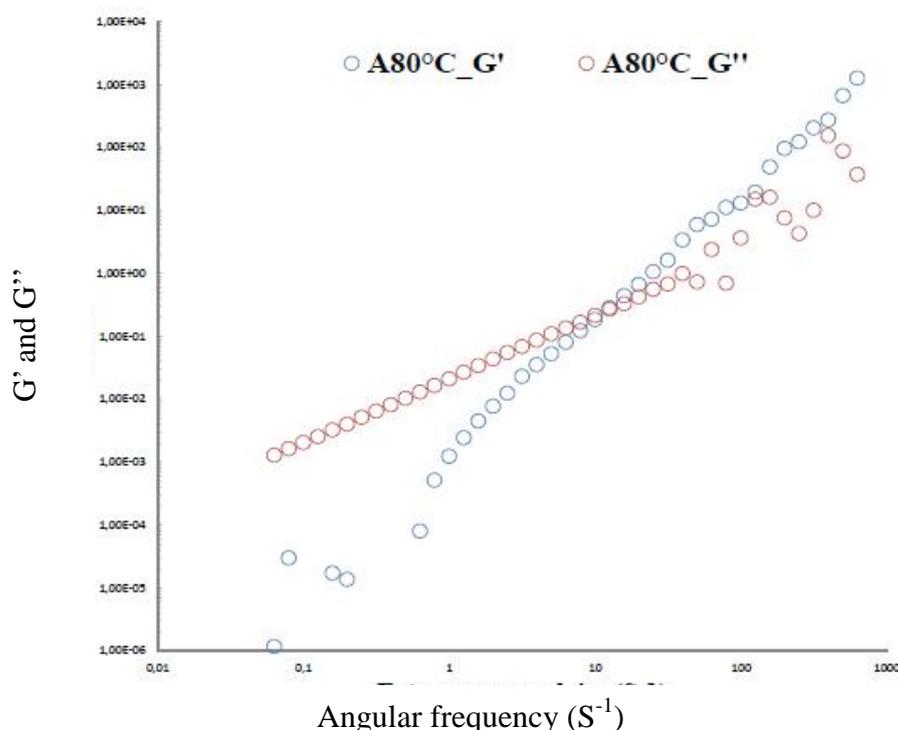


Fig.6.6. Evolution of elastic (G') and viscous (G'') modulus as a function of angular frequency for Albian water-based fluid at 80 °C (A80 °C)

2.6. Influence of water type

The viscosity variation as a function of the shear rate for both distilled and Albian water-based formulations for different temperatures is shown on the Figure 6.7 to investigate the effect of the water type and composition on the fracturing rheological properties. The results show that viscosity decreases as the shear rate increases, this decrease is relatively important for formulations of both ED80°C and A50°C samples. This shows that viscosity is dependent on shear rate, while formulations A80°C, ED50°C and EDTam showing that viscosity are insensitive to shear rate. The ATam formulation based on Albian water indicates that viscosity decreases at shear levels below 100 S⁻¹, then viscosity shows a plateau at rates above 100 S⁻¹. It should also be noted that the two distilled water-based formulations (ED50°C and EDTam) show a higher viscosity than the Albian water-based formulations. The formulations containing Albian water at 80°C, on the other hand, are extremely viscous compared to those containing distilled water, see Figure 6.7. This is because Albian water is a high saline density liquid filled with ions which bind at high temperature to free molecules of chemical additives to form a network (cross-linking) that will lead to increased flow resistance, thereby enhancing the fluid's viscosity [44,45].

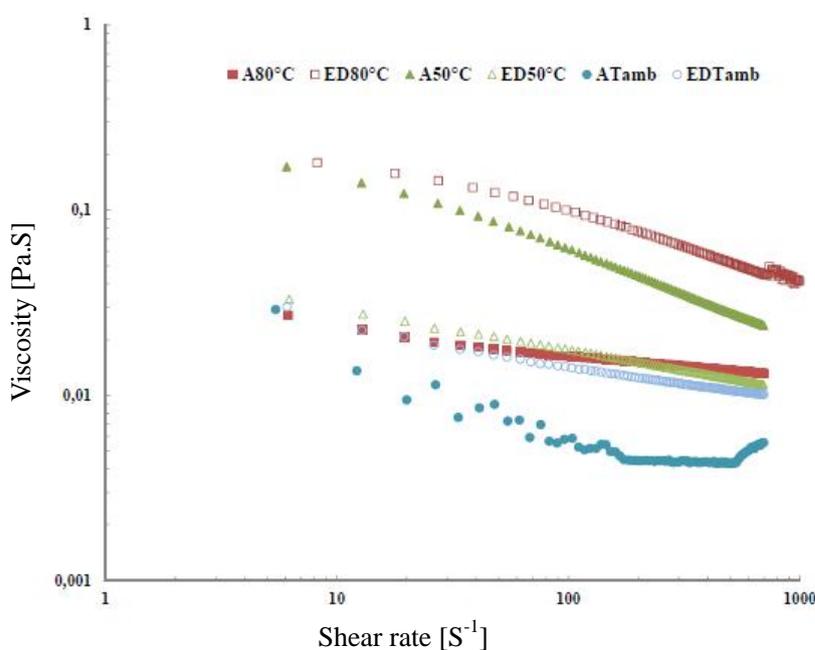


Fig.6.7. Evolution of viscosity as a function of shear rate for all samples indicating the effect of the water type and composition

3.7. Deformation as a function of time

As mentioned above, does the time scale for a deformation affect the elastic nature of a material dominated by its viscous nature?. If a sample is subject to a stress, how quickly would the response to gel stress occur? And what time scale can predict the formation of gel during extrusion through fractures? Through the obtained results, it should be noted that the A50 °C sample, see figure 6.8, shows a stable behavior (Hooke) up to 15 minutes for 10% deformation. Therefore, the fluid changes its behavior towards a Newtonian fluid under the influence of the network destruction generated between the particles [46]. It should also be noticed that the two samples A80 °C and ATAMB show the same behavior for a deformation 10 times higher than the sample A50 °C. As described later, there is a threshold temperature above which the sample changes Newtonian behavior to the viscoelastic character [47].

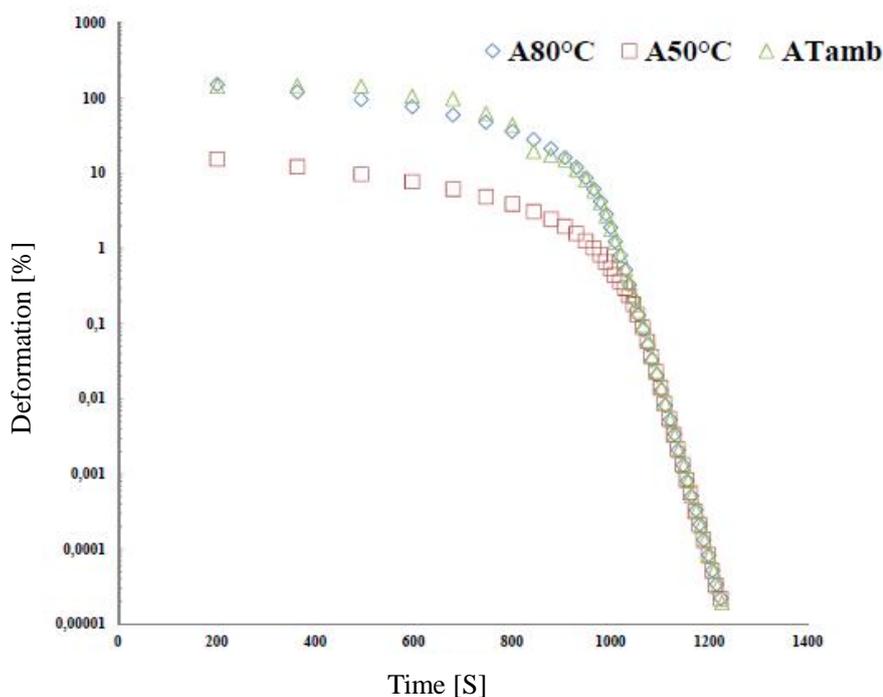


Fig.6.8. Evolution of deformation as a function of time for the Albian water-based sample at 80 °C, 50 °C and ambient temperature

3. CONCLUSION

Once the stresses were applied, the oscillatory rheology experiments allowed the actions of the fracturing fluids to be indirectly elucidated by the results of the present work. It has been shown through the tests carried out that fluids exhibit visco-elastic behavior that allows them to carry the proppants and place them in fractures. It also has to be established that the minimum stress of these fluids helps the liquid to flow. This stress varies depending on the temperature to a yield point where the fluid changes behavior. Distilled water-based fracture fluids have higher viscoelastic properties than Albian water-based fluids during these experiments, and This is because the temperature of the yield point promotes cross-linking in the fluid.

4. REFERENCES

- [1] M. Janszen, T. Bakker, and P. L. J. Zitha. SPE-174231-MS, chapter Hydraulic Fracturing in the Dutch Posedonia Shale, page 34. Society of Petroleum Engineers, Budapest, Hungary, 2015. ISBN 978-1-61399-396-5. doi : 10.2118/174231-MS. URL <https://doi.org/10.2118/174231-MS>.
- [2] Ghaithan A. Al-Muntasheri, Feng Liang, and Katherine L. Hull. Nanoparticle-enhanced hydraulic-fracturing fluids : A review. SPE Production & Operations, 32(02) :186–195, 2017. ISSN 1930-1855. doi : 10.2118/185161-PA. URL <https://doi.org/10.2118/185161-PA>.
- [3] M. Vishkai, G. Hareland, and I. D. Gates. ARMA-2014-7360, chapter Influence of Stress Anisotropy on Hydraulic Fracturing, page 6. American Rock Mechanics Association, Minneapolis, Minnesota, 2014. ISBN 978-0-9894844-1-1. URL <https://doi.org/>.
- [4] R. G. Keck. Spe-21860-ms. page 12, 1991. doi : 10.2118/21860-MS. URL <https://doi.org/10.2118/21860-MS>.
- [5] Subhash N. Shah. Effects of pipe roughness on friction pressures of fracturing fluids. SPE Production Engineering, 5(02) :151–156, 1990. ISSN 0885-9221. doi : 10.2118/18821-PA. URL <https://doi.org/10.2118/18821-PA>.
- [6] Reza Barati and Jenn-Tai Liang. A review of fracturing fluid systems used for hydraulic fracturing of oil and gas wells. Journal of Applied Polymer Science, 131(16), 2014. doi : <https://doi.org/10.1002/app.40735>. URL <https://onlinelibrary.wiley.com/doi/epdf/10.1002/app.40735>.

1002/app.40735.

- [7] Jonathan Koplos, Mary Ellen Tuccillo, and Brent Ranalli. Hydraulic fracturing overview : How, where, and its role in oil and gas. *Journal American Water Works Association*, 106(11) :38–46, 2014. doi : <https://doi.org/10.5942/jawwa.2014.106.0153>. URL <https://awwa.onlinelibrary.wiley.com/doi/abs/10.5942/jawwa.2014.106.0153>.
- [8] Tanya J Gallegos, Brian A Varela, Seth S Haines, and Mark A Engle. Hydraulic fracturing water use variability in the u nited s tates and potential environmental implications. *Water Resources Research*, 51(7) :5839–5845, 2015. doi : <https://doi.org/10.1002/2017WR022130>. URL <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2017WR022130>.
- [9] Ryan WJ Edwards and Michael A Celia. Shale gas well, hydraulic fracturing, and formation data to support modeling of gas and water flow in shale formations. *Water Resources Research*, 54(4) :3196–3206, 2018. doi : <https://doi.org/10.1002/2017WR022130>. URL <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2017WR022130>.
- [10] Matthew S. Mandarich and Greg Neal. SPE-141523-ms. page 7, 2011. doi : 10.2118/141523-MS. URL <https://doi.org/10.2118/141523-MS>.
- [11] Diankui Fu, Andrey Fedorov, Artem V. Prudnikov, Kevin D. Mauth, and Bernhard R. Lungwitz. SPE-132523-MS, chapter New Polymer Fluid for Hydraulic Fracturing in Russia, page 11. Society of Petroleum Engineers, Tunis, Tunisia, 2010. ISBN 978-1-55563-296-0. doi : 10.2118/132523-MS. URL <https://doi.org/10.2118/132523-MS>.
- [12] H. K. van Poollen. ARMA-57-0113, chapter Theories Of Hydraulic Fracturing, page 16. American Rock Mechanics Association, Golden, Colorado, 1957. URL <https://doi.org/>.
- [13] Ibrahim Al-Hulail, Ahmed BinGhanim, Waseem Abdulrazzaq, Hicham El-Hajj, and Osman Abdullatif. SPE-192234-MS, chapter High Resolution Analysis of Sand-Based Composition for Hydraulic Fracturing Application, page 12. Society of Petroleum Engineers, Dammam, Saudi Arabia, 2018. ISBN 978-1-61399-620-1. doi : 10.2118/192234-MS. URL <https://doi.org/10.2118/192234-MS>.
- [14] R. S. Seright and J. Liang. SPE-26991-MS, chapter A Survey of Field Applications of Gel Treatments for Water Shutoff, page 11. Society of Petroleum Engineers, Buenos Aires, Argentina, 1994. ISBN 978-1-55563-470-4. doi : 10.2118/26991-MS. URL <https://doi.org/10.2118/26991-MS>.

-
- [15] R.D. Sydansk and P.E. Moore. Gel conformance treatments increase oil production in Wyoming. *Oil and Gas Journal* ; (United States), 90 :3, 1 1992. ISSN 0030-1388.
- [16] D. C. Borling. Spe-27825-ms. page 14, 1994. doi : 10.2118/27825-MS. URL <https://doi.org/10.2118/27825-MS>.
- [17] G. P. Hild and R. K. Wackowski. Reservoir polymer gel treatments to improve miscible co2 flood. *SPE Reservoir Evaluation & Engineering*, 2(02) :196–204, 1999. ISSN 1094-6470. doi : 10.2118/56008-PA. URL <https://doi.org/10.2118/56008-PA>.
- [18] R. H. Lane and G. S. Sanders. Spe-29475-ms. page 12, 1995. doi : 10.2118/29475-MS. URL <https://doi.org/10.2118/29475-MS>.
- [19] A. Richard Sinclair. Rheology of viscous fracturing fluids. *Journal of Petroleum Technology*, 22(06) :711–719, 1970. ISSN 0149-2136. doi : 10.2118/2623-PA. URL <https://doi.org/10.2118/2623-PA>.
- [20] P. C. Harris. Effects of texture on rheology of foam fracturing fluids. *SPE Production Engineering*, 4(03) :249–257, 1989. ISSN 0885-9221. doi : 10.2118/14257-PA. URL <https://doi.org/10.2118/14257-PA>.
- [21] A. Acharya. Spe-16221-ms. page 11, 1987. doi : 10.2118/16221-MS. URL <https://doi.org/10.2118/16221-MS>.
- [22] Y. Liu and M. M. Sharma. Spe-96208-ms. page 12, 2005. doi : 10.2118/96208-MS. URL <https://doi.org/10.2118/96208-MS>.
- [23] Dongkeun Lee, Kaustubh Shrivastava, and Mukul M. Sharma. Arma-2017-0725. page 8, 2017. URL <https://doi.org/>.
- [24] H. M. Princen and A. D. Kiss. Rheology of foams and highly concentrated emulsions : Iv. an experimental study of the shear viscosity and yield stress of concentrated emulsions. *Journal of Colloid and Interface Science*, 128(1) :176–187, 1989. ISSN 0021-9797. doi : [https://doi.org/10.1016/0021-9797\(89\)90396-2](https://doi.org/10.1016/0021-9797(89)90396-2). URL <http://www.sciencedirect.com/science/article/pii/0021979789903962>.
- [25] J. R. Cameron, D. C. Gardner, and R. W. Jr Veatch. Insights on rheological testing and flow behavior of delayed-crosslinked fracturing fluids. *SPE Production Engineering*, 5(02) :157–165, 1990. ISSN 0885-9221. doi : 10.2118/18209-PA. URL <https://doi.org/10.2118/18209-PA>.

-
- [26] A. M. Gomaa, D. V. S. Gupta, and P. Carman. Spe-168113-ms. page 17, 2014. doi : 10.2118/168113-MS. URL <https://doi.org/10.2118/168113-MS>.
- [27] R. S. Seright. Gel placement in fractured systems. SPE Production & Facilities, 10(04) :241–248, 1995. ISSN 1064-668X. doi : 10.2118/27740-PA. URL <https://doi.org/10.2118/27740-PA>.
- [28] R. S. Seright. Gel propagation through fractures. SPE Production & Facilities, 16(04) :225–231, 2001. ISSN 1064-668X. doi : 10.2118/74602-PA. URL <https://doi.org/10.2118/74602-PA>.
- [29] Baojun Bai, Yuzhang Liu, Jean-Paul Coste, and Liangxiong Li. Preformed particle gel for conformance control : Transport mechanism through porous media. SPE Reservoir Evaluation & Engineering, 10(02) :176–184, 2007. ISSN 1094-6470. doi : 10.2118/89468-PA. URL <https://doi.org/10.2118/89468-PA>.
- [30] V. G. Reidenbach, P. C. Harris, Y. N. Lee, and D. L. Lord. Rheological study of foam fracturing fluids using nitrogen and carbon dioxide. SPE Production Engineering, 1(01) :31–41, 1986. ISSN 0885-9221. doi : 10.2118/12026-PA. URL <https://doi.org/10.2118/12026-PA>.
- [31] R. E. Blauer, B. J. Mitchell, and C. A. Kohlhaas. Spe-4885-ms. page 12, 1974. doi : 10.2118/4885-MS. URL <https://doi.org/10.2118/4885-MS>.
- [32] Ashkan Haghshenas and Hisham A. Nasr-El-Din. Effect of dissolved solids on reuse of produced water at high temperature in hydraulic fracturing jobs. Journal of Natural Gas Science and Engineering, 21 :316–325, 2014. ISSN 1875-5100. URL <http://www.sciencedirect.com/science/article/pii/S1875510014002479>.
- [33] A. V. Tobolsky and J. J. Aklonis. A molecular theory for viscoelastic behavior of amorphous polymers. The Journal of Physical Chemistry, 68(7) :1970–1973, Jul 1964. ISSN 0022-3654. doi : 10.1021/j100789a050. URL <https://doi.org/10.1021/j100789a050>.
- [34] Toufiq Ahmed and Kenji Aramaki. Temperature sensitivity of wormlike micelles in poly(oxyethylene) surfactant solution : Importance of hydrophilic-group size. Journal of Colloid and Interface Science, 336(1) :335–344, 2009. ISSN 0021-9797. doi : <https://doi.org/10.1016/j.jcis.2009.03.040>. URL <http://www.sciencedirect.com/science/article/pii/S0021979709003439>.

-
- [35] Meng Yu, Yan Mu, Guanqun Wang, and Hisham A. Nasr-El-Din. Impact of hydrolysis at high temperatures on the apparent viscosity of carboxybetaine viscoelastic surfactant-based acid : Experimental and molecular dynamics simulation studies. *SPE Journal*, 17(04) :1119–1130, 2012. ISSN 1086-055X. doi : 10.2118/142264-PA. URL <https://doi.org/10.2118/142264-PA>.
- [36] H. Rehage and H. Hoffmann. Viscoelastic surfactant solutions : model systems for rheological research. *Molecular Physics*, 74(5) :933–973, Dec 1991. ISSN 0026-8976. doi : 10.1080/00268979100102721. URL <https://doi.org/10.1080/00268979100102721>.
- [37] Peter Fischer and Heinz Rehage. Rheological master curves of viscoelastic surfactant solutions by varying the solvent viscosity and temperature. *Langmuir*, 13(26) :7012–7020, Dec 1997. ISSN 0743-7463. doi : 10.1021/la970571d. URL <https://doi.org/10.1021/la970571d>.
- [38] Vania Croce, Terence Cosgrove, Geoff Maitland, Trevor Hughes, and Göran Karlsson. Rheology, cryogenic transmission electron spectroscopy, and small-angle neutron scattering of highly viscoelastic wormlike micellar solutions. *Langmuir*, 19(20) :8536–8541, Sep 2003. ISSN 0743-7463. doi : 10.1021/la0345800. URL <https://doi.org/10.1021/la0345800>.
- [39] A. Ruma Acharya. Particle transport in viscous and viscoelastic fracturing fluids. *SPE Production Engineering*, 1(02) :104–110, 1986. ISSN 0885-9221. doi : 10.2118/13179-PA. URL <https://doi.org/10.2118/13179-PA>.
- [40] T. N. Castro Dantas, V. C. Santanna, A. A. Dantas Neto, E. L. Barros Neto, and M. C. P. Alencar Moura. Rheological properties of a new surfactant-based fracturing gel. *Colloids and Surfaces A : Physicochemical and Engineering Aspects*, 225(1) :129–135, 2003. ISSN 0927-7757. doi : [https://doi.org/10.1016/S0927-7757\(03\)00355-8](https://doi.org/10.1016/S0927-7757(03)00355-8). URL <http://www.sciencedirect.com/science/article/pii/S0927775703003558>.
- [41] Caili Dai, Kai Wang, Yifei Liu, Hui Li, Ziyang Wei, and Mingwei Zhao. Reutilization of fracturing flowback fluids in surfactant flooding for enhanced oil recovery. *Energy & Fuels*, 29(4) :2304–2311, Apr 2015. ISSN 0887-0624. doi : 10.1021/acs.energyfuels.5b00507. URL <https://doi.org/10.1021/acs.energyfuels.5b00507>.
- [42] Wayne C. Yount, David M. Loveless, and Stephen L. Craig. Small-molecule dynamics and mechanisms underlying the macroscopic mechanical properties of coordinatively

cross-linked polymer networks. Journal of the American Chemical Society, 127(41) :14488–14496, Oct 2005. ISSN 0002-7863. doi : 10.1021/ja054298a. URL <https://doi.org/10.1021/ja054298a>.

[44] B. Bohloli and C. J. de Pater. Experimental study on hydraulic fracturing of soft rocks : Influence of fluid rheology and confining stress. Journal of Petroleum Science and Engineering, 53(1) :1–12, 2006. ISSN 0920-4105. doi : <https://doi.org/10.1016/j.petrol.2006.01.009>. URL <http://www.sciencedirect.com/science/article/pii/S0920410506000210>.

[45] Cornelis J. de Pater, Yufei Dong, and Bahman Bohloli. Spe-105620-ms. page 10, 2007. doi : 10.2118/105620-MS. URL <https://doi.org/10.2118/105620-MS>.

[46] Mian Wang, Xiaoshan Fan, Warintorn Thitsartarn, and Chaobin He. Rheological and mechanical properties of epoxy/clay nanocomposites with enhanced tensile and fracture toughnesses. Polymer, 58 :43–52, 2015. ISSN 0032-3861. doi : <https://doi.org/10.1016/j.polymer.2014.12.042>. URL <http://www.sciencedirect.com/science/article/pii/S0032386114011422>.

[47] Michèle Marcotte, Ali R. Taherian Hoshahili, and H. S. Ramaswamy. Rheological properties of selected hydrocolloids as a function of concentration and temperature. Food Research International, 34(8) :695–703, 2001. ISSN 0963-9969. doi : [https://doi.org/10.1016/S0963-9969\(01\)00091-6](https://doi.org/10.1016/S0963-9969(01)00091-6). URL <http://www.sciencedirect.com/science/article/pii/S0963996901000916>.

How to cite this article:

Akkal R and Khodja M. Rheological properties study of fracturing fluids using local sands. J. Fundam. Appl. Sci., 2020, 12(1S), 158-176.