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RHEOLOGICAL CHARACTERIZATION OF PERUVIAN COPPER ORE SLURRIES

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Abstract.
Mining companies are always seeking for the best method to reduce energy consumption, especially in the grinding process that usually request about 40% to 75% of the total energy used in a mineral process plant. Under this objective, any effort to reduce the energy consumption in mineral process, which involves slurries, should starts with the characterization of the fluid. Therefore, the main objective of this work involves the rheological characterization of the copper ore slurry from a Peruvian mine deposit. For this study, it was considered to characterize the slurry (66 wt.%) from the output of the ball mill of the mineral concentrating plant. Furthermore, to explore the effect of the concentration of solids on the rheological behavior of those slurries, four additional slurries, at different concentrations (50 wt.%, 60 wt.%, 66 wt.% and 70 wt.%), were produced in the laboratory using a batch type ball mill.
Rheological experiments were performed at shear rate ranging from 10-500 s^{-1} using a rotational rheometer. From those experiments, copper ore slurries show shear thinning behavior at any concentration. The results showed that the apparent viscosity increases with the increment of the concentration. Also, for two slurries with the same concentration, the apparent viscosity increases with the number of coarse particles. The experimental flow curves were fitted with the model of Carreau-Yasuda.

Keywords: *Copper Ore, slurry ,rheology, grinding*

1. INTRODUCTION

Copper mining is considered an essential activity for the development of humanity since the products directly or indirectly derived from it are present in several economic activities of daily life. One of the most important countries for this mining industry is Peru, where are located nearly 90 companies in current operation which extracted around 2.5 million of tons during 2019, according the reports of the Peruvian Ministry of Energy and Mining. Throughout the centuries, mining has been part of the history, promoting and supporting the economy and one of its current challenges is to reduce the energy consumption for economic and environmental purposes. Currently, in mineral processing, the crushing and milling operations (comminution), represents between 60 to 80% of the operating cost of a concentrator plant. To be specific, grinding represents between 40 to 75% of the total consumption of the plant, in terms of energy. Due to the high energy consumption compared to other operations and the inefficiency of the comminution equipment, it is important to study the possibilities to reduce the aforementioned energy consumption by optimizing such processes (Levesque *et al.*, 2014).

Mineral processing often involves the transport of mixtures of water and/or chemical solutions carrying crushed or grinded mineral, known as mineral-slurries (Mular *et al.*, 2002). Mineral-slurry transportation involves, indeed, multiphase flows featuring solid, liquid and gas phases. Consequently, in order to optimize mineral-slurry transporting systems, the associated complex flows need to be carefully characterized. Based on their rheological behavior, mineral-slurries may exhibit Newtonian or non-Newtonian rheological properties (Michaelides *et al.*, 2016). Additionally, particle size distribution, slurry density, slurry viscosity, mass flow rate, and friction losses are the main parameters to design or select transport systems for slurries (Mular *et al.*, 2002). The present work aims to characterize the rheological behavior of the copper ore slurry from a Peruvian mining deposit. For this study, it was considered to characterize the slurry (66 wt.%) from the output of the ball mill of the mineral concentrating plant. Furthermore, to explore the effect of the concentration of solids, four additional slurries, at different concentrations (50 wt.%, 60 wt.%, 66 wt.% and 70 wt.%), have been produced in the laboratory using a batch type ball mill. This characterization allows to known the mineral slurry rheological complex behavior.

2. MATERIALS AND METHODS

2.1 The slurry

The copper ore used for this study was extracted from a mine located in the southern coast of Peru. According the mineralogical analysis, the material contains 5% of chalcopyrite, 15% of magnetite, 78% of gangue and 2% of mineral traces. The mineral was crushed to a size under 3.36 mm (mesh 6) before the grinding process. To obtain the slurries, two grinding process, at 50% and 66% of weight concentration (wt.) in water, were conducted in a laboratory scale ball mill. The product of the grinding at 66 wt.% was dried and hydrated with deionized water to generate slurries at 50 wt.%, 60 wt.%, 66 wt.% and 70 wt.%. This process was done in order to increase the number of concentrations to analyze. The use of deionized water reduces the influence related to pH or ionic effects of the liquid phase. To validate the method, the rheological characteristics of the slurry from the grinding process at 50 wt.% will be compared with the slurry grinded at 66 wt.% and hydrated at 50%. Additionally, a slurry from the output of ball mill of a copper concentrator plant was used. This plant processes the same copper mineral described above.

2.2 Particle size distribution (PSD) measurement

As a conventional and economical method (Singh *et al.*, 2018), sieve shaking standard mesh was used to determine the particle size distribution (PSD) of the slurries. This method measures the amount of powder which passed a determine sieve (finer). The set of standard sieves used includes sizes from mesh 16 to mesh 230.

2.3 Rheology measurement

The rheological characterization was conducted with a Discovery HR-3 rotational rheometer (TA Instruments Ltd., US). A concentric cylinder Couette geometry with a stationary outer cylinder (cup) and a rotating inner cylinder (bob or rotor) was utilized (rotor height = 42 mm, rotor diameter = 28 mm and gap = 2 mm). This geometry is suitable and recommended to measure suspensions because it reduces the possibility of settlement during the test, due to the enough vertical distance of the gap (Chun *et al.*, 2010; Zhang and Peng, 2015). Two important effects regarding the particles take place during the test: particle interactions and settlement. For a constant share rate, the particle interaction produces a constant stress response, but from the onset of settlement, the shear stress becomes depended on time (Blakey and James, 2003). This is the reason why the rheology measurements were made at constant shear rates for a defined time of 60 seconds. In that way, it is possible to see when the gravity effect shows up and to select the data which represents exclusively the particle interaction effects.

For this study, 08 different shear rates, from 10 to 500 s^{-1}, were evaluated. This range is enough representative for most of the processes in industrial equipment and transport of slurries (Bhattacharya *et al.*, 1998). All the measurements were made at 24°C, similar than the majority of mining processes with slurry (Blakey and James, 2003). This temperature was controlled with a Peltier cell, embedded in the rheometer, and a fluid thermal controller Thermo CUBE. To ensure the certainty of the measurements, each test was repeated three times.

3. RESULTS AND DISCUSSION

3.1 Particle size distribution (PSD)

The experimental PSD results are shown in the figure 1. To extrapolate the results, they were fitted using the Gates-Gaudin-Schumann (GSS) model, which is well used as a mathematical model of PSD (Singh *et al.*, 2018) and is presented in the Equation (1), where $F(d)$ is the percentage of finer, d is the diameter of the mesh and, a and l are parameters from the model. In the table 1, the parameters for each slurry are presented.

$$F(d) = 1 - exp[-(d/l)^a] \tag{1}$$

Table 1. Parameters from GSS model.

Slurry	a	l
Laboratory grinding 66 wt.%	1.1984	4.4833
Laboratory grinding 50 wt.%	3.4109	15.257
Mine grinding 66 wt.%	1.4714	8.0961

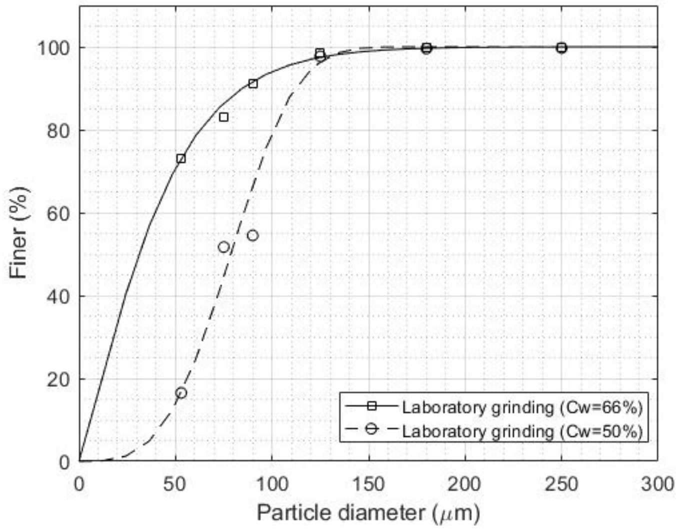

Figure 1. PSD of slurries grinded in the laboratory facilities.

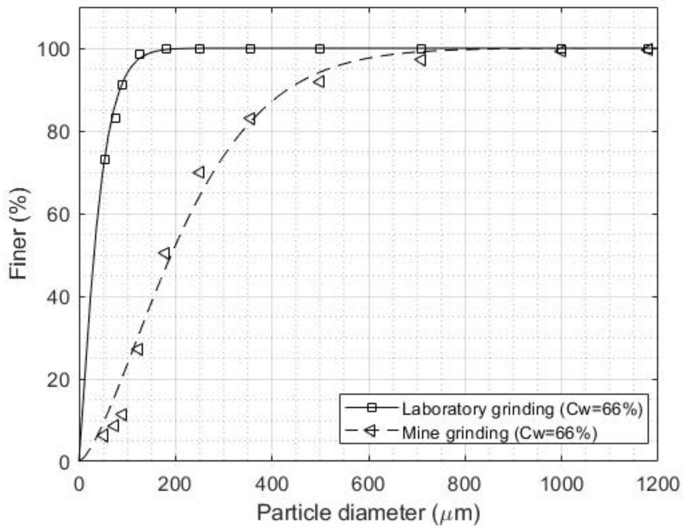

Figure 2. PSD of slurry grinded at laboratory facilities and slurry from mine grinding.

According the results in the figure 1 and table 2, it is possible to see that the mineral grinded at 66 wt.% generates more fine particles than the one grinded at 55wt.%. This behavior is expected because at high concentrations, the probability of collision between balls and mineral particles is bigger, then the particles for the are finer.

The PSD related to the slurry collected form the output of a ball mill of a copper concentrator plant (mine grinding) is showed in the figure 2 and table 2. From the results, it is possible to see that this slurry has coarser particles than the slurry grinded in the laboratory facilities at the same concentration. The differences are related to the rotation velocity, the scale of the grinding system and the ball distribution inside the mill. The influences of those differences on the rheological behavior will be discussed forwards.

Table 2. Characteristics particle diameters from PSD.

Slurry	$d_{50}(\mu\text{m})$	$d_{80}(\mu\text{m})$
Laboratory grinding 66 wt.%	31.0	62.7
Laboratory grinding 50 wt.%	78.7	100.7
Mine grinding 66 wt.%	191.2	338.9

3.2 Effect of grinding concentration on slurry rheology

According the methodology, explained in the point 2.2., two slurries, at 50 and 66 wt.% were produced in the laboratory scale ball mill. The slurry grinded at 66 wt.% was dried and hydrated to obtain different concentrations (50, 60, 66 and 70 wt.%). The contrast between the rheology of the slurry grinded at 50 wt.% and the slurry grinded at 66 wt.% but diluted at 50 wt.% is showed in the figure 3. The results show that the flow curve has the same trend for both slurries and the apparent viscosity has the same order or magnitude, with a relative difference around 10%. This validate the premise that a slurry grinded at 66 wt.% and diluted at different concentrations reproduces a similar flow curve that they would be grinded originally at such concentrations in the same grinding system.

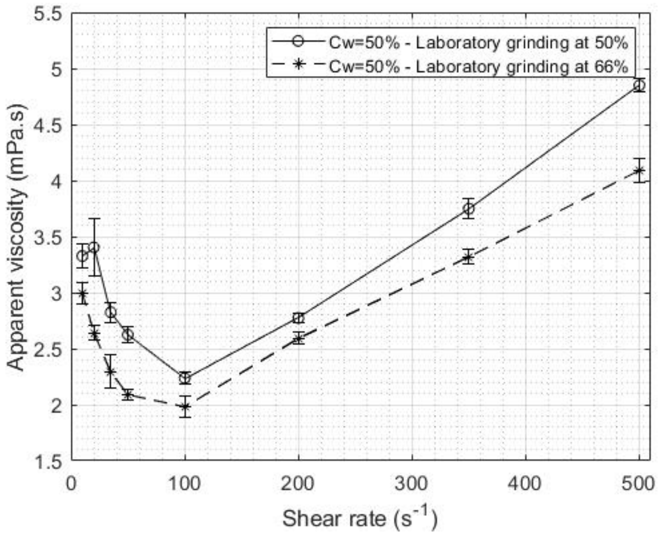

Figure 3. Flow curve contrast between the slurry grinded at 50 wt.% and the slurry grinded at 66 wt.% but diluted at 50 wt.%.

It is important to note that the slurry grinded at 66 wt.% (d_50=31.0 um) exhibits a viscosity lower than the slurry grinded at 50 wt.% (d_50=78.7 um). It occurs basically because the possibility of particle interaction and the viscosity are directly proportional to square of the particle size (Phillips *et al.*, 1992; Siqueira and Carvalho, 2017); and the slurry grinded at 66 wt.% has the finest PSD (see figure 1).

3.3 Effect of particle concentration on slurry rheology

The experimental flow curves from the slurry grinded at 66 wt.% and hydrated at 50 wt.%, 60 wt.%, 66 wt.%, 70 wt.% were showed in the figure 4. From this figure is possible to observe that the apparent viscosity reduces while the share rate increases, which means that this mineral slurry could be characterized as non-Newtonian fluid in the category of shear thinning or pseudoplastic. In addition, these results show that the magnitude of viscosity grow up with the increment of particle concentration. This effect is attributed to the increment of interaction between particles (Mangesana *et al.*, 2008) . Also, it is important to note the measurements at low concentrations (50 and 60 wt.%) and high shear rates (higher than 100 1/s), they exhibit an increment of viscosity which disagrees with the monotonic shear thinning behavior. This discrepancy used to be related to the presence of secondary flow during the experiments. Theses flow path appears when the fluid layers, that moves uniformly between the rotor and the cup, lose their stability, develop inner rotations and generate an aleatory distribution of particles as well as an increment of shear stresses which increases the viscosity (Barnes *et al.*, 1989; Chossat and Looss, 1992). Thus, these measurements do not represent the original behavior of the fluid.

The experimental rheological characterization presented in the figure 4 was fitted with the theoretical model Carreau-Yasuda (C-Y), which is well used to represent the behavior of pseudoplastic fluids, since they are bi-viscous fluids (two levels of viscosity) (Bird *et al.*, 2002). The C-Y model follows the equation 2, where η_0 and η_∞ represent the threshold of the viscosity at shear rate cero (0) and infinite (∞), λ is the relaxation time of the fluid and n is the power index. All of them were obtained from the experimental data and are summarized in the table 3. There is possible to see that these parameters change with the particle concentration in the slurry.

$$\frac{\eta - \eta_\infty}{\eta_0 - \eta_\infty} = [1 + (\lambda\dot{\gamma})^2]^{\frac{n-1}{2}} \qquad (2)$$

In accordance with the figure 5, the results presented in this work concur with the previous investigations regarding

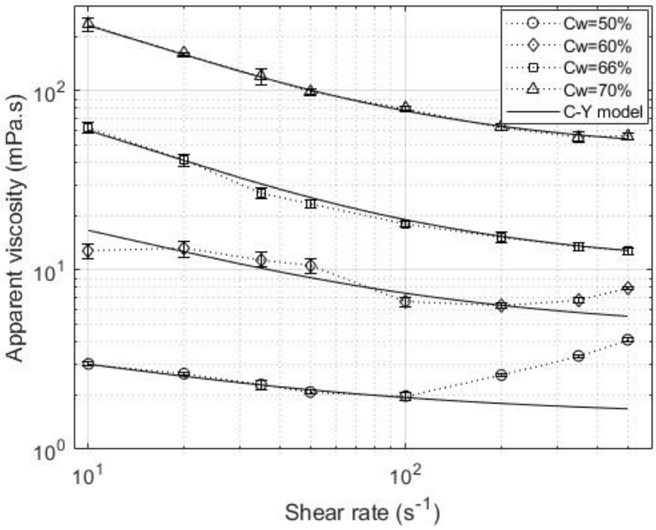

Figure 4. Flow curve of the slurry at different particle concentrations.

Table 3. Parameters from Carreau-Yasuda model.

Parameter	50 wt.%	60 wt.%	66 wt.%	70 wt.%
η_0	3.8	25	105	400
η_∞	1.5	4.5	10.5	45
λ	0.2	0.2	0.2	0.2
n	0.45	0.35	0.2	0.2

the rheological characterization of mineral slurries. All of them exhibit a shear thinning behavior, which validates the results of the present work. The investigations from Zhang and Peng (2015) and Sun *et al.* (2010) used ores with similar composition than this work and the apparent viscosity, for similar particle concentrations, appears in the same order of magnitude. However, the works conducted by Singh *et al.* (2018) and Bhattacharya *et al.* (1998), which used iron ores and lateritic nickel slurries, respectively, present high levels of viscosity for concentrations less than 50%, which led to the conclusion that the rheological behavior is also strongly dependent on the mineral composition, because each ore requires specific grinding system, therefore different PSD.

3.4 Effect of grinding system on slurry rheology

As is showed in the figure 6, the slurry extracted from the output of ball mill of a copper concentrator plant (mine griding) also exhibit shear thinning behavior. Additionally, from the same figure is possible to note that the slurry from mine grinding follow the same trend as the slurry from laboratory grinding but it is slightly shifted upwards. This increment of the viscosity level for the same particle concentration is related to the grinding system which provides different PSD. The slurry from mine grinding has more coarse particles than the slurry grinded in the laboratory (see figure 1) and that increases the particle interaction, consequently the apparent viscosity, as was explained in the point 3.3. Furthermore, coarse particles have more inertia that makes the effect of acceleration and retardation during the interaction requires more energy, which traduces in an increment of apparent viscosity (Mangesana *et al.*, 2008).

Finally, the liquid phase from the slurry grinded in the concentrator plant was filtered and tested in the rheometer following the same methodology than the slurry. The results are presented in the figure 7 and according them, the liquid phase of this slurry showed a constant apparent viscosity, as a Newtonian behavior, with a value around 1mPa.s, similar than water. The results above shear rate 100 1/s should not be considered because of the presence of secondary flows as was explained in the point 3.4.

This probes that the rheology of the liquid phase was not affected by any chemical components that could be used during the grinding process in the concentrator plant.

4. CONCLUSIONS

In the present work, the experimental rheological characterization of Peruvian copper ore (5% chalcopyrite) slurries was performed using two sources, (i) slurry grinded in a laboratory scale ball mill and (ii) slurry extracted from the output of ball mill of a copper concentrator plant. These slurries were utilized to study the influence of (i) particle

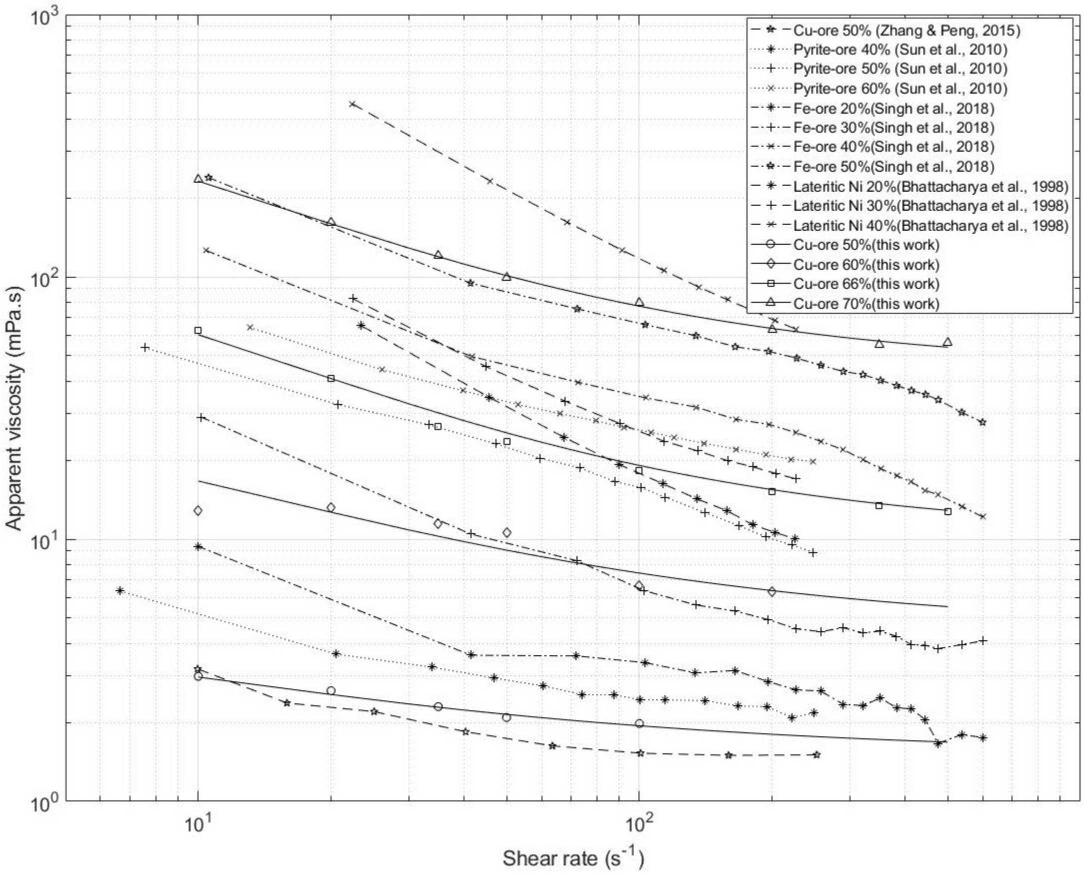

Figure 5. Rheology of mineral slurries according previous works.

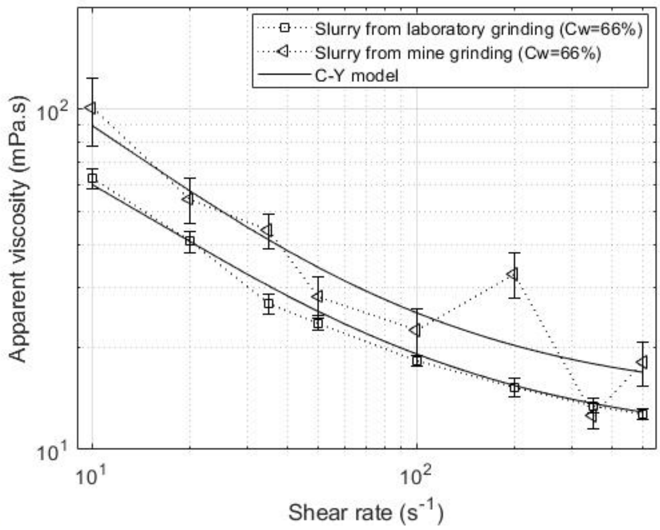

Figure 6. Flow curve of the slurry extracted from a copper concentrator plant.

size distribution due to different concentrations during the grinding process or due to different grinding system, and (ii) particle concentration in the slurry, on the rheologic behavior of such slurries. Emphasis was placed on the effect of particle concentration on the rheology of the slurry, which led to the conclusion that this mineral slurry has shear thinning behavior for all the concentrations analyzed. Also, the results show that the slurry apparent viscosity rises with the increment of the particle concentration as a consequence of more particle interaction. All these results were compared to previous works, which agree with the behavior and order of magnitude of the present work.

Additionally, the rheological characterization of the slurry from the concentrator plant was presented and exhibit the same shear thinning behavior, although it has higher level of viscosity than the slurry from the laboratory grinding, at

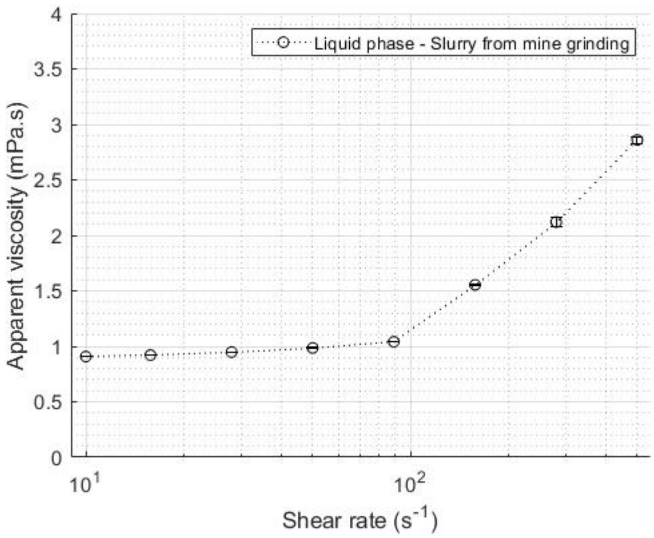

Figure 7. Flow curve of the liquid phase of the slurry extracted from a copper concentrator plant.

the same particle concentration. This occurs because the slurry from the concentrator plant has coarser particles and the inertia of bigger particles during the particle migration develops more apparent viscosity. Finally, the experimental data was accompanied by a fitting curve following the Carreau-Yasuda model, which could be useful to develop numerical modeling around grinding or transport processes with copper ore slurries.

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