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EFFECT OF PARTICLE SIZE DISTRIBUTION ON RHEOLOGY OF HIGH CONCENTRATION LIMESTONE–WATER SLURRY FOR ECONOMIC PIPELINE TRANSPORTATION

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In the present study, the settling experiments pertaining to maximum static settled concentration ($C_{W\text{-}max}$) and rheological measurements were carried out for an Indian limestone samples in the slurry concentration range of 60-78.5% by mass. Five representative samples with mono-modal, bimodal and multimodal size distribution were prepared by blending the fines with other three distinct coarse fractions. The rheological behaviour of the slurry samples indicated non-Newtonian flow behaviour and fitted well to Bingham Plastic model in the concentration range of 60-78.5% by mass. The slurry samples with bimodal and multimodal packing characteristics indicated substantial reduction in slurry viscosity, yield stress and improved solids loading as compared to mono-modal one. The higher $C_{W\text{-}max}$ values obtained for the set of blended (fines with coarse) limestone slurry samples were attributed to the packing effect and was correlated to the ratio of surface to surface separation for the coarse particles (β) to the average fine particle size ($d_{50\text{-}f}$) to achieve higher solids concentration. The reduction in slurry viscosity observed for the specific limestone samples was further substantiated by correlating the distribution modulus (ψ) derived from Farris theory. It may be inferred that these theoretical treatments correlating the experimental data can provide highly reliable guidance to the preparation of high concentration limestone slurry for economic pipeline transportation.

KEY WORDS: Limestone slurry; Packing characteristics; Rheology.

1. INTRODUCTION

The pipeline transport of minerals and ores slurry is considered as one of the essential operations in today's mining and mineral processing industries. The bulk utilization of ground limestone powder as a filler material pertains to paints, pigments, foods, plastics and pharmaceuticals industries. Besides, a substantial quantity of this material is used as a fluxing agent in iron & steel industries for operation of blast furnace and steel melting shop. The transportation of limestone from mine's processing site to plant end by rail and road not only incurs huge cost but also liable to losses due to theft and spoilages. Pipeline transportation of limestone slurry may be considered as an economically viable technology due to its reliability, low maintenance and environmental friendly nature. Therefore, the preparation of a highly dispersed homogeneous suspension of limestone particles in water or other carrier medium is quite essential prior to transporting the bulk slurry through pipelines. Besides, the rheological behaviour of the concentrated slurry requires careful investigation with respect to viscosity and other slurry flow parameters for negotiating the pumping power with minimum specific energy consumption (Govier and Aziz, 1972). It is well known that the viscosity of a particulate suspension increases significantly with increase in solids loading and by broadening the particle size distribution (PSD); the viscosity can be lowered significantly. Therefore, optimizing PSD is an effective way to obtain high solids concentration with low viscosity (Barnes et al., 1989; Zaman and Moudgil, 1998). Polydispersity can give a lower viscosity at the same solids concentration or allow a higher solids loading of particles at the equivalent viscosity (Farris, 1968; Greenwood et al., 1998; Storms et al., 1990; Chang and Powell, 1994; Larson, 1999; Metzner, 1985). Two major parameters: size ratio (λ) and blend ratio (ξ) may be employed to describe the poly-dispersive nature of suspension (Toivakka and Eklund, 1995). The size ratio is defined as the ratio of d_{large} to d_{small} and blend ratio can be expressed as the fraction of a particle class in relation to the other classes. The manipulation of the parameters λ and ξ can increase the maximum volume fraction in a suspension (Farris, 1968; Storms et al., 1990; Barnes, 2000; Hoffman, 1992). The reduction in slurry viscosity is also very much influenced by the distribution modulus (ψ) and expressed as follows:

$$\psi = \frac{\ln V_l}{\ln k} \tag{1}$$

Where V_l is the volume fraction of liquid in the slurry and k is the ratio of d_{small} to d_{large}. The ability to achieve high solids concentration is a function of the average separation β of the large particles to the size of the fine material (Miller, 1993). In the present analysis, the average surface-to-surface separation for the coarse limestone particles can be written as:

$$\beta = \left[\left(K_V / \phi_b \right)^{\frac{1}{3}} - 1 \right] d_b \tag{2}$$

Where, K_V is the column shape factor i.e. π/6, ϕ_b and d_b are the volume fraction and median diameter of coarse limestone particles. A limited study on rheological behaviour of limestone slurry has been cited in literature. The flow behaviour of limestone slurry samples was characterized by yield pseudo-plastic model at high solids concentrations (He et al., 2006). The relative viscosity data of an Indian limestone sample were compared with some of the existing empirical models (Senapati et al., 2009). The reduction in viscosity through small dosages of sodium water glass and calcareous as additives was observed by Jaworska and Bartosik, (2014) while investigating the flow behaviour of limestone slurry. The economic pipeline transport of slurry affected by pipe diameter, solids concentration and particle size has been investigated by some authors (Hashemi and Sanders, 2014; Ihle et al., 2014; Yildiz, 2014). An attempt has been made in this paper to investigate the effect of manipulating the particle size distribution on the preparation and flow behaviour of high concentration limestone slurry (60-78.5% by mass) samples.

2. EXPERIMENTAL

2.1. CHARACTERIZATION STUDIES

The limestone samples used for the study were procured from an Indian limestone mine situated in Rourkela, Odisha (Eastern part of India). The true density of limestone sample was found to be 2630 kg/m^3. Initially, limestone samples with four distinct particle size ranges; i.e. < 38 μm, 38-90 μm, 90-210 μm and 210-300 μm were obtained by controlled grinding in a laboratory-size ball mill followed by screening using standard sieves. Five representative limestone samples with mono-modal, bimodal and multimodal characteristics were prepared from the aforementioned four distinct particle size ranges by blending the coarse fractions (38-90 μm, 90-210 μm and 210-300 μm) with finer fractions (< 38 μm) in a fixed blend ratio (mass ratio) of 0.6: 0.4 and labeled as S-1, S-2, S-3, S-4 and S-5. The particle size distribution (PSD) of these five representative samples was determined by using HORIBA LA-960 Laser Scattering Particle Size Distribution Analyzer. The diameters (d_{10}, d_{50} and d_{90}) on cumulative percentages are given in Table 1.

Table 1

Particle size distribution of five representative limestone samples used for the study

Diameter on cumulative %	S-1 (μm)	S-2 (μm)	S-3 (μm)	S-4 (μm)	S-5 (μm)
d_{10}	3.73	6.78	6.7	7.4	7.3
d_{50}	10.58	44.45	94.56	253.21	70.28
d_{90}	22.01	105.48	197.78	474.78	364.1

2.2. MAXIMUM STATIC SETTLED CONCENTRATION (SEDIMENTATION) TEST OF LIMESTONE SLURRY

The settling tests were carried out in the laboratory for the five limestone samples following standard procedure to ascertain the limiting concentration of the slurry. Initially, slurries were prepared in mass concentration range of 60-78.5% and poured into standard graduated glass cylinders having 250 ml capacity. Then the slurries were allowed to settle in the cylinders for about 72 hours after which no further settling occurs. By noting down the interface readings between settled slurry and free water at the top, the maximum settled concentration was computed using the following relationship:

$$C_{W\max} = \frac{M_S}{M_S + M_W} \tag{3}$$

Where M_S is the mass of solids in the settled bed and M_W is the mass of water present in the settled mass.

2.3. RHEOLOGICAL MEASUREMENTS

The rheological experiments for the five limestone samples in slurry concentration range of 60-78.5% by mass were carried out using a HAAKE Rotational Rheometer (Model: RheoStress 1, Thermo Fisher Scientific). Depending upon the nature of particle size and slurry concentration, two types of geometry mainly "Cup and Bob" and "Parallel-Plate" sensor systems were employed for the rheological characterization of the samples. The Cup and Bob sensor system Z comprises of a collapsible beaker Z43 with radius 21.7 mm and rotors Z38 and Z41 with radii 19.01 and 20.71 mm respectively. The Parallel-Plate sensor system RS1-PP60 consists of a measuring plate with diameter 60 mm and gap of 1 mm between the stationary and movable plate. The Cup and Bob sensor systems with rotors Z38 and Z41were used for rheological measurements of samples S-2, S-3, S-4 & S-5 whereas, the Cup and Bob sensor system with rotor Z41 and Parallel-Plate sensor system (RS1-PP60) were used for sample S-1. Slurries prepared at the desired concentrations were subjected to rheological measurements under controlled shear rates (0 to 300 s^{-1}) and at room temperature of 30 ^{O}C.

3. RESULTS AND DISCUSSION

3.1. EFFECT OF BLENDING COARSE WITH FINES ON MAXIMUM STATIC SETTLED CONCENTRATION OF LIMESTONE SLURRY

From the maximum static settled concentration tests data as indicated in Table 1, one can observe that the $C_{W\,max}$ values increased with increase in slurry concentration from 60% to 78.5% by mass. The blended four samples (S-2 to S-5) with bimodal and multimodal particle size distributions influenced the maximum static settled concentration data very much as indicated in Table 2.

Table 2

Maximum Static Settled Concentration (sedimentation) test data for limestone samples (S-1 to S-5)

Limestone samples	Median particle size (d_{50})	C_W, %	C_W, %	C_W, %	C_W, %	C_W, %	C_W, %
		60	65	70	72.5	75	78.5
			Calculated values of $C_{W\,max}$				
S-1	10.58 μm	64.631	69.149	72.165	74.215	75.756	78.635
S-2	44.45 μm	71.289	74.409	76.238	76.953	78.125	79.624
S-3	94.56 μm	74.874	76.471	78.106	78.875	79.365	80.461
S-4	253.213 μm	75.081	77.415	78.683	79.764	80.645	81.103
S-5	70.28 μm	74.935	76.592	78.212	79.236	79.787	80.536

By comparing the $C_{W\,max}$ values of sample S-1 with the other four samples, it was observed from Table 1 that at an overall slurry mass concentration of 78.5%, the percentage increase in $C_{W\,max}$ values was found to be 1.257%, 2.322%, 3.138%, and 2.417% for samples S-2, S-3, S-4 & S-5 respectively. The ratio of β to $d_{50\text{-}f}$ strongly influences the $C_{W\,max}$ values with bimodal and multimodal characteristics at a given solids concentration of limestone slurry. Because the selected fine limestone particles can readily fill the void spaces between the selected coarse particles and therefore higher loading can be obtained. Thus, with reduction in particle size, the excluded–volume effect becomes increasing important and enhances the $C_{W\ max}$ values at these concentrations for samples S-2 to S-5. It is further observed from Table 2 that sample S-4 with bimodal distribution and having d_{90} as 474.778 µm indicated maximum value of $C_{W\ max}$ as compared to other four samples. Sample S-5 with multimodal characteristics could not provide the highest in maximum limestone loading as expected. This may be due to the presence of ultrafine and fine particles may form agglomerates or compact structures within the voids between the relatively coarse particles and reduce the free space available for packing.

3.2. RHEOLOGICAL BEHAVIOUR OF LIMESTONE SLURRY

The flow characteristics of the limestone slurry indicated Bingham plastic flow behaviour as observed from the shape of the rheograms τ–$\dot{\gamma}$ and the data for samples S-1 & S-5 are plotted in Fig.1.

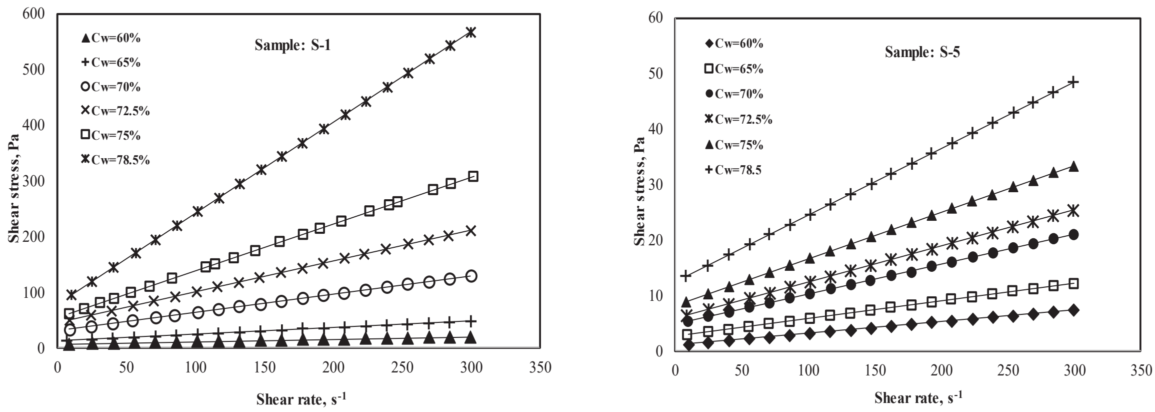

Fig. 1 Rheogram of limestone slurry at different C_W for sample S-1 & S-5

The shear stress values increased with increase in mass concentration and hence, the viscosity of the slurry increased with increase in solids loading. The R^2 coefficients for the fit of different curves were found to be in the range of 0.998 – 1 and the Bingham plastic model was fitted very well to the experimental data in slurry concentration range of 60-78.5% by mass which can be expressed as:

$$\tau = \tau_0 + \eta_p \dot{\gamma} \tag{4}$$

Where τ (Pa), is the shear stress, $\dot{\gamma}$ (s^{-1}) is the shear rate, τ_0 (Pa) is the yield stress and η_p (Pas) is the plastic viscosity. The rheological parameters τ_0 (Pa) and η_p (Pas) values obtained for the five limestone samples in the studied range of concentrations are presented in Table 3. The existence of yield stress (τ_0) observed for the limestone slurry samples was attributed to the presence of flocculated structure and inter particle frictional forces. From Table 3, it is observed that τ_0 increased sharply beyond a slurry concentration of 70% by mass for sample S-1. The other four samples with bimodal and multimodal particle size distribution indicated lesser yield stress as compared to sample S-1. This is because by blending the fine with coarse particles, the samples S-2 to S-5 incurred lower yield stress due to reduction in no. of flocculated structures with decrease in attractive force with larger inter particle distance. Shivaram et al. (2013) while characterizing the flow behaviour of ultrafine mallee biochar slurry made similar type of observations. It is also seen from Fig.1that the smaller the particle size, the more evident was the increase in yield stress at a given concentration. The influence of particle size distribution on yield stress for fine cement and coarse fly ash slurry indicated similar behaviour as investigated by Bentz et al. (2012).

Table 3

Rheological parameters for the limestone slurry samples at different C_W, %

Sample No.	Slurry Concentration by mass, C_W,%					
	60	65	70	72.5	75	78.5
	Yield Stress (τ_0), Pa					
S-1	6.664	12.04	30.54	44.81	53.4	78.04
S-2	1.76	3.85	8.13	10.36	14.37	22.35
S-3	0.78	1.72	3.72	4.33	6.41	11.16
S-4	0.38	0.71	1.71	2.06	2.9	4.73
S-5	1.01	2.57	4.85	5.84	9.02	12.47
	Plastic Viscosity (η_P), Pas					
S-1	0.043	0.092	0.37	0.552	1.132	1.56
S-2	0.022	0.0291	0.0903	0.148	0.2424	0.322
S-3	0.0192	0.027	0.045	0.065	0.1074	0.1548
S-4	0.0184	0.0262	0.044	0.062	0.09	0.113
S-5	0.021	0.0276	0.0532	0.091	0.124	0.168

3.3. EFFECT OF PARTICLE SIZE DISTRIBUTION ON VISCOSITY OF LIMESTONE SLURRY

The plot of size ratio versus viscosity for the five limestone samples in slurry concentration range of 70-78.5% by mass at shear rate 300 s^{-1} are shown in Fig. 2(a). The reduction in viscosity for fine-coarse mixture samples may be due to bidisperse nature of suspension and the viscosity is greatly influenced by size ratio (λ). It is indicated from Fig. 2(a) that the viscosity increases exponentially with decrease in size ratio (λ) for the five limestone samples in the studied range of concentrations. The increase in viscosity at a given shear rate may be due to stronger inter particle attractions with relatively larger amount of finer particles at a given concentration. The reduction in Bingham plastic viscosity (η_P), observed for the five limestone samples was further substantiated by correlating the distribution modulus (ψ) derived from Farris theory (Farris, 1968). The plot of Bingham viscosity against the computed values of ψ in slurry concentration range of (70 - 78.5%) is presented in Fig. 2(b). It is observed from the plots that minimum viscosity was achieved by the set of limestone samples with ψ values ranging from 0.15 to 0.21. The sample S-4 with ψ value ranging from 0.1527 to 0.2093 indicated near minimum viscosity at higher solids concentrations of 70-78.5% and achieved maximum packing density as discussed in the earlier section. Therefore, the distribution modulus value is in remarkable agreement with the theoretical prediction of Farris where the optimum ψ values were in the range of 0.174 to 0.221 for the set of coal water slurries having ratio of a largest particle diameter in the distribution to the smallest particle diameter in a broad distribution of coal particles (Farris, 1968).

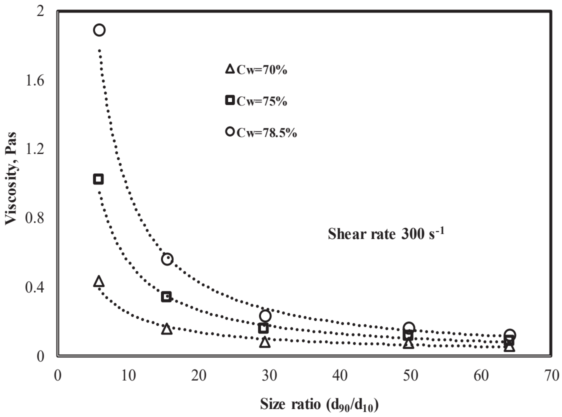

Fig. 2(a) Effect of size ratio (λ) on viscosity for the five limestone samples

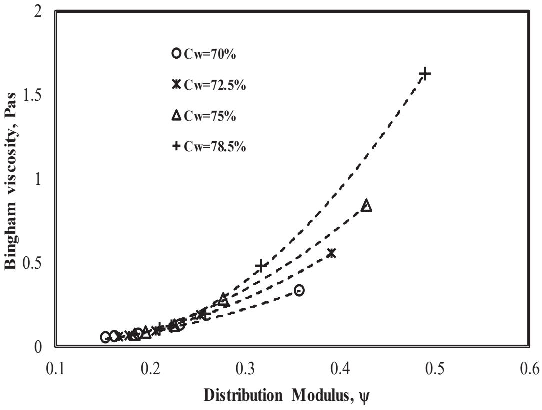

Fig. 2(b) Experimental values of Bingham Viscosity vs. distribution modulus (ψ) at different C_W

4. CONCLUSIONS

The study indicates that it is quite feasible to prepare high concentration limestone slurry by manipulating the particle size distribution through blending the fine with coarse fractions in a fixed mass ratio. The flow behaviour of the concentrated limestone slurry could be characterized by Bingham plastic model. The maximum amount of reduction in viscosity and yield stress values obtained in respect of sample S-4 could be explained by correlating the viscosity to particle size ratio (λ) and volume fraction of solids. The sample S-4 with distribution modulus (ψ) value of around 0.21 indicated near minimum viscosity and maximum packing density, which was in reasonable agreement with the theoretical prediction of Farris. The results thus illustrates that the magnitude of viscosity reduction and maximum solids concentration could be achieved by controlling the diameter ratio and composition of fine to coarse limestone particles. This will be quite beneficial for efficient and economic pipeline transport of high concentration limestone slurry by lowering the pumping costs and energy.

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