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SENSITIVITY OF NON-NEWTONIAN SLURRY VISCOUS PROPERTIES TO TEMPERATURE

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This paper presents an investigation into the effect of temperature on the rheological properties of a typical non-Newtonian suspension (kaolin clay slurry). Two kaolin clay slurry samples were investigated (referred to as "flocculated" and "un-flocculated"), with the difference between the two being the method of preparation. The slurry temperature was varied between approximately 20ºC and 90ºC. An Anton Paar Rheolab QC rotational viscometer with temperature control jacket was used to conduct the viscosity measurements. Each viscometer test data set (flow curve) was analyzed by applying the Herschel-Bulkley model, which describes the relationship between shear stress (τ) and shear rate ($\dot{\gamma}$) in terms of yield stress (τ_y), fluid consistency index (K) and the flow behaviour index (n). The flow behaviour index (n) was set to a value of 0.30 for all test data sets as this was found to best fit the curvature of all data sets. An error analysis was applied to determine best-fit values of yield stress (τ_y) and fluid consistency index (K) for each data set over the shear rate range 10 to 300 s^{-1}. The yield stress was found to increase approximately linearly with temperature, with an increase in the order of 75% for the temperature range investigated. The fluid consistency index remained approximately constant.

KEY WORDS: Temperature, Viscosity, Non-Newtonian.

1. INTRODUCTION

There appears to be very limited research into the effect of temperature on the viscous properties of non-Newtonian mineral slurries. Understanding the influence of temperature on slurry viscosity and yield stress is of relevance to situations where slurries are transported at elevated temperatures, for example autoclave circuits for mineral extraction, operated at temperatures in the order of 200ºC (and elevated pressure) and the tailings from this process (slurry temperatures in the order of 70ºC).

Where water is the fluid phase in the slurry, it would seem reasonable to assume that the slurry viscous properties (typically yield stress and plastic viscosity for a Bingham plastic mixture) will scale with temperature in line with water viscosity.

Variations in yield stress and viscosity (due to temperature) could have an impact on parameters such as deposition velocity, laminar-turbulent transition velocity and pipeline friction pressure gradients. The authors have found only very limited literature on this topic, and so initiated this experimental investigation as a start towards building a body of data for reference. This paper presents the results of an experimental investigation into the effect of temperature on the rheology of kaolin clay, being a common and well-studied non-Newtonian suspension.

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1.1 LITERATURE REVIEW

A study on the effect of slurry temperature, slurry pH and particle degradation on rheology and pressure drop of coal-water slurry was reviewed. It was found that the apparent viscosity and degree of pseudo-plasticity sharply decrease with increasing slurry temperature. This can be accounted for by the decrease in the water's resistance, with an increase in temperature, (EL-Molla et al, 2007). The reduced viscosity with shear rate can be explained by assuming that the loosely packed particle aggregates are broken up by shear forces, thereby releasing trapped water and subsequently reducing the effective volume solids concentration.

The important role of temperature on rheology was again demonstrated in a research article investigating, 'Temperature effects on rheological properties of fresh thickened copper tailings that contain cement'. A series of rheological tests were conducted covering a range of temperatures (20°C, 30°C, 40°C, and 60°C). The results from this study showed an increase in the shear stress and apparent viscosity of the samples as temperature was raised, (Yong et al, 2018).

Temperature was found to significantly affect the rheological behavior of Wyoming Na-bentonite in water dispersions. The temperature range was between 25 °C and 80 °C. The experimental results indicated an increase in shear stresses at lower shear rates when temperature was raised, while the effect was less significant at higher shear rates. The yield stress increased linearly with temperature by almost three-fold, the flow consistency index decreased exponentially with temperature by almost five-fold, and the flow behavior index increased, tending towards a Newtonian value, (Vryzas et al, 2017).

Apart from an increase in temperature, various physical and chemical properties of a slurry, such as solids concentration, particle size distribution and shear rates, have significant influences on the slurry rheology due to the modification in the surface properties of the particles. This was demonstrated in an investigation that examined the rheological behavior of limestone-water slurry samples for different; volume concentration, particle size distribution and slurry temperature. The relative viscosity of the slurry was found to decrease with increasing temperature in the temperature range studied (30 to 50 °C). The authors propose that the trend of decreasing viscosity at elevated temperatures occurs due to increased kinetic energy of the particles, promoting the breakage of intermolecular bonds between adjacent layers which results in decrease in viscosity of the limestone slurry, (Senapati et al, 2009).

2. METHODS

2.1 SLURRY SAMPLES AND PREPARATION

This investigation was conducted with slurries prepared from kaolin clay sourced from Serina Trading in Cape Town. Kaolin was selected as a convenient commercially available and well-studied mineral which forms a non-Newtonian electrochemically active slurry. The solids density of the kaolin (2.65 t/m^3) was measured using a helium gas pycnometer. The particle size distribution shown in Figure 1 was measured by using laser diffraction by the use of a Malvern Mastersizer 3000 particle size analyzer.

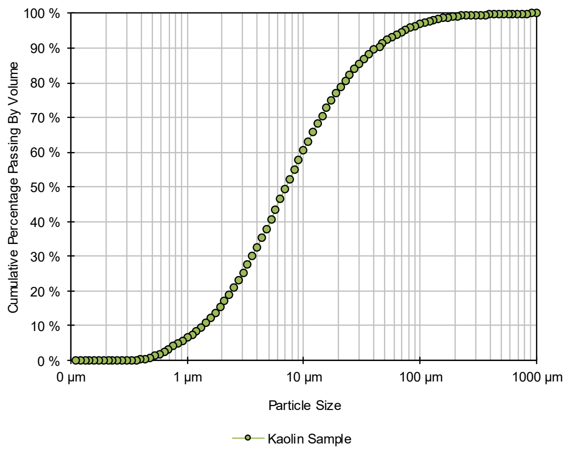

Figure 1. Kaolin Clay Measured Particle Size Distribution

The investigation into the effect of temperature on the slurry viscous properties was done using two samples of kaolin clay slurry (referred to as "flocculated" and "un-flocculated"), with the difference between the two being the method of preparation:

The **un-flocculated** sample was prepared by mixing dry kaolin clay with potable water with an agitator until it was well-mixed. The mass of the solids and water was varied accordingly to achieve the target slurry concentration of 40% (see Table 1). The pH and conductivity of the make-up water at 16 °C was 9.8 and 0.96 mS/cm respectively.

The **flocculated** sample was prepared from a dilute kaolin clay slurry (prepared with potable water as described above) and fed to a bench top 100 mm diameter dynamic thickening apparatus where a polymer flocculant (Magnafloc 5250) was dosed to encourage the formulation of flocs. The settled flocculated ("thickened") kaolin slurry was withdrawn from the thickener underflow, with the thickener being operated in continuous steady-state mode, until sufficient flocculated sample had been collected. The thickener underflow sample was at a solids concentration of 46% by mass. The sample at 46% was diluted using potable water to target concentration of 40%. Furthermore, the slurry pH and conductivity of the samples were recorded.

2.2 SLURRY TEMPERATURE CONTROL

An initial flow curve was measured at ambient temperature (nominally 20 ºC), and then subsequent flow curves were recorded for the sample at progressively elevated temperatures. The temperature of the kaolin slurry sample was raised by placing the beaker containing the sample into a heated water bath. The water bath was covered to maintain a water vapor saturated atmosphere to prevent evaporation from the sample. Once the sample had reached the target temperature, it was stirred and then 60 ml withdrawn with a syringe and transferred to the viscometer cup. The viscometer cup is surrounded by a temperature control jacket (also set to the target temperature) to maintain the sample temperature during the test. This procedure was repeated to cover the temperature range. The temperature of the sample in the viscometer cup was checked with a digital thermometer at the start and end of each test, and the average temperature recorded is summarized in Table 1.

Table 1

Summary of Test Scope

Slurry Sample	Parameter	Test				
		Test 1	Test 2	Test 3	Test 4	Test 5
Un-flocculated, 40% mass concentration	Temperature	21.1 °C	43.1 °C	60.4 °C	79.9 °C	89.0 °C
	pH	8.6	8.4	8.2	8.0	7.9
	Conductivity	1.06	1.20	1.31	1.43	1.49
Flocculated, 40% mass concentration	Temperature	22.5 °C	36.7 °C	55.7 °C	77.6 °C	85.0 °C
	pH	8.1	8.1	8.2	8.2	8.2
	Conductivity	1.23	1.32	1.43	1.56	1.61

2.3 VISCOMETER TESTS

An Anton Paar Rheolab QC rotational viscometer with temperature control jacket was used to conduct the viscosity measurements using the Searle system where the bob rotates and the cup is stationary (Steffe, 1996). The CC35/HR measuring system was used and the dimensions are as follows; bob radius = 17.5 mm, cup radius = 21.0 mm, gap length = 52.5 mm, and cone angle of 120°.

For each viscometer test (for a specific temperature), 60 ml of slurry sample was transferred into the viscometer cup with a syringe. The rotational viscometer torque and rotational speed are recorded over a shear rate range of 10 to 300 s^{-1}. The corrected torque and rotational speed were converted to wall shear stress and shear rate respectively according to ISO 3219 standard procedures. In order to calculate the corrected torque, which correlates to the wall shear stress in the annular gap between the rheometer rotor and the stator, the torque measurement of the conical part of the bob immersed in slurry is deducted from the torque measurement of the whole bob immersed in the slurry at the same concentration.

3. RESULTS

3.1 FLOW CURVES

The flow curves for the un-flocculated and flocculated samples at 40% (concentration by mass) are presented in Figure 2 and Figure 3 respectively. There is a clear and consistent temperature dependency. Increasing slurry temperature results in an upward shift in the flow curve. It appears that the general shape and slope of the flow cure remains approximately constant, but there is a noticeable and approximately uniform increase in shear stress across the shear rate recorded.

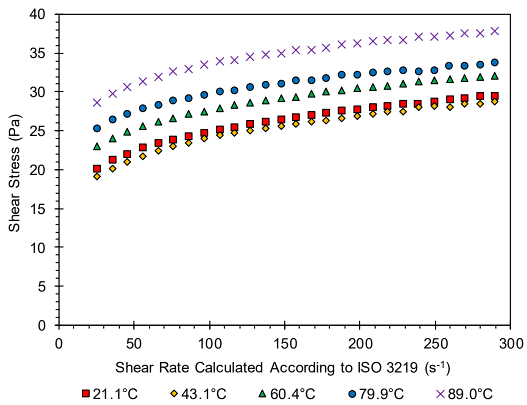

Figure 2. Flow Curves - Un-Flocculated Kaolin at 40%m

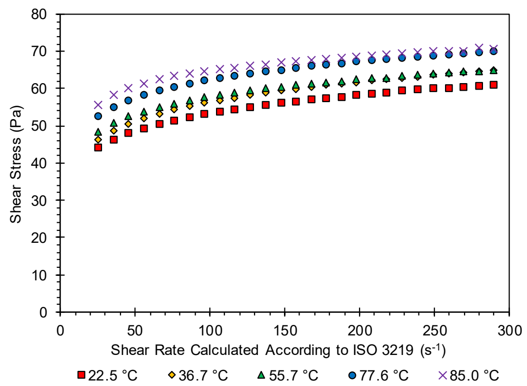

Figure 3. Flow Curves - Flocculated Kaolin at 40%m

3.2 RHEOLOGICAL MODEL PARAMETER FITTING

Each viscometer test data set (flow curve) was analyzed by applying the Herschel-Bulkley model, which describes the relationship between shear stress (|) and shear rate ($\dot{\gamma}$) in terms of yield stress (τ_y), fluid consistency index (K) and the flow behaviour index (n):

$$\tau = \tau_y + K\dot{\gamma}^n \qquad (1)$$

The flow behaviour index (n) was set to a value of 0.30 for all test data sets as this was found to best fit the curvature of all the flow curves. An error analysis was applied to determine values of yield stress (τ_y) and fluid consistency index (K) for each data set over the shear rate range 10 to 300 s^{-1}. The values for the Herschel-Bulkley model parameters are presented in Table 2 and Table 3 for the un-flocculated and flocculated slurry samples respectively. The results for the 40% concentration samples are presented in graphical form in Figure 4 and Figure 5. The graphs illustrate the approximately constant fluid consistency index, and linearly increasing yield stress over the temperature range.

Table 2

Summary of Rheological Model Parameters – Flocculated Kaolin Sample.

Slurry Concentration	Test Temperature (°C)	Yield Stress, τ_y (Pa)	Fluid Consistency Index, K (Pa.s^n)	Flow Behaviour Index, n
40%m	22.5	30.2	5.73	0.30
	36.7	31.0	6.26	0.30
	55.7	35.4	5.52	0.30
	77.6	38.7	5.82	0.30
	85.0	45.1	4.80	0.30

Table 3

Summary of Rheological Model Parameters – Un-Flocculated Kaolin Sample

Slurry Concentration	Test Temperature (°C)	Yield Stress, τ_y (Pa)	Fluid Consistency Index, K (Pa.s^n)	Flow Behaviour Index, n
40%m	21.1	11.9	3.26	0.30
	43.1	10.7	3.32	0.30
	60.4	15.0	3.15	0.30
	79.9	18.4	2.83	0.30
	89.0	20.9	3.13	0.30

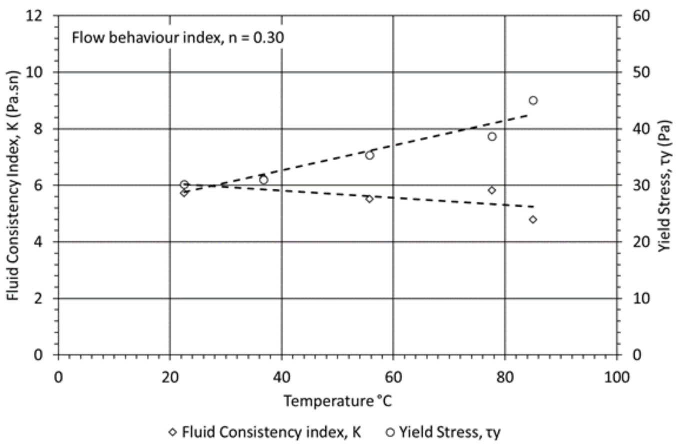

Figure 4. Rheological Parameters versus Slurry Temperature – Flocculated Kaolin

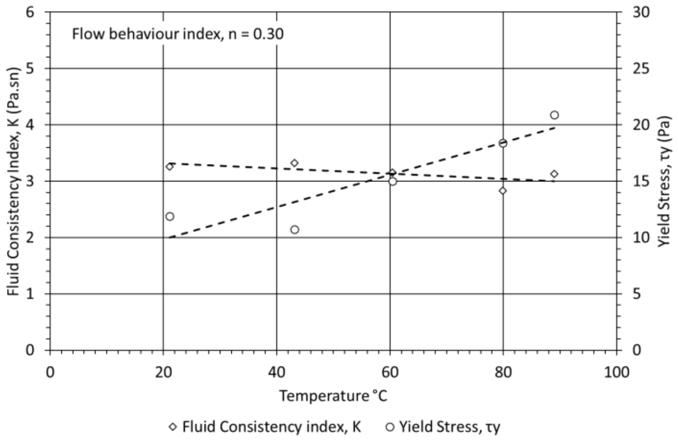

Figure 5. Rheological Parameters versus Slurry Temperature – Un-Flocculated Kaolin

3.3 APPARENT VISCOSITY

For a further illustration of the observed temperature dependence of the viscosity of kaolin slurry, plots of apparent viscosity (evaluated at shear rate 50 s^{-1}) are presented in Figure 6. This plot shows an approximately linear increase in apparent viscosity over the temperature range, as would be expected from the results already presented.

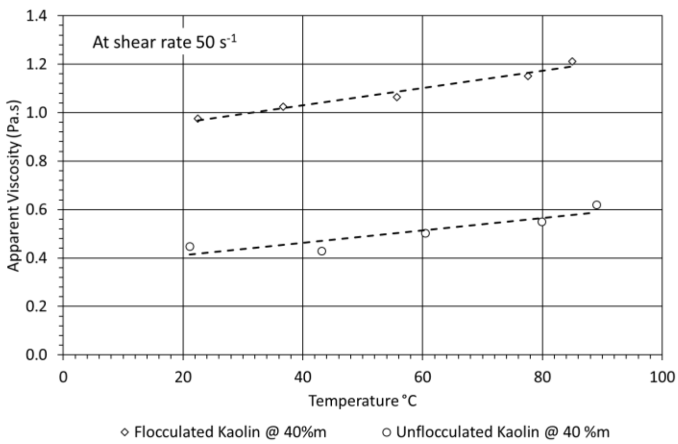

Figure 6. Apparent Viscosity (at 50 s^{-1} shear rate) versus Slurry Temperature

4. DISCUSSIONS AND CONCLUSIONS

This paper presented the results of an experimental investigation into the effect of temperature on the rheology of kaolin clay being a common and well-studied non-Newtonian suspension. The yield stress was found to increase approximately linearly, with an increase in the order of 75% for the temperature range investigated. The fluid consistency index remained approximately constant.

These results were unpredicted as a general reduction in viscosity with increasing temperature was expected; in line with the relationship between temperature and viscosity for water. Decreasing viscosity with increasing temperature had been reported in an investigation that examined the rheological behaviour of limestone-water slurry (Senapati et al, 2009). However, it is noted that the results observed in this study are in line with that reported in the experiment of the effect of temperature on Wyoming sodium bentonite slurries, (Vryzas et al, 2017). It is suspected that the temperature dependence of the rheological properties of the kaolin clay slurries (as opposed to Newtonian slurries such as limestone) relates to their interaction between particle surface charge and the water chemistry.

Despite the results obtained in this study, further studies are necessary to provide a better understanding of the effect of temperature on the rheological properties of non-Newtonian slurries.

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