Experimental Investigations of the Effect of Chemical Additives on the Rheological Properties of Highly Concentrated Iron Ore Slurries†

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Abstract

Chemical additives are widely used in iron ore industry in various processing steps such as classification, crushing, grinding, and pelletization. These additives are also used in transportation of iron ore through highly concentrated slurry pipelines which are currently operating and coming up in large number across the world. These additives are usually categorized by their functions rather than chemical composition. In this study, the effect of quick lime (QL), hydrated lime (HL), Sodium hexametaphosphate (SHMP) and Acti-Gel on the rheological behaviors of iron ore slurries at volumetric concentrations ($C_v$) of 18.8%, 22.1% and 25.8% and dosages of additives ranging from 0.05–2% were investigated. The rheological parameters were measured using computerized rotational rheometer. All the sample data were best represented by Herschel-Bulkley model. Minimum shear stress and viscosity were obtained at 2% dosage of QL for 18.8% and minimum flow behaviour index was obtained at 25.8% with 2% additive dosage. The addition of HL markedly increases all the rheological parameters. When SHMP is used, minimum shear stress and viscosity were obtained at dosage of 1.5%, 2% and 2% for $C_v$ of 18.8%, 22.1% and 25.8% respectively. Acti-Gel resulted higher values of yield stress and flow behaviour indices at all solid concentrations.

Keywords: iron ore slurry, highly concentrated slurry, chemical additive, rheological property, Herschel-Bulkley fluid

1. Introduction

The demand of transporting a large quantities of iron ore fines, which are generated during mining and washing, through pipeline is increased very rapidly in the last decades. To mention one, recently in India the Essar Steel Company completed 253 km-long slurry pipeline that connects its ore washery plant at Dabuna, in Keonjhar district with its pelletization unit at Paradip. The design of this slurry pipeline entails predicting the power requirement per unit of solids delivered over a unit distance. This pump power demand is mainly a function of pressure drop. For establishing the pressure drop requirements the rheology of slurry has been identified as a critical parameter. Therefore, it would be useful to study the rheological behaviours of the slurry to estimate pressure drop and hence pumping capacity.

A number of factors influence the rheological behaviours namely the parent solid materials, the solid content, the particle size and its size distribution, slurry temperature, the pH and the presence of electrolytes and chemical additives (He et al., 2004). As stated by Jones and Harsley (2000) certain chemical additives enhance the fluidity of the slurries and hence enable the slurries to be pumped at much higher concentrations thus reducing the water requirements. So, the selection of appropriate additives should be recognized as one of the most essential factors in the preparation of slurries for transportation. It is, therefore, relevant to investigate the effects of chemical additives on the rheological behaviours of slurries. According to Schick and Villa (1983), the chemical additives must be chosen such that they should provide sufficient viscosity, electro-kinetic potential and the desired stability. A wide range of chemical additives have been used at various processing stages of iron ore mining industries in order to improve the rheological behaviours. These chemical agents might have been acted as dispersants, coagulants, surfactants, or anti-settling agents.

Qiu G. et al. (2003) investigated the functions and molecular structure of ideal organic binders for iron ore pelletization based on the molecular design, interface chemistry, polymer science as well as failure model of a
binding system. Their investigations proved that -COO and -OH are ideal polar and hydrophilic groups of organic binders, respectively. They concluded that good organic binders for iron ore pelletization should contain structurally sufficient polar groups and hydrophilic groups.

He et al. (2004) reviewed the slurry rheology in ultrafine grinding, methods for the characterization of the slurry rheology, empirical equations for modelling the rheological behaviours and use of dispersants which affect the slurry rheology. They concluded that the effect of dispersant is crucial since the solids content of a ground material with an appropriate dispersant in a stirred media mill increases by about 30 wt.% and the fineness of the final product significantly enhances. They also concluded that for the slurry rheology control polyacrylic acid or its salts is the mostly used dispersant as a grinding aid. Pearse (2005) reviewed in detail the predominant reagents used and their mode of action in the mineral processing industry. According to this revision, lime and sulphuric acid are the highest volume bulk inorganic reagents used in mineral processing. Lime is being used for pH adjustment, coagulation, heavy metal precipitation, causticization and depression of pyrite in flotation whereas Sulphuric acid is used for pH adjustment as well as for leaching. He concluded that polyDADMAC (diallyldimethyl ammonium chloride) and quaternized polyamines are the main coagulants used in the minerals industry and low molecular mass polymers of sodium polyacrylate are used as the dispersing reagents.

Marcos and Antonio (2012, 2013) investigated the effects of the slurry’s rheological behavior and the state of aggregation and dispersion on wet ultrafine grinding of an iron ore concentrate. They observed that the addition of lime caused an increase in specific energy consumption, with significant increase in yield stress and consistency index of the fluid. According to the review of Assefa and Kaushal (2015a) on the effects of various chemical additives on the flow behaviours of coal ash and iron ore slurries, all the chemical studied are capable of changing the flow behaviours of the slurries under considerations. They also concluded that the function of these chemical additives is almost always very specific in nature in which some additives are proprietary products with highly specific functions that work well in some systems but cannot be used in others. Hence, correct additive selection is important to get the intended results. Many other chemical additives are being used in the mineral processing industries such as in iron ore transportations (Mahiuddin et al., 1989; Sandra et al., 2013). A summary of some of the chemical additives and their functions are given in Table 1.

Generally speaking, the use of chemical additives in the iron ore processing varies from simple to the use of complex combinations of additives in classification, concentration, crushing, grinding, and pelletization. Many additional studies related to these have been published but there is still little understanding of the influence of chemicals on the flow behaviours of highly concentrated iron ore slurries. In the present study, the influence of four chemical agents, which have different nature, namely lime (quick lime and hydrated lime), Sodium hexametaphosphate (SHMP), and Acti-Gel®, on the rheological behaviours of high concentrate iron ore slurries were investigated.

2. Materials used

2.1 Parental solid material

The material used for this particular study was iron ore obtained from mine situated at the outskirt of Bangalore city, Karnataka state, India. The measured pH values are between 7.52–7.24 for slurry concentration of 18.8–25.8 % by volume without the addition of chemicals agents.

2.2 Chemical additives used

i) Lime

The two types of lime used for this study are quick lime (CaO) and hydrated lime (Ca(OH)2). Usually both

<table>
<thead>
<tr>
<th>Name of the chemicals</th>
<th>Functions/effects</th>
<th>Parental solids</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tapioca, Potato and corn starch; Sodium Silicate &amp; SHMP</td>
<td>Flocculants; Dispersants</td>
<td>Iron ore tailings</td>
<td>Hanumantha and Narasimhan, 1985</td>
</tr>
<tr>
<td>Magnafloc and Rishfloc; Sodium petroleum and CTAB</td>
<td>Flocculants; Surfactants</td>
<td>Iron ore fines</td>
<td>Singh &amp; Besra, 1997</td>
</tr>
<tr>
<td>Calcium lignosulphonate</td>
<td>Surfactants</td>
<td>Ferrosilicon and magnetite</td>
<td>Mabuza et al., 2005</td>
</tr>
<tr>
<td>Magnafloc-1011-anionic and Magnafloc-333- non-ionic</td>
<td>Flocculants</td>
<td>Iron ore tailings</td>
<td>Dash et al., 2011</td>
</tr>
<tr>
<td>limestone</td>
<td>Increased reducibility</td>
<td>acid iron ore pellets</td>
<td>Iljana et al., 2015</td>
</tr>
</tbody>
</table>
lime act as a coagulants or flocculants and often added to the iron ore mixture to assist in binding the material to improve productivity and give a stronger sinter. The main difference between the two are their reactivity and chemical composition. Quick lime has a heavy density and is more reactive than hydrated lime. The pH values are much more alkaline (Table 2).

ii) Sodium Hexametaphosphate (SHMP)

It is mainly used as a deflocculant or as a dispersing agent. The dispersant reduces the particle-particle interaction by altering the surface charge, which prevents the particles from aggregating and effectively reduces the yield stress of the suspension. Several examples of viscosity modification in industrial slurries have been described although the cost of modifiers limits their general application. SHMP is more commonly used in laboratory procedures to sustain suspensions in the determination of particle size distribution.

iii) Acti-Gel

According to the Active Minerals International, LLC website (ActiveMinerals, 2016), Acti-Gel® 208 is a highly purified Magnesium Alumino-Silicate and used in a wide variety of water based industrial applications. It is chemically inert and stable between pH 2 and pH 13. It is a low-dose (~0.05 % to ~0.20 % total dry weight material basis) rheology modifier and anti-settling agent that provides superior particle suspension, stabilizes mixtures, and dramatically improves the workability, flowability, pumpability and performance of slurries and pastes.

2.3 Water

In the real transportation of iron ore as slurries through pipelines, ordinary water is commonly used as a medium. Hence, ordinary tap water was chosen for the preparation of iron ore slurry for this particular investigation.

3. Measurement set up and range of parameters

3.1 Measuring device and sample preparations

The experiments were carried out in the Water Resources Simulation Laboratory of Civil Engineering Department, Indian Institute of Technology Delhi. The rheological data measurements were obtained with the help of an advanced computerized rotational rheometer, RheolabQC, manufactured by Anton Paar Company Ltd., Germany. It works according to the Searle principle in which the viscosity is proportional to the motor torque that is required for turning the measuring bob (rotor) against the fluid’s viscous forces. It determines the required force for rotating a bob in a fluid at known speed and works by defining the exact volume of sample which is to be sheared within a test cell, the torque required to achieve a certain rotational speed is measured.

The components of the rheometer and how the data can be read is explained in Assefa and Kaushal (2015b). Two setting options are available for test: controlled shear rate (CSR) and controlled shear stress (CSS). These options, together with the wide speed and torque ranges and very short motor response times, bring innumerable benefits for the application to investigate the conventional flow and viscosity behaviours of slurries and others. Details of the specifications of the rheometer geometry are shown in Table 3.

For the tests, around 80 to 100 g of the slurry was prepared by mixing the required quantity of solid materials with tap water to obtain the desired concentration by weight \( C_w \). The samples were weighed by an electronic balance with a deviation of ±10–4 g. Then, the volumetric solid concentration \( C_v \) is computed as:

\[
C_v = \frac{100 C_w}{C_w + S_g (100 - C_w)} \tag{1}
\]

Where \( S_g \) is the specific gravity of the sample.

CSR between 30 to 300 s–1 at 10 equal intervals was applied for about 2 minutes to measure the corresponding shear stress and viscosity. All the measurements were repeated several times to minimize errors occur during tests. The repeated sets of sample data on shear stress and viscosity agreed within ±2 %. The pH were recorded at each measurements.

Once the sample is prepared and the measurement is done, different analysis method can be added in the analysis window interface. And hence, the measured data will be approximated using the chosen equations and the pa-
Parameters are estimated by weighting of relative error. From the various equations inbuilt in the Rheoplus Software, Herschel-Bulkley and Bingham models have been chosen.

Using the given input data points of shear rate, in this particular study ranges from 30 to 300 s⁻¹, the parameters such as shear stress and apparent viscosity are estimated. After running the analysis, the model results are obtained together with the statistical results of correlation ratio, $R$ and $R^2$, as well as standard deviations relation to yield stress. For a single data the model selection can be done using this value. But in this case, since for each samples data at least five replications have been made, the average of the series data were considered. Then, the rheological data obtained was fit to the Herschel-Bulkley and Bingham models and the best fit model was chosen using $R^2$.

### 3.2 Range of Parameters

The investigations were carried out at $C_v$ of 18.8, 22.1 and 25.8%. For all chemicals except Acti-Gel, the additive proportions of 0.05, 0.1, 0.5, 1, 1.5 and 2% were used. But for Acti-Gel, proportions of 0.05, 0.1 and 0.2% were used.

### 4. Results and discussions

Analysing the chemical reactions or change in the chemical properties of the slurry is not the intention of this particular study. It merely focuses on the influence of chemicals on the rheological properties of the iron ore slurries.

#### 4.1 Physical properties of the sample

As shown in Fig. 1, the median particle diameter ($d_{50}$) is 12 μm. The maximum particle size is 300 μm and around 89% of the particle sizes are below 75 μm. Hence, the sample can be categorized as finer particles. The specific gravity of iron ore fine was measured by sedimentation technique and found to be 4.32 and static settled concentration is 53.04% by volume.

#### 4.2 pH values

Fig. 2 shows the effects of concentration of chemical agents on pH values of iron ore slurries at different concentrations. From the figure, it is seen that pH values were highly affected by the addition of QL and HL. Abrupt increase in the pH values was observed when these chemicals were added even in small proportions (0.05%). But then onwards, the rate of increment was decreased as the amount of chemical agents increased. The minimum and the maximum values registered for both lime were 9.83 and 12.57 at 0.05% on $C_v$ of 25.8% and at 2% additives on $C_v$ of 18.8% respectively. When SHMP was used, the pH values were decreased as the additive proportion was increased for all slurry concentrations and...
a minimum and a maximum values of 7.72 and 6.37 were measured on $C_v$ of 18.8 % at 0.05 % additive and on $C_v$ of 25.8 % at 2 % additive respectively. In contrary, addition of Acti-Gel showed insignificant change in the pH values at all solid concentrations due to its inert properties.

4.3 Slurries rheological properties and model representation

The shear stress data were fitted to the models of Herschel-Bulkley and Bingham, which are expressed as:

Herschel-Bulkley model: $\tau = \tau_y + K\dot{\gamma}^n$ (2)

Bingham model: $\tau = \tau_y + \eta_p \dot{\gamma}$ (3)

Where, $\tau_y$ is the yield stress, $K$ is a measure of the average viscosity of the fluid (or the flow consistency index) and $n$ is a measure of the deviation of the fluid from Newtonian (or the flow behaviour index), $\eta_p$ is the plastic viscosity and $\dot{\gamma}$ is the shear rate.

The average rheological data obtained from exact shear stress- shear rate data using the rotational rheometer and those obtained from the two models for $C_v$ of 18.8, 22.1, and 25.8 % without chemical additives and $C_v$ of 18.8 % with the addition of QL are shown in Fig. 3(a–i). The same trends were followed for the rest of the data. For all the samples data, the range of $R^2$ were from 0.8993–0.9998 and from 0.4253–0.9997 for Herschel-Bulkley and Bingham model respectively. Hence, it is concluded that the variation of the shear stress with shear rate at all solid

**Fig. 3 (a–i).** Selection of best fit model to the measured data of QL at different $C_v$ and chemical proportions.
concentrations with and without the addition of chemicals follow a power law with yield stress and best represented by Herschel-Bulkley model.

The values of $K$ and $n$ were determined by regression analysis of the logarithmic form of Eqn. (2) using sets of shear stress and shear rate data read from the flow curves. For all data sets, the values of $n$ are greater than one which indicate that the samples exhibit yield shear thickening behaviours (Tables 4–7). Furthermore, it shows an increasing degree of shear thickening with increase in solid contents. It may also be mentioned that the increase in apparent viscosity with iron ore content is almost proportional to the value of $K$.

4.4 The Effects of chemical additives

The Effects of different concentrations of chemical agents on the rheological behaviours of iron ore slurries are shown in Figs. 4–15. Figs. 4–6 show the effects of QL on the shear stress and viscosity of iron ore slurries at $C_v$ of 18.8 %, 22.1 % and 25.8 % and at additives concentrations of 0, 0.05, 0.1, 0.5, 1, 1.5 and 2 %.

It is showed that for all additives dosages the values of shear stress and viscosity registered were higher than the values without the chemical additives at $C_v$ of 22.1 % and 25.8 %. Similarly, the increased in rheogram values were observed with increasing the solid concentrations and higher rate of increments were also shown in all additives dosages. But in the case of $C_v$ of 18.8 %, the shear stress and viscosity were increased up to 0.5 % of additives and then decreased as the additives proportions increased and the minimum rheogram data were registered at the maximum additive concentration (2 %). The rate of decrement in viscosity at the lower shear rate ranges was higher than at higher shear rate ranges for all the solid concentrations and chemical additives proportions. Table 4 displayed the results of the rheological parameters yield stress, flow behaviour index and consistency index as a function of proportions of QL. It is shown that the values of $n$ were decreased as the solid concentrations increased for the same additives concentrations and minimum $n$ values were registered at $C_v$ of 25.8 %. Furthermore, for all solid concentrations, the additions of QL increased the yield stresses.

Figs. 7–9 present the shear stress and viscosity at $C_v$ of 18.8, 22.1, and 25.8 % as a function of dosages of HL. Both the shear stresses and viscosities with the additions of this chemical agent were markedly higher compared

<table>
<thead>
<tr>
<th>QL (%)</th>
<th>$C_v$ = 18.8 %</th>
<th>$C_v$ = 22.1 %</th>
<th>$C_v$ = 25.8 %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\tau_y$ (Pa)</td>
<td>$n$ (–)</td>
<td>$K$ (μPa.s$^n$)</td>
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<tr>
<td>0</td>
<td>0.086</td>
<td>1.7</td>
<td>5034</td>
</tr>
<tr>
<td>0.05</td>
<td>0.934</td>
<td>1.63</td>
<td>723</td>
</tr>
<tr>
<td>0.1</td>
<td>0.836</td>
<td>1.7</td>
<td>504</td>
</tr>
<tr>
<td>0.5</td>
<td>0.766</td>
<td>1.45</td>
<td>2119</td>
</tr>
<tr>
<td>1</td>
<td>0.369</td>
<td>1.39</td>
<td>3133</td>
</tr>
<tr>
<td>1.5</td>
<td>0.403</td>
<td>1.47</td>
<td>2031</td>
</tr>
<tr>
<td>2</td>
<td>0.329</td>
<td>1.47</td>
<td>1948</td>
</tr>
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<table>
<thead>
<tr>
<th>HL (%)</th>
<th>$C_v$ = 18.8 %</th>
<th>$C_v$ = 22.1 %</th>
<th>$C_v$ = 25.8 %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\tau_y$ (Pa)</td>
<td>$n$ (–)</td>
<td>$K$ (μPa.s$^n$)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1.26</td>
<td>6625</td>
</tr>
<tr>
<td>0.05</td>
<td>0</td>
<td>1.35</td>
<td>4482</td>
</tr>
<tr>
<td>0.1</td>
<td>0.755</td>
<td>1.57</td>
<td>1125</td>
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<tr>
<td>0.5</td>
<td>0.399</td>
<td>1.39</td>
<td>3330</td>
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<td>1</td>
<td>0.604</td>
<td>1.36</td>
<td>3858</td>
</tr>
<tr>
<td>1.5</td>
<td>0.541</td>
<td>1.4</td>
<td>3185</td>
</tr>
<tr>
<td>2</td>
<td>0.548</td>
<td>1.42</td>
<td>2807</td>
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with the reference rheogram data (without the addition of chemical agents) at all solid concentrations and additive ranges. The same trends as that of QL were observed at low and high shear rates. Unlike the QL, the lower values of $n$ were registered at $C_v$ of 22.1% for all additive dosages (Table 5).

### Table 6  Rheological parameters data at various concentrations and chemical additives of SHMP.

<table>
<thead>
<tr>
<th>SHMP (%)</th>
<th>$C_v = 18.8%$</th>
<th>$C_v = 22.1%$</th>
<th>$C_v = 25.8%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_y$ (Pa)</td>
<td>$n$ (-)</td>
<td>$K$ (μPa.s$^n$)</td>
<td>$\tau_y$ (Pa)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1.39</td>
<td>3760</td>
</tr>
<tr>
<td>0.05</td>
<td>0</td>
<td>1.64</td>
<td>940</td>
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<tr>
<td>0.1</td>
<td>0.087</td>
<td>1.44</td>
<td>2623</td>
</tr>
<tr>
<td>0.5</td>
<td>1.567</td>
<td>2.12</td>
<td>48.5</td>
</tr>
<tr>
<td>1</td>
<td>1.367</td>
<td>2.03</td>
<td>82.7</td>
</tr>
<tr>
<td>1.5</td>
<td>0.818</td>
<td>1.97</td>
<td>122</td>
</tr>
<tr>
<td>2</td>
<td>1.297</td>
<td>1.85</td>
<td>219</td>
</tr>
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</table>

### Table 7  Rheological parameters data at various concentrations and chemical additives of Acti-Gel.

<table>
<thead>
<tr>
<th>Acti-Gel (%)</th>
<th>$C_v = 18.8%$</th>
<th>$C_v = 22.1%$</th>
<th>$C_v = 25.8%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_y$ (Pa)</td>
<td>$n$ (-)</td>
<td>$K$ (μPa.s$^n$)</td>
<td>$\tau_y$ (Pa)</td>
</tr>
<tr>
<td>0</td>
<td>0.106</td>
<td>1.43</td>
<td>2493</td>
</tr>
<tr>
<td>0.05</td>
<td>0.72</td>
<td>1.81</td>
<td>277.2</td>
</tr>
<tr>
<td>0.1</td>
<td>0.88</td>
<td>1.69</td>
<td>509.3</td>
</tr>
<tr>
<td>0.2</td>
<td>0.668</td>
<td>1.84</td>
<td>231.5</td>
</tr>
</tbody>
</table>

Fig. 4  Rheogram of iron ore slurries at QL dosages of 0 to 2% and $C_v$ of 18.8%.
Fig. 5  Rheogram of iron ore slurries at QL dosages of 0 to 2% and $C_v$ of 22.1%.

Fig. 6  Rheogram of iron ore slurries at QL dosages of 0 to 2% and $C_v$ of 25.8%.
Fig. 7  Rheogram of iron ore slurries at HL concentrations of 0 to 2% and $C_v$ of 18.8%.

Fig. 8  Rheogram of iron ore slurries at HL concentrations of 0 to 2% and $C_v$ of 22.1%.
Fig. 9  Rheogram of iron ore slurries at HL concentrations of 0 to 2 % and $C_v$ of 25.8 %.

Fig. 10  Rheogram of iron ore slurries at SHMP concentrations of 0 to 2 % and $C_v$ of 18.8 %.
Fig. 11  Rheogram of iron ore slurries at SHMP concentrations of 0 to 2 % and $C_v$ of 22.1 %.

Fig. 12  Rheogram of iron ore slurries at SHMP concentrations of 0 to 2 % and $C_v$ of 25.8 %.
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Figs. 10–12 illustrate the relationship between shear stress versus shear rate and viscosity versus shear rate for the iron ore slurries at \(C_v\) of 18.8%, 22.1% and 25.8% using different dosages of SHMP as a dispersing agent. It can be seen that low shear stress and viscosity were obtained at additive dosage of 1.5% for \(C_v\) of 18.8% and at 2% for \(C_v\) of 22.1 and 25.8%. The same trends also observed as that of lime (QL and HL) at low shear, particularly less than 60 s\(^{-1}\), the rheogram values increased at all solid concentrations and additives dosages but the rate of increment is higher than lime. Furthermore, the values of \(n\) were decreased as the solid concentrations increased for additives concentrations 0.05% and then increased for the remaining dosages of additives for all concentrations (Table 6).

The effects of Acti-Gel dosages on the shear stress and viscosity of iron ore slurries at \(C_v\) of 18.8, 22.1 and 25.8% are presented in Figs. 13–15. From these figures it can be observed that minimum shear stress was registered at 0.2% of Acti-Gel for \(C_v\) of 18.8% and at 0.1% for 22.1%
and 25.8% of solid concentrations. It can also be seen that viscosity was increased drastically at the lower shear rate (usually less than 90 s⁻¹) for all additives and solid concentrations. A minimum yield stress was obtained at additive concentrations of 0.2%, 0.1% and 0.05% for \( C_v \) of 18.8, 22.1 and 25.8% respectively. But these minimum values were higher than the yield stress at 0% additive (Table 7). Furthermore, it is also shown that the values of \( n \) were higher when this chemical was added for all range of solid concentrations which indicate that the slurry shows more yield thickening behaviours.

5. Conclusions

The iron ore slurries, with and without the additions of chemical agents, considered in this particular study exhibit shear thickening properties and best represented by Herschel-Bulkley model. The shear stress and viscosity were decreased beyond 0.5% of QL and minimum results were registered at the maximum additive dosage (2%) on 18.8% solid concentration. Furthermore, the addition of QL increased the yield stress and minimum flow behaviour index was obtained at 25.8% solid concentration with 2% additive dosage. In contrary to the above, the addition of HL increased markedly the values of shear stress, viscosity, flow consistency and flow behavior indices. When SHMP is used, minimum shear stress and viscosity were obtained at a dosage of 1.5% for \( C_v \) of 18.8% and at 2% for \( C_v \) of 22.1% and 25.8%. Acti-Gel resulted higher values of \( \tau_y \) and \( n \) for all ranges of solid concentrations.

The pH values of the slurries were remarkably increased when QL and HL were used in all solid concentrations and additive dosages. On the other hand Acti-Gel showed negligible effect on pH due to its inert property and the friction factors increased at all solid concentration and Acti-Gel dosages.

Further investigation is needed on how these most effective chemical agents change the chemical composition and properties of the iron ore slurries for the intended purposes.

Acknowledgements

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Nomenclature

- \( C_w \): Concentration by weight (%)
- \( C_v \): Volumetric solid concentration (%)
- \( D \): Pipe diameter (m)
- \( f \): Fanning friction factor (–)
- \( f_0 \): Reference fanning friction factor (–)
- \( f' \): Normalized friction factor (–)
- \( HL \): Hydrated lime
- \( K \): Flow consistency index (Pa sⁿ)
- \( n \): Flow behaviour index (–)
- \( QL \): Quick lime
- \( Re \): Reynolds number (–)
- \( S_g \): Specific gravity (–)
- \( SHMP \): Sodium hexametaphosphate
- \( U \): Flow velocity (m/s)
- \( \rho_m \): Density of mixture (kg/m³)
- \( \tau_y \): Yield stress (Pa)
- \( \eta_p \): Plastic viscosity (Pa s)
- \( \dot{\gamma} \): Shear rate (s⁻¹)

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Author’s short biography

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Mr Assefa received his BSc degree from Hawassa University (then Debub University), Ethiopia in 2004. In 2009, he obtained his MSc degree from Haramaya University, Ethiopia. Currently, he is a Ph.D. Scholar in the Department of Civil Engineering at Indian Institute of Technology (IIT) Delhi. His main research interests are in Rheology, Slurry/Sediment Transport, Multiphase Flows, Computational Fluid Dynamics and Hydraulics.

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Dr. D. R. Kaushal was trained to be a slurry pipeline designer during his Ph.D. at IIT Delhi and Postdoctoral Research at KIT Japan. He has been an Associate Professor of Hydraulics in Water Resources Engineering Section of Civil Engineering Department at IIT Delhi since 2004. He has visited KIT Japan and KCT Japan as visiting Professor. During his teaching and Postdoctoral research, he has been carried out several research and consultancy projects. He has worked with several mining, mineral-processing and production companies, either through direct consultation or through collaboration with other companies or research organizations.