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PREDICTION OF PRESSURE DROP AND OPTIMIZATION OF OPERATIONAL PIPE FLOW PARAMETERS FOR HYDRAULIC TRANSPORTATION OF CONCENTRATED IRON ORE FINES SLURRY

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Pipeline transportation of iron ore fines slurry at high solids concentration from the source to the site of its utilization has technological as well as economical implications. In the present scenario, major Indian iron and steel producers are aiming for transporting the run-of-mine (ROM) iron ore through slurry pipelines at a competitive price. Thus, it is quite imperative to study the flow characteristics of concentrated iron ore fines slurry for predicting the pumping pressure as well as designing such commercial slurry pipelines. This paper presents the results of the flow behaviour of specific Indian iron ore samples in a solids concentration range of 60-78% by mass using a HAAKE Rotational Rheometer (Model: RheoStress 1, Thermo Fisher Scientific). The rheological characteristics of the fines slurry samples indicated non-Newtonian flow behaviour and fitted the Bingham Plastic model well in the studied range of concentrations. The influence of solids concentration on yield stress and viscosity of the iron ore fines slurry samples were discussed and presented in the paper. The pressure drop for the concentrated slurry in larger size pipes (300, 350, 400 & 450 mm NB pipes) were predicted by employing non-Newtonian head loss models. Attempts have been made to optimize the operational pipe flow parameters with respect to specific energy consumption (*SEC*) and the basic design of a commercial scale iron ore slurry pipeline with annual conveying capacity of ~ 12.6 million tons has been worked out.

KEY WORDS: iron ore, slurry rheology, high concentration, pressure drop.

1. INTRODUCTION

The technical success of transporting high density ores and mineral slurries with low capital investment and operating costs points the way to increased application and need to gain a better understanding of the rheological behaviour of these slurries. Concentrated iron ore slurries especially containing considerable amount of fines content exhibit non-Newtonian characteristics and, therefore, determination of pipeline operational conditions correlating the rheological characteristics is quite cumbersome. In order to reduce specific water consumption per ton of steel produced, the transportation of iron ore slurry at high solids concentration may be considered as an innovative solution. Thus, the slurry pipeline

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will go a long way in reducing the problems of pollution and the congested transportation network in the mining areas. A limited study on rheological behavior of concentrated iron ore slurry has been cited in the literature: Jennings, (1969); Abro et al., (2010); Vieira and Peres, (2012); Moraes et al., (2013); Assefa and Kaushal, (2017); Sahoo et al., (2017); Senapati et al., (2018). The influence of pipe diameter, solids concentration and particle size affecting the energy efficiency of slurry transport has been investigated by some authors: Parida et al., (2000); Wu et al., (2010); Aziz & Mohamad, (2013); Yildiz et al., (2014); Hashemi & Sanders, (2014); Ihle et al., (2014). Only meager attempts have been made to correlate the head loss of iron ore slurry empirically: Hayashi et al., (1980); Lokon et al., (1982). Ercolani & Ferrini, (1979) investigated the limit deposit conditions of magnetite slurries using electric and thermic probes for scaling up commercial pipelines at higher volumetric solids concentrations.

Considering the limited literature on the flow behaviour and pipeline transportation of highly loaded iron ore fines/concentrate slurry, an attempt has been made in this paper to characterise the flow behaviour and then to evaluate the pressure drop of iron ore slurry in the solids concentration range of 60-78% by mass.

2. EXPERIMENTAL

2.1 CHARACTERIZATION STUDIES

The iron ore samples for the present investigation were collected from M/s NMDC Ltd., Bailadila area, Chhattisgarh, India. Initially, the lumpy ores with 8-10 mm sizes were ground in a ball mill and fines samples (–45 μm size) were prepared through wet sieving followed by drying in a laboratory oven. The average true density of the iron ore sample determined by laboratory tests was found to be 4484 kg/m^3. The particle size distribution (PSD) of the representative sample was determined by using HORIBA LA-960 Laser Scattering Particle Size Distribution Analyzer and the median particle size, d_{50} of the sample was found to be 11.12 μm. The d_{10} & d_{90} of the samples were found to be 2.23 and 27.31 μm respectively. The chemical compositions of the bulk ore samples were carried out by Philips PW2440-X-ray Spectrometer (PAN analytical, the Netherlands) and the composition of major elements were Fe: 62.05%, Al: 1.04%, SiO_2: 1.46% and LOI: 2.9%. The pH of the slurry was measured by a standard pH meter (Model: ORION STAR, A211) for a period of 6 hours and the slurry samples were found to be slightly alkaline (pH: 7.09-7.17) during the mixing period. The maximum static settled concentration tests for the samples prepared in distilled water medium indicated a $C_{W\text{-}max}$ value of 83.33% by mass. Different settling rates may have been measured if process water containing electrolytes had been used.

2.2 RHEOLOGICAL MEASUREMENTS

The rheological experiments for the NMDC iron ore fines samples in the slurry concentration range of 60-78% by mass were conducted using a HAAKE Rotational Rheometer at room temperature (30^o C) & in the shear rate range of 0 to 300 s^{-1} for a period of 2 minutes under controlled rate. The shear stress-shear rate data obtained for the slurry samples in the concentration range of 60-78% by mass are shown in Figure 1.

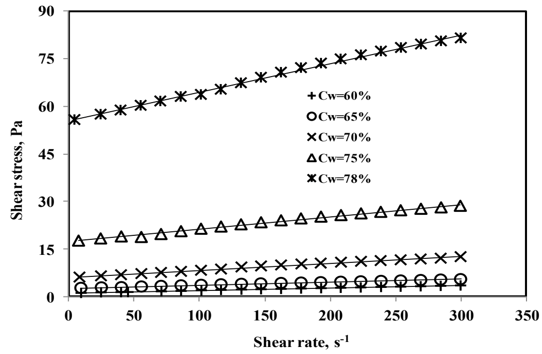

Figure 1. Rheograms of NMDC iron ore fines slurry at different mass concentrations

3. RESULTS AND DISCUSSION

3.1 RHEOLOGICAL BEHAVIOUR OF IRON ORE SLURRY

It is seen from the Figure 1 that the flow characteristics of the iron ore slurry samples indicated non-Newtonian behaviour as observed from the shape of the rheograms & the data were fitted to Bingham plastic model, which can be represented by the following equation:

$$\tau = \tau_0 + \eta_b \dot{\gamma} \quad (1)$$

where τ (Pa) is the shear stress, γ (s^{-1}) is the shear rate, τ_o (Pa) is the yield stress and η_b is the plastic viscosity (Pa s). The rheological parameters such as τ_o & η_b for the slurry samples in the studied range of concentrations is given in Table 1.

Table 1

Yield stress (Pa) and Bingham plastic viscosity (Pa.s) at different C_W

Cw, (%)	**Bingham parameters at different slurry concentrations by mass**	
	Yield stress, τo (Pa)	Bingham plastic viscosity ηb (Pa.s)
60	1.05	0.008
65	2.62	0.009
70	6.05	0.022
75	17.3	0.039
78	55.3	0.09

As indicated in Table 1 both the yield stress and viscosity values increase with increase in solids concentration. Further, both the yield stress and viscosity values increase markedly beyond a slurry concentration of 75% by mass.

3.2 PREDICTION OF PRESSURE DROP

The accurate estimation of pressure drop and especially the operational flow parameters such as pipe size, pipe wall thickness, design velocity, pump discharge pressure and pump horse power (HP) is important for the commercial design of high concentration slurry pipelines. In the present investigation, the iron ore slurry samples supplied by NMDC exhibited Bingham plastic behaviour with a yield stress in slurry concentration range of 60-78% by mass.

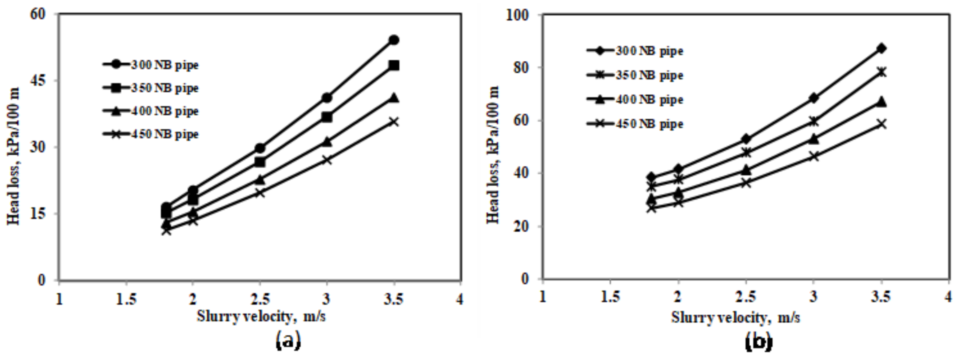

Figure 2. Predicted pressure drop for NMDC iron ore slurry samples: (a) C_W=65%; (b) C_W=75%.

Darby et al. proposed a combined laminar-turbulent Fanning friction factor for determining the pressure drop of concentrated slurries (Darby & Melson, 1981; Darby et al., 1992). Using the Darby et al. relationship, the pressure drop for the iron ore slurry in the velocity range of 1.8 – 3.5 m/s was predicted in the investigated range of slurry concentrations for larger pipe diameters. The flow regime of the slurry samples were found to be turbulent in the investigated range of velocities, concentrations and pipe diameters except for the highest concentration of 78% by mass. The transition velocity as limiting velocity criteria was considered for predicting the pressure drop and the predicted pressure drop data in 300 mm, 350 mm, 400 mm and 450 mm NB pipes at solids concentrations of 65% and 75% are plotted in Figures 2(a) & 2(b). As is to be expected, it is observed from these plots that the pressure drop increased with increase in slurry velocity and decreased with increase in pipe size at a specific solids concentration of the slurry.

3.3 DESIGN AND OPERATIONAL PARAMETERS

3.3.1 MINIMUM DESIGN VELOCITY

It is universally accepted that the limit deposit velocity also called the deposition velocity should always remain higher than the minimum design velocity to attempt to ensure deposit free slurry flow and to exclude any possibility of pipeline plugging and has been taken as 0.3 m/s higher than the limit deposit velocity. By using the following equation similar to the empirical equation given by Durand (Govier & Aziz, 1972), the minimum design velocity for iron ore slurry can be evaluated which may be expressed as:

$$V_d = F_L\,[2gD_i(S_S - S_m)]^{0.5} + 0.3 \quad (2)$$

where, F_L is the modified Froude number, g is the acceleration due to gravity in m/s^2, D_i is the pipe internal diameter in m, S_S and S_m are specific gravity of solids and slurry respectively. F_L is a function of particle size and volumetric concentration of the particles in slurry. A chart given by Durand can provide F_L at different particle sizes up to a volume concentration of 15% & for higher concentrations; the F_L values were determined by using Parzonka et al. plot (Parzonka et al., 1981). The F_L values were found to be 0.5, 0.44, o.4, 0.4 & 0.4 at C_W values of 60, 65, 70, 75 & 78%. Accordingly, the limit deposit velocities, V_L, and corresponding design velocities, V_d, for commercially-sized pipelines in the slurry concentration range of 60-78% by mass are presented in Table 2.

Table 2

Computed values of limit deposit and design velocities in larger pipe sizes

Cw, %	**300 mm NB Pipe**		**350 mm NB Pipe**		**400 mm NB Pipe**		**450 mm NB Pipe**	
	VL, m/s	Vd, m/s	VL, m/s	Vd, m/s	VL, m/s	Vd, m/s	VL, m/s	Vd, m/s
60	1.92	2.22	2.01	2.31	2.16	2.46	2.3	2.6
65	1.64	1.94	1.72	2.02	1.84	2.14	1.96	2.26
70	1.44	1.74	1.51	1.81	1.62	1.92	1.72	2.02
75	1.37	1.67	1.44	1.74	1.54	1.84	1.64	1.94
78	1.33	1.63	1.4	1.7	1.5	1.8	1.58	1.88

3.3.2 SOLIDS FLOW RATE AND SPECIFIC ENERGY CONSUMPTION (SEC)

The specific energy consumption (*SEC*) is defined as the hydraulic power (*kW*) required by the pump for transporting 1 ton of dry solids through one kilometer length of the pipeline and is given as:

$$SEC = P_H / W_S \quad (3)$$

where, P_H is the hydraulic power in *kW* and W_S is the solids flow rate in tons/hr. through the pipeline. P_H and W_S can be computed as:

$$P_H = \frac{Q.\rho_m.g.\Delta H}{3.6\,X\,10^6} \quad (4)$$

$$W_S = Q.\rho_m.C_W \quad (5)$$

where, Q is the slurry flow rate in m^3/hr., ρ_m is the slurry density in kg/m^3, g is the acceleration due to gravity in m/s^2, ΔH is the pressure loss of slurry in m of water per kilometer, C_W is the solids concentration as a mass fraction and D_i is the pipe internal diameter in m. The *SEC* as a function of C_W at different slurry flow velocities in 350 mm and 450 mm NB pipes is plotted in Figures 3(a) & 3(b). It is indicated in Figure3 that the polynomial curves fitted the data quite well for both slurry pipe diameters. The *SEC* values initially exhibited a decreasing and then an increasing trend with increase in velocity at the studied range of slurry concentrations and indicated a minimum value at a slurry concentration of 65% by mass. The increase in *SEC* was then slow and gradual up to a slurry concentration of 70% and beyond this concentration, *SEC* increased quite appreciably. Thus, for economic pipeline operation, the iron ore fines slurry may be transported in the solids concentration range of 60-70% by mass.

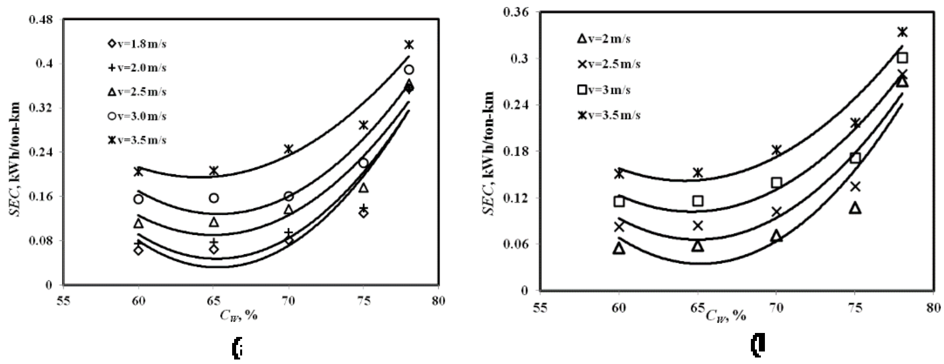

Figure 3. Specific Energy Consumption (SEC) for iron ore slurry at different wt. concentrations: (a) in 350 mm NB pipe; (b) in 450 mm NB pipe.

3.3.3 OPERATIONAL RANGE & OPTIMUM TRANSPORT CONCENTRATION

It is seen from Figure 3 that *SEC* indicated a minimum value at a slurry concentration of 65% by mass for both 350 mm and 450 mm NB pipes. Thus, C_W at 65% can be considered as the optimum transport concentration for the iron ore slurry. It is desirable to operate the commercial slurry pipelines around the designed concentration & minimum design velocity to avoid erosion & to reduce power consumption. Further, certain change in transport velocity urges to maintain the slurry flow under full suspension of solids. In this context, the operating range is determined by plotting the constant solids flow rate lines over the minimum design velocity curve. For a constant solids flow rate, the slurry velocities at different solids concentrations can be calculated from the following expression:

$$V = \left(\frac{4}{\pi \, x \, 3600}\right)\left(\frac{W_S}{D_i^{\,2} \, \rho_m C_W}\right) \quad (6)$$

where, V is the slurry velocity in m/s, W_S is the solids flow rate in tons/hr., D_i is the pipe internal diameter in meter, C_W is the solids mass fraction, ρ_m is the slurry density in tons/m^3.

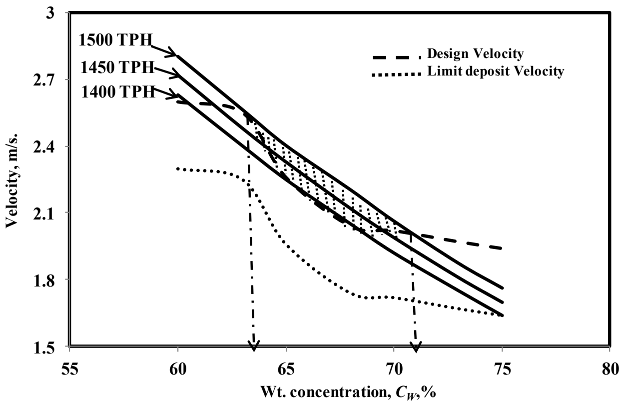

Figure 4. Operational range of 450 mm NB iron ore slurry pipeline

Three sets of solids flow rates between 1400 tons/hr to 1500 tons/hr were chosen for a 450 mm NB pipe in the studied range of solids concentrations. The slurry velocity curves at the constant solids flow rates as well as the design velocity curve were plotted as a function of solids mass concentration in Figure 4.

Table 3

Design & operational parameters of Iron ore slurry pipeline

Nominal Bore Pipe size:	450 mm
Pipe outside diameter:	457.2 mm
Pipe inside diameter:	409.6 mm
Pipe wall thickness:	23.8 mm
Operating concentration:	70% by mass
Slurry density:	2190 kg/m^3
Limit deposit velocity:	1.72 m/s
Design transport velocity:	2.02 m/s
Slurry volume flow rate	958 m^3/hr
Solids disposal rate:	1470 tons/hr
Rated conveying capacity:	1440 tons/hr
Head loss/km length of pipeline:	18.7 m of water
Specific Energy consumption (*SEC*):	7.28 x 10^{-2} kWh/ton-km

The point of intersection of the solids flow rate line with the design velocity curve indicates the concentration and the minimum design velocity at which the given solids flow rate can be achieved. Since the optimum solids concentration is taken as 65%, the solids flow rate corresponding to the minimum design velocity at this concentration, would give the rated capacity of the pipeline. But in actual operational practice, the solids concentrations may be required to be varied to some extent. Thus, the mass concentration range in which the pipeline may operate can be assumed to from 63.5% to 71%. The corresponding solids flow rates at these concentrations express the range of solids conveying capacities of the pipeline. The operational ranges are indicated by the shaded area for 450 mm nb pipeline. The rated conveying capacity and the operational range for the pipeline are 1440 tons/hr. and 1410 – 1470 tons/hr. respectively. The design and operational parameters for hydraulic transportation of iron ore fines slurry at high solids concentration (C_W = 70%) in a 450 mm nominal bore pipe size is summarized in Table 3.

4. CONCLUSIONS

The rheological characteristics of iron ore fines samples at high solids concentration in the range of 60-78% by mass indicated non-Newtonian flow behaviour and the rheological data were characterised well using the Bingham plastic model. By using the Darby et al. correlation, the combined laminar-turbulent friction factor and the pressure drop of the slurry in four different pipe sizes (300 mm, 350 mm, 400 mm & 450 mm NB) were predicted. The optimum transport concentration of the slurry in the larger pipe sizes was evaluated to be 65% by mass and for economic pipeline operation, the iron ore fines slurry may be transported in the solids concentration range of 60-70% by mass. The operating range of solids concentration in a 450 mm NB pipe was evaluated with respect to design velocity and solids flow rates by allowing for a certain amount of fluctuations in the slurry concentrations. The rated conveying capacity and the operational range for the pipeline were computed to be 12.61 Mt and 12.35–12.9 Mt per annum respectively. The studies indicate that it is quite feasible to transport iron ore fines slurry through pipelines at high solids concentrations which may reduce water consumption drastically and curb environmental pollution.

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