

STUDY OF RHEOLOGICAL BEHAVIOR OF BOTTOM ASH WITH ADDITIVES

*Thesis submitted in partial fulfillment of the requirements
for the award of degree of*

Master of Engineering

In

CAD/CAM & Robotics

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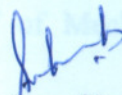
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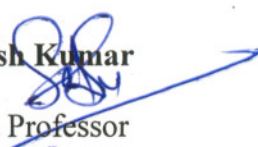
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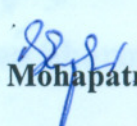
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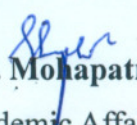
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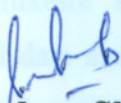
ACKNOWLEDGEMENT

I am highly grateful to the authorities of Thapar University, Patiala for providing this opportunity to carry out the research/Theses work.

I would like to express a deep sense of gratitude and thank profusely my thesis guide **Mr. Satish kumar**, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala and **Dr. S.K. Mohapatra**, Senior Professor, Mechanical Engineering Department, Thapar University, Patiala for their sincere & invaluable guidance, suggestions and attitude which inspired me to submit report in the present form.

I am also thankful to other faculty members and all the workshop staff of Mechanical Department, Thapar University, Patiala for their support.

My special thanks are due to my family members and friends who constantly encouraged me to complete this study.


Sandeep Sharma

ABSTRACT

Slurry pipelines are used to transport solid materials using water or any other liquid as a carrier fluid for short or long distance haulage of bulk materials. These pipelines are used in many industrial applications involving transportation of variety of materials like mineral ores to processing plants, coal to thermal power plants, disposal of waste materials like fly ash, tailings materials etc. Slurry pipeline has been accepted as a safe, reliable and attractive mode of solid transportation by various industries, due to its low maintenance, round the year availability and being eco-friendly. One of the most important input data needed for the design of the slurry transportation system is the rheological behavior of the slurry at various concentrations and flow conditions. The rheological properties of slurries must be determined as accurately as possible under conditions that closely resemble actual site conditions rheological behaviors.. In the present study reports the effect of additive rheological characteristic of bottom ash slurry at high concentration for bottom ash with or without additive . Sodium bi carbonate has been used as additive. Rheological study are also carried out with bottom ash and fly ash mixture slurry at different concentration A good agreement is observed between experimental data and model (prediction). The plots reveal that the viscosity of the suspension increases with increasing solid concentrated Rheological behavior with addition of fly ash and additive observe that viscosity value decreases. The study indicated that the viscosity is very much sensitive to the concentration of solids..

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NOMENCLATURE AND ABBREVIATIONS

H	Total head developed by the pump (meter of water column, or mwc)
P_a	Atmospheric pressure (Pa)
P_d	Delivery pressure (Pa)
P_s	Suction pressure (Pa)
g	Gravitational acceleration (m/s^2)
Z_s	Suction datum head (mwc)
Z_d	Delivery datum head (mwc)
V_d	Delivery pipe velocity in m/s
V_s	Suction pipe velocity in m/s
C_w	Weight concentration of solids (%)
N	Revolution per minute (r/min)
Q	Flow rate (m^3/s)
S	specific gravity
u	Impeller peripheral velocity (m/s)
ρ_l	Mass density of the carrier fluid (kg/m^3)
ρ_m	Mass density of the mixtures (kg/m^3)
ρ_s	Mass density of the solid particles (kg/m^3)
sH	Specific head
sQ	specific discharge
sP	specific power
D	Diameter of impeller (m)
\vec{v}_r	Relative velocity (the velocity viewed from the rotating frame)(m/s)
$\overline{\omega}$	Angular velocity of the rotating frame (m/s)
\vec{v}	Absolute velocity of stationary frame (m/s)
\vec{r}	Position vector in the rotating frame (m)
$\overline{\tau}$	Stress tensor
\vec{F}	Body force (N)

CHAPTER 1

INTRODUCTION

Rheology is the study of deformation and the flow of matter under the action of forces. The word rheology comes from rheo from the Greek word for flow and ology meaning study of. Scientists who study the mathematical relationships that describe the behavior of fluids are called rheologists. The rheological properties are heavily dependent on the solids concentration of the slurry

1.1 VISCOSITY:

Molecules of fluids exert forces of attraction on each other. In liquids this is strong enough to keep the mass together but not strong enough to keep it rigid. In gases these forces are very weak and cannot hold the mass together. When a fluid flows over a surface, the layer next to the surface may become attached to it (it wets the surface). The layers of fluid above the surface are moving so there must be shearing taking place between the layers of the fluid.

1.2 TYPE OF VISCOSITY:

1.2.1 Shear Viscosity

The measure of the internal friction of a fluid. This friction becomes apparent when a layer of fluid is made to move relatively to another layer. Friction the greater the amount of force required to cause this movement which is called shear. The greater the amount of force required to cause this movement which is called shear.

Shearing occurs whenever the fluid is physically moved by pouring, spreading, spraying, mixing, etc. High viscous liquids require more force to move than less viscous liquids .mixing etc. High viscous liquids require more force to move than less viscous liquids (McCabe et al, 2001) mixing etc. High viscous liquids require more force to move than less viscous liquids speed through the liquid, or the velocity gradient.

If we have two parallel planes of fluid of equal area A and they are separated by a distance dx and are moving in the same direction at different velocities v_1 and v_2 .

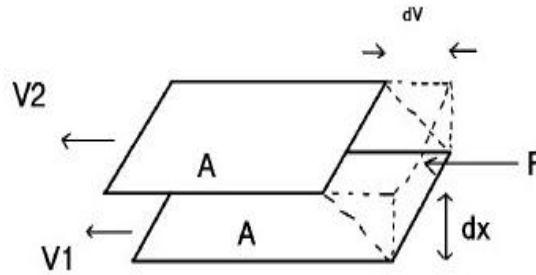


Figure.1.1 sliding of two plates over each other

1.2.2 Shear Rate

The velocity gradient, dv/dx , is a measure of the speed at which the intermediate layers move with respect to each other. It describes the shearing the liquid experiences and is called shear rate – R and its unit of measure is called reciprocal second (sec^{-1}).

1.2.3 Shear Stress

The term F/A indicates the force per unit area required to produce the shearing action and it is called shear stress – S and its unit is N/m^2 . So viscosity can be defined as: viscosity = shear stress S / shear rate R . The fundamental unit of viscosity is the poise. A material requiring a shear stress of one dyne per square centimeter to produce a shear rate of s^{-1} has a viscosity of 1 poise or 100 centipoises. One Pascal-second ($\text{Pa}\cdot\text{sec}$) is equal 10 poise.

1.2.4 Newtonian Fluids

Below graphs show the relationship between shear stress S and shear rate R and the fluid's viscosity at a varying shear rate R . Typical Newtonian fluids include water and thin motor oils.

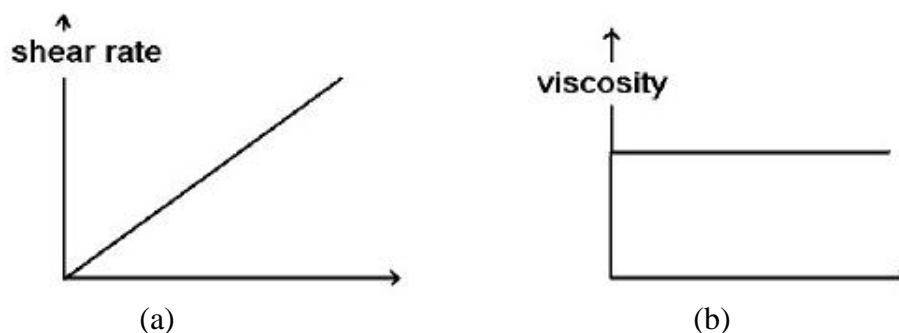


Figure.1.2: Plot of (a) shear rate vs. shear stress (b) shear rate vs. viscosity

So, at a given temperature the viscosity of a Newtonian fluid remains constant regardless of

which viscometer model, spindle or speed is used to measure it.

The behavior of Newtonian liquids in experiments conducted at constant temperature and pressure has the following features:

- The only stress generated in simple shear flow is the shear stress S , the two normal stress differences are zero.
- The shear viscosity doesn't vary with shear rate.
- The viscosity is constant with respect to the time of shearing and the stress in liquid falls to zero immediately the shearing is stopped

The viscosities measured in different types of deformation are always in simple proportion to one another. A fluid showing any deviation from the above features is called non-Newtonian.

1.2.5 Non-Newtonian Fluids

A non-Newtonian fluid is defined as one for which the relationship S/R is not constant. The viscosity of non-Newtonian fluids changes as the shear rate is varied. Thus, the parameters of viscometer model, spindle and rotational speed have an effect on the measured viscosity. This measured viscosity is called apparent viscosity and is accurate when explicit experimental parameters are adhered to. There are several types of non-Newtonian flow behavior, characterized by the way a fluid's viscosity changes in response to variations in shear rate

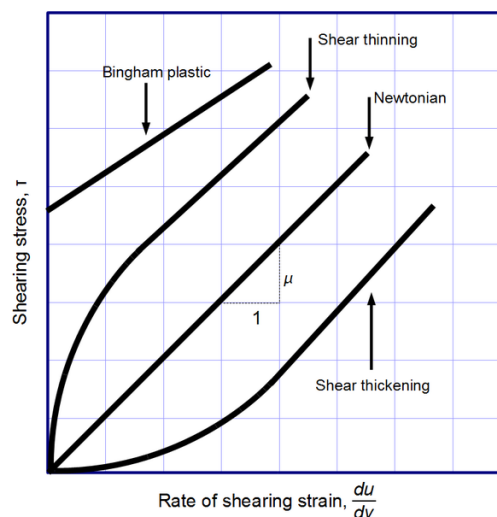


Figure.1.3 Shear Stress vs. Shear Rate for different fluids

The knowledge of rheological properties for different materials for slurry preparation is of

great importance. These topics are studied and severely important for several technical applications e.g. process control in chemical engineering, casting of ceramics, storage, transport of solids in pipelines and atomization.

1.3 VISCOSITY MEASUREMENTS:

Viscosity is measured with two types of instruments

- Viscometers
- Rheometers.

1.3.1 Viscomete

Viscometer is used to measure the viscosity of fluid only and some extend up to paste fluid application. Viscometers only measure under one flow conditions



Figure.1.4 Viscometer

1.3.2 Standard viscometers for liquids:

1.3.2.1 U-Tube Viscometer

These devices also are known as glass capillary viscometers or **Ostwald viscometers**, named after Wilhelm Ostwald. Another version is the viscometer, which consists of a U shaped glass tube held vertically in a controlled temperature bath. In one arm of the U is a vertical section

of precise narrow bore (the capillary). Above this is a bulb, with it is another bulb lower down on the other arm.

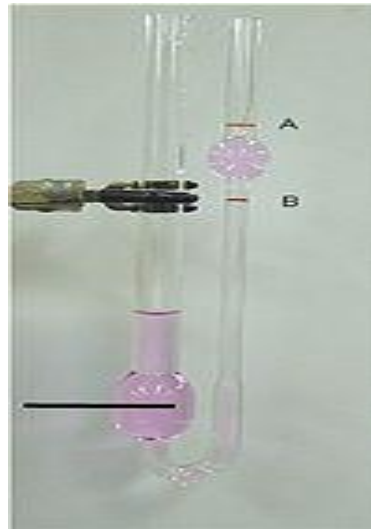


Figure.1.5 U-Tube Viscometer

Such viscometers are also classified as direct flow or reverse flow. Reverse flow viscometers have the reservoir above the markings and direct flow is those with the reservoir below the markings. Such classifications exist so that the level can be determined even when opaque or staining liquids are measured,

1.3.2.2 Falling sphere viscometer

Stokes' law is the basis of the falling sphere viscometer, in which the fluid is stationary in a vertical glass tube. A sphere of known size and density is allowed to descend through the

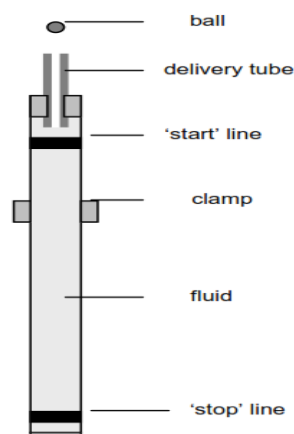


Figure.1.6 Falling sphere viscosity

liquid. If correctly selected, it reaches terminal velocity, which can be measured by the time it takes to pass two marks on the tube. Electronic sensing can be used for opaque fluids. Knowing the terminal velocity, the size and density of the sphere, and the density of the liquid, Stokes' law can be used to calculate the viscosity of the fluid. A series of steel ball bearings of different diameter is normally used in the classic experiment.

1.3.2.3 Oscillating Piston Viscometer

The Oscillating Piston Viscometer technology has been adapted for small sample viscosity and micro-sample viscosity testing in laboratory applications. It has also been adapted to measure high pressure viscosity and high temperature viscosity measurements in both laboratory and process environments. The viscosity sensors have been scaled for a wide range of industrial applications such as small size viscometers for use in compressors and engines, flow-through viscometers for dip coating processes, in-line viscometers for use in refineries, and hundreds of other applications.

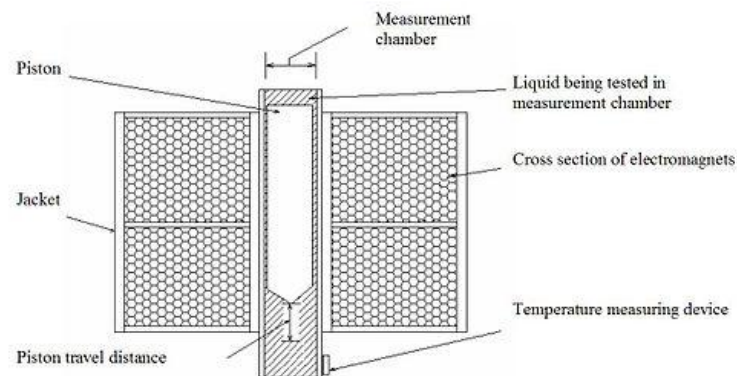


Figure.1.7 Piston Viscometer

1.3.3 Rheometer

A **rheometer** is a laboratory device used to measure the way in which a liquid, suspension or slurry flows in response to applied forces. It is used for those fluids which cannot be defined by a single value of viscosity and therefore require more parameters to be set and measured than is the case for a viscometer. It measures the rheology of the fluid.



Figure.1.8 Rheometer

There are two distinctively different types of rheometer. Rheometer that control the applied shear stress or shear strain are called rotational or shear rheometer, whereas rheometer that apply extensional stress or extensional strain are extensional rheometer. Rotational or shear type rheometer are usually designed as either a native strain-controlled instrument (control and apply a user-defined shear strain which can then measure the resulting shear stress) or a native stress-controlled instrument (control and apply a user-defined shear stress and measure the resulting shear strain)

1.3.4 TYPE OF SHEAR RHEOMETER:

1.3.4.1 Pipe or Capillary Rheometer

Liquid is forced through a tube of constant cross-section and precisely known dimensions under conditions of laminar flow. Either the flow-rate or the pressure drop are fixed and the other measured. Knowing the dimensions, the flow-rate can be converted into a value for the shear rate and the pressure drop into a value for the shear stress. Varying the pressure or flow allows a flow curve to be determined. When a relatively small amount of fluid is available for rheometric characterization, a micro fluidic rheometer with embedded pressure sensors can

be used to measure pressure drop for a controlled flow rate. For Newtonian fluids, the pressure drop increases linearly with flow rate and the measured viscosity does not depend upon applied deformation rate or stress. On the other hand, since non-Newtonian fluids or complex fluids can display shear thinning or shear thickening, the pressure drop versus flow rate data must be analyzed using Weissenberg-Rabin witch-Mooney equation.

1.3.4.2 ROTATIONAL CYLINDER:

The liquid is placed within the annulus of one cylinder inside another. One of the cylinders is rotated at a set speed. This determines the shear rate inside the annulus. The liquid tends to drag the other cylinder round, and the force it exerts on that cylinder (torque) is measured, which can be converted to a shear stress. One version of this is the Fann V-G Viscometer, which runs at two speeds, (300 and 600 rpm) and therefore only gives two points on the flow curve.



Figure.1.9 Rheometer with cylinder measuring system (left) and cone/plate measuring system (right)

This is sufficient to define a Bingham plastic model which used to be widely used in the oil industry for determining the flow character of drilling fluids. In recent years rheometers that spin at 600, 300, 200, 100, 6 & 3 RPM have been used. This allows for more complex fluids models such as Herschel-Bulkley to be used. Some models allow the speed to be continuously increased and decreased in a programmed fashion, which allows the measurement of time-dependent properties.

1.3.4.3 Extensional Rheometers:

The development of extensional rheometer has proceeded more slowly than shear rheometer, due to the challenges associated with generating a homogeneous extensional flow. Firstly, interactions of the test fluid or melt with solid interfaces will result in a component of shear flow, which will compromise the results. Secondly, the strain history of all the material elements must be controlled and known. Thirdly, the strain rates and strain levels must be high enough to stretch the polymeric chains beyond their normal radius of gyration, requiring instrumentation with a large range of deformation rates and a large travel distance.

Extensional rheometer is commonly performed on materials that are subjected to a tensile deformation. This type of deformation can occur during processing, such as injection moulding fibre spinning, extrusion, blow-moulding, and coating flows. It can also occur during use, such as decohesion of adhesives, pumping of hand soaps, and handling of liquid food products.

1.4 DIFFERENCE BETWEEN RHEOMETER AND VISCOMETER:

In order to know the difference between viscometer and rheometer, we should first know the difference between viscosity and rheology. Viscosity is a measure of the resistance of fluid or liquid to an applied stress or shear force. In common terminology, it means the thickness of a fluid or gas. For example, water has a low viscosity so it looks thin while honey has a higher viscosity so it looks thick. Rheology on the other hand is a complex study of the flow of matter. Basically, it studies liquids and also other forms of liquids like soft solids, gels, pastes, sludges, mud's, suspensions, polymers, and even solid materials that exhibit some level of flow, including petrochemicals and biological materials.

Viscosity and rheology are measured by testing methods based on rotational devices that rotate a spindle merged in a sample. By applying a controlled force and measuring the resulting force, it is possible to measure viscosity and rheological properties of a material. The two most common instruments used are viscometer and rheometer.

The difference between a viscometer and rheometer is basically the components quality and control capabilities. A rotational viscometer is a device in which a spindle rotates in a single

direction. Viscometers are limited to be applied to more viscous materials. It is suitable for simple material, production or process tests that need simple flow measurements. It is more or less portable and hence can be used to do remote or field testing, and highly suitable for quality control testing.

1.5 RHEOLOGICAL PROPERTIES OF FLUID

The rheological properties of slurries must be determined as accurately as possible under conditions that closely resemble actual site conditions rheological behaviors. Which can be calculated by Rheometer. The rheological properties are heavily dependent on the solids concentration of the slurry. At low solids concentrations, constant viscosity, Newtonian behavior is observed, but as the solids concentration increases the rheological behavior becomes increasingly complex and non-Newtonian with the viscosity becoming dependent on the shear rate. Below graph showing

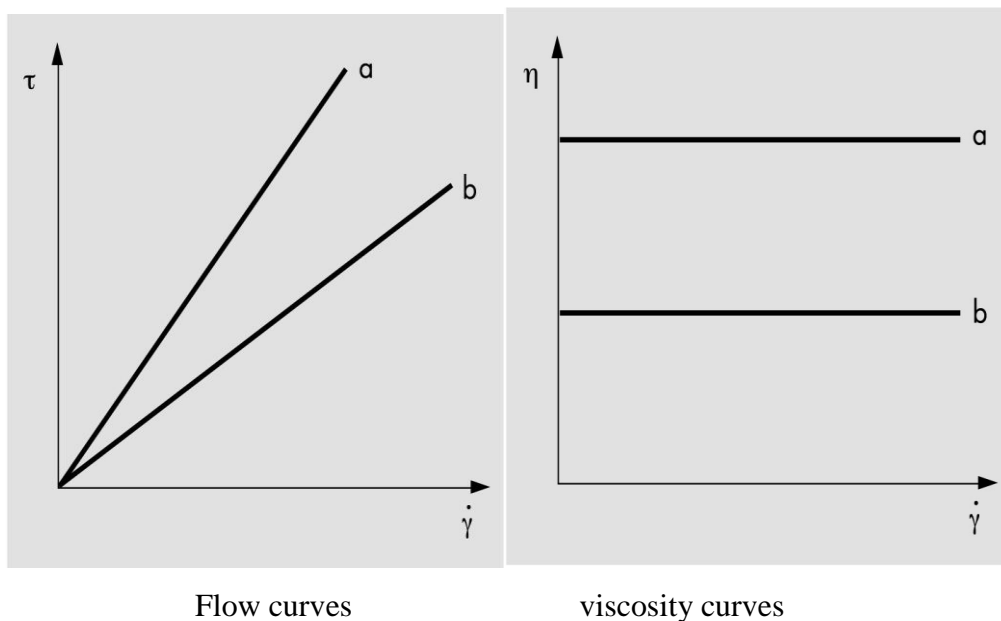


Figure 1.10: - Newtonian flow behaviour

The nature of the non-Newtonian behavior depends on the solids concentration, the particle shape, the particle size, the particle size distribution and the suspending liquid rheological properties. The suspension/slurry may develop a yield stress and/or become time dependent in nature as structures develop within the fluid at higher solids concentrations.

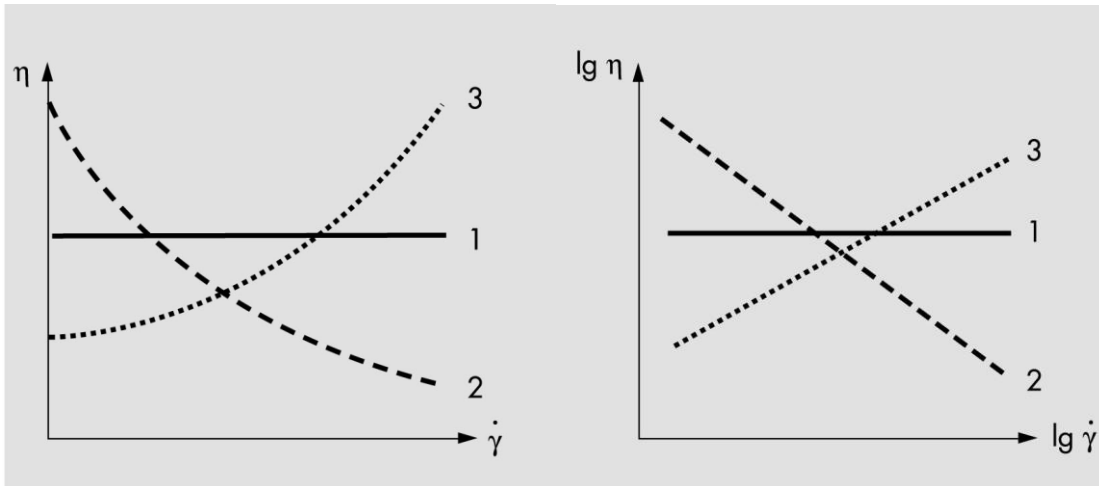


Figure 1.11 :-Flow and Viscosity Curves

Above graph showing flow and viscosity curves 1: ideal viscous (Newtonian) 2: shear-thinning (pseudoplast) 3: shear-thickening (dilatant). Two typical types of time-dependent behaviors are possible Thixotropy, where the fluid thins with shear and time and the opposite rheopexy, where the fluid thickens with shear and time. This study however, is primarily focused on the measurement of the rheological properties of settling slurries where it is necessary to continuously circulate or shear the slurries to prevent settling. Under these conditions, it assumed that the fluid will be fully sheared and that the rheological properties will be unlikely to change further with time. Thus time-dependent effects will not be investigated further and the discussion will focus only on time independent behavior.

Slurry pipelines are used to transport solid materials using water or any other liquid as a carrier fluid for short or long distance haulage of bulk materials. These pipelines are used in may industrial applications involving transportation of variety of materials like mineral ores to processing plants, coal to thermal power plants, disposal of waste materials like fly ash, tailings materials etc. to the disposal sites. Slurry pipeline has been accepted as a safe, reliable and attractive mode of solid transportation by various industries, due to its low maintenance, round the year availability and being eco-friendly. For wider applications, these pipelines can also be laid over difficult terrain to exploit the mineral rich remotest areas such as mountains, across water bodies and under the deep-sea, which are other side not accessible, by conventional modes of transportation. Some of the other additional features of these pipelines, which make them more attractive mode of transportation, are reduction in

traffic congestion, air and noise pollution, and accidents. At optimum operating conditions they are more energy efficient and have minimal adverse effect on the ecology.

1.6 Thermal Power Station

A thermal power station is a power plant in which the prime mover is steam driven. Water is heated, turns into steam and spins a steam turbine which drives an electrical generator. After it passes through the turbine, the steam is condensed in a condenser; this is known as a Rankine cycle. The greatest variation in the design of thermal power stations is due to the different fuel sources. Some prefer to use the term energy center because such facilities convert forms of heat energy into electrical energy. Almost all coal, nuclear, geothermal, solar thermal electric, and waste incineration plants, as well as many natural gas power plants are thermal. Natural gas is frequently combusted in gas turbines as well as boilers. The waste heat from a gas turbine can be used to raise steam, in a combined cycle plant that improves overall efficiency. Such power stations are most usually constructed on a very large scale and designed for continuous operation.

The electric efficiency of a conventional thermal power station, considered as saleable energy produced at the plant busbars compared with the heating value of the fuel consumed, is typically 33 to 48% efficient, limited as all heat engines are by the laws of thermodynamics (Carnot cycle). The rest of the energy must leave the plant in the form of heat. This waste heat can be disposed of with cooling water or in cooling towers. If the waste heat is instead utilized for e.g. district heating, it is called cogeneration. An important class of thermal power station are associated with desalination facilities; these are typically found in desert countries with large supplies of natural gas and in these plants, freshwater production and electricity are equally important co-products.

1.7 Ash Handling:

All the available coals have some percentage of ash. When the coal is burnt in a boiler furnace, about 10 to 20% of quantity of coal used results in ash. In the modern large steam power plants where huge amounts of coal are used, the amount of ash may be go upto many thousands tonnes of ash per year. Theoretically whole of the ash from the furnace should get

deposited in the ash hoppers, but actually from 5 to 40% of it leaves with the outgoing gases.

Ash handling comprises the following operations:

1. Removing the ash from the furnace ash hoppers.
2. Conveying this ash to a fill or storage by means of conveyors.
3. Disposal of the stored ash.

To handle huge amounts of ash per day, mechanical means are employed. The advantage of mechanical handling over manual handling has been already enumerated under the topic of coal handling. The ash handling and disposal system can work continuously or intermittently. The following are some of the places where the ash can be disposed off:

- Where seaborne coal is used, barges may take the ash to sea for disposal into a water grave.
- Disused quarries within reasonable distance of the power station may be used for dumping the ash into evacuated land.
- Building contractors may use it to fill the low lying areas.
- Wasteland sites may be reserved for the disposal of the ash.
- Deep ponds may be constructed and the ash can be dumped into these ponds and when they are completely filled, they may be covered with soil and seeded with grass.

Ash handling is a major and difficult problem due to the following difficulties encountered in its handling and disposal:

1. Ash is dusty and so irritating and annoying in handling.
2. It is hot when it comes out of the boiler furnace.
3. It is abrasive and wears out the containers.
4. Poisonous gases are produced.
5. Corrosive acids are produced in water.
6. It forms clinkers by fusing together in lumps.

The following points should be kept in view while handling and disposing ash:

- Locate the ash plant on the leeward side of the power station to avoid blowing in and drawing into the buildings of the dry ash.

- If the ash is cold and cannot be disintegrated, it may be better to crush it before passing it further or otherwise it might choke the sluiceway.
- In case of pulverised fuel firing, 60 to 80% of ash is in the form of dust and fly ash; the plant should be designed accordingly.

1.8 Ash Handling Systems Presently Adopted In India

Basically there are two types of ash produced in a pulverized coal fired boilers, fly ash and bottom ash. The quantity of ash at different collection points varies with the 'type of fuel used, design of the boiler, collecting equipment etc. In pulverized coal fired boilers the percentages only ash and bottom ash in total ash generated is about 80-90% and 10% -20% respectively

1.9 COAL ASH:

Coal ash is a solid fossil fuel combustion residue from coal burning power plants. This includes combustion residues such as fly ash, bottom ash, flue gas desulfurization sludge (FGDS), fluidized bed combustion waste (FBC), and some by-products including chemosphere, which are used as a lightweight filler in many products. Both the quantity and quality of coal ash are important to consider when managing this residue.

Coal ash contains certain elements (B, Se, As) in concentrations that may create toxic conditions when entering the food chain via plant uptake or by leaching into the ground and surface waters. Therefore, it is critical to define and characterize coal ash to ensure proper use and disposal procedures.

The following should be considered when characterizing and managing coal ash:

- pH
- Total metals
- leachable metals (if total metal concentration are high)
- sodium adsorption ratio.
- physical form (dispersible, aggregate, etc.)

The quantity available, the physical form, and the chemical make up of coal ash are important factors when identifying potential negative effects on the environment, and may significantly affect the management options and handling procedures.

1.10 TYPES OF COAL ASH:

- Fly ash
- Bottom ash

1.10.1 Fly Ash

Fly ash is the finest of coal ash particles. It is called "fly" ash because it is transported from the combustion chamber by exhaust gases. Fly ash is the fine powder formed from the mineral matter in coal, consisting of the non combustible matter in coal plus a small amount of carbon that remains from incomplete combustion. Fly ash is generally light tan in colour and consists mostly of silt-sized and clay-sized glassy spheres. This gives fly ash a consistency somewhat like talcum powder. Properties of fly ash vary significantly with coal composition and plant-operating conditions.



Figure 1.12: Fly ash

Fly ash can be referred to as either cementations or pozzolanic. A cementations material is one that hardens when mixed with water. A pozzolanic material will also harden with water but only after activation with an alkaline substance such as lime. These cementations properties are what make some fly ashes useful for cement replacement in concrete and many other building applications.

1.10.2 Bottom Ash

Coal bottom ash and fly ash are quite different physically, mineralogical, and chemically. Bottom ash is a coarse, granular, incombustible by-product that is collected from the bottom of furnaces that burn coal for the generation of steam, the production of electric power, or both. Bottom ash is coarser than fly ash, with grain sizes spanning from fine sand to fine gravel. The type of by-product produced depends on the type of furnace used to burn the coal.



Figure 1.13: Bottom ash

1.11 PROPERTIES OF ASH:

1.11.1 Physical properties:

Fly ash consists of fine, powdery particles that are predominantly spherical in shape, either solid or hollow, and mostly glassy (amorphous) in nature. The carbonaceous material in fly ash is composed of angular particles. The particle size distribution of most bituminous coal fly ashes is generally similar to that of silt (less than a 0.075 mm or No. 200 sieve). Although sub bituminous coal fly ashes are also silt-sized, they are generally slightly coarser than bituminous coal fly ashes. The specific gravity of fly ash usually ranges from 2.1 to 3.0, while its specific surface area (measured by the Blaine air permeability method) may range from 170 to 1000 m²/kg.

The color of fly ash can vary from tan to gray to black, depending on the amount of unburned carbon in the ash. The lighter the color the lower the carbon content. Lignite or sub bituminous fly ashes are usually light tan to buff in color, indicating relatively low amounts

of carbon as well as the presence of some lime or calcium. Bituminous fly ashes are some shade of gray, with the lighter shades of gray generally indicating a higher quality of ash.

1.11.2 Chemical properties:

The chemical properties of fly ash are influenced to a great extent by those of the coal burned and the techniques used for handling and storage. There are basically four types, or ranks, of coal, each of which varies in terms of its heating value, its chemical composition, ash content, and geological origin. The four types, or ranks, of coal are anthracite, bituminous, sub bituminous, and lignite. In addition to being handled in a dry, conditioned, or wet form, fly ash is also sometimes classified according to the type of coal from which the ash was derived.

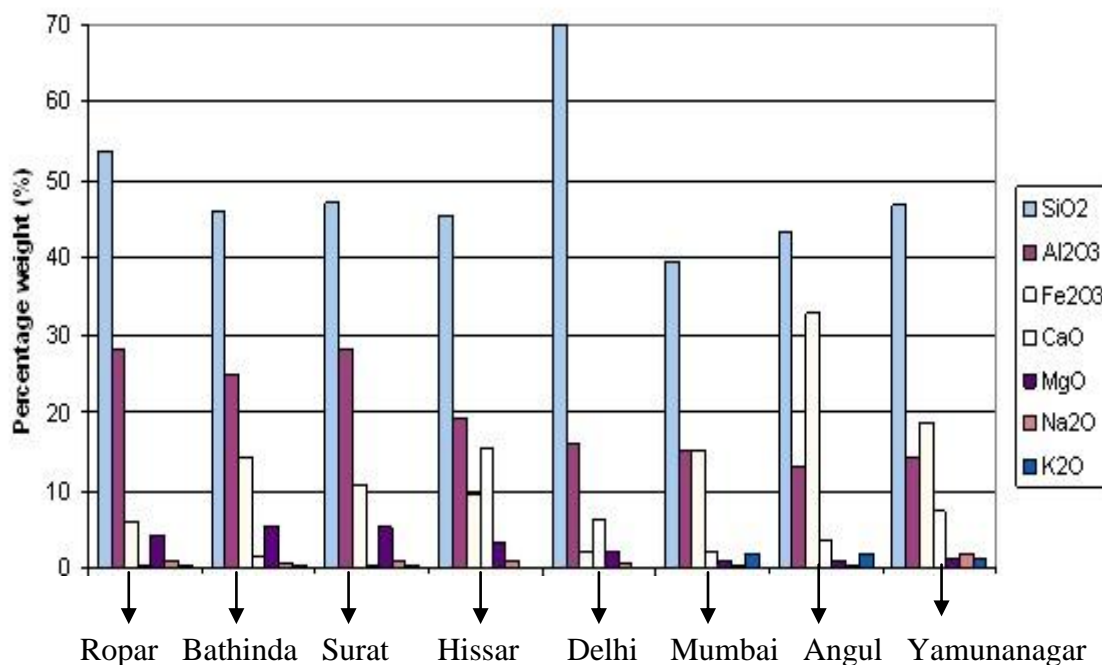


Figure 1.14 Major Elements in Different Thermal Power Station (Concentration in %)

The principal components of bituminous coal fly ash are silica, alumina, iron oxide, and calcium, with varying amounts of carbon, as measured by the loss on ignition (LOI). Lignite and sub bituminous coal fly ashes are characterized by higher concentrations of calcium and magnesium oxide and reduced percentages of silica and iron oxide, as well as lower carbon content, compared with bituminous coal fly ash. Very little anthracite coal is burned in utility boilers.

So there are only small amounts of anthracite coal fly ash. The loss on ignition (LOI), which is a measurement of the amount of unburned carbon remaining in the fly ash, is one of the most significant chemical properties of fly ash, especially as an indicator of suitability for use as a cement replacement in concrete.

1.12 IMPORTANCE OF SLURRY RHEOLOGY IN THE DESIGN OF SLURRY TRANSPORTATION SYSTEM:

One of the most important input data needed for the design of the slurry transportation system is the rheological behavior of the slurry at various concentrations and flow conditions. If the rheological data is available, it may be used to find the flow rate-pressure drop relationship. Rheological parameters also help in determining the power requirement in agitating the slurry in the agitation tank. It also helps in determining the wear rate and life of the pipeline. Knowledge of suspension rheology is also important to ensure a stable/energy efficient pipeline transportation system. The rheological characteristics of a slurry depends on several parameters such as shape, size and size distribution of particles, solids concentration, carrier fluid properties etc. By suitably manipulating the particle size distribution, if other parameters are same, it is possible to obtain a stabilized slurry suspension. The particle size is also important from the dewatering view point. If the solids' are coarse then the cost of dewatering is less but the flow becomes more heterogeneous whereas if the particles are fine then the flow is homogenous but the slurry becomes non-Newtonian and the cost of dewatering also increases. Thus in a slurry transportation system, a compromise has to be made between the particle size and the cost of dewatering.

The rheological behavior of the slurry is also required to predict the head requirement for pumping the slurry. The presence of solid particles in the slurry affects the performance characteristics of the pump. In addition, surfaces of the impeller and the walls of the casing wear more rapidly due to solid particles. Shaft sealing also becomes a significant problem in slurry pumps.

The characterization of rheological behavior of slurry is complicated due to the fact that a large number of factors influence it. Historically, the rheology of suspension has been investigated mostly through experimentation on equalized particulate suspension. Correlations have been derived, on the basis of the above data, to predict the Newtonian

viscosity of suspension. However, in commercial slurry, all the particles of the material will not be equalized and the ratio of the size of the largest particles to that of the smallest particles may be of the order of 1000 or even more. Further, the particles of different materials will differ in various properties like density, shape etc. Thus the actual flow pattern that exists in a slurry pipeline will differ from material to material. Also the behavior of the slurries is generally non-Newtonian at the concentrations that are commercially used.

Non-Newtonian slurries make the principles of fluid mechanics more complex since the resistance to flow 'viscosity' now must be defined through a physical model reflecting process conditions. It is essential that a good understanding of the methods of characterizing rheological properties and extrapolating these characteristics to commercial slurries be obtained. In the absence of any suitable correlations for predicting the rheological parameters of non-Newtonian slurries contains large sized particles and wide particle size distribution, viscometric tests are unavoidable. For slurries containing large sized particles in a low viscosity carrier liquid, viscometric measurements are difficult because the large particles tend to settle down during measurements thus affecting the homogeneity of the suspension. Also the geometric interference of particles with the walls of the viscometer places a limit to the largest size particles that can be accommodated during tests. To overcome these problems the large sized/heavy particles may have to be scalped (removed) from the original sample and rheometric tests are performed with the remaining fine particulate slurries. At present, the effect of removal of large sized particles is not fully understood.

CHAPTER 2

LITERATURE REVIEW

Wright & Brown (1979) described the engineering and operational aspects of hydraulic disposal systems for pulverized fuel ash (i.e. fly ash) from the Midland region power stations, U.K. nearly 12 million tonne of fly ash were generated by a number of thermal power stations in the region and were mainly disposed hydraulically. Slurry pipelines varying in length from 5 kms to 13 kms and diameter from 230 mm to 410 mm were operated for the purpose. The design slurry concentration varied from 25% to 40% by weight and the flow velocity from 1.5 to 2.5 m/sec. The pipe materials included bitumen coated mild steel, and spun cast iron, Ni-hard and other wear resistant alloys, Basalt, Asbestos, Cement and plastics. Two types of disposal systems were employed in the Midland region depending upon the requirement. In the ONE-THROUGH systems fly ash slurry was transported through pipelines to the disposal lagoons. The filling operations required very specific planning aimed at reclaiming the land. The carrier water in such cases was not used. But in the RECIRCULATORY systems employed in cases where water scarcity is faced, the carrier water is returned to the pumping station through another set of pipelines. This return water in addition to the necessary make-up water were used for preparing fresh slurry. The Midland region fly-ash particles contained a thin outer layer which was effectively an acidic surface, surrounded by an alkaline core which contained some free lime. The total soluble matter was about 2% which mainly appeared in water as sodium, potassium and calcium sulphates. So, while preparing the slurry, the dissolution of acid layer first made the water acidic but over a period of one hour, the alkaline core reacted and the carrier water become alkaline. As regards the environmental aspects for such hydraulic disposal, there was a possibility of dust nuisance, when a lagoon was full and began to dry out prior to final reclamation. Various methods of temporary sealing of the surfaces of the ash were employed such as (i) spraying the surface with an organic material to form a film (ii) creating a thin layer of grass mixed with a light coating materials or (iii) covering the surface with earth wherever top soil is available.

Verkerk (1982) has conducted some very useful investigations on the hydraulic transportation of fly ash of South African power stations. The disposal of such fly ash has been conceived keeping in view formation of ash dumps, ash dams and limited backfilling of coal mines. The chemical composition of fly ash indicated 47% silica, 26% alumina, 10%

calcium and 2% FeO₂. The ash samples have a fine content (less than 45 microns in size) of 80% and d₅₀ of the sample was around 12 microns. The average particle density was 2.2 g/cc. It was found that there is a reasonable correlation between the average particle size. Verkerk conducted studies on fly ash at low concentrations and as well as high concentrations. A 100 m long pipeline-test loop with a pipe diameter of 100 mm was used for the test. A centrifugal pump was employed for lower concentration slurries of 0-30% by weight and a reciprocating piston pump for high concentration pastes of 65 to 70% by weight. The water used for slurry preparation contained calcium carbonate which after reaction with lime in the ash, generated insoluble calcium carbonate. This resulted in the problem of scaling in the pipelines for which the pipelines were pigged and the pumps flushed with water after every test.

The slurry head loss results obtained by Verkerk from the loop tests were consistent with the typical homogeneous slurry characteristic curves. A kink in the curve was observed when the head loss data plotted in logarithmic scale at a flow rate of about 20-25 m³/hr which corresponded to the visual observation of the onset of deposition on the bottom of the pipeline. Tests at high concentrations indicated presence of a yield stress which was due to the non-Newtonian behaviour of the slurry. The slurry changed from fluid like character to one that tended to form sliding planes at 68-69% weight concentration. The pumping of high concentration paste above 69% concentration incurred high pressure loss. However it was observed that a paste having a fraction of bottom ash incurred substantially less pressure drop. But Streat (1986) in his paper has raised certain questions on the decrease in pressure drop in presence of coarse particles, terming the phenomenon as surprising and needing explanation.

Lazarus and Sive (1984) studied the rheological behaviour of fly ash slurry from South African Power Stations using a novel balanced – beam viscometer. The d₅₀ of the fly ash samples was 17 microns and the solid specific gravity of the sample was 2.3. Experiments were conducted for solid concentrations varying from 10-30% by volume. The rheology results indicated that the fly ash slurries tested would be described by Bingham plastic model. Pipeline loop tests were also conducted in a test pipe of 140mm internal diameter at solids concentration between 10% and 30% by volume and the pipeline test results of slurry head loss were compared with the head loss values predicted using the rheological test data. In this connection, the authors used a modified version of Torrance for smooth pipes was added with a pipe relative roughness term in a similar way as done with Colebrook & White equation, so

that the head loss of non-Newtonian fly ash slurry in rough pipes could be computed. But this modification was not fully satisfactory since it under-predicted the head loss of fly ash slurries. The authors therefore readjusted the constants in the equation, so that the equation could correlate the pipeline test results.

Lazarus and Sive (1985) studied the rheological property on fly ash obtained from a South Africa coal fired power station using a Balance Beam Tube Viscometer. These viscometer results were then scaled up and compared with data obtained from a test system pumping the same fly ash. The fly ash used was well graded with a particle size $d_{50} = 17\mu\text{m}$ and a solid water relative density was 2.23. The rheological study was conducted on slurries with a C_w up to maximum of 48%.

Bunn et al (1990) have undertaken a number of studies on high concentration slurries of fly ash from some of the Australian power stations. The d_{50} of the fly ash samples varied from 7 microns to 40 microns. Rotary viscometers and tube viscometers were used for rheological measurements at concentration varying between 60 to 80% by weight. The fly ash slurries were found to be time independent and exhibited non-Newtonian behavior for solids concentration greater than 60%, a Bingham model closely fitted the measured curve. At high concentrations, the rheology curve deviated from Bingham plastic model. At high strain rates, the agreement between the data and Bingham model was good but below a critical shear rate, pseudo-plastic exponential model closely fitted the measured data.

Studies on the dense phase hydraulic conveying of fly ash at Vales Point power station in Australia have been reported by some authors (Bunn, 1989; Bunn et al. 1993). It was indicated that the optimum concentration of slurry in the pipeline would be around 60% by weight. The fly ash was conveyed to a mechanical mixer using an air slide, the flow rate of the fly ash being controlled by a rotary feeder. The fly ash was mixed with a controlled quantity of water in a twin screw mixer mounted directly to the pump station. The pump was twin cylinder hydraulically driven positive displacement type, discharging into a 150 diameter, 1740m long pipeline. In their paper the authors have also reported the environmental aspects of such type ash disposal, plant start-up and shut-down conditions, commissioning experiences etc.

Bunn et al (1991) studied the rheological properties of fly ash slurries. Their studies reveal that fly ash slurries are time independent and exhibited non-Newtonian behaviour for C_w

>40%(by weight). For C_w close to 60%, a Bingham model closely fitted the measured flow curve. At higher C_w and at low shear rates, the measured flow curves deviated from an ideal Bingham plastic model.

Gahlot et al (1992) have studied extensively the rheological behaviour of fly ash slurries at medium concentrations and found that top particle size and particle size distribution significantly influences the rheological behaviour of the fly ash slurries.

Vlasak et al (1993) in his paper has highlighted the use of peptizing agent to decrease the viscosity and yield stress depressing the strong non-Newtonian behaviour of the slurry due to presence of colloidal particles. The tests were performed on Kaolin water suspensions for laminar and turbulent regimes using an experimental test loop of 17.5 mm inner diameter and rotational rheometer. Also studied the ash slurry behavior for the purpose of hydraulic backfilling in underground coal mines. The filling technology required the transportation of ash in the form of quickly hardening slurry with a minimal amount of free water. For this purpose, ash was to be mixed with cement at a mass ratio of 9:1, so that the slurry of required concentration filling the mine cavities would gradually harden without bleeding. The d_{50} of the fly ash sample was 30 microns. The flow characteristics of ash and ash cement slurry were investigated in 50 mm, 80 mm and 100 mm pipeline test loops with volume concentration varying from 20% to 55% where the slurry velocity varied from 0.5 to 3.5 m/sec. The flow behaviour of ash and ash-cement slurries was found to be similar. Two methods were adopted for correlating the pipeline flow data for the determination of the relationship between the slurry viscosity and slurry pressure drop with respect to the slurry concentration. In the first method, an empirical relation was proposed to correlate the relative head loss (the ratio of slurry head loss to water head loss) as a power function of volume concentration. In the second method, the viscosity of the slurry at different concentrations were obtained through back calculations from Colebrook-White friction factor equation and an empirical equation for relative viscosity of fly ash was found. Since the viscosity and pressure drop values were tending to shoot-up when the volume concentration exceeded 50%, the equation obtained was valid for volume concentration below 50%. Empirical techniques were used by the authors for predicting head loss in commercial size pipes in the volume concentration range of 30 to 40%.

Cooke and Lazrarus (1993) present some of the aspects of pipeline design for backfilling with dense phase tailing slurry in gold mines. Singh et al. (1998) investigated the rheological properties of fly ash-water slurry at obtained from three different sources. The difference in the behavior of the fly ash water slurries from different power stations was attributed to the nature of mineral matter in the coal, size distribution of the pulverized fuel and the combustion conditions in the boiler. He concludes that the development of high concentration slurry disposal system is very much dependent on the source of fly ash.

Gahlot et al(1993) have also concluded that static settled concentration is a useful parameter to account for the effect of particle size distribution and the reduced volumetric concentration can be used to relate the rheological parameters of slurries with reasonable accuracy.

Verkerk et al (1993) also attempted to correlate the pressure gradient of fly ash slurry-flow at lower concentrations by applying the head loss models of Newitt, Wasp, Durand and others. He also correlated the head loss with respect to equations for normal Newtonian fluids and observed that the predicted values correlated better with the experimental data compared to predictions by other models.

Studies on fly ash transportation were conducted at Institute of Minerals and Materials Technology, Bhubaneswar in a program sponsored by Engineer India Limited, New Delhi .The fly ash samples were from Talcher Thermal Power Station having a material density of 2.05 g/cc. The fine content (less than 45 microns in size) was around 50%, the d_{50} of the samples being 50 microns. The chemical composition of the fly ash indicated 64% Silica, 23.5% Alumina, 6.5% iron oxide and 2.0% Titanium Dioxide. The rheological studies conducted at 40% to 50% weight concentration showed Newtonian nature for fly ash slurry viscosity. Pipeline tests were conducted in 50mm, 100 mm and 150mm test loops at slurry weight concentration varying from 20 to 50%. The pressure drop results were typical of a homogeneous Newtonian fluid and could be correlated by applying a Newtonian head loss model. The deposition behaviour of the fly ash particles in slurry flow was also investigated and it was observed that both the limit deposit velocity and the stationary deposit velocity gradually reduce with slurry concentration. It was also reviled that the variation of deposit velocity with solids concentration was less significant in bigger pipes than in smaller pipes conveying fly ash slurry. A scale up model was proposed for critical velocity of fly ash slurry flow.

Heywood et al (1993) assessed the flow characteristics of pulverized fuel ash slurries at high concentration in the range of 68 to 70% weight concentration, the d_{50} of the sample being 38 microns. The purpose was to pump the slurry through pipelines directly into the disused mines or land fill sites adjacent to the power station without the need for a de-watering stage. The authors established pressure loss-flow rate relationship by conducting experiments in a 72 mm ID, 8.34m long polypropylene plastic pipe. A power law model was fitted to the lower shear rate range data appropriate for prediction of frictional losses in 150 mm and 200 mm diameter pipelines over a distance of 8 km. The power laws exponent “n” was found to be largely constant at around 0.46 for two types of pulverized fuel ash investigated. The analysis showed that for transporting the ash at a rate of around 100 tonne/hour in either 150mm or 200mm pipe, the resultant pressure loss would not exceed 100 bar. This pressure could be generated by a single stage piston pump. The specific power consumption (SPC) was also computed by the authors at different slurry concentrations and the results indicated that the SPC increases with increase in slurry concentration.

Biswas et al (1994) have determined the rheological properties of slurries of coal ash produced in Indian thermal power plants, and developed a procedure for pressure drop prediction at medium concentration using Torrence correlation. They also found that the rheological properties and other physical properties of the Indian coal ash are different for different thermal power plants spread across the country and a similar conclusion has also been drawn by Bunn and Chambers for Australian coal ash. Thus, for the fly ash suspensions the literature reveals that at low concentration ($C_w < 40\%$), the behaviour of the suspension is Newtonian with viscosity increasing with concentration and above 40% solid concentration, the fly ash slurries behave as a non-Newtonian fluid.

Kolar (1994) has studied the rheological properties of suspensions to establish the effect of polymer additive (polyacrilamide) on viscosity. He has suggested that the visco-elastic properties of the liquid phase strongly influence the flow of suspensions. Concentration of additive and solid particles, pipe diameter, and material of pipe walls and roughness of their surface are not other factors which were found to influence the pressure drop. Horsely has investigated the rheological properties of a good slime using a HAKKE rotary viscometer and 40 mm diameter test loop. Rheograms have been obtained for 75% concentration, (by weight) with sodium phosphate as an additive. The results show that visco-metric data can be used to predict pressure gradients in slurry pipelines as long as the concentration is kept high.

Kundu and Peterson (1994) have highlighted the use of a new transport medium, which requires at most, half the amount of water. Due to superior particle suspension ability, stability and visibility of the foam, it has a much higher solid carrying capacity than water. The other advantage that has been highlighted is in the reduction of almost elimination of some of the processes required for the slurry preparation and drying of transported materials.

Kaji et al (1994) have studied the effect of two different types of dispersants, anionic and non ionic, on highly concentrated coal water mixtures and have through light on the mechanisms of the particle dispersion in both mixtures.

Walmsley and Duffy (1994) have highlighted the use of flocculated fibre at low concentrations to support coarse and fine coal particles in suspension as well to improve the slurry flow characteristics by simply reducing the friction loss (by 30%). The flocculated fibre also acts as a drag reducing agent.

Horsley (1995) studied experimentally the effect of viscosity reducing agent in a 50 mm diameter pipe carrying red-mud in steady laminar flow. The viscosity reducing agent, when injected at the pipe wall, gave a pressure reduction of 70% and thus the pumping cost was lowered down.

Schirck et al (1995) have reported, on the basis of bench scale tests, the cause of attrition and abnormality in the pressure drop in pipeline loop tests. They have also recommended some commercially available wetting agents and detergents such as Tide, Drift, Calgon and Sears, automatic dishwasher detergent, which do not reverse the hydrophobic character of the metallurgical coal properties for this purpose. They suggested the use of viscosity destroying agents or the frothing agents such as potassium permanganate and sodium hypochlorite for reducing pressure drop. The effect of solids concentration, particle size, PSD and surface characteristics on the viscosity of the suspension has been investigated by

Ghanta et al (1996) using two different solids namely coal and copper ore. These solids have different surface characteristics. They observed that coarse size coal-in-water slurries exhibit lower viscosities compared to fine size coal-in-water slurries, whereas copper ore behaves in a reverse way due to its opposite surface characteristics. The results have also shown that PSD has market influence on viscosity of suspension. The studies reveal that mixing fines particles with coarse slurry could reduce the viscosity of the suspension. For

coal water system 60:40 weight proportion gave maximum reduction and for copper ore-water system 40:60 gave maximum reduction.

Thomas and Sobota (1996) have highlighted the use of additives, which could be any other waste being added to the fly ash slurry disposal system, along simultaneous solution to two disposal problems at much lower pressure drop.

MacInnes (1996) has presented the results of an investigation into the effects of slurry thinners such as poly-acrylates sodium lingo-sulphonates on the rheological properties of chalk slurry. Poly acrylates removes almost total yield stress while sodium lingo-sulphonates retains the yield stress along with reduced sedimentation. Iwanami & Tachibana (1970) conducted some pioneering studies on the viscosity and pipe flow behaviour of fly ash slurry. Two samples of fly ash were investigated where one sample was having the material density 1.97 gm/cc with a mean particle diameter of 19.8 microns and the other sample having 2.15 gm/cc. material density and 15.4 microns mean particle diameter. The visco-metric studies were conducted using water and aqueous solution of lead nitrate as carrier medium. Since the fly ash with in the slurry exhibited highly settling tendencies, a short tube viscometer in which the slurry is agitated by agitating blades, was used for measuring the viscosity. The authors established the optimum conditions of agitation and derived a correlation method to quantify the influence of agitation. The experiments were conducted at slurry temperatures of 10⁰ C, 20⁰ C and 28⁰ C and slurry concentrations of 10, 20, 30 and 40% by weight. The viscosity results indicated that the fly ash slurry exhibited Newtonian behavior within this range of concentration. The relative viscosity (ratio of slurry viscosity to water viscosity) plotted against concentration was found to be independent of slurry temperature and a function of volume concentration only.

They also conducted two sets of pipeline test with pipes of 1.5" dia and 3" dia. For the 1.5" (37.3 mm diameter) pipe, the pressure drops were measured at 0, 4.9, 10.7, and 17.1 and 25.9% volume concentrations. For the 3" pipe (76.2 mm diameter), the measurements were done at 0, 2.4, 7.2, 12.0, 16.8, 21.6 and 26.5% volume concentrations. The friction factors for slurry flow computed from the experimental values of head loss were compared with the friction factor curves obtained from Lander's Misses and Colebrook's friction factor equations. The comparison established that the friction loss of fly ash slurry could be expressed by the relationship between friction factor and Reynolds's number same way as

clean water. While calculating the Reynolds's number the viscosity values used were obtained as a product of water viscosity and volume concentration. Use of experimental values of slurry viscosity was also found to be equally satisfactory.

Parida et al (1996) investigated the rheological and pipe flow behaviour of ash samples from Talcher Thermal Power Station, Orissa. The viscosity of the fly ash slurry was found to be Newtonian in nature up to a solids concentration (C_w) of 50% and above this concentration the viscosity is non-Newtonian. The power law pseudo-plastic model correctly characterizes the non-Newtonian models the head loss of the slurry were predicted. It was indicated that the transportation cost of fly ash slurry reduces drastically if the same is transported at high concentrations instead of low concentrations.

Ward et al (1999) investigated the hydraulic transportation of dense fly ash slurry using a stabilizing additive to prevent sedimentation of fly ash particles. But the addition of stabilizing additive increased the slurry viscosity for which a dispersing additive was to be used to solve the problem.

Einstein (2002) was the pioneer person to propose a linear correlation for the suspension viscosity through theoretical derivation. Unfortunately, the commercial slurries handled are completely different from the one for which the equation has been developed and consequently, the applicability of the Einstein's equation of viscosity is limited.

Parida et al (2003) using the flow and head loss characteristics of high concentration fly ash-bottom ash mixture slurry carried out the pipeline design for hydraulic back-filling of coal mines by considering the effects of solids concentration, bottom ash fraction, pipe diameter and flow velocity. A design chart was formulated to determine the pipe size and design transport velocity for a given backfilling rate and given H/L ratio i.e. length of vertical section of pipe (m) to length of horizontal section of the pipe (m).

Senapati et al (2006) conducted the static studies, rheological behavior and design scale-up procedure for predicting head loss for fly ash samples collected from NALCO, Angul, India. Studies indicated that the maximum static settled concentration ($C_{w\ max}$) of around 69% can be achieved for the slurry and hence a slurry in the range of 60-67% by weight can be prepared for transporting through pipeline in laminar mode due to its non-settling nature. The preparation of such slurry was done using a helical ribbon mixture and a slurry concentration

of 67% was easily achieved. The flow behavior of the ash slurry was affected by addition to bottom ash indicating lesser viscosity. The head loss of fly ash slurry was predicted using a non-Newtonian power law model.

Thomas (2006) performed a critical analysis of the extensive experimental data on the relative viscosity of the suspensions of uniform spherical particles. The scattering of the data was reduced from $\pm 75\%$ to $\pm 13\%$ up to a solid volume fraction of 0.50 by extrapolation techniques. The coefficients in the power series relating relative viscosity and solid volume fraction were determined using least squares procedure and a new expression for viscosity containing six terms was proposed.

Vlasak et al (2007) investigated the pipeline transportation of fly ash slurry at volume concentrations in the range of 22% - 31% and indicated that by adding bottom ash fractions the fly ash-bottom ash slurries reached slightly higher maximum concentration. He also revealed that a substantial reduction of the flow resistance can be achieved by addition of some drag reducing agents or by arrangements of particle size distributions or adopting some mechanical treatments. The flow behaviour of the slurry was approximated by Yield-power law model. Since the addition of drag reducing agents causes a decrease of head loss therefore it is possible to use a lower operational velocity for the stabilized slurry, which brings a significant reduction in head loss. The effect of addition of Sodium hexa-metaphosphate at 0.1% concentration (by weight) as an additive or rheological flow behavior of ash slurry was studied by Seshadri et al. (2006). By using the rheological data the head loss of fly ash slurry at high concentrations ($C_w = 60\%$, 65% and 68%) were predicted using a Bingham plastic model. Since the additive modified the rheological behavior of the ash slurry a substantial reduction in head loss and energy consumption could be achieved.

Jinescu (2007) in his classical study on rheology of suspensions covering as many as 133 literature references concluded that suspensions of solid particles in a non-Newtonian liquid have a non-Newtonian viscous behaviour or even viscous-plastic behaviour. Comparing the experimental data with the Einstein equation he has proposed a general correlation for spherical ellipsoidal and rod shaped particles. In the correlation the shape factor coefficient is expressed as a function of concentration, shape, dimensions of the particles, nature of the particle material, and the surface and the shear conditions, and the time elapsed since the start of flow.

Pullum et al (2007) have calculated the performance reduction of the centrifugal slurry pump by using Hydraulic Institute method for handling non-Newtonian coarse particle suspensions. Suspensions up to 38% v/v of coarse particles with mean diameters in the range of $1.1 < d_{50} < 3.4$ mm suspended in carrier fluids with dynamic yield stresses of $0 < \tau_y < 17.2$ Pa and shear thinning indices in the range $0.35 < n < 0.79$ were examined. They found that the reduction in the head is the function of coarse solid concentration.

Vlasak et al (2009) investigated the pipeline transportation of fly ash slurry at volume concentrations in the range of 22%-31% and indicated that by adding bottom ash fractions the fly ash-bottom ash slurries reached slightly higher maximum concentration. He also revealed that a substantial reduction of the flow resistance can be achieved by addition of some drag reducing agents or by arrangements of particle size distributions or adopting some mechanical treatments. The flow behavior of the slurry was approximated Yield-power law model. Since the addition of drag reducing agents causes a decrease of head loss therefore it is possible to use a lower operational velocity for the stabilized slurry, which brings a significant reduction in head loss. The effect of addition of Sodium hexametaphosphate at 0.1% concentration (by weight) as an additive on rheological flow behavior of ash slurry was studied.

Sturge and Cumpsty(2009) reported a method for calculating two-dimensional incompressible and inviscid flow within a centrifugal impeller when the flow separation from the suction side has been developed. They assumed that mixing of the through flow with the separated region is suppressed. The flow in an impeller passage was divided into two regions. The flow in the main region was regarded as inviscid and irrotational, while in the wake region there was no flow. The axial inlet and radial outlet impeller was used for calculation. In this report, they had shown the streamline pattern and the overall parameters for the flow in a centrifugal impeller which were observed to change by altering the flow rate and the impeller shape.

Gandhi et al (2009) have carried out experimental investigation on effect of speed on the performance characteristics centrifugal slurry pump. From the experimental study of pump characteristics at different pump speeds, it is observed that the affinity relations applicable to conventional pumps for head and capacity can be applied to the slurry pumps handling water

and slurries at low solid concentrations less than 20% by weight. For higher solid concentrations, these relationships need to be corrected by taking into account the effect of solids.

Jai Krishnan .et al (2009) investigate the Particle Velocities in a Slurry Pump Using (PIV) and concluded that the particle image velocimetry technique was successfully utilized to investigate the velocities and kinetic energy fluctuations of slurry particles at the tongue region of an optically-clear centrifugal pump. The tongue region separates the flow into two streams where the location of the stagnation point on the tongue was not significantly affected by either the pump speed or the solid concentration in the ranges tested. In the impeller passage region, the highest velocities are generated on the suction side of the blade and in the blade trailing edge region as the blade sweeps through. However, these particle velocities are slower than the circumferential velocity of the blade tip ~8.96 m/s for 725 rpm pump speed and 12.36 m/s for 1000 rpm pump speed!. The tangential velocity component and the radial velocity component are significant in this region. In contrast, the particles that are moving through the discharge region are much slower and are nearly tangential horizontal. The up-coming blade does not appear to substantially affect the flow velocity.

P.V. Skudarnov et al (2010) studied the slurry transport experiments were performed with five double-aspects slurries composed of glass beads and water. The double-species glass beads were various combinations of beads having two widely different densities and three narrow particle size distributions. Pressure gradients for double-species slurries were compared to those for individual components at the same solids volume concentrations. Effect of mean particle diameter on pressure gradient of double-species slurry in the pipe was studied. Experiments were performed in a horizontal pipe flow loop of 23 mm internal diameter. Obtained data are useful for pipeline system design and also valuable for verification of numerical simulation of the slurry flows.

A review analysis on experimental and theoretical work on the rheological properties of suspensions was done by Jeffrey and Acrivos [86] assuming that an effective viscosity solely depends on volume fraction of the particles. The experimental evidence strongly supports the view that the suspensions behave macroscopically as non-Newtonian fluids whose rheological properties are influenced by a large number of factors.

The above review shows that most of the studies reported on suspension rheology are for specific slurries at varied solid concentration. The correlations developed are mostly of limited use and are found to be inadequate for universal application. Most of the above methods can alter a suspension or slurry formulation irreversibly in the sense that a significant cost arising from extra capital and operating requirements may be incurred to return the slurry to its original state once the slurry has been transported through the pipeline.

CHAPTER 3

MESURMENT OF PROPERTIES OF ASH

Around 3.5 tons of fly ash sample including 0.5 tones of bottom ash samples were procured from different zones of electrostatic precipitator hoppers of Guru Nanak Dev Thermal Power Plant Bathinda, Punjab. Prior to conducting the rheological studies, the characterizations studies such as particle size distribution, material density, morphological features and mineral characteristics and chemical composition of the ash samples were determined. In order to ascertain the effect of mixing time on pH and maximum settled concentrations achievable for the specific fly ash samples, mixing and settling studies were conducted .Ash refers to the non-combustible constituents of coal with traces of combustibles embedded in forming clinkers and sticking to hot side walls of a coal-burning furnace during its operation. The portion of the ash that escapes up the chimney or stack is, however, referred to as fly ash. The clinkers fall by themselves into the water or sometimes by poking manually, and get cooled. The clinker lumps get crushed to small sizes by clinker grinders mounted under water and fall down into a trough from where a water ejector takes them out to a sump. From there it is pumped out by suitable rotary pumps to dumping yard far away.

3.1 PROPERTIES OF ASH

3.1.1 Physical properties

Ash has angular particles with a very porous surface texture. Particles range in size from a fine gravel to a fine sand with very low percentages of silt-clay sized particles. ash is predominantly sand-sized, usually with 90 to 100 percent passing below 2000 micron sieve size, 90 to 80 percent passing a below 1400 micron sieve size, 30-20 percent passing below 75 micron sieve size. Boiler slags have a smooth surface texture, but if gases are trapped in the slag as it is tapped from the furnace, the quenched slag will become somewhat vesicular or porous.

3.1.2 Chemical properties

Ash and boiler slag are composed principally of silica, alumina, and iron, with smaller percentages of calcium, magnesium, sulfates, and other compounds. The composition of the bottom ash or boiler slag particles is controlled primarily by the source of the coal and not by the type of furnace.

3.1.3 Particle Size Distribution (PSD)

The variation in the size of the particles in the solid sample and the percentage of particles present in different pre-selected size ranges are determined to establish the particle size distribution (PSD).

Two methods namely sieve analysis and hydrometer analysis, are employed to get this distribution. For coarser particle size distribution i.e. above 100 μm , sieve analysis is used whereas hydrometer analysis is used for finer particles i.e. below 100 μm .

A known weight of representative sample of solid particles is taken and washed over a B.S. 200 mesh (75 μm). Both the material retained over the sieve as well as the finer particulate material are dried in an oven. The dried coarser material is sieved through a set of standard sieves. Special care is taken to ensure that the sample is properly dried.

The sample retained on each sieve is collected and the percentage retained on each sieve is calculated using the standard procedure. The particle size distribution of the fine particles collected (<75 μm) is then determined using the standard hydrometer analysis..

$$\text{Weight mean diameter (dwm)} = \frac{\sum_{i=1}^n (W_i * D_i)}{\sum W_i}$$

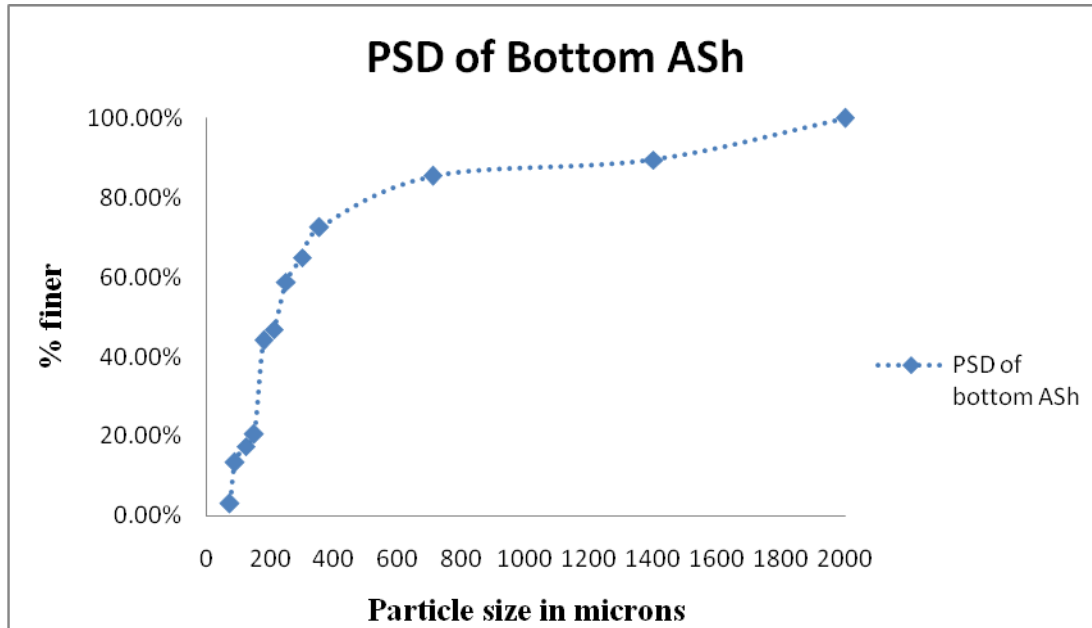


Figure 3.1 Variation of particle size with % finer.

3.1.4 Specific Gravity of Bottom Ash

In the present study, the specific gravity of solid particles (bottom Ash) is determined using Standard Pyknometer Method. In this method first take 50 ml Pyknometer and clean it thoroughly, keep it in the oven in order to remove moisture from pyknometer. After 2 hours, take out the pyknometer from an oven and allow it to cool down, and then take the weight of pyknometer (W_b). After weight put some solids (over dried) about 30 grams in it and weight it again and note down this weight (W_{bs}). After this slowly pour water (distilled) in the pyknometer so that no air is entrapped in it and shake it well, and keep on pouring the water. Shake it well each time till all the solid get wet. Fill $3/4^{\text{th}}$ of bottle with water and put the thumb on the mouth of the bottle and shake it well for 5 minutes. Keep it for at least 2 Hours, so that air bubbles get out from the bottle. Then fill the bottle of water and cork it. Clean it with cloth/tissue paper and weight it. Note down the weight (W_{bsw}). Now remove the solids from the bottle and clean it, Thoroughly, Dry it and fill it with distilled water. Note down the weight (W_{bw}). Calculate the specific gravity of solids as given below.

$$\text{Specific Gravity of solids} = \frac{(W_{bs} - W_b)}{(W_{bw} - W_{bsw} + (W_{bs} - W_b))}$$

Where W_b = Weight of beaker

Wbs = Weight of beaker and solid

Wbw = Wight of beaker and water

Wbsw = weight of beaker, solid and water

Table 3.2 Specific Gravity of Bottom Ash

S.No.	Weight of beaker (Wb) gm	Weight of beaker+solid (Wbs)gm	Wbsw (gm)	Wbw(gm)	Specific Gravity
1	32.4105	62.4118	167.26	150.2206	2.314575795
2	32.7065	62.8265	163.436	146.7342	2.244712406
3	33.4172	63.4178	161.9163	145.2747	2.245721985

Density of solid= Specific gravity * Density of Liquid

Specific gravity	Density of Liquid kg/m ³	Density of Bottom Ash (kg/m ³)
2.252711808	998.2	2248.656926



Figure: - 3.2 Pyknometer



Figure: - 3.3 Oven

3.1.5 Material density of ash sample

Calibrated specific bottles were used for determining the material density of ash samples by using standard specific gravity bottle. The material density of the fly ash and bottom ash samples determined in the laboratory experiments were found to be 2123 kg/m³ and 2165 kg/m³ respectively

3.1.6 Static Settled Concentration

The static settled concentration is an important parameter which decides the performance of the pump at different levels of slurry concentration. Static settling predicts the behavior of the ash with water or transporting fluid. It is the procedure to test the time and speed at which the ash particles settle themselves in the containing fluid. The static settled concentration depends on parameters like specific gravity, shape and particle size distribution, density and viscosity, of carrier fluid etc. It is well accepted that the optimum concentration for solids transportation is around 5 to 10% lower than the static settled value.

In the present study, the static settled concentration has been determined by preparing a slurry sample of intermediate concentration i.e. 30% (by weight) and allowing it to settle in a graduated measuring beaker till the level of the particles of ash become constant. This value of solid concentration in the settled portion of slurry is the static settled concentration. The readings of slurry levels are taken at regular intervals of time to determine the settling rate of the slurry.

In this test take 150 gm of Bottom ash in jar and put 350 gm water in jar to make the 30% concentration by weight. Then keep the mixture unshaken for 2 hours. After 2 hours, shake the jar well enough to mix the ash properly with the carrier fluid. Reading levels are taken every 10 seconds in the initial stage. Note the reading till you get steady state. The computations for settled concentration of ash with specific gravity and the volume of the concentration are done. Then concentration v/s time graphs are generated to get static concentration. The experimental results of Static Settled Concentration of bottom ash is shown below.

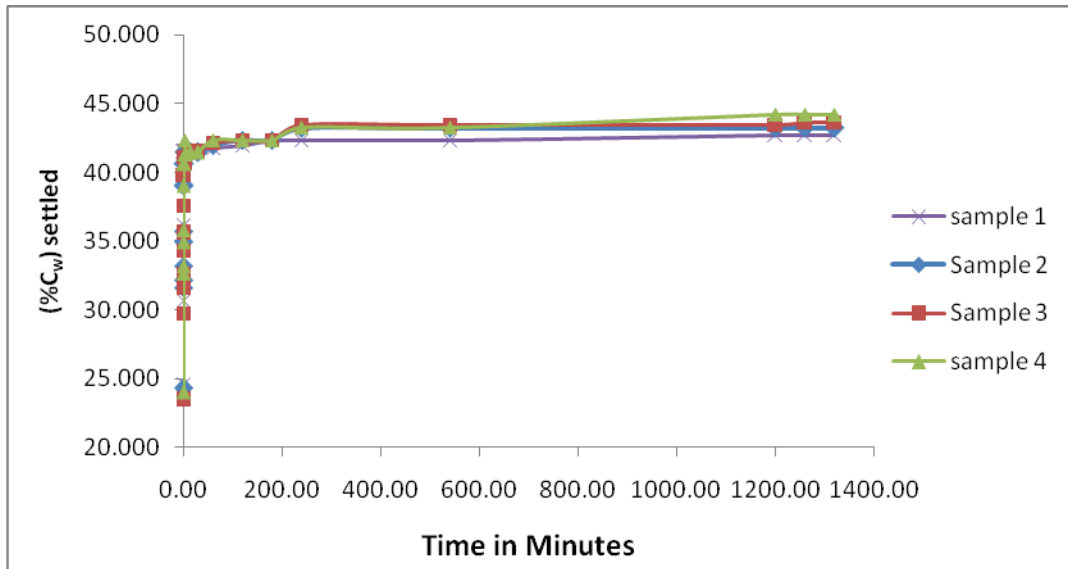


Figure 3.4 :- Static Settling Characteristics of Bottom Ash



Figure :-3.5 Beakers used for Static Settled Conc. of Bottom Ash

3.1.7 P^H VALUE

A pH meter was used for measurement of the pH value of the slurry of any given solid concentration. The electrode of the meter was first moistened with tap water and then calibrated with a buffer solution of a known pH value. It is cleaned by rinsing vigorously with distilled water and then immersed in the slurry sample whose pH value was to be determined. The pH suspension was read on the digital display unit when equilibrium value was reached. The experimental results of ph value of bottom ash are shown in **table 3.3 in (Annexure 3)**

In this test first prepare 7 PH or 4 PH solution dissolve 1 buffer tablet in 100 ml of distilled water. Insert the probe PH meter in the solution and wait for 5 minutes till readings get stabilized. If reading is not equivalent to the PH of solution, then change the control and make the readings equivalent to the PH value of solution. Remove the probe and dip into the distilled water beaker and then dip into the solution or slurry of which PH value is to be determined. Wait for 5 minutes till the reading is stabilized.

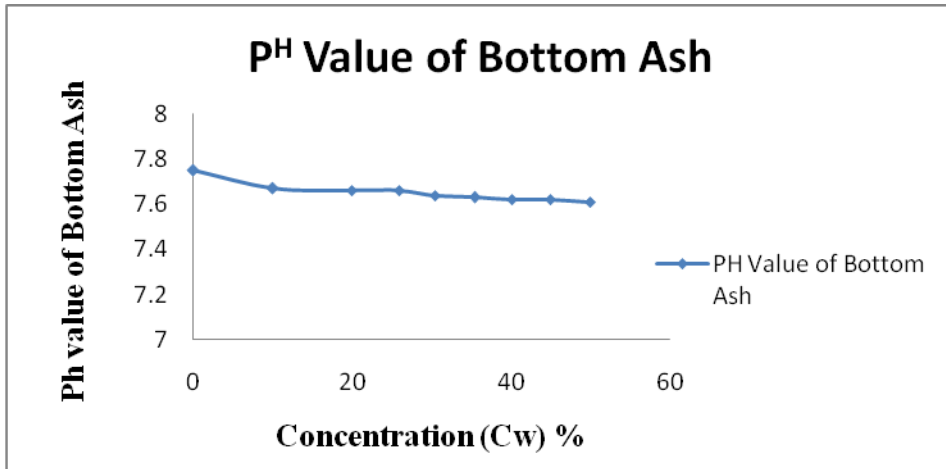


Figure 3.6: - Ph value of bottom ash at different concentration.

3.1.8 Rheological Behavior of Solid-Liquid Mixture

Rheology is the study of the flow of matter: primarily in the liquid state, but also as 'soft solids' or solids under conditions in which they respond with plastic flow rather than deforming elastically in response to an applied force. It applies to substances which have a complex molecular structure, such as muds, sludges, suspensions, polymers and other glass formers (e.g. silicates), as well as many foods and additives, bodily fluids (e.g. blood) and other biological materials.

To predict the level of input energy in transporting slurry through pumps, viscosity measurement is an important aspect. Presence of solid particles alters the viscosity of carrier fluid. Addition of solids in the carrier fluid beyond a certain proportion results in the mixture depicting Non-Newtonian behavior. Therefore the variation of shear stress with shear-rate has been measured for a wide range of concentrations varying from 20 to 40% (by weight) for bottom ash and water slurries to establish the rheology of the mixtures.

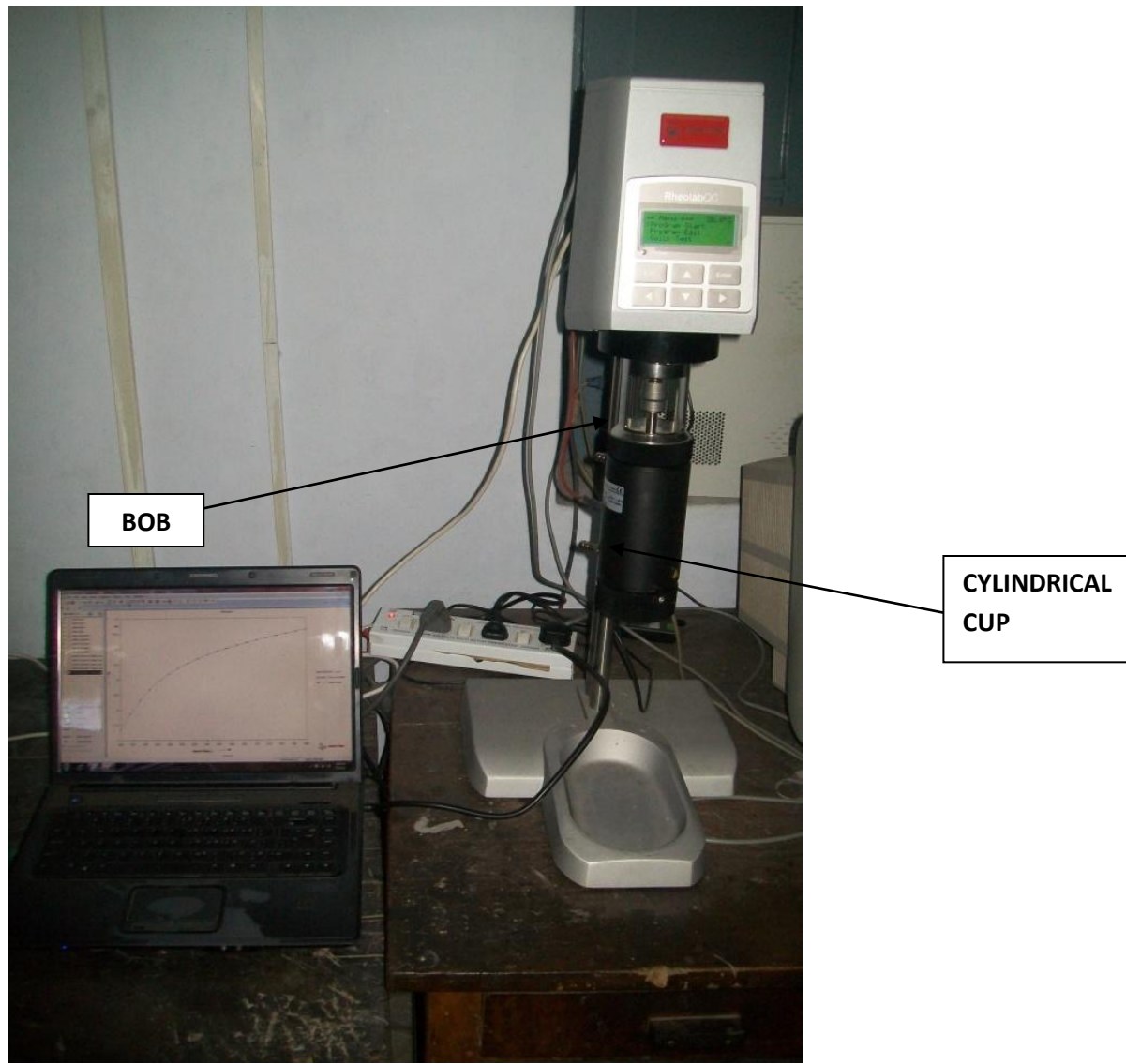


Figure 3.7: Setup of Rheometer

The Rheometer, (Make: Anton Paar, Gurgoan) shown in figure 3.7, is an instrument to measure the viscosity of composite fluids. It comes up with different types of geometries which have to be used depending on the size of particles of the slurry. With us, Double gap geometry has been used for determination of rheological characteristics of the slurries. Slurry is subjected to shear stress with the rotation of the bob immersed in the slurry.

Before conducting tests on rheometer, the bob and cup assembly are kept in line with the geometry, which is done using a locking device and slurry is added into cup (cylinder) up to the particular mark. In this Rheometer, the experiment is done on CSR (controlled shear

rate) in which we input the particular shear rate [s^{-1}] and accordingly get the viscosity of particular concentration. The viscosity, shear stress and shear rate are recorded for each combination of shear rate and particular time intervals. The experimental results of viscosity of bottom ash ..

CHAPTER 4

RHEOLOGICAL STUDIES OF BOTTOM ASH WITH ADDITIVES

Rheology is the study of deformation and the flow of matter under the action of forces. Several investigators have studied the rheology of suspensions of different materials. However no universal correlation for the prediction of the rheological parameters of a suspension is available. This is mainly due to the fact that a large number of factors affect the rheological behaviour of suspension. When a liquid containing solid particles is subjected to shear, additional energy dissipation takes place. This dissipation is dependent on parameter like the rate of shear, the volume fraction of solid particle and other various solids properties. The presence of solid particle in the fluid in variably results in an increase in the viscous resistance of the resulting suspension at the same time it may also result in a change in the character of the liquid from that of a Newtonian fluid to that of a non Newtonian suspension. Bunn et al. 1991; Kumar 2002, Verma 2004 and Seshadri et al. 2005; it is observed that fly ash slurries at higher concentration ($C_w \approx 50\%$, by weight) behave a like non-Newtonian fluid with rheological equation showing Bingham behaviour. They found that the values of yield stress and Bingham plastic viscosity of slurry increases rapidly with increase in concentration. Verma (2004) has reported that the use of de flocculants and soap solution as additives to the fly ash slurries reduces the rheological parameters and can result insubstantial saving in energy consumption.

The thermal power plants in India produce approximately 20% bottom ash of the total ash .The hydraulic transportation of bottom ash mixture slurry is done at a very lean concentration of around 20%.

Due to settling nature of the coarse bottom ash particles the transportation are generally done under turbulent conditions incurring higher pressure drops. Also the anticipated bed load transport of such slurries may not be ignored. These cumulative effects of turbulent flow and bed load transport conditions result in erosion problems requiring frequent replacement of piping and valves thus affecting pipe economics. To avoid such situations, it is conceived in the present study that bottom ash mixture with additive's slurry can be transported hydraulically at higher concentrations under laminar flow conditions without settling of coarse ash particles. In the above context, it is essential to conduct rheological studies of bottom ash with additive mixture slurry at higher concentrations to ascertain the influence of

bottom ash on the flow behaviour of the mixture slurry. For this purpose the rheological studies on fly ash bottom ash mixture were investigated using the fly ash and bottom ash samples procured from the Guru Nanak Dev Thermal Power Plant Bathinda, Punjab.

4.1 RHEOLOGICAL TEST SETUP AND MEASUREMENTS

A rheometer (M/s. Anton Paar) has been used for obtaining the rheological characteristics of the fly ash slurries at various concentrations. It is equipped with a motor and gear box drive unit. The motor used is a three-phase synchronous motor having a rating of 1hp at 415 volts running at 1500 rpm. The gear box provided offers 60 selected speeds in the equal ratio of 1:1.259. The main components of the rheometer are base, main drive, two-way drive box, and column. The column is fitted at the back of the main drive box. It carries the torsion head, the gap-setting transducer, and ancillaries. The control and measuring instruments are mounted in a standard housing. A linear variable differential transducer (LVDT) type transducer measures the tensional displacement of the bar. For tests with slurry, a concentric cylinder type of platen was used. The cylindrical bob (diameter: 50.0276mm and height: 50.3846mm) is attached to a torsion bar and the concentric cup (diameter: 54.9021mm) can be rotated at the desired speed. Due to the rotation of the platen, the slurry undergoes shearing action. For rheumatic tests, 50mL of the suspension was prepared by mixing the required quantity of fly ash with distilled water to obtain the desired concentration (C_w).

An electronic balance with a resolution of 10⁻⁴ gm was used for weighing the materials accurately. The suspension was mixed gently by a glass rod, taking care to avoid attrition of the particles. The complete slurry was poured into the cup. The desired speed of rotation was selected by adjusting the gear ratios. The slurry was well stirred by a glass rod and the bob was quickly lowered into the cup so that the free surface touched the top of the bob. The motor was started and the deflection of the torsion bar was noted through the output of the LVDT-type transducer. Such measurements were made over a wide range of rotational speeds. Between successive readings the bob was raised and the slurry stirred well so that the effect of settling of solids was avoided in the measurements. Measurement at any given speed was repeated to ensure precision of the data. Further, at each concentration, measurements were done on at least two samples of the same material to assess the extent of repeatability. The two sets of data on shear stress at any given shear rate agreed with in 2%

4.2 SAMPLE PREPARATION

The particle size of raw coal sample was initially reduced to less than three cm using jaw crusher and the dryer grounded by the laboratory size disc mill. The discharge space between the two disc of mill was controlled to obtain a suitable product which was tested to obtain a feed sample characterized by whole particle size distribution of 250 microns maximum size. The solid concentration was kept constant at 40% solid by weight in some test and 40% total concentration of solid with additives. The procedure of preparation of all the samples is standardized. Weighted amount of tap water was transferred into 500cm³ glass beaker and then the weighted ash sample was slowly transferred in the beaker. The content was stirred by magnetic stirrer for about 20 to 30%.

Then the beaker was allowed to stand for about 10 hours to ensure the release of entrapped air. Before testing the slurry were always thoroughly mixed by hand shaking, and stirrers to ensure the homogeneity of slurry the same conditions was repeated with this condition also. The selective additive were prepared in the pre determined ratio and dissolved in a little amount of water before adding them to the slurry stabilizers were tested always in conjugation with different dispersants were tested also alone.

4.3 RESULTS AND DISCUSSION

The plots of experimental data in terms of shear stress and shear rate in the range from 0 to 300 s⁻¹ were analyzed for identifying the rheological model. It is seen that the variation of the shear stress with shear rate at all concentrations with and without additives for these fly ash sample follows a straight-line behavior. The straight-line equation is expressed in the form $\tau = \mu \dot{\gamma} + \tau_0$. The straight-line equation was fitted for each set of data, using the method of least squares. It was seen that the values of τ_0 are nonzero for all sets of data. This implies that the fly ash slurry, for the data presented, shows a Newtonian behavior and can be represented by a Bingham plastic model fluid. A typical rheogram of fly ash and bottom slurry from 10% to 40% concentration is shown in Figure given below..

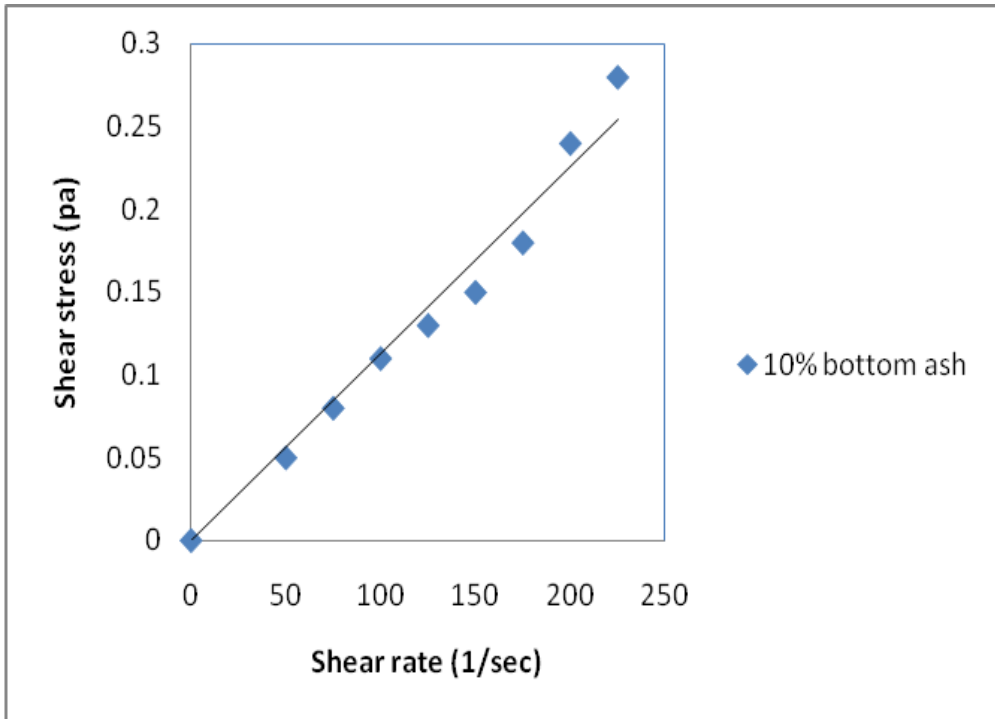


Figure:- 4.1 shear stress vs shear rate of bottom ash at concentration = 10% by weight where ——— Straight line shows Newtonian flow behaviour

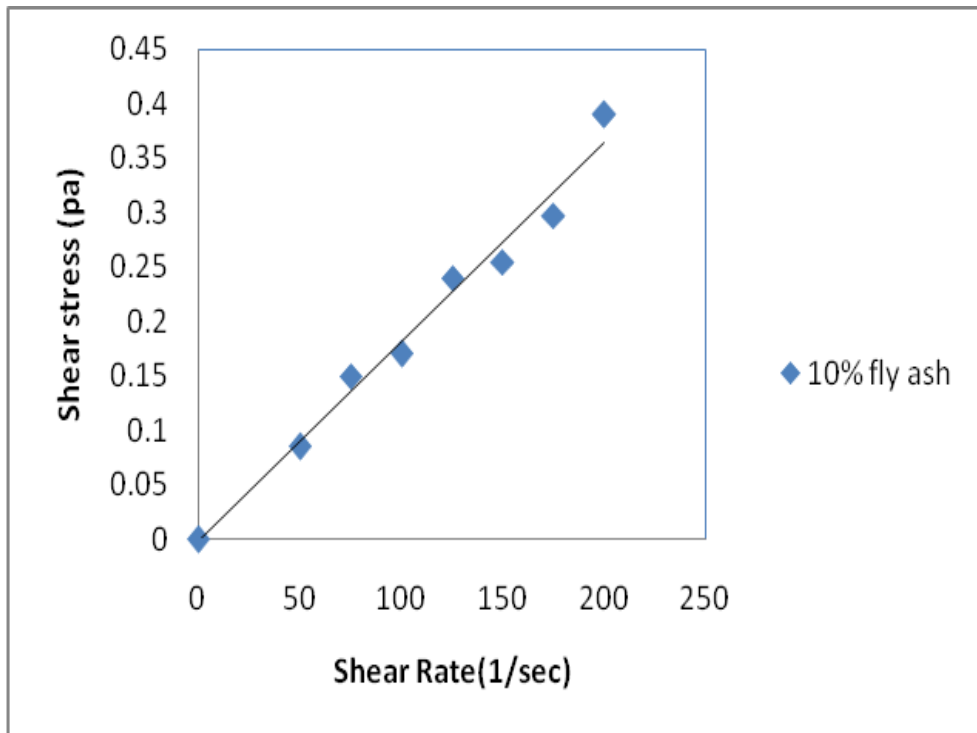


Figure:- 4.2 shear stress vs shear rate of fly ash at concentration = 10% by weight. where ——— Straight line shows Newtonian flow behaviour

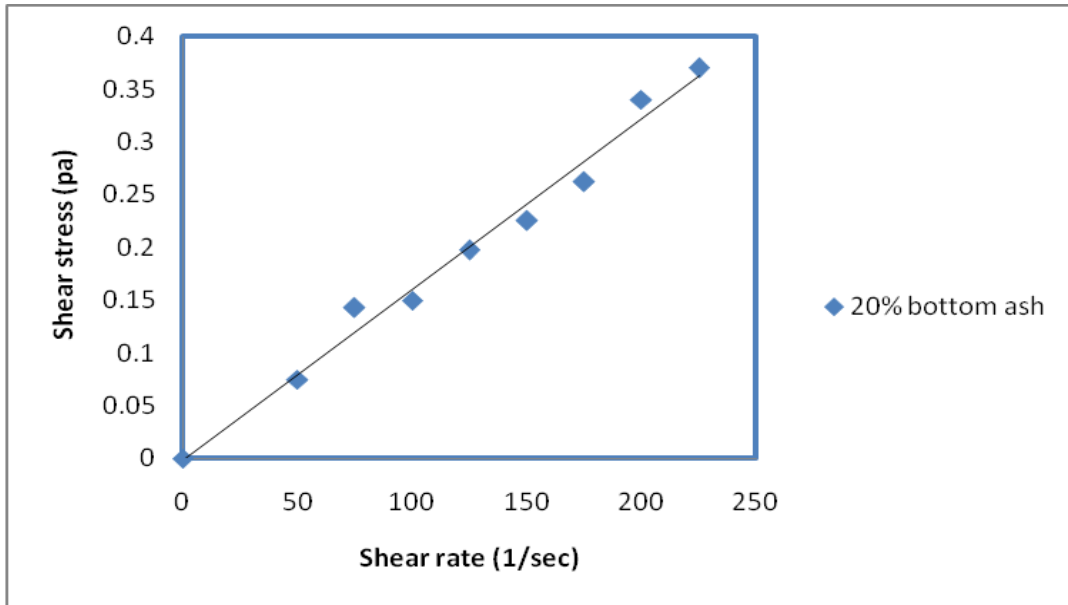


Figure:- 4.3 shear stress vs shear rate of bottom ash at concentration = 20% by weight
 where ——— Straight line shows Newtonian flow behaviour

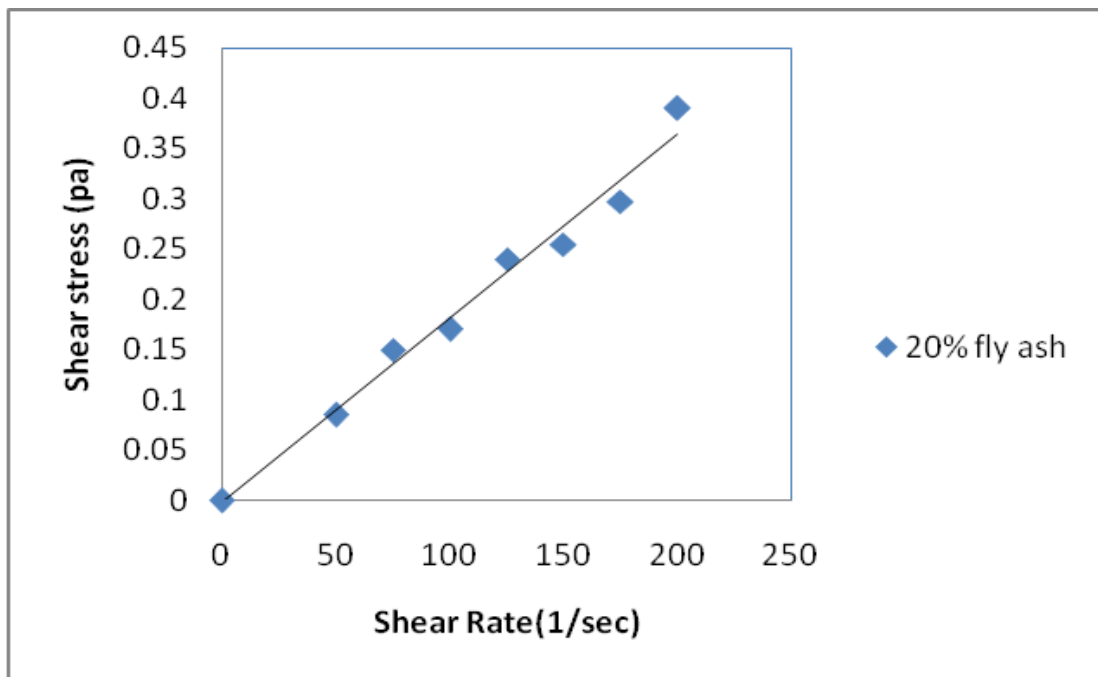


Figure:- 4.4 shear stress vs shear rate of fly ash at concentration = 20% by weight
 where ——— Straight line shows Newtonian flow behaviour

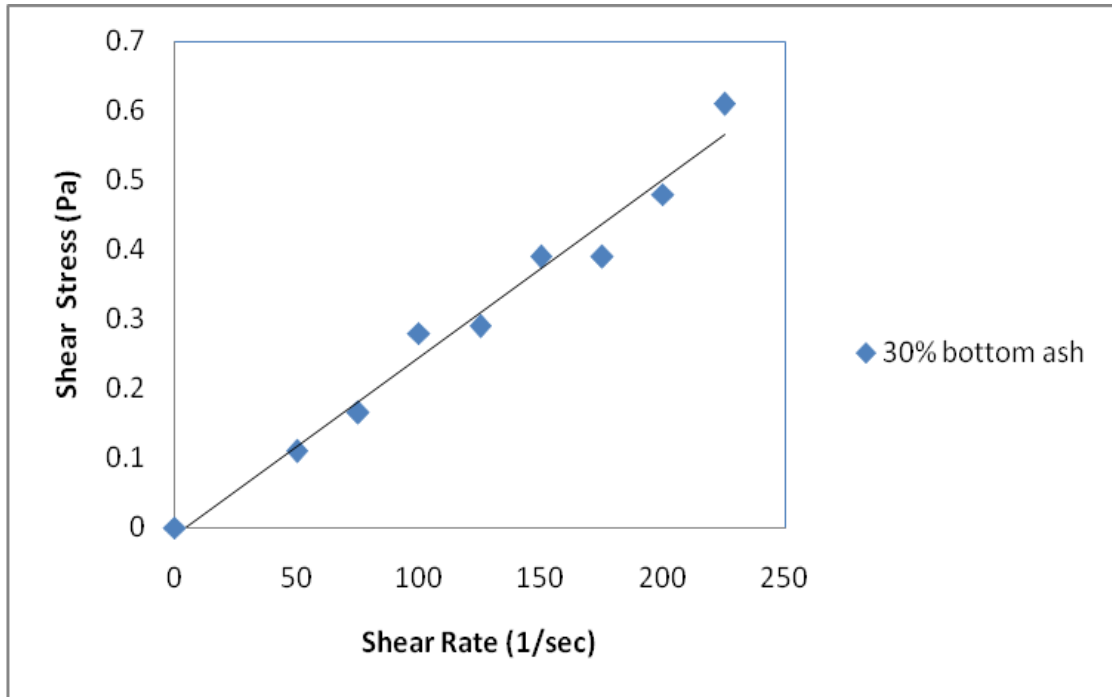


Figure:- 4.5 shear stress vs shear rate of bottom ash at concentration = 30% by weight
 where ——— Straight line shows Newtonian flow behaviour

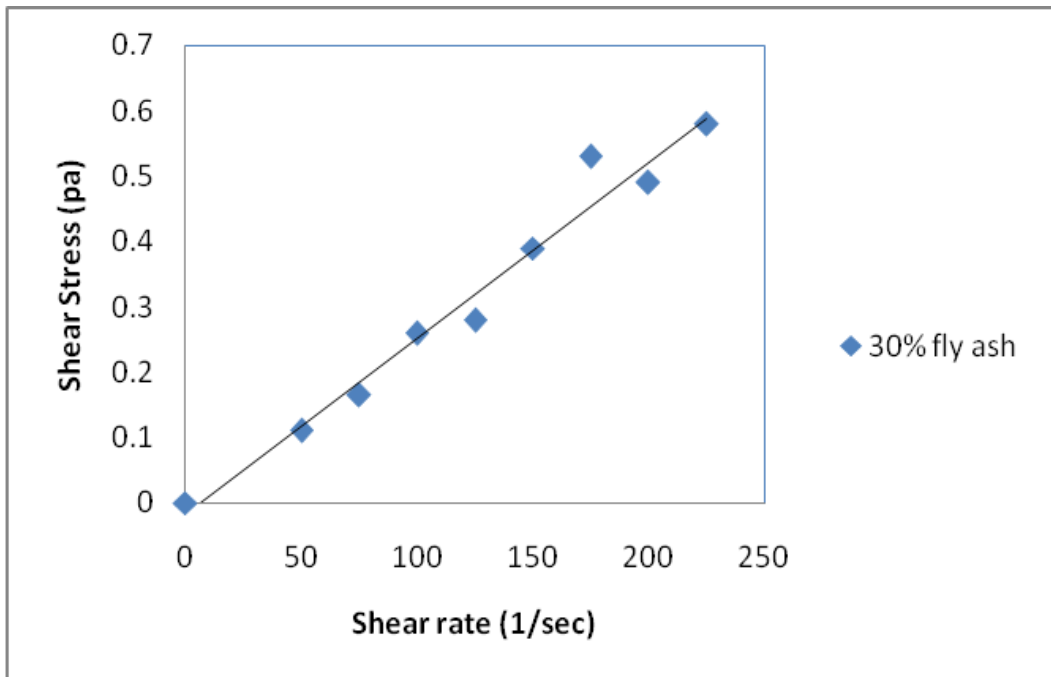


Figure:- 4.6 shear stress vs shear rate of fly ash at concentration = 30% by weight.
 where ——— Straight line shows Newtonian flow behaviour

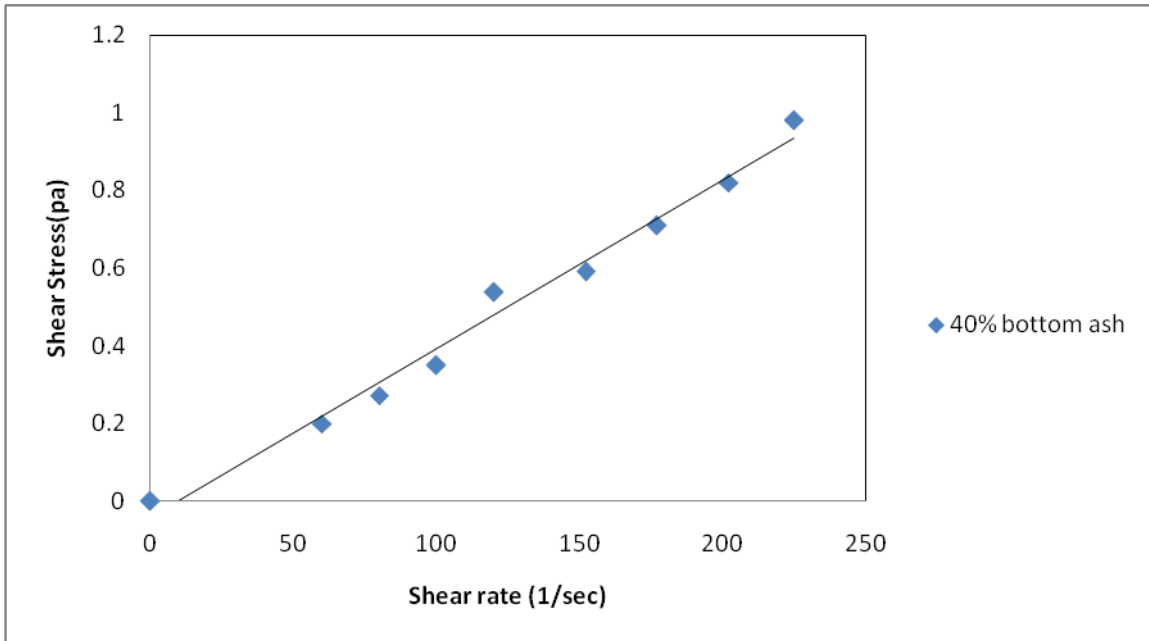


Figure:- 4.7 shear stress vs shear rate of bottom ash at concentration = 40% by weight.
 where ——— Straight line shows Newtonian flow behaviour

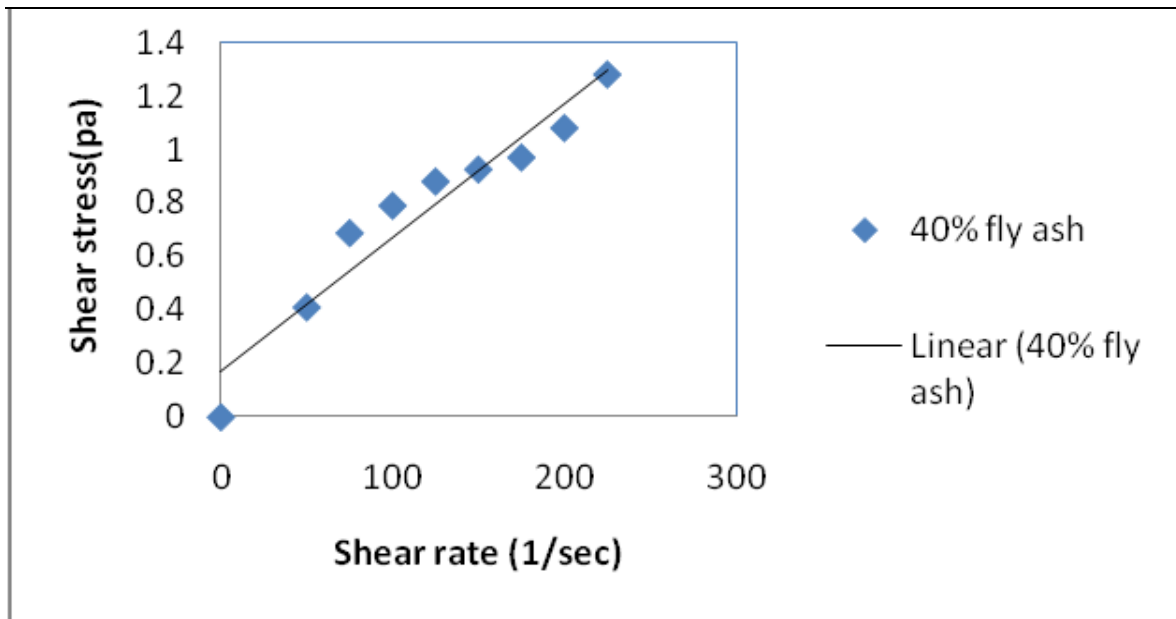


Figure:- 4.8 shear stress vs shear rate of fly ash at concentration = 40% by weight.
 where ——— Straight line shows Newtonian flow behaviour

4.3.1 Effect of Solid Concentration on Slurry Rheology

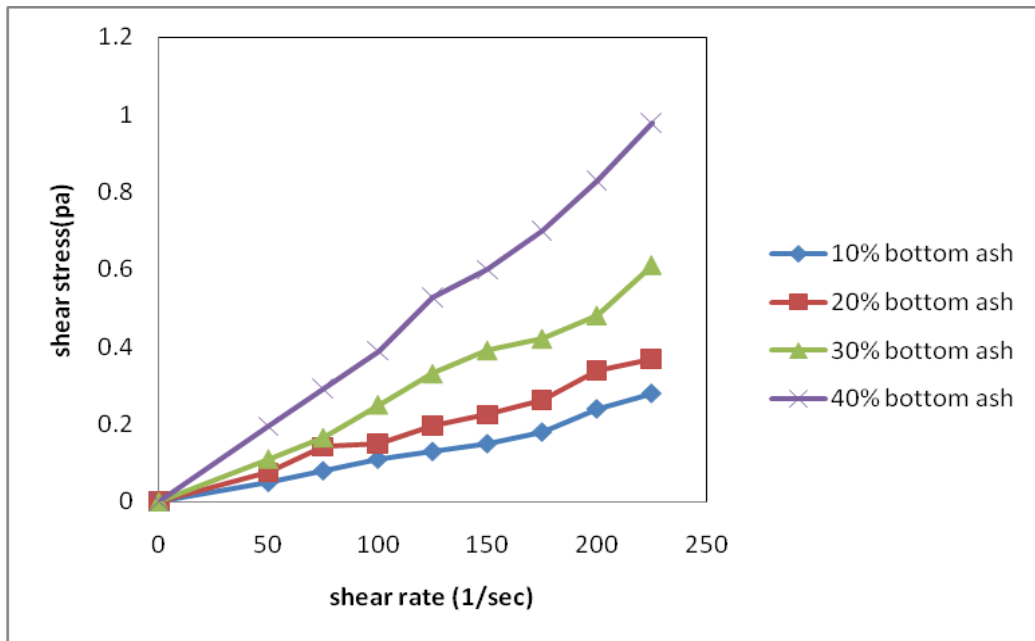


Figure:-4.9 shear stress vs shear rate of bottom ash slurry at different constructions

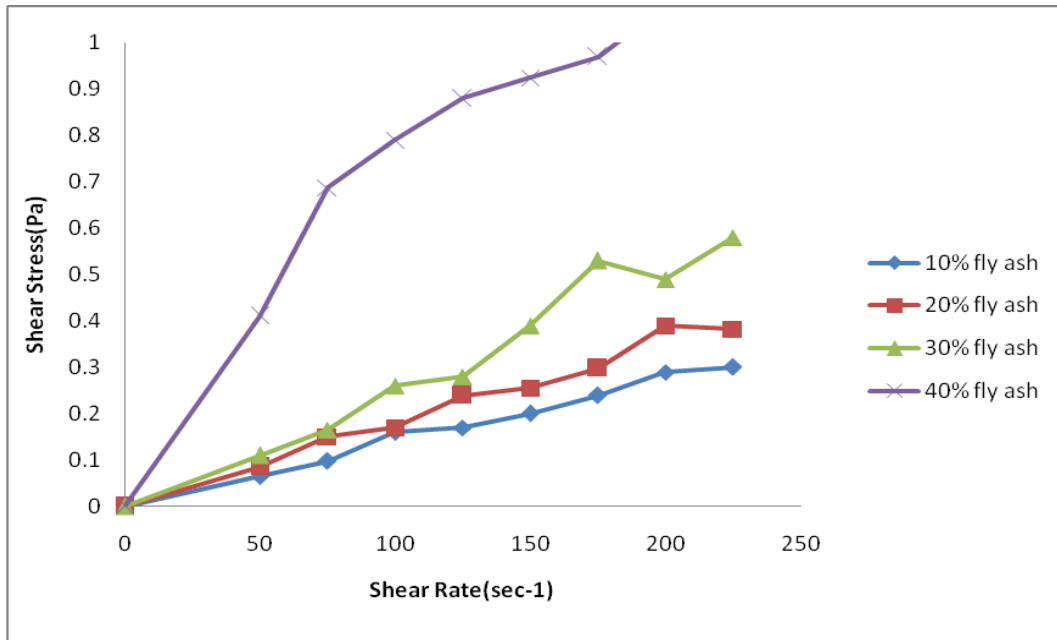


Figure:-4.10 shear stress vs shear rate of fly ash slurry at different constructions

Figure 4.9 and 4.10 we can observe that the shear stress increases with shear rate at different concentration of fly ash varying from 10% to 40 % by weight. The graph shows the Newtonian behavior.

The effect of a mixture of fly ash as additive in the ratio Data shows that decrease in viscosity of the bottom ash 40% and varying fly ash Concentration 10% ,20,30% .

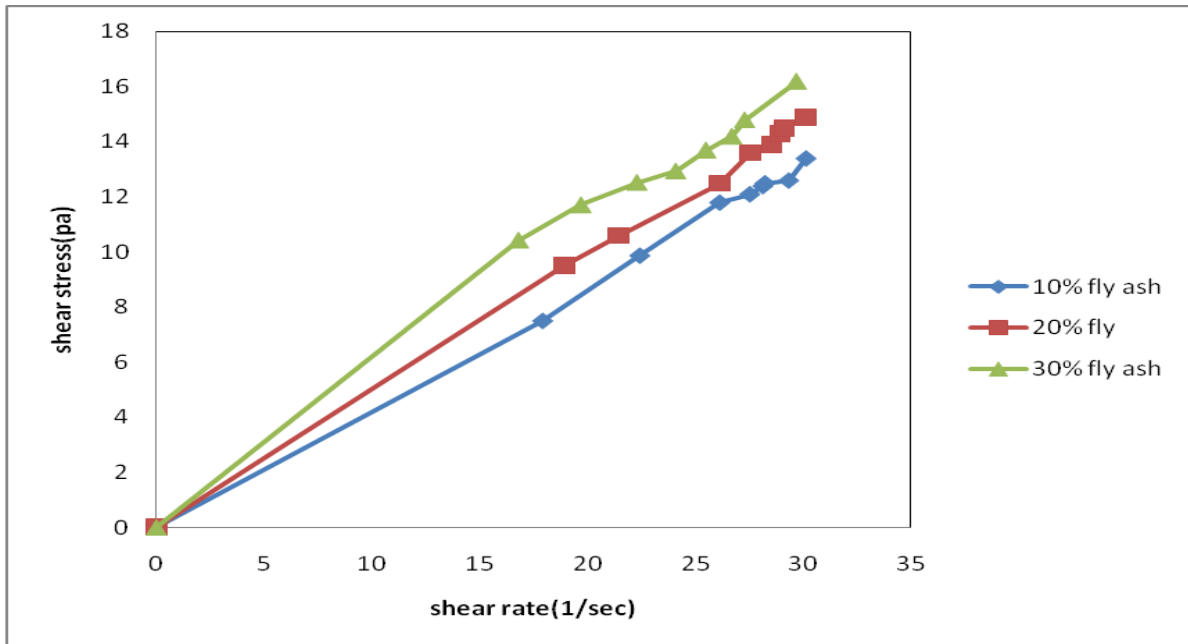


Figure:-4.11 shear stress vs shear rate at different constructions of fly and bottom ash mixture.

4.3.2 Effective of Additive on Bottom Ash Slurry Rheology

The effect of mixture of sodium bicarbonate additive in the ratio of (2,4%.6%,8%,10 % by weight) on viscosity at different concentration data shows a mark decreases in the viscosity of slurry data also shows that the mixture of sodium bi carbonate drastically decreases the shear stress of fly ash slurry. From the result it is observed that mixture of sodium bi carbonate as additive reducer both viscosity and stress of fly ash slurry significantly. The reason behind reduction in viscosity is that in the turbulent flow regime there is a reduction in inter particle friction. From this graph we can see that by increasing the size ratio enhanced the shear thinning character of the suspensions. The viscosity of suspensions increased with the addition of fine particles, imposing some practical limitations in terms of volume fraction of fines that can be added.

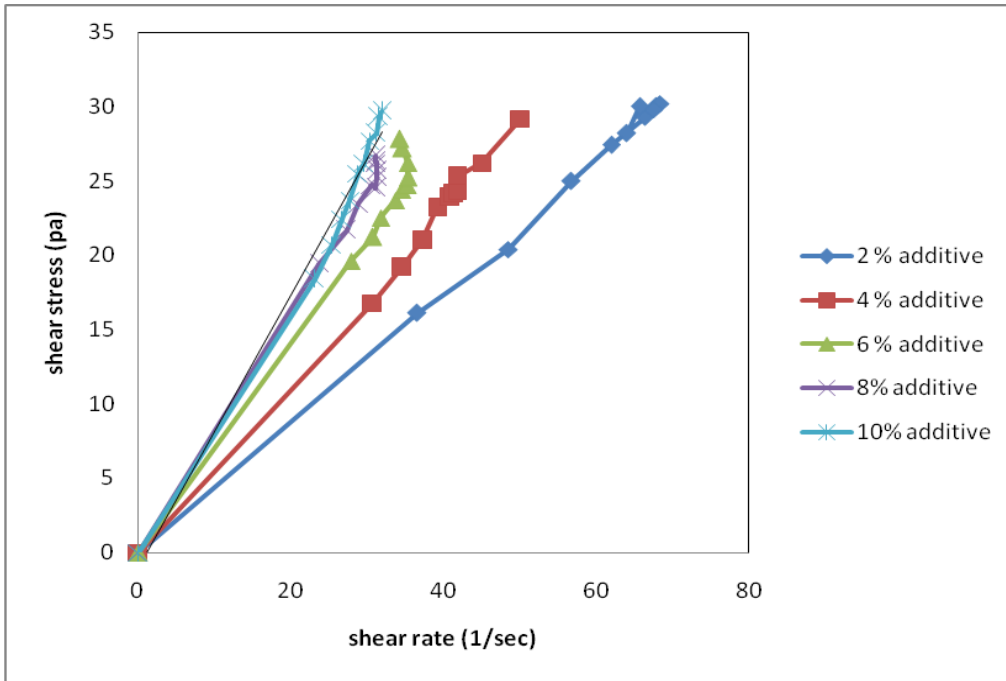


Figure:-4.12 Shear stress vs shear rate at different concentration at additives in 40% concentration of bottom ash.

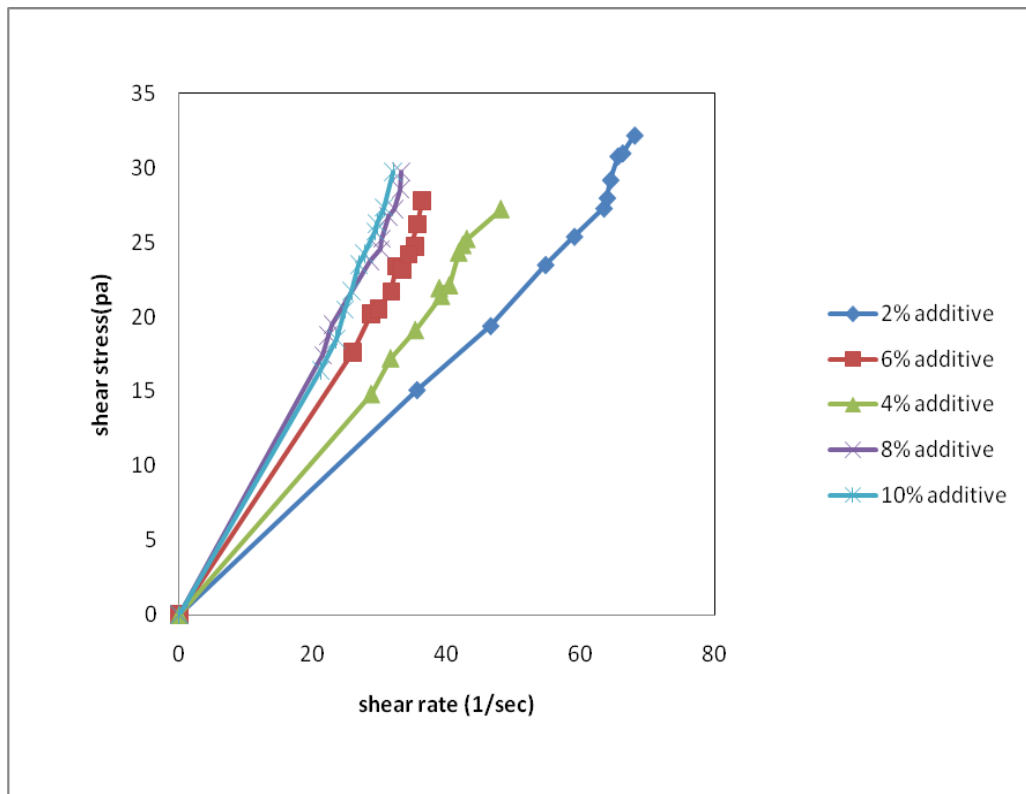


Figure 4.13 Shear stress vs shear rate at different concentration of additives at 30% concentration of bottom ash.

Figure 4.13 and 4.14 shows the nature of the curve for slurry mixture of sodium bicarbonate (additive) in bottom ash at fix concentration from the fig we can observe that viscosity decreases as the concentrations of additive was increased in concentration of bottom ash at 40% and 30%.

CHAPTER 5

RESULT AND DISCUSSION

Slurry pipelines are used to transport solid materials using water or any other liquid as a carrier fluid for short or long distance haulage of bulk materials. These pipelines are used in many industrial applications involving transportation of variety of materials like mineral ores to processing plants, coal to thermal power plants, disposal of waste materials like fly ash, tailings materials etc. to the disposal sites. Slurry pipeline has been accepted as a safe, reliable and attractive mode of solid transportation by various industries, due to its low maintenance, round the year availability and being eco-friendly. One of the most important input data needed for the design of the slurry transportation system is the rheological behaviour of the slurry at various concentrations and flow conditions. If the rheological data is available, it may be used to find the flow rate-pressure drop relationship. Present work is to study the rheological behaviour of bottom ash with additives. A good agreement is observed between experimental. The plots reveal that the viscosity of the suspension increases with increasing solid concentration. Rheological behaviour with addition of fly ash and additive observe that viscosity value decreases. The study indicated that the viscosity is very much sensitive to the concentration of solids.

Future scope

1. The Rheology studies can be performed with fly ash.
2. The computational approach can be used to simulate the similar work with different operating conditions.
3. The different additive studies can be used at same concentration to extended the study.

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Annexure 1

Table 3.1 Experimental Results of Particle Size Distribution of Bottom As

S . N o	Size in (u)	Size in microns	Sam ple 1	Sample 2	Sampl e 3	Sample 4	Average (Wi)	% total	Di	Wi*Di	Dwm
1	below 2000	Above 1400	26	25	28	26	26.25	10.50	600	15750	162.13
2	1400	710-1400	10	10	9	11	10	4.00	690	6900	
3	710	355-710	33	30	35	31	32.25	12.90	355	11448.75	
4	355	300-355	19	20	17	20	19	7.60	55	1045	
5	300	250-300	16	14	16	16	15.5	6.20	50	775	
6	50	212-250	30	30	29	31	30	12.00	38	1140	
7	212	180-212	5	8	6	8	6.75	2.70	32	216	
8	180	150-180	60	56	59	60	58.75	23.50	30	1762.5	
9	150	125-150	8	9	8	7	8	3.20	25	200	
10	125	90-125	9	11	9	10	9.75	3.90	35	341.25	
11	90	75-90	24	30	26	25	26.25	10.50	15	393.75	
12	75	below75	6	4	5	3	4.5	1.80	75	562.5	
		Total	246	247	247	248			600	40534.75	
		Lost	4	3	3	2	3	1.20	690		

Annexure 2

Table 3.2:- Static settled Concentration of Bottom Ash

S. No	Time (min)	(%C _w) settled			
		Sample 1	Sample 2	Sample 3	Sample 4
1	0.166666667	24.622	24.323	23.466	24.030
2	0.333333333	30.662	31.632	29.749	32.665
3	0.5	32.665	32.140	31.632	32.665
4	0.666666667	33.768	33.207	32.665	33.207
5	0.833333333	34.348	34.948	34.348	34.948
6	1	36.213	35.696	35.569	35.824
7	1.166666667	40.627	39.041	37.574	39.041
8	2 Min	41.470	40.627	39.818	40.627
9	3 Min	41.470	41.470	40.627	42.348
10	4 Min	41.470	41.470	41.129	41.298
11	5 Min	41.470	41.470	41.129	41.298
12	15 min	41.470	41.470	41.470	41.470
13	30 min	41.470	41.470	41.470	41.470
14	60 min	41.816	41.992	42.169	42.348
15	120 min	41.992	42.348	42.348	42.348
16	180 min	42.348	42.348	42.348	42.348
17	240 min	42.348	43.264	43.452	43.264
18	540 min	42.348	43.264	43.452	43.264
	Maximum static settled conc. (%C _w)	42.709	43.264	43.641	44.220

Annexure 3

Table 3.3: - Ph value of Bottom Ash at different Concentration

Sr. No	Weight of bottom ash (gms)	Weight of water (gms)	Concentration. (%)	PH Value
1	0	100	0	7.75
2	25	100	20	7.67
3	35	100	25.9	7.66
4	44	100	30.5	7.66
5	55	100	35.4	7.64
6	67	100	40.1	7.63
7	82	100	45	7.62
8	100	100	50	7.62

Annexure 4

Table 4.1 Rheology of bottom ash concentration 10 % by weight

temp	concentration. bottom	viscosity	shear rate	Shera stress
			0	0
26	10	0.00102	50	0.05
26	10	0.00102	75	0.08
26	10	0.00102	100	0.11
26	10	0.00102	125	0.13
26	10	0.00102	150	0.15
26	10	0.00102	175	0.18
26	10	0.00102	200	0.24
26	10	0.00102	225	0.28

Annexure 5

Table 4.2 Rheology of bottom ash concentration 20 % by weight

temp	concentration	viscosity	shear rate	Shear stress
			0	0
26	20	0.0015	50	0.075
26	20	0.0015	75	0.1425
26	20	0.0015	100	0.15
26	20	0.0015	125	0.1975
26	20	0.0015	150	0.225
26	20	0.0015	175	0.2625
26	20	0.0015	200	0.34
26	20	0.0015	225	0.37

Annexure 6

Table 4.3 Rheology of bottom ash concentration 30 % by weight

temp	concentration	viscosity	shear rate	Shear stress
			0	0
26	30	0.0022	50	0.11
26	30	0.0022	75	0.165
26	30	0.0022	100	0.25
26	30	0.0022	125	0.33
26	30	0.0022	150	0.39
26	30	0.0022	175	0.42
26	30	0.0022	200	0.48
26	30	0.0022	225	0.61

Annexure 7

Table 4.4 Rheology of bottom ash concentration 40 % by weight

temp	concentration	viscosity	shear rate	Shear stress
			0	0
26	40	0.0039	50	0.195
26	40	0.0039	75	0.2925
26	40	0.0039	100	0.39
26	40	0.0039	125	0.5275
26	40	0.0039	150	0.6
26	40	0.0039	175	0.7
26	40	0.0039	200	0.83
26	40	0.0039	225	0.98

Annexure 8

Table 4.5 Rheology of bottom ash concentration 30 % & fly ash concentration 10% by weight

temp	concentration bottom	concentration fly	viscosity	shear rate	shear stress
	0	0	0	0	0
26	30	10	100	17.9	7.5
26	30	10	110	22.4	9.87
26	30	10	121	26.1	11.8
26	30	10	132	27.5	12.1
26	30	10	142	28.1	12.4
26	30	10	153	28.2	12.5
26	30	10	163	29.3	12.6
26	30	10	174	30.1	13.4

Annexure 9

Table 4.6 Rheology of bottom ash concentration 20 % & 20% fly by weight

temp	concentration bottom	concentration fly	viscosity	shear rate	shear stress
	0		0	0	0
26	20	20	100	18.9	9.5
26	20	20	110	21.4	10.6
26	20	20	121	26.1	12.5
26	20	20	132	27.5	13.6
26	20	20	142	28.5	13.9
26	20	20	153	28.9	14.3
26	20	20	163	29.1	14.5
26	20	20	174	30.1	14.9

Annexure 10

Table 4.7 Rheology of bottom ash concentration 10 % & fly 30% by weight

temp	concentration bottom	concentration fly	viscosity	shear rate	shear stress
	0		0	0	0
26	10	30	100	16.8	10.43
26	10	30	110	19.7	11.71
26	10	30	121	22.3	12.53
26	10	30	132	24.1	12.94
26	10	30	142	25.5	13.7
26	10	30	153	26.7	14.2
26	10	30	163	27.3	14.8
26	10	30	174	29.7	16.2

Annexure 11

Table 4.8 Rheology of bottom ash concentration 40 % with 2 % by weight

temp	concentration bottom	concentration additive	viscosity	shear rate	shear stress
	0		0	0	0
26	40	2	99.9	36.5	16.1
26	40	2	111	48.5	20.4
26	40	2	121	56.7	25
26	40	2	132	62	27.4
26	40	2	142	66.4	29.3
26	40	2	153	67.9	30
26	40	2	163	68.4	30.2
26	40	2	174	67.5	29.8
26	40	2	184	65.7	30
26	40	2	195	64	28.2

Annexure 12

Table 4.9 Rheology of bottom ash concentration 40 % with additive 4% by weight

temp	bottom concentration	concentration additive	viscosity	shear rate	shear stress
	0		0	0	0
26	40	4	100	30.7	16.8
26	40	4	110	34.6	19.2
26	40	4	121	37.3	21
26	40	4	132	39.2	23.2
26	40	4	142	40.9	23.9
26	40	4	153	41.4	24.1
26	40	4	163	41.8	24.3
26	40	4	174	41.8	25.3
26	40	4	184	45	26.2
26	40	4	195	50.1	29.2

Annexure 13

Table 4.10 Rheology of bottom ash concentration 40 % & additive 6% by weight

temp	concentration bottom	concentration additive	viscosity	shear rate	shear stress
	0		0	0	0
26	40	6	100	27.9	19.6
26	40	6	110	30.7	21.2
26	40	6	121	31.8	22.5
26	40	6	132	33.7	23.7
26	40	6	142	34.5	24.4
26	40	6	153	35.2	24.7
26	40	6	163	35.3	25.2
26	40	6	174	35.3	26.2
26	40	6	184	34.6	27.2
26	40	6	195	34.3	27.8

Annexure 14

Table 4.11 Rheology of bottom ash concentration 40 % & additive 8% by weight

temp	concentration bottom	concentration additive	viscosity	shear rate	shear stress
	0		0	0	0
26	40	8	99.9	23.7	19.4
26	40	8	111	27.3	21.7
26	40	8	121	28.9	23.45
26	40	8	132	30.6	24.7
26	40	8	142	31.1	24.5
26	40	8	153	31.3	25.2
26	40	8	163	31.3	25.7
26	40	8	174	31.2	26.2
26	40	8	184	31.1	26.3
26	40	8	195	31.1	26.7

Annexure 15

Table 4.12 Rheology of bottom ash concentration 40 % & additive 10% by weight

temp	Concentratin bottom	Concentratin additive	viscosity	shear rate	shear stress
	0		0	0	0
26	40	10	100	23.1	18.4
26	40	10	110	25.4	20.7
26	40	10	121	26.7	22.45
26	40	10	132	27.7	23.7
26	40	10	142	28.8	25.5
26	40	10	153	29.6	26.2
26	40	10	163	30.3	27.7
26	40	10	174	31.2	28.2
26	40	10	184	31.5	29.3
26	40	10	195	31.9	29.7

Annexure 16

Table 4.13 Rheology of bottom ash concentration 30 % & additive 2% by weight

temp	concentration additive	concentration bottom	viscosity	shear rate	shear stress
			0	0	0
26	2	30	99.9	35.5	15.1
26	2	30	111	46.5	19.4
26	2	30	121	54.7	23.5
26	2	30	132	59	25.4
26	2	30	142	63.4	27.3
26	2	30	153	63.9	28
26	2	30	163	64.4	29.2
26	2	30	174	65.5	30.8
26	2	30	184	66.2	31
26	2	30	195	68	32.2

Annexure 17

Table 4.14 Rheology of bottom ash concentration 30 % & additive 4 % by weight

temp	concentration additive	concentration bottom	viscosity	shear rate	shear stress
			0	0	0
26	4	30	100	28.7	14.8
26	4	30	110	31.6	17.2
26	4	30	121	35.3	19.1
26	4	30	132	39.2	21.4
26	4	30	142	38.9	21.9
26	4	30	153	40.4	22.1
26	4	30	163	41.8	24.3
26	4	30	174	42.4	24.8
26	4	30	184	43	25.2
26	4	30	195	48.1	27.2

Annexure 18

Table 4.15 Rheology of bottom ash concentration 30 % & fly 6% by weight

temp	concentration additive	concentration bottom	viscosity	shear rate	shear stress
			0	0	0
26	6	30	100	25.9	17.6
26	6	30	110	28.7	20.2
26	6	30	121	29.8	20.5
26	6	30	132	31.7	21.7
26	6	30	142	32.5	23.4
26	6	30	153	35.2	24.7
26	6	30	163	33.3	23.2
26	6	30	174	34.3	24.2
26	6	30	184	35.6	26.2
26	6	30	195	23	26.5

Annexure 19

Table 4.16 Rheology of bottom ash concentration 30 % additive 8% by weight

temp	concentration additive	concentration bottom	viscosity	shear rate	shear stress
			0	0	0
26	8	30	99.9	21.5	17.4
26	8	30	111	22.3	18.7
26	8	30	121	22.9	19.45
26	8	30	132	28.6	23.7
26	8	30	142	30.1	24.5
26	8	30	153	30.3	25.2
26	8	30	163	31.3	26.7
26	8	30	174	32.2	27.2
26	8	30	184	33.1	28.5
26	8	30	195	33.2	29.7

Annexure 20

Table 4.16 Rheology of fly ash concentration 10 % by weight

temp	concentration fly ash	viscosity	shear rate	Shear stress
			0	0
26	10	0.0013	45	0.065
26	10	0.0013	75	0.0975
26	10	0.0013	100	0.16
26	10	0.0013	125	0.17
26	10	0.0013	400	0.2
26	10	0.0013	175	0.24
26	10	0.0013	200	0.29
26	10	0.0013	225	0.3

Annexure 21

Table 4.16 Rheology of fly ash concentration 20 % by weight

temp	concentration fly	viscosity	shear rate	Shear stress
			0	0
26	20	0.0017	50	0.085
26	20	0.0017	75	0.15
26	20	0.0017	100	0.17
26	20	0.0017	125	0.24
26	20	0.0017	150	0.255
26	20	0.0017	175	0.2975
26	20	0.0017	200	0.39
26	20	0.0017	225	0.3825

Annexure 22

Table 4.16 Rheology of fly ash concentration 30 % by weight

temp	concentration fly	viscosity	shear rate	Shear stress
			0	0
26	30	0.0022	50	0.11
26	30	0.0022	75	0.165
26	30	0.0022	100	0.26
26	30	0.0022	125	0.28
26	30	0.0022	150	0.39
26	30	0.0022	175	0.53
26	30	0.0022	200	0.49
26	30	0.0022	225	0.58

Annexure 23

Table 4.16 Rheology of fly ash concentration 40 % by weight

temp	Concentration fly	viscosity	shear rate	Shear stress
			0	0
26	40	0.0053	50	0.41
26	40	0.0053	75	0.6875
26	40	0.0053	100	0.79
26	40	0.0053	125	0.88
26	40	0.0053	150	0.925
26	40	0.0053	175	0.97
26	40	0.0053	200	1.08
26	40	0.0053	225	1.28