



## Experimental study of the rheological behaviour of water-in-crude oil emulsions

Ridha Mazouzi<sup>a,\*</sup>, Abdelkader Karas<sup>b</sup>

<sup>a</sup>Faculty of Technology, FIMA Laboratory, University of Khemis-Miliana, Algeria

<sup>b</sup>Fac. Applied Sciences, Synthesis and Catalysis Laboratory LSCT, University of Tialet, Algeria

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### ABSTRACT

In this study, the rheological behaviour of water-in-crude oil emulsions is experimentally studied. Emulsions are prepared with water concentration of 30%, 40%, 50% and 60%. The influence of water content, temperature, salinity and time on the emulsions rheology is examined. The viscosity of these samples was measured with a rheometer at 20°C, 40°C and 60°C, with shear rates ranging from 0.1 s<sup>-1</sup> to 100 s<sup>-1</sup>. These measurements are also taken after a rest period of 4 hours, 4 days, and 13 days. From the analysis of the results, it was revealed that crude oil has a Newtonian behaviour, while emulsions are non-Newtonian fluids with shear thinning behaviour. Viscosity increases with water content and decreases with water salinity and rest time.

## 1 Introduction

Emulsions are omnipresent in several fields, particularly in industry. The study of emulsions is complex but essential in the industrial field to ensure stable products with the properties expected by the consumer. Crude oil and water often mix together to form emulsions with very different rheological properties than water and crude oil alone [1, 2]. Water-in-oil (W/O) emulsions can be found in all stages of the oil industry such as drilling, production, and transportation [3-5]. Oil production is almost always accompanied by the production of water from the reservoir. During transport from the wellhead to the surface installations, these two immiscible fluids pass through areas of intense agitation (pumps, valves, bends, etc.) which often lead to the formation of a water-in-oil emulsion. A good knowledge of oil emulsions is therefore necessary for controlling and improving processes at all stages [6]. In this regard, the study of the rheological behaviour of emulsions and in particular the viscosity during shear flow is of great importance. Many studies have been carried out on the rheological behaviour of water-in-oil emulsions [7-10]. The viscosity of the emulsion is significantly influenced by the shear rate, temperature, fraction of water volume, aging time, and pressure, etc. [11, 12]. Rheological properties of the

\* Corresponding author. Tel.: +213 54652037.

E-mail address: r.mazouzi@univ-dbk.m.dz

emulsion can be determined by measuring the relationship between stress and strain, temperature and time. A rheology study on crude oil-water emulsions is important in order to find the best method to transport the oil. It is also important in the sizing of the oil pipelines. The presence of water in a crude oil causes considerable increase in the emulsion viscosity, and can have a negative impact on the oil production rate and the cost of the operation. It is also undesirable to have a stable water-in-crude oil emulsion because of the difficulty in separating the oil from the water. Several studies have been conducted during the past years to analyze the rheological behaviour of crude oils and their emulsions [13-15].

The main objective of this research is to study the rheological behaviour of W/O emulsions. The rheological properties were examined for both fresh and salt water using an MCR 302 rotary rheometer with imposed stress. The volume fraction of the aqueous phase varies from 30% to 60%, and the shear rates from  $0.1 \text{ s}^{-1}$  to  $100 \text{ s}^{-1}$  at temperatures of  $20^\circ\text{C}$  to  $60^\circ\text{C}$ .

## 2 Experimental

### 2.1 Materials

The crude oil was used in this study from the Hassi Messaoud field (southern Algeria). The physical properties of crude oil used in the experiment has as given in Table 1. For fresh water (FW), tap water was used. Salt water (SW) is obtained by the addition of 3 wt% NaCl to the aqueous phase.

**Table 1 - Properties of crude oil [16]**

Analysis	Crude oil
Density at $20^\circ\text{C}$ ( $\text{g}/\text{cm}^3$ )	0.8191
Viscosity at $20^\circ\text{C}$ (cSt)	4.124
Sulphur content (wt%)	0.0792
Freezing point ( $^\circ\text{C}$ )	-33
Flash point ( $^\circ\text{C}$ )	8.1

### 2.2 Methods

#### 2.2.1 Emulsion preparation

The following procedure was used to prepare the samples: The defined volume of water was gradually added to the crude oil, the whole thing is stirred for 15 minutes with a magnetic stirrer. The emulsions were prepared at the ambient temperature with different volume fraction of water (i.e. 30%, 40%, 50% and 60%) as shown in Figure 1. In the same way four other samples are prepared, this time using salt water.

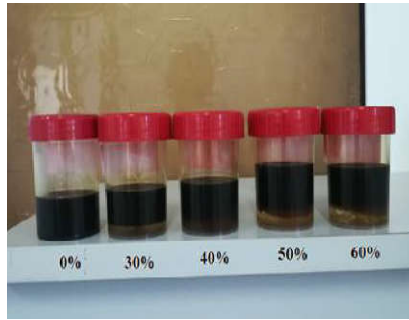


Fig. 1 – Photograph of fresh water emulsions in crude oil

### 2.2.2 Rheological measurements

The samples were tested with a Physica MCR 302 (Anton Paar, Graz, Austria) rotational rheometer (Fig. 2(a)) with a double-gap geometry (Fig. 2(b)), connected to a computer running the RheoCompass software. In order to study the rheological behaviour of these emulsions, the flow curve and the viscosity curve must be determined for each emulsion. For the configuration of the measurement parameters: 100 measurement points have been selected and the shear rate varies from  $1 \text{ s}^{-1}$  to  $100 \text{ s}^{-1}$ . This handling is carried out at temperatures of  $20^\circ\text{C}$ ,  $40^\circ\text{C}$  and  $60^\circ\text{C}$ . These measurements are performed for both freshwater and saltwater emulsions so that the effect of salinity on the behaviour of these emulsions can be studied. To address the effect of time (aging of the emulsion), these measurements are repeated after 4 hours, 4 days and 13 days.

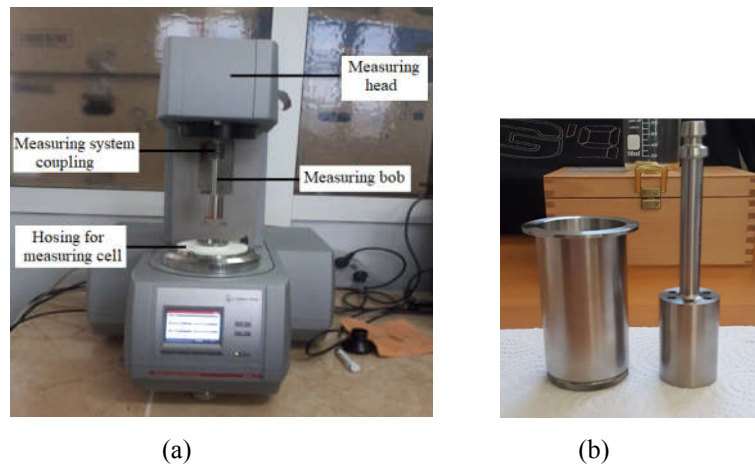


Fig. 2 – a) Anton Paar MCR 302 rheometer; b) Double gap system

## 3 Results and discussions

### 3.1 Rheological behaviour of emulsions

The Ostwald-de Waele relationship is used to identify the rheological behaviour of fluids, this equation is as follows:

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

where  $n$  is the power law index,  $k$  is the consistency index and  $\tau$  is the shear constraint. The viscosity of the fluids following the power law is defined by the equation:

$$\eta = k\dot{\gamma}^{(n-1)} \quad (2)$$

In order to obtain the indices  $n$  and  $k$ , the logarithmic diagram of shear stress as a function of shear rate is plotted and then the indices are calculated by the equation below:

$$\ln(\tau) = \ln(k) + n\ln(\dot{\gamma}) \tag{3}$$

Figure 3 shows the variation in shear stress as a function of shear rate for two types of emulsions as well as for crude oil. In this figure, it can be seen that the rheological behaviour of an emulsion is different from that of crude oil. To determine the rheological behaviour of these fluids accurately, the index of the power law  $n$  must be determined from equation (3).

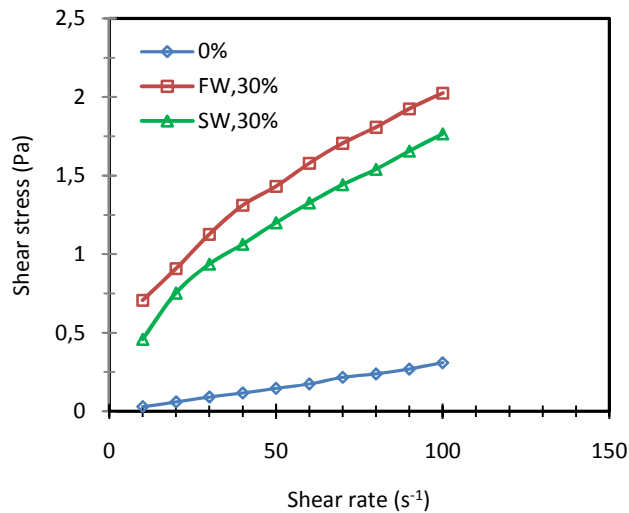


Fig. 3 – Relationship between shear stress and shear rate

Figure 4 shows the logarithmic diagram of shear stress as a function of shear rate. The values of the index  $n$  are determined from the linear regression of the data with a correlation coefficient ( $R^2$ ) greater than 0.999. These values are mentioned in Table 2. According to this table, the power law index of the crude oil is close to 1 ( $n=1.016$ ) which means that crude oil has a Newtonian behaviour. However, the index  $n$  of emulsions at 30% with fresh and salt water is less than 1, which means that these emulsions are non-Newtonian with shear thinning behaviour.

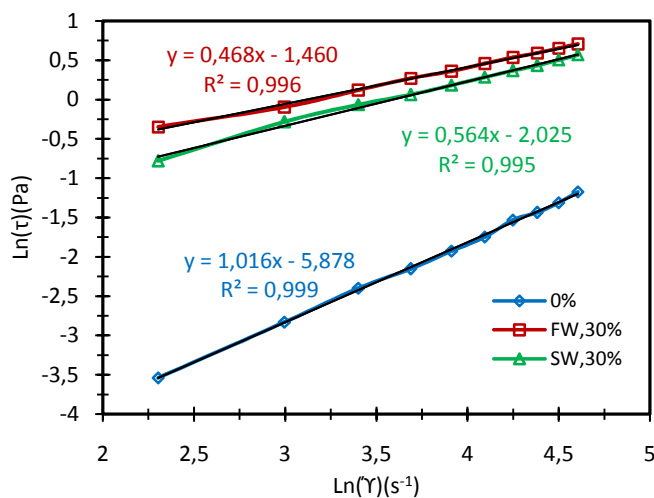


Fig. 4 – Logarithmic diagram of shear stress as a function of shear rate

**Table 2 - Power law Indices of emulsions**

Emulsion	index of the power law (n)
FW 0%	1.016
FW 30%	0.4682
SW 30%	0.5644

### 3.2 Effect of water content

Figure 5 represents the variation in apparent viscosity as a function of shear rate at different freshwater concentrations, the figure shows that higher water content results in higher apparent viscosity. The difference between the viscosity of emulsions is more remarkable at low water content.

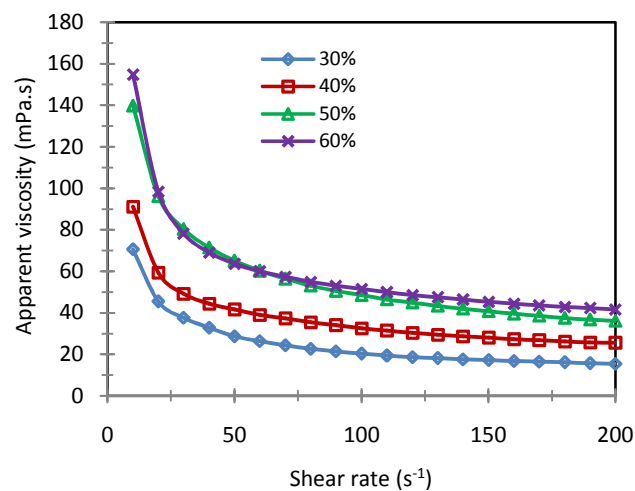


Fig. 5 – Variation of apparent viscosity as a function of the shear rate of emulsions with different water content

Figure 6 shows the variation in emulsion viscosity as a function of water content. The results are presented for two different shear rates. The viscosity of the emulsions increases with a water content from 10% to 50%, then decreases above 50% for a shear rate of  $30 \text{ s}^{-1}$  and stabilizes for a shear rate of  $80 \text{ s}^{-1}$ . A larger quantity of dispersed phase droplets directly causes significant friction between the droplets. The viscosity becomes higher when water content is increased corresponding to Maneintr et al., [17] and Farah et al., [18] which is found that when volume of water increases, the droplet-droplet interaction and water-oil interfacial area are greater. This phenomenon influences the contribution of the increase in interfacial viscosity. However, for water contents above 50%, the dispersed phase droplets begin to coalesce and form larger droplets, resulting in a decrease in the specific surface area. Once the amount of droplets is reduced, friction between the droplets is also reduced. This results in a decrease in viscosity. Another reason for the decrease in viscosity from a water content of 50% is probably due to the inversion of the oil continuous system to the water continuous system.

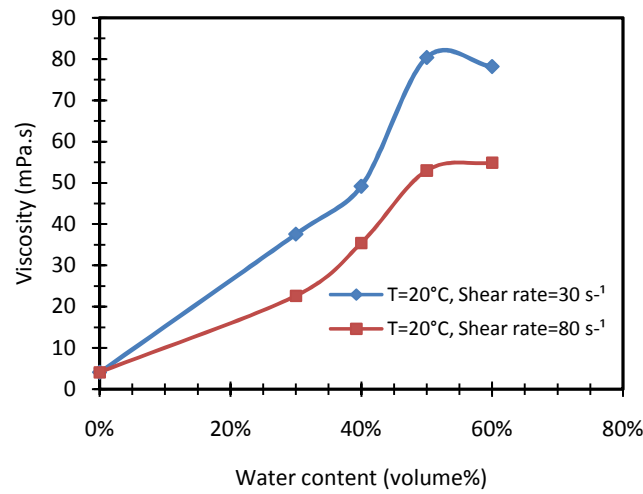


Fig. 6 – Variation in emulsion viscosity as a function of water content for two shear rates at a temperature of 20°C

### 3.3 Effect of temperature

Figure 7 and Figure 8 show that shear stress and apparent viscosity increase at lower temperatures for the same emulsion. And for the same temperature, the emulsion with a higher water content has a higher shear stress and a higher apparent viscosity. This is likely due to the fact that, for emulsions with higher water cuts, the possibility of droplets deformation is significantly higher as a result of greater collisions caused by the applied shear. Such deformation can lead to the droplets sliding over each other, and thereby making the emulsion less resistant (less viscous) to the applied shear and resulting to higher drop in viscosity values [19]. The figure clearly demonstrates the non-Newtonian shear thinning behaviour over the range of shear rates at which the apparent viscosity decreases significantly. Therefore, the apparent viscosity depends on the shear rate at constant temperature and decreases with increasing temperature.

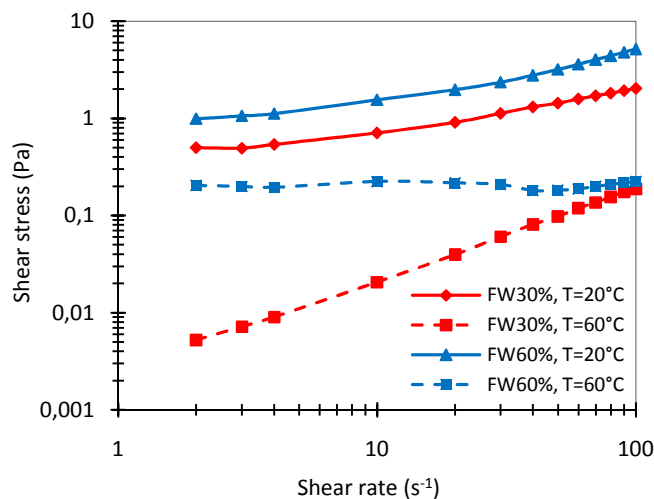


Fig. 7 – Shear stress as a function of shear rate. For two emulsions 30% and 60%, tested at two temperatures 20°C and 60°C

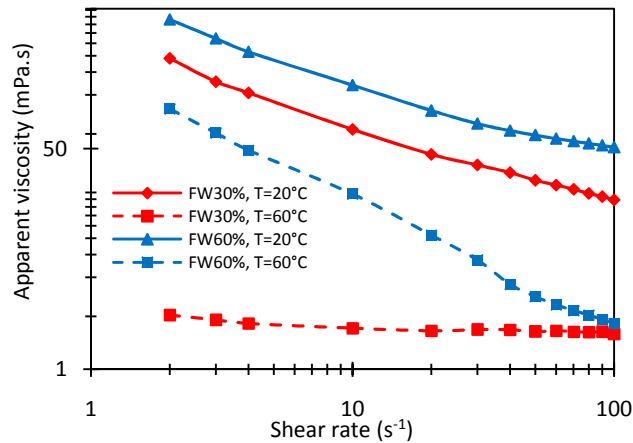


Fig. 8 – Apparent viscosity as a function of shear rate. For two emulsions 30% and 60%, tested at two temperatures 20°C and 60°C

Figure 9 shows the apparent viscosity of emulsions at shear rates of  $10 \text{ s}^{-1}$  and  $100 \text{ s}^{-1}$ . The water content and shear rate have a more influence on the apparent viscosity at low temperatures. At high temperatures, water content and shear rates are less important, as most emulsions and fluids reach a low viscosity when heated. Although water content and temperature clearly have a strong impact on the viscosity of the emulsion, it seems that water content is the most dominant factor.

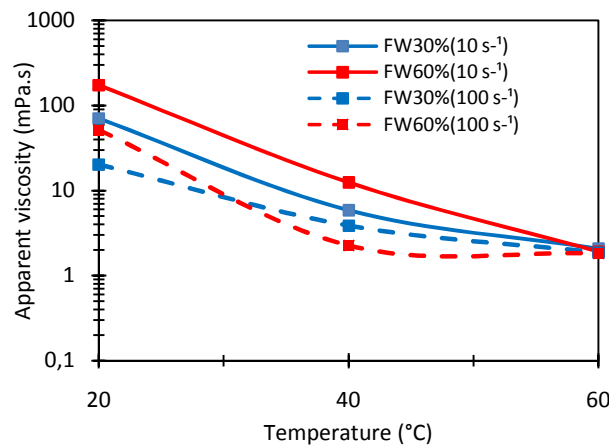


Fig. 9 – Apparent viscosity as a function of temperature. For two freshwater emulsions of 30% and 60% at two shear rates of  $10 \text{ s}^{-1}$  and  $100 \text{ s}^{-1}$

### 3.4 Effect of salinity

Figure 10 shows the variation in viscosity as a function of water content for an emulsion with fresh water and another with salt water. Measurements are performed at  $20^\circ\text{C}$  and at a shear rate of  $50 \text{ s}^{-1}$ . It can be seen in the figure that for a content that varies between 0% and 30%, the rheological behaviour is identical between the two emulsions and the viscosity is practically the same. Above 30%, the curves diverge. For a freshwater emulsion, the viscosity increases until the emulsion inversion (50%). On the other hand, for a saltwater emulsion, the viscosity decreases and reaches a minimum

viscosity at a content of 40%, then it increases beyond 40%. In general, the salinity of the water causes a decrease in the viscosity of the emulsion compared to the emulsion with fresh water.

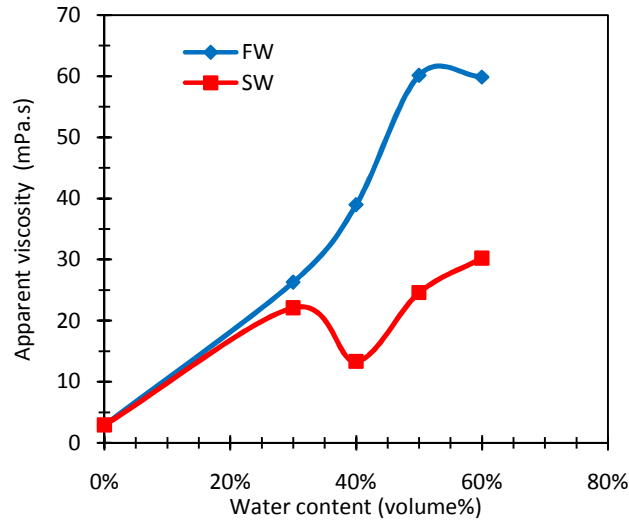


Fig. 10 – Variation of apparent viscosity as a function of freshwater and saltwater content

### 3.5 Effect of aging

It is important to have an emulsion that does not change properties such as viscosity and stability over time. The emulsion can also be prepared at one time and studied at another time. It is therefore important to know how the properties change over time. After the emulsions were prepared, their viscosity was measured after 4 days and 13 days. Figure 11 is an illustration of the emulsion immediately after preparation, then after 4 days, and after 13 days. We can observe that after 13 days, there is almost a total separation between the two phases. Over time, the emulsion begins to break and the colour also begins to change. Several instability mechanisms that lead to phase separation in emulsions such as sedimentation, creaming and coalescence.

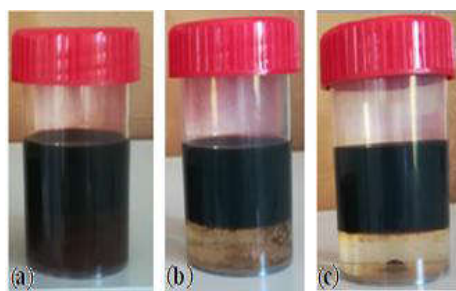


Fig. 11 – Emulsion with 60% water content after (a) preparation, (b) 4 days and (c) 13 days

Figures 12 and 13 represent the variation in shear stress and apparent viscosity as a function of the shear rate for a 40% fresh water emulsion. This variation is measured over time. In general, we notice that shear stress and apparent viscosity decrease over time. The rheological characteristics of a fresh emulsion are very different from those of 4 hours and 13 days. It should be noted that the values on the y-axis cover a very short interval, so that the apparent viscosity is barely visible and the fluid behaves almost like a Newtonian fluid.



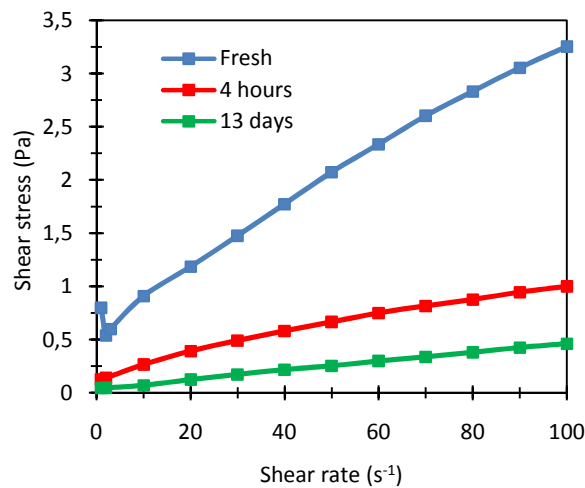


Fig. 12 – Shear stress as a function of the shear rate of the emulsion at 40% water

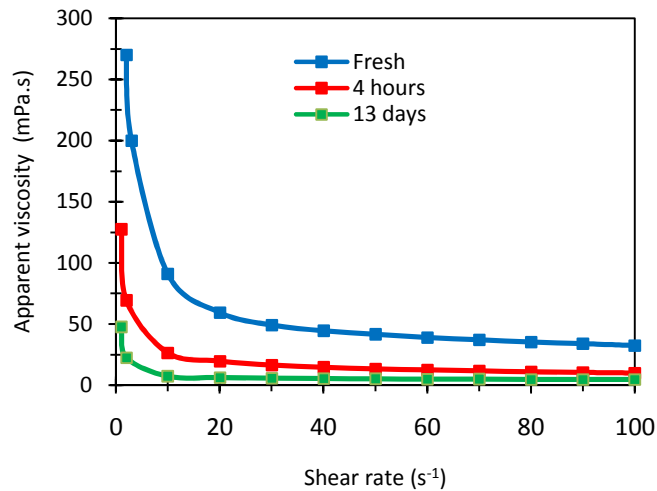


Fig. 13 – Apparent viscosity as a function of the shear rate of the emulsion at 40% water

## 4 Conclusion

To identify the characteristics of water-in-crude oil emulsions, the rheological behaviour of these emulsions was studied. The influence of certain parameters on the rheology of emulsions such as: water content, temperature, salinity and time was examined. The main conclusions resulting from this work are listed below :

- Crude oil has a Newtonian behaviour. The emulsions are non-Newtonian with shear thinning behaviour.
- For a variable shear rate, more water content is higher, more apparent viscosity is higher. At a fixed shear rate and water contents above 50%, a decrease in viscosity is observed.
- Shear stress and apparent viscosity increase at lower temperatures for the same emulsion. For all temperatures, and at low shear rates ( $<10 \text{ s}^{-1}$ ), emulsions have a shear thinning behaviour, beyond this shear rate, emulsions tend towards Newtonian behaviour. The water content and shear rate have a greater influence on the apparent viscosity at low temperatures. At high temperatures, water content and shear rates have less importance.

- The salinity of the water causes a decrease in emulsion viscosity compared to the emulsion viscosity with fresh water.
- Shear stress and apparent viscosity decrease over time.

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