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Rheology of Slurry: A Review

Sai Swapnesh Mishra[1], Ashish Kumar Parida[2], Anurag Das[3], Shrutam Saha[4], Tushar Kumar[5]
[1]*JSW Steel Ltd., Barbil, Odisha, India*
[2, 3, 4, 5]*Department of Mechanical Engineering, Institute of Technical Education & Research, S'O'A Deemed To Be University, Bhubaneswar, Odisha-751030, India*

Abstract: In this paper, the rheological parameters, characterisation, and the rheological behaviour of mineral ore slurry are reviewed and discussed in detail. Rheology is a study of flow phenomenon of matter, parameters like viscosity and the relationship between stress, strain, and time for the matter are helpful in defining rheology, these parameters have helped in classification of fluids into two broad categories - Newtonian and Non-Newtonian fluids. The rheological characteristics have a great impact in design and operation of the pipelines. This paper has a special emphasis on the iron ore slurry and its rheological behaviors which are highly affected by several physical and chemical properties (particle shape, particle size distribution, shear rate, pH value, solid concentration, viscosity, and slurry temperature) which also have been explained in particulars. The importance of rheology in slurry transportation makes it really important to define ways for controlling rheology that have proven to be helpful in stabilizing the slurry thus making the operation more efficient. Rheology is a major factor that affects the process of pipeline transportation of slurry which makes it such an important topic of study and research.
Keywords: Rheology, Viscosity, Iron-ore slurry, Newtonian & Non-Newtonian fluids

I. INTRODUCTION

Rheology is a rather young branch of science, that came into repute only after the conclusion of World War - II. Yet, in a sense, it is also considered as a really old branch of science, with roots in olden times. Greek philosopher Heraclitus and the Jewish prophetess Deborah Notable are amongst those who have (inadvertently) popularized a number of concepts which are now recognized as "rheological". Various crucial rheological postulations were studied through the centuries and long before the conventional introduction of the term rheology in 1929. This coincided with the founding of the American Society of Rheology in Washington DC and the formal definition of rheology is invariably associated with Professor Eugene Bingham, department of chemistry, Lafayette College, Easton, Pennsylvania. Professor Bingham, G. W. Scott Blair and Marcus Reiner of Israel of the U.K were the three organizers of the meeting held in 1929 C.E. An appropriate description of rheology, which is generally acknowledged, is: "The science of the deformation and flow of matter" [1].

Rheology is defined as the science of deformation and its root lies in the Greek word for flow. The term 'Rheology' was coined by Eugene Bingham who also founded the society of rheology in the USA.

Rheological categorization and sorting of materials give an all-inclusive idea about the viscoelastic flow behavior of system. Rheology is paramount to every material because the rheological feedbacks are closely related to the final designing and modeling of systems. Now, rheology is an effective tool which has been in use for years now, to link physical properties of the concerned material with its various other properties.

Using accustomed and standard rheometric procedures, various other behaviors like yield stress, flow profiles and fractural behaviors can be easily regulated, and the slurry transportation process can be enhanced [2,3].

Slurry is a suspension of solid particles in a carrier liquid and transportation of these raw materials in the form of slurry through pipelines is an environment friendly method. When raw materials are suspended in water, it is a hydraulic transport or conveying [4]. Nowadays slurry transportation is widely used all over the world due to its benefits over other means of transport and for designing an accurate and well-organized slurry pipeline we must have a great understanding of the Rheology of slurries which is used to describe the fluid flow properties. While developing a slurry pipeline system, compiling good rheological data is crucial as it will help largely in choosing pipes and pumps for the pipeline, and as a result, it's a contributing element in failure or success of a project. Rheological studies help in determining shear stress, shear strain and yield stress which are further used in knowing the viscosity, design velocity and as a result of which rheology ultimately tells us about best pumping conditions for transportation of slurry [5,6].The transportation of slurry is defined by its rheology. This paper primarily focuses on rheological properties, characteristics, and behavior of slurry systems and also the industrial applications related to iron ore slurry [47,49].

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II. BASICS OF RHEOLOGY

Rheology is defined as the study of flow phenomena of matter in response to applied forces and stresses. It can also be defined as the science of deformation and flow phenomena. The flow process can be described via parameters like viscosity and the relationship between stress, strain, and time for the matter [47].

A. *Rheological Parameters*

1) *Viscosity (η):* Viscosity of a fluid is defined as the estimate of its resistance to flow. It occurs when one layer of fluid is caused to move with respect to another layer of the same fluid. The S.I unit of viscosity is Pascal seconds (Pa.s) or $kg.m^{-1}.s^{-1}$ [7] .Change in temperature causes change in viscosity but it does not change considerably when there is a difference in pressure. In the case of a liquid, an increase in temperature causes the viscosity to decrease because of the rise in the molecular spacing but whereas in terms of gases viscosity increases with the rise in temperature [8].

$$\text{Viscosity } (\eta) = \frac{Shear\ Stress}{Rate\ of\ Shear\ Strain}$$

2) *Shear Stress (σ):* The force per unit area which acts coplanar to the infinitesimal small element/part of the fluid to cause shearing action is called shear stress. The S.I unit of shear stress is N/m^2. The following equation is used to calculate shear stress [4,7]:

$$\text{Shear Stress } (\sigma) = \frac{Force\ (F)\ (in\ N)}{Surface\ area\ (A)\ (in\ m^2)}$$

3) *Shear Strain (ϒ):* It is defined as a tangent of the change in angle that occurs between two-line segments which were mutually perpendicular to each other initially. It is denoted by gamma and measured in radiance. It is a dimensionless quantity [7,9].

$$\text{Shear Strain } (\Upsilon) = \frac{\text{Change in length } (\Delta X)\text{ (in m)}}{\text{Original Length (X) (in m)}}$$

4) *Shear Rate ($\mathring{y}$):* Velocity gradient $\frac{dv}{ds}$ are defined as the speed at which the intermediate layers of a fluid move relatively to one another. This causes a shearing effect in the liquid and thus is defined as shear rate. The S.I unit of shear rate is reciprocal of second (s^{-1}) [7].

$$\text{Shear Rate } (\mathring{y}) = \frac{\text{Change in strain } (d\Upsilon)\text{ (unitless)}}{\text{Change in Time (dt) (in seconds)}}$$

B. *Characterization On The Basis Of Rheological Parameters*

According to scientific data and observations, a fluid provides more resistance when it is thick/thickened, and it has a lower resistance to flow if it is thinner. Viscosity, as mentioned earlier, is defined as the property of a fluid to resist its flow and based on the formula of viscosity, fluids are categorized into two types: (i) Newtonian fluids, in which η (Viscosity) is constant, and (ii) Non-Newtonian fluids, in which η (Viscosity) is variable.

1) *Newtonian Fluid:* These are the type of fluids which exhibit constant viscosity for a comprehensive range of shear rates and at a constant temperature and pressure [4]. They have a zero-shear rate at zero shear stress thus having a linear relationship between shear stress and shear rate. These fluids obey Newton's law of viscosity [7, 8].

$$\tau = \mu \frac{dv}{dy}$$

where, μ = Viscosity, τ = Shear stress (F/A), and $\frac{dv}{dy}$ = Rate of shear deformation

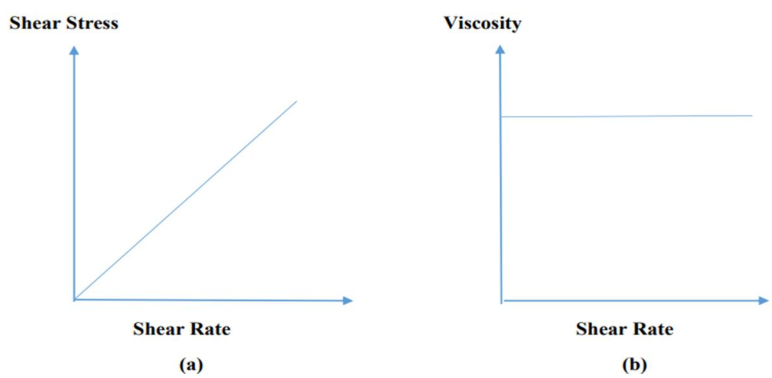

Fig. 1 –Rheogram for flow of (a) shear stress vs shear rate, and (b) viscosity vs shear rate [4].

2) *Non-Newtonian Fluids:* These are the type of fluids that don't follow Newton's law of viscosity and their viscosity does not remain constant as it changes according to the force applied. The various non-Newtonian fluids are Bingham plastics, dilatants, pseudoplastics and yield pseudoplastics [9,10].

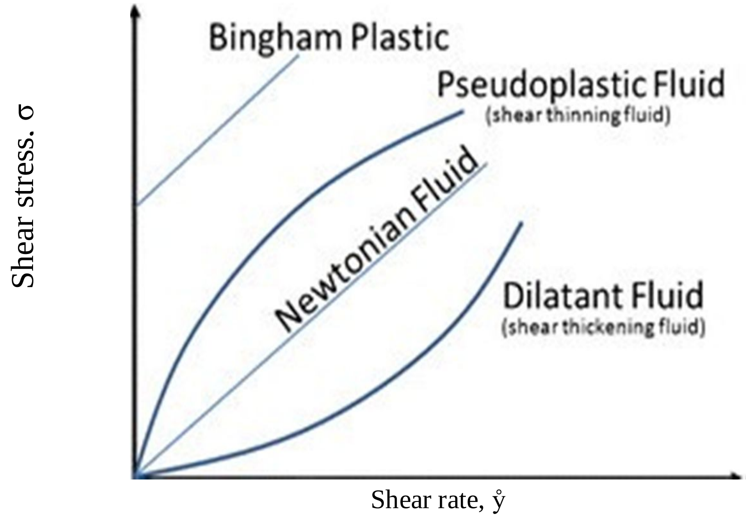

Fig. 2 - Flow behavior outline of non-Newtonian Fluids (Shear Stress vs Shear Rate) [14]

C. *Types Of Flow*

Flow regimes can be categorized into three distinct types, namely, laminar, turbulent, and transitional flow. Reynolds number is used to determine if the concerned fluid flow falls into either of the aforementioned categories, to determine if the fluid flow is laminar, transitional, or turbulent. The flow is said to be: Laminar, if Reynolds number is less than 2300 (i.e., if Re<2300);Transitional, if Reynolds number lies in the range 2300–4000 (i.e., if 2300< Re <4000);or, Turbulent, if Reynolds number is greater than 4000 (i.e., if Re>4000).

1) *Laminar Flow:* It is a type of flow in which the motion of the fluid particles is smooth and orderly, the particles are in a well-ordered arrangement and the fluid moves in infinitesimal parallel layers with no disorganization between them. Properties like pressure and velocity remain constant at every point [10, 11,12]

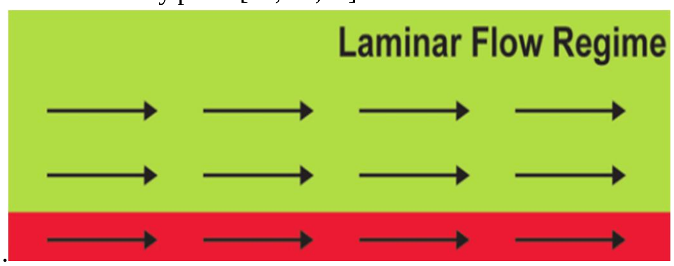

Fig. 3 - Laminar Flow [12]

2) *Turbulent Flow:* Turbulent flow is the type of flow in which the motion of the fluid is irregular, and the magnitude and the direction of velocity is inconsistent at any given point, therefore the flow speed of the fluid keeps changing constantly. Blood flow in arteries and flow of wind and water in river are the common examples of turbulent flow [10, 11,12].

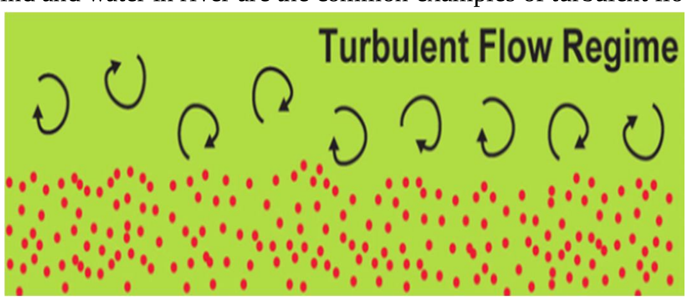

Fig. 4 - Turbulent flow [12]

3) *Transitional Flow:* Transitional flow is the fusion between laminar and the turbulent flow and it is an arduous task to recognize this type of flow. Transition region is used to determine the conditions of the flow of the fluid when it changes from laminar to turbulent[4,12,13,14].

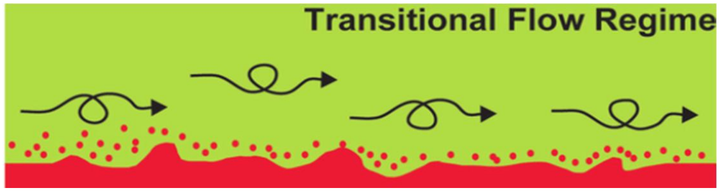

Fig. 5 – Transitional flow [12]

All fluids could be categorized into 2 fundamental types, namely, Newtonian fluids, and non-Newtonian fluids on the basis of change in viscosity with applied shear stress. A flow can either be laminar, turbulent, or transitional depending on its nature and Reynolds number is used to classify and determine the type of flow. These parameters help us to understand the rheology and flow pattern in a more effective and efficient way [45].

III. RHEOLOGICAL CHARACTERISTICS

While numerous important factors are considered while designing a pipeline, characteristics of the slurry have the most influence on its design and operation. The ore with a density higher than that of water is kept in a suspension mode for transportation. Thenceforth, all the parameters have to be kept in check for free flow of the stream without any impediments.

A. Rheological Characteristics Of Minerals

Minerals have several rheological characteristics which affect the rheology and hence the flow of the slurry. These points are kept in mind while designing pipelines. Several research activities have been carried out to determine the effect of these by research persons from all around the globe. Some of their findings are listed in the table below.

Table 1 – Literature review of rheological characteristics of minerals.

Serial Number	Name of the Author	Rheological characteristics	Research Fields, Activities and Findings
1.	(i) Zengeni B.T etal. [7] (ii) KongasM. et al [15].	Particle size distribution	The particle size evaluation of mineral slurries is crucial due to the probable impact of particle size allocation on various downstream processes.It is an attempt to emphasize the relative properties ofthe varying particle sizes the concerned sample comprises of.
2.	Abro M. I et.al.[17]	Slurry pH and temperature	The pH testing method is used to determine the acidity or basicity of the aqueous slurry. Change in pH causes a change in viscosity. With rise in pH value the percentage entrapment of fine particles decreases, and the settling rate escalates. Temperature plays crucial role as viscosity was noticed to reduce with a rise in temperature until a certain point after which it tends to increase.
3	Zengeni B.T etal. [7]	Particle micrographs	A tiny total of the specimen was sprinkled on to aluminum remnant overlaid with carbon glue. It was then covered with a carbon film in the evaporation coater. It was then placed into the electron micrograph and was observed at various magnifications. This whole process was carried out to demonstrate the variance in shape of the particles.

4	Zengeni B.T etal. [7]	Solid density and slurry mixture density measurements	Solid density is calculated using a helium gas pycnometer. Helium gas pycnometer is used to compute solid density of particles. The slurry mixture density was estimated with the help of a 250 ml volumetric flask. Density of the water was taken as 1000kg/m^3. The following equation is used to determine mixture density of the specimens. $\rho_{m} = \frac{M_{slurry}}{250-(M_{water}/\rho_W)}$
5	Zengeni B.T etal. [7]	Mass solid concentration	The mass solid concentration (C_{m}) of the slurries is calculated using the oven drying method. The following equation is used to determine mass solid concentration: $C_m = \frac{M_s}{M_m}$ Where, M_s= mass of solids, and M_m=mass of the mixture
6	Zengeni B.T etal.[7]	Volumetric solid concentration	The volumetric solid concentration (C_v) is the function of mixture density (ρ_m), mass solid concentration (C_m)and solid density(ρ_s). It is calculated using the following equation:$C_v = \frac{\rho_m}{\rho_s} \times C_m$
7	Matoušek V. etal.[18]	Freely settled bed packing concentration	The freely settled bed packing concentration by volume is determined by a familiar volume of solids that form the freely settled bed. Then the volume of the freely settled bed is calculated subsequently. It is carried out by allowing the slurry to settle down which comprises of dried and pre-weighed solids. The following equation is used to calculate the freely settled bed concentration ($C_{b,free}$): $C_{bfree} = \frac{(Volume\ of\ solids)}{(Volume\ of\ freely\ settled_{bed})}$
8	Assefa K. M etal. [19]	Chemical additives	Chemical additives can be categorized as dispersants, flocculants, surfactants, and anti- settling agents on the basis of their functionalities. They can enrich and amplify the fluidity of slurries.

B. Rheological Characteristics Of Pipeline

1) *Slope And Elevation Of Pipe:* Kesely etal.have discussed in their paper that the slope and elevation of the pipeline are influenced according to the measurement and proportions of the particles. More often than not, a high solid concentration and an ascending slope are used to convey the finer particles for even flow through the pipelines [20].
2) *Thickness Of Pipe:* Miguez etal. reviewedthat while constructing a pipeline, factors like concentration of solids, solid distribution, flow velocity, and cost are taken into consideration. Hence, the thickness and diameter of the pipe are selected accordingly [21].
3) *Corrosion And Erosion Of Pipe*: Javaheri etal. talked through about the effects of corrosion and erosion on pipelines. Slurry velocity and particle size affect the corrosion and erosion in the pipeline to a great extent. Corrosion and erosion rate are also taken into consideration while designing the thickness of the pipeline. Chemicals are added accordingly to regulate the pH of the slurry [22].

Table 2 – Some of the chemical additives and their functions on the iron ore slurries [19].

Name of the chemicals	Functions/effects	Parental solids
Tapioca, Potato and corn starch, Sodium silicate & SHMP [23]	Flocculants, Dispersants	Iron ore tailings
Magnafloc and Rishfloc; Sodium petroleum and CTAB [24]	Flocculants; Surfactants	Iron ore fines
Calcium lignosulphonate [25]	Surfactants	Ferrosilicon and magnetite
Magnafloc-1011-anionic and Magnafloc – 333- non-ionic [26]	Flocculants	Iron ore tailings
Limestone [27]	Increased reducibility	Acid iron ore pellets

C. *Factors Affecting Rheology*

1) *Size And Shape:* Kawatra etal. and Eisele etal. noticed that at a given concentration of solids, depletion inthe size of the particles will lead to an increase slurry viscosity. Furthermore, density of slurry rises, with a descension in particle size, for a constant volume of slurry. In addition to that, the settling velocity of the coarse particle is higher than that of the fine particles [28].

Table 3 Solids density of typical minerals [29]

Minerals	Solid density (g/cm^3)*	Largest particle Diameter (microns)**
Iron concentrate	4.9	149
Copper concentrate	4.1	212
Zinc concentrate	4.0	212
Phosphate concentrate	3.2	212
Bauxite concentrate	2.6	297
Kaolin concentrate	2.6	297
Coal	1.4	1190

* Typical densities

** Typical, but can vary depending on specific circumstances and pipeline length

2) *Concentration Of Solid:* Mangesana etal. discussed that the viscosity of a suspension increases with increase in solids concentration. Solid concentration depends on the size of the solid and viscosity of the slurry. Moreover, maximum concentration at which the viscosity of the slurry increases sharply after increasing a small concentration of the solid is defined as the optimal solid concentration [30].
3) *Viscosity Of Slurry:* Sahoo et al. investigated on the basis of the ANOVA results procured, solid concentrations, particle diameter, microwave exposure time and shear rate were discovered to have notable effects on the apparent viscosity of iron ore-water slurry, with shear rate striking the most substantial effect on apparent viscosity of iron ore-water slurry, while on the contrary, solid concentration had the least effect on the response [31].
4) *Slurry Flow Rate:* Silva et al. discussed that the slurry flow rate is dependent on the solid concentration and particle size distribution. The slurry velocity varies from 1.60 m/s to 1.86 m/s depending on the size of the particles and the flow rate can vary between 1,826 m^3/h and 2,105 m^3/h to minimize the solid particle bed deposition, which reduces the overall efficiency of the pipeline [32].

There is no standard accessible technique that is referred to while designing slurry pipelines, each slurry and circumstance is distinct and discrete. So consequently, nearly all the data available for the design aspect is centered on experience.

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IV. RHEOLOGICAL BEHAVIOR OF IRON-ORE SLURRY

Iron ore slurry being a solid liquid mixture undergoes plastic deformation when subjected to stress. Investigation and study of rheological characteristics has been a topic of interest since years due to its industrial applications. Study of the rheology of the iron ore suspension is highly complicated and no single parameter can solely explain it. Physical and chemical properties like solid concentration, particle size distribution, particle shape, pH value, shear rate, viscosity, and slurry temperature highly affect the rheology of iron ore slurry [23,58].

A. Effect Of Solid Concentration On Apparent Viscosity

Senapati et al. [27] investigated the non-Newtonian flow characteristics of the iron ore slurry and concluded the Bingham plastic flow behavior from the rheogramτ (shear stress (Pa)) – $\dot{\gamma}$ (shear rate (s^{-1})) plotted in Figure 3 with observation that the increase in mass concentration, shear stress values increase. At low concentrations of the iron ore, the flow pattern may be Newtonian with viscosity η independent of the shear rate. With gradual increase in concentration, it advances to acquire non-Newtonian properties with a steeply increasing viscosity as the shear rate decreases (Fig. 2) [8, 34,37].

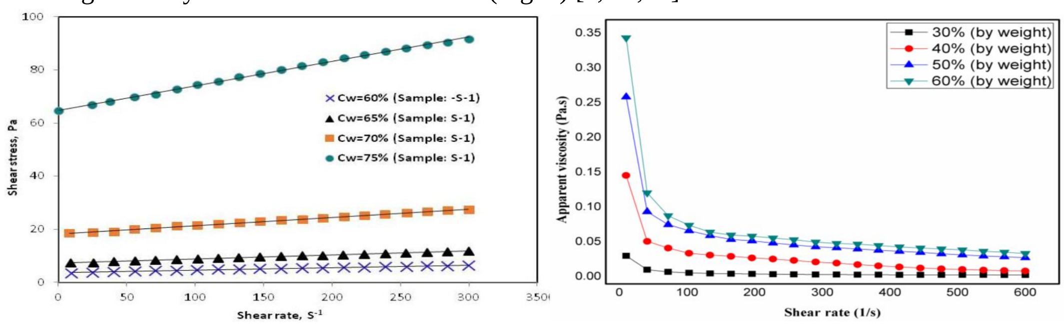

Figure 6 – (a) Rheogram of iron ore at different solid concentrations by mass, (b) Variation of apparent viscosity with shear rate at different solid [33].

B. Effect Of Particle Size And Particle Size Distribution

Senapati et al. [34] conducted a series of experiments blending fine particles in coarser slurry suspensions of iron ore in fixed blend ratio of 4:1 thereby attaining a bidisperse suspension. The size ratio (λ) that is the ratio of larger diameter to smaller particles given by, $\lambda = \frac{d_{large}}{d_{small}}$ highly affects the the viscosity of the slurry. So the apparent viscosity increases with the decrease in size ratio for thethree particle size distribution depicted by Figure 4(a). Bingham yeild stress rapidly increases beyond a slurry concentration with unimodal particle size distribution while with bimodal and multimodal particle size distribution lesser yield stress is indicated. A high solid concentration with small inter-particle distance generates a high attractive force and a specific shear force is required to break apart incoherent flocs and overcome internal friction between fine particles to intiate flow [35,36]. It is hence observed that the bimodal and multimodal particle distribution of iron ore influence the apparent viscosity than the unimodal distribution from the Figure 4(b) [34,37,50].

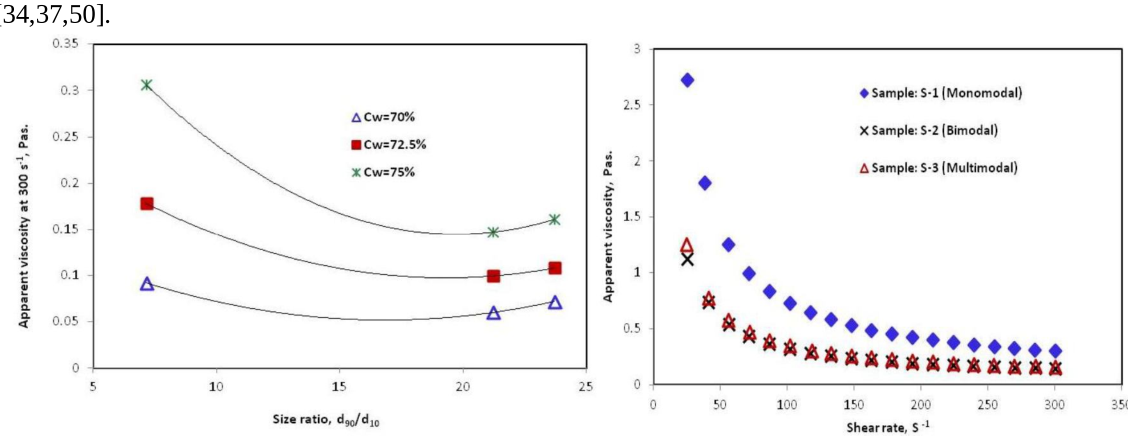

Figure 7 – (a) Effect of size ratio (λ) on the apparent viscosity for the three iron ore particle distributions, and (b) Effect of particle size distribution on apparent viscosity of iron ore slurry at high solid concentration [34].

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C. Effect Of Temperature On Iron Ore Slurry

Temperature is one the major factors that has a strong effect on yield stress and apparent viscosity of the slurry. Peforming rheology experiments Kumar et al. [33] noticed the reduction in the apparent viscosity with the rise in temperature.The increase in temperature of the iron ore suspensions results in the increase in the kinetic energy of the slurry particles and reduces the intermolecular forces within the layers of the fluid and thereby leads to the decrease in viscosity. Temperature highly affects the yield stress of the slurry as well as its apparent viscosity because of the variation in viscosity of the carrier fluid. In lower temperature ranges the yield stress is decreased with increasing temperature and at higher temperatures an increase in yield stress is observed. It is quite evident from Figure 5 [33], the yield stresss and viscosity dependancy on temperature that is necessary for evaluating the slurry rheology [8,50,51,55].

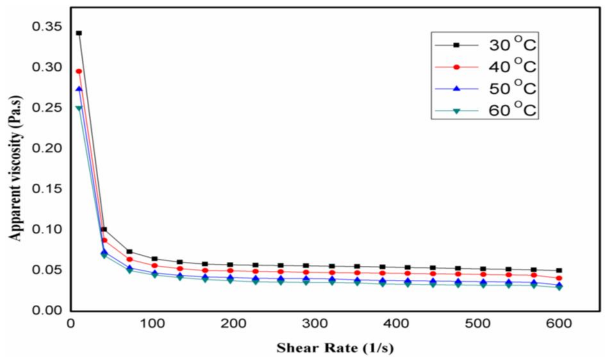

Figure 8 - Effect of temperature on apparent viscosity of iron ore slurry [23].

D. Effects Of Chemical Additives On Rheological Properties Of Highly Concentrated Iron Ore Slurry

At an experiment conducted by Senapati et al. [34] it is observed that some selective additives can influence the flow behaviour and acts as a stabilising agent of iron ore slurry. The fundamental role of chemical dispersants is to decrease or completely terminate the yield stress of slurry. Aqueous suspension of mineral ores has inter-particle forces which consists of van der Waals forces and electrostatic forces, use of a potent additive can alter the surface charge of the slurry thus making the inter-particle forces completely repulsive which results in reduction of yield stress and stabilization the slurry.Having an elementary knowledge about the effects and side effects of an additive on highly concentrated iron ore slurry is really important for selection of a suitable additive[8]. The prominent additives selected for stabilization of iron ore slurry are hydrated lime, quick lime, Acti-Gel and Sodium Hexametaphosphate (SHMP).

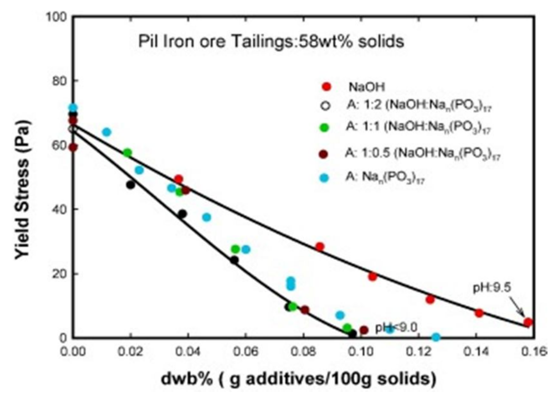

Figure 9 - Effect of chemical additives on yield stress of iron ore slurry [59]

Quick lime (CaO) and hydrated lime (CaOH) both used as flocculants and can also be frequently mixed with iron ore mixture to enhance the output. Sodium Hexametaphosphate (SHMP) is generally used as a deflocculant agent; it reduces the particle-particle interactions which prevents aggregations of particles and thus successfully reducing the yield stress of the iron ore slurry. Acti-Gel which is highly purified Magnesium Alumino-Silicate according to the Active Minerals International LLC website is used for water based industrial application, with a pH between 2 and 13. The Acti-gel being chemically inert acts as a rheology modifier and anti-settling agent that yields a higher quality particle suspension, boosts the workableness, slurry performance and flowability by stabilizing the mixture, [38,55].

E. Effects Of Velocity Of Iron Ore Slurry

For iron ore slurries where the solid particles are not properly suspended in the carrying liquid determining the operating velocity is important. Operating velocity of the iron ore slurry should not be too high or low as it can have a negative impact on the slurry transportation. It is important to determine the operating velocity that is higher than the superficial velocity to avoid settling and sedimentation of solid particles thus preventing blockage of pipeline, but the determined velocity should not be much above the superficial velocity as that leads to extreme wear and tear of the pipeline and pumps. For the iron ore slurry, the operating velocity is normally kept around 1.7m/s [37,39].

The present study shows the influence of solid concentration, particle size distribution, surface characteristics, additives, and temperature on the rheological behavior of iron-ore slurry. The non-Newtonian flow behavior of the solid-liquid suspension integrates quite well with the Bingham plastic model. The specific multimodal iron ore samples with a broad size distribution indicates a considerable reduction in slurry viscosity, yield stress and improved solid loading compared to monomodal ones. Recently, it was found that microwave pre-treatment of iron ore reduces the slurry viscosity and yield stress exhibiting shear-thinning or pseudo-plastic behavior. The viscosity and density of microwave treated ore is always lower than that of untreated [31,37,52].

V. METHODS TO CONTROL RHEOLOGY

Pipelines have been the major conveyance to transport solids on large scale than the conventional modes of transportation since the last decades. Pipelines are used for long distance transportation of different solid materials such as coal, fly ash, limestone, zinc tailings, rock phosphate Gilsonite, copper concentrate and iron concentrate. Rheology control is of paramount importance for designing the slurry pipeline system. Rheology of slurry is controlled by mechanical means that includes maintenance of high-pressure gradient and ultra-sonication, adding chemical additives or Nano-stabilizers. [5,53]

A. Mechanical Methods For Controlling Rheology

After conducting a large number of experiments scientists have discovered some mechanical methods for controlling rheology. Maintaining high pressure gradient and ultra-sonication are one the best mechanical methods for rheology control.

(i)Maintenance of high-pressure gradient –Gillies et al. [40] predicted the pressure drop in slurry pipelines and his Saskatchewan Research Council (SRC) two-layer model predicts that the pressure gradient and deposition velocity as a function of the particle diameter, pipe diameter, particle concentration and the mixture velocity based on his experimental correlations [49]. The pressure gradient ($^{\Delta P}/_{L}$), where ΔP is the pressure drop for pipeline flow of solid-liquid suspension and L is the length of the pipe - of the solid–liquid slurry is generally higher than that of an equal flow rate of pure liquid because the particles produce additional dissipation. The pressure gradient has its dependency on the four distinct flow regimes of particle conveyance as per the experiments carried out by Newitt et al. [41] and Durand [42] predicting the critical deposition velocity of slurry.

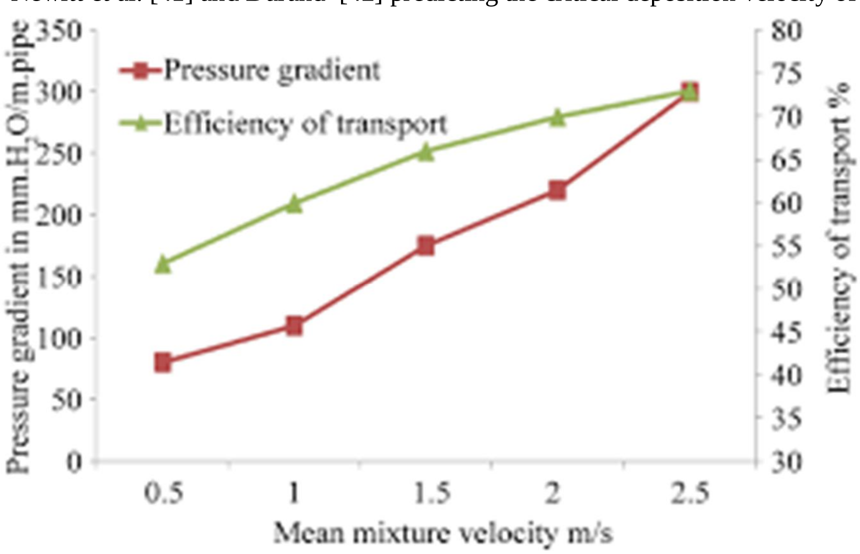

Figure 10 – Variation of slurry performance characteristics for slurry of iron oxide with solid concentration 1% by volume and particle diameter d_s = 1 mm. versus mean mixture velocity.[44]

The pressure gradient variation is shown as the non-dimensional variable expresses the pressure drop divided by the mixture weight [43]:

$$j_m = dP/(dx\, \rho_m\, g)$$

where, j_m is the pressure gradient in height of mixture / length of pipe, dx is the differential axial distance, ρ_m is the mean density and g is the specific gravity of the mixture. Hence, Aziz et al. [44] concluded that the increase in the input concentration and specific gravity leads to the increase in pressure gradient and as the mixture velocity increases, the efficiency of the transport increases [37,57].

(ii)Ultrasonic Treatment – Ultrasonic treatment in solid-liquid system is an economic approach that is capable of producing a high transient temperature and pressure at the place of its application. Li et al. [45] studied the ultrasonic irradiation on coal water slurry that effectively improved the static stability of the slurry. It favors the pseudo plastic flow of the non-Newtonian fluid and decreases the apparent viscosity with increasing shear rate. For a sufficient period of treatment promotes a sharp decrease in apparent viscosity and highly improves the static stability [36,46].

B. Chemical Means For Controlling Rheology

Addition of chemical additives, viscosity modifiers and Nano stabilizers are some well-known methods that can be used to control slurry rheology by chemical means.

1) *Addition Of Chemical Additives:* The fundamental role of chemical dispersants is to decrease or completely terminate the yield stress of slurry. Aqueous suspension of mineral ores has interparticle forces which consists of van der Waals forces and electrostatic forces, the use of a potent additives can alter the surface nature of the slurry thus making the interparticle forces completely repulsive which results in reduction of yield stress thus the slurry rheology is improved[8]. Most of the potent additives are water soluble polymers with low molecular weights along with other prominent additives such as lime, sodium silicate, sodium Hexametaphosphate (SHMP), sodium phosphate, NaOH or KOH, etc. [38]. Determining a proper dosage of a potent chemical additives is important as an insufficient amount will lead to flocculation which will increase the viscosity of slurry and an excessive amount can cause slurry destabilization [8].
2) *Addition Of Viscosity Modifiers:* This method is used for decreasing viscosity of the mineral ore slurries by the addition of a viscosity modification agents. The viscosity of highly concentrated mineral ore slurry is often troublesome in operations involving transportation, pumping and agitation. In an experiment conducted by Perez et al. [47] it was observed that the mineral ores are primarily, made of gangue or the waste particles, they are the largest component of the mineral ore slurry therefore the selection of favourable viscosity modification agents can be based upon the type of gangue particles present in the mineral ore.

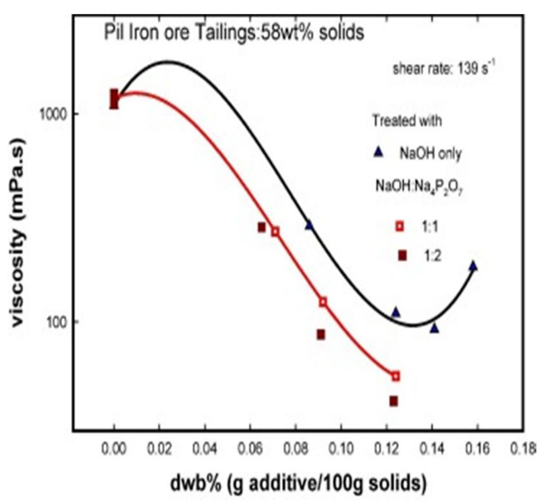

Figure 11- Effect of Viscosity modifiers on apparent viscosity of iron ore slurry.[59]

Viscosity modifiers are anionic surfactants mostly sodium salts of inorganic and organic sulphonates the addition of one or more viscosity modifiers in an effective amount can decrease the viscosity thus reducing the cost and problems related to transport pumping and agitation thus improving the slurry rheology [47].

C. Adding Nano-Stabilizers To Control The Rheology Of The Slurry

Nano stabilizers have gain importance as a rheology controlling agent in recent times. Addition of nano-stabilisers to the iron ore slurry increases the stability of the slurry and efficiency of the operation. Stabilisation of slurry will make it easy to transport it to longer distances with greater ease [48]. Discoveries of the mechanical and chemical methods for controlling and manipulating the rheology of slurry has made transportation through slurry pipelines easier over the years. Research is going on to find ways to make these methods more efficient. As chemical dispersants have a great effect on the slurry rheology, research is going as we need a bit more understanding on the effect of molecular weight of the dispersants and the methods for determining the proper dosages of potent dispersants also need refinement [36].

VI. CONCLUSION

The slurry flow mannerism is governed by its rheology, which elucidates its deformation and flow behavior. Rheology is also authoritative to fluids with complex microstructures that are used in various other industries. Numerous factors such as solid concentration, slurry viscosity, slurry flow rate etc. condition of the rheology of the slurry. The most crucial rheological characteristic is the slurry viscosity and fluids may further be categorized into two categories namely, Newtonian fluids, and non-Newtonian fluids, in accordance with it. Rheology has a pivotal role in the designing and construction aspect of pipeline and cost optimization is a top priority in the course of construction and manufacturing. Alterations involving length and inclination of the pipe can be carried out to curtail pressure losses. Petroleum coke oil slurry was made to undergo ultrasonic treatment to evaluate its effects. Experiments are being carried out by taking two petroleum cokes and mixed with paraffin to prepare the slurry fuel, and then investigations are also being carried to study the effect of ultrasonic treatment on slurry, where the results showed that the petroleum coke oil slurry fuel not only decreased the viscosity but also aided their static stability. Similarly, several other research activities, investigations, and projects on the rheology of slurry are currently in process to make the slurry transportation process through pipelines more effective and efficient. Slurry transportation through pipelines is an emerging sector, and as mentioned earlier in this paper, almost all data available for design and construction through pipelines is experience based, so research work in more depth on rheology must be carried out to enhance the transportation system [51]. Nevertheless, lots of scope for further research in the field of rheology still remains with the ever-growing need to investigate and to have appropriate relations between the rheology and mineralogy of iron-ore slurry.

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