

**RHEOLOGICAL INVESTIGATION OF COAL WATER SLURRIES  
WITH AND WITHOUT ADDITIVE**

*A Thesis Report Submitted  
in partial fulfillment of the requirements for  
the award of degree of*

**MASTER OF ENGINEERING  
IN  
THERMAL ENGINEERING**

**Submitted by**

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**July 2012**

## DECLARATION

I hereby certify that the work which is being presented in the report entitled, "RHEOLOGICAL INVESTIGATION OF COAL WATER SLURRIES WITH AND WITHOUT ADDITIVE" in partial fulfillment of the requirements for the award of degree of Master of Engineering in Mechanical Engineering with specialization in THERMAL ENGINEERING submitted in Mechanical Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Mr. Satish Kumar and refers other researcher's works which are duly listed in the reference section.

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

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## **ABSTRACT**

Coal Water Slurries (CWS) are concentrated suspensions of coal particles in water and are used as fluid fuels. The rheological properties of Coal Water Slurries depend on a number of factors such as the type of coal, the solid content and its size distribution, the temperature, the pH and the presence of electrolytes and chemical additives. In the present study rheological behavior of Indian coal water slurry (CWS) was investigated using an Anton Parr RheolabQC rheometer. The objective of the current work was to determine the effect of concentration, particle size and additive on the rheological behaviour of coal water slurries. It is observed that the coal water slurry exhibits shear thinning/thickening effects at low concentrations while at 50% Cw and above the slurry prepared from both coal samples consistently shows shear thinning behaviour. The slurry prepared from finer coal particles (53-75 $\mu$ m) is more viscous as compared to coarser particles (75-106 $\mu$ m) for a given coal slurry sample at all concentrations. The increase of viscosity is found to be exponential with concentration. The viscosity is significantly affected by surfactant Triton X-100 which is observed to lower the viscosity at all selected dosages (i.e.: 0.5%-2.4% by weight of slurry). The optimal dosage is 1.5% of additive by weight of slurry. The maximum reduction in viscosity is about half at 1.5% additive dosage at 50% Cw of slurry. From work on surfactant loading it can be concluded that it might be possible to produce pumpable coal slurries at concentrations of 50% and above by adding suitable dispersant/additive at optimal dosage.

# INDEX

<b>Contents</b>	<b>Page No.</b>
DECLARATION	ii
ACKNOWLEDGEMENT	iii
ABSTRACT	iv
Chapter 1:INTRODUCTION	1
1.1:Rheometry	1
1.2:Slurry	3
1.3:Viscosity Measurement	5
1.4:Rheology Measurement	7
1.5:Rheological properties of fluids	9
1.6:Coal and its types	11
1.7:Coal Water Slurry Fuels	12
1.8: Role of slurry rheology in slurry transportation system	14
Chapter 2:LITERATURE REVIEW	16
2.1: Rheology And Pipeline Transportation Studies On Coal And Coal Ash Slurries	16
2.2: Rheology And Pipeline Transportation Studies Of Coal And Coal Ash Slurries In The Presence Of Chemicals/Surfactants	20
Chapter 3:STUDY ON PROPERTIES OF COAL AND COAL WATER SLURRIES	23
3.1: Physical/Chemical Properties Of Coal	23
3.2: Rheological Behaviour Of Coal Water Slurries	28
Chapter 4: RHEOLOGY STUDY OF COAL SLURRIES WITH ADDITIVE	34
4.1: Surfactants	34
4.2: Effect of Triton X-100 on Coal Water Slurry Rheology	37
Chapter 5: CONCLUSION AND FUTURE SCOPE	39
REFERENCES	40
ANNEXURE	42

## LIST OF FIGURES

<b>Figure No.</b>	<b>Item Description</b>	<b>Page No.</b>
1.1	Sliding of two plates over each other	1
1.2	Plot of (a) shear rate vs. shear stress (b) shear rate vs. viscosity For Newtonian fluids	2
1.3	Shear Stress vs. Shear Rate for different fluids	3
1.4	Homogeneous mixture	4
1.5	Pseudo homogeneous mixture	4
1.6	Heterogeneous mixture, partially stratified	5
1.7	Heterogeneous mixture, fully stratified	5
1.8	U-Tube Viscometer	5
1.9	Falling sphere viscometer	6
1.10	Piston Viscometer	7
1.11	Rheometer with measuring system	8
1.12	Newtonian flow behaviour	10
1.13	Flow and Viscosity Curves	10
3.1	Particle size distribution for coal A and B	23
3.2	S.E.M image of coal A	25
3.3	S.E.M image of coal B	25
3.4	Spectrum 1 for E.D.S of coal A	26
3.5	Portion selected for EDS analysis of coal B	27
3.6	Rheometer setup	28
3.7	Cylindrical cup and rotating Bob	28
3.8	Coal A and B at 10% Cw for particle size 53-75 $\mu$ m and 75-106 $\mu$ m(Rheogram)	29
3.9	Coal A and B at 20% Cw for particle size 53-75 $\mu$ m and 75-106 $\mu$ m(Rheogram)	29
3.10	Coal A and B at 30% Cw for particle size 53-75 $\mu$ m and 75-106 $\mu$ m(Rheogram)	30
3.11	Coal A and B at 40% Cw for particle size 53-75 $\mu$ m and 75-106 $\mu$ m(Rheogram)	30

3.12	Coal A and B at 50% C <sub>w</sub> for particle size 53-75μm and 75-106μm(Rheogram)	31
3.13	Viscosity Vs concentration (53-75μm)	32
3.14	Viscosity Vs concentration (75-106μm)	32
4.1	Surface-Active Agent or Surfactant	34
4.2	Surfactant classification according to the Head: nonionic,anionic,cationic,amphoteric	35
4.3	Triton X-100	36
4.4	Coal A (40% C <sub>w</sub> )with Additive	37
4.5	Coal A(50%C <sub>w</sub> ) with Additive	38

# CHAPTER 1

## INTRODUCTION

### 1.1 RHEOMETRY

Rheometry refers to a set of standard techniques that are used to experimentally determine rheological properties of materials (fluid or solid). The idea underpinning rheometry is to realize flows, where the stress and/or strain fields are known in advance, which make it possible to deduce rheological properties from measurement of flow Properties.

A rheometer is usually an instrument, which can exert a torque/force on a material and accurately measures its response with time (or conversely, it can impose a strain and measures the resulting torque).

**Shear:** viscosity is 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. The greater the friction the greater the amount of force required to cause this movement which is called shear. Shearing occurs whenever the liquid require more force to move than less viscous liquids.

If we have two parallel planes of fluid of equal area they are separated by a distance  $dx$  and are moving I the same direction at different velocities  $v_1$  and  $v_2$ .The force required to maintain this difference in velocities is proportional to the difference in speed through the liquid, or the velocity gradient:

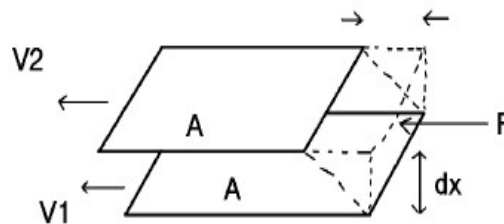


Fig. 1.1: sliding of two plates over each other

**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 experience and is called shear rate –  $R$  and its units of measure is called reciprocal second ( $\text{sec}^{-1}$ ).

**Shear Stress:** The term  $f/a$  indicates the force per unit area required the shearing action and It is called shear stress- $S$  and its unit is  $\text{N/m}^2$ . 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 rate  $R$  and the fluid's viscosity at a varying shear rate  $R$ . Typical newtonian fluids include water and thin motor oils.

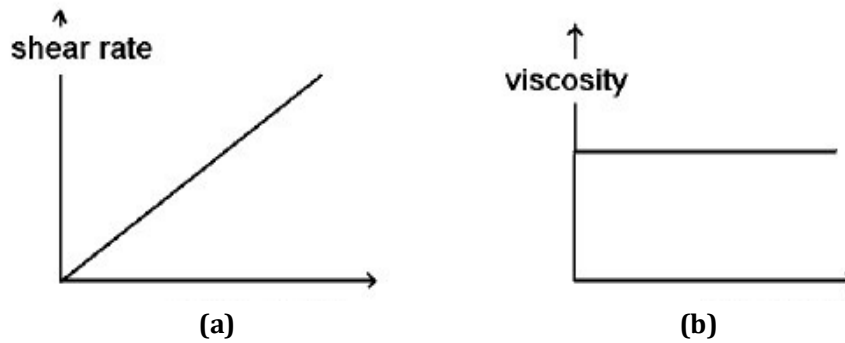


Fig.1.2: Plot of (a) shear rate vs. shear stress (b) shear rate vs. viscosity For Newtonian fluids.

So, at a given temperature the viscosity of a newtonian fluid remains constant regardless of which rheometer model, spindle or speed is used to measure it.

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

1. The only stress generated in simple shear flow is the shear stress  $S$ , the two normal stress differences are zero.
2. The shear viscosity doesn't vary with shear rate.
3. 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 viscosity measured in different types of deformation is always in simple proportion to one another. A fluid showing any deviation from the above features is called non-newtonian.

**Non-Newtonian Fluids:** A non-newtonian fluids is defined as one for which the relationship  $S/\dot{\gamma}$  is not constant. The viscosity of non-newtonian fluids changes as the shear rate is varied. Thus, the parameter of rheometer model, spindle and rotational speed has 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.

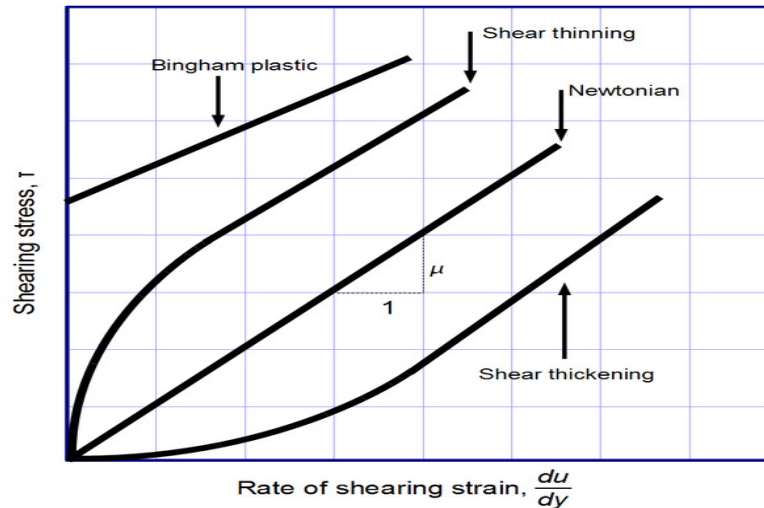


Fig.1.3: shear Stress vs. Shear Rate for different fluids

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.

## 1.2 SLURRY

The mixture of solids and liquids is known as slurry. The physical characteristics of slurry are dependent on many factors such as particle size and distribution, solid concentration in the liquid phase, turbulence level, temperature, conduit size, and viscosity of the carrier. Slurry is a mixture of a solid particles and fluid held in suspension. Water is the most commonly used fluid. Theoretically, for laminar to a turbulent flow a single-phase liquid of low absolute (or dynamic) viscosity can be allowed to flow at slow speeds. However, slurry which is two-phase mixture must overcome a deposition critical velocity or a viscous transition critical velocity. The speed of slurry flow is sufficiently high to maintain the particles in suspension. The mixture resists the flow in highly viscous mixtures because of excessively low shear rate in the pipeline.

### Slurry parameters:

**Particle size and distribution Particle size ( $d_{85}$ ):** is a measure of the percentage of particles in the slurry with a certain size or smaller. The value is determined by sifting the solids through screens with varying mesh and then weighing each fraction. A sieve curve can then be drawn and the percentage of particles of different sizes read. Ex:  $d_{85} = 3$  mm means that 85% of the particles have a diameter of 3 mm or less.

**Mass fraction of small particles:** It is defined as the fraction of particles smaller than 75  $\mu\text{m}$ . It is important to determine the percentage of small particles in the slurry. Particles smaller than 75  $\mu\text{m}$  can to some extent facilitate the transport of larger particles. However, if the percentage of particles smaller than 75  $\mu\text{m}$  exceeds 50%, the character of the slurry changes towards non-settling.

**Concentration of solids:** The concentration of particles in the slurry can be measured as a volume percentage,  $C_v$  (i.e volume of solids to the volume of carrier fluid) and a weight percentage,  $C_m$  (i.e mass of solids/mass of carrier fluid).

**Slurry characteristics:** Slurries can be divided up into **settling** and **non settling** types, depending on the parameters

**Non-settling slurry:** Slurry in which the solids do not settle to the bottom, but remain in suspension for a long time. A non-settling slurry acts in a homogeneous, viscous manner, but the characteristics are non-newtonian. Particle size: less than 60-100  $\mu\text{m}$ . Non-settling slurry can be defined as a homogeneous mixture (A mixture of solids and liquid in which the solids are uniform)

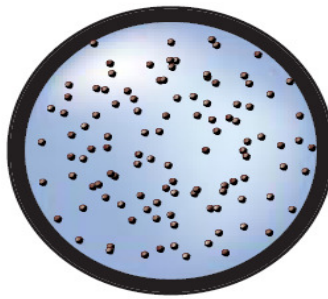


Fig1.4: Homogeneous mixture

**Settling slurry:** This type of slurry settles fast during the time relevant to the process, but can be kept in suspension by turbulence. Particle size: greater than 100  $\mu\text{m}$ . Settling slurry can be defined as a pseudo homogeneous or heterogeneous mixture and can be completely or partly stratified.

**Pseudo-homogeneous mixture:** A mixture in which all the particles are in suspension but where the concentration is greater towards the bottom.

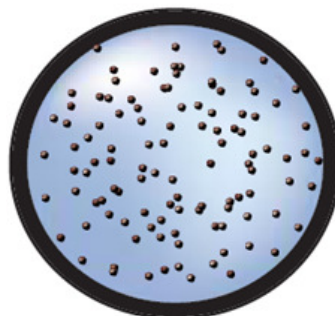


Fig 1.5: Pseudo homogeneous mixture

## Heterogeneous mixture

A mixture of solids and liquid in which the solids are not uniformly distributed and tend to be more concentrated in the bottom of the pipe or containment vessel (compare to settling slurry).

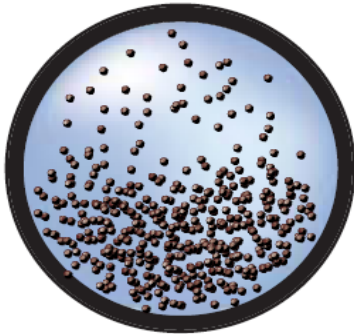


Fig 1.6: Heterogeneous mixture, partially stratified

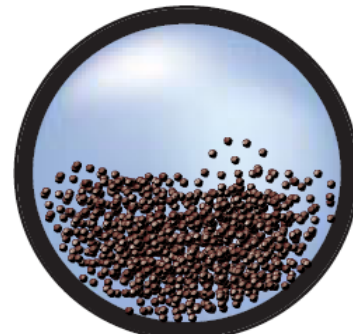


Fig1.7: Heterogeneous mixture, fully stratified

## 1.3 VISCOSITY MEASUREMENT

Viscometer is used to measure the viscosity of fluid only and some extend up to paste fluid application.

### Standard viscometers for liquids

**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.

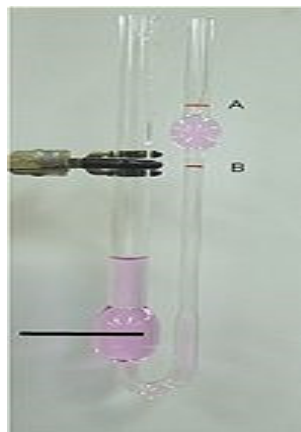


Figure.1.8:U-Tube Viscometer

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. 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.

**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

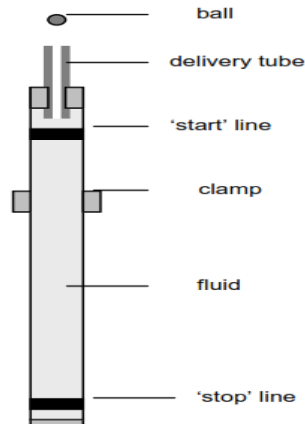


Figure 1.9: Falling sphere viscosity

through the 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.

**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.

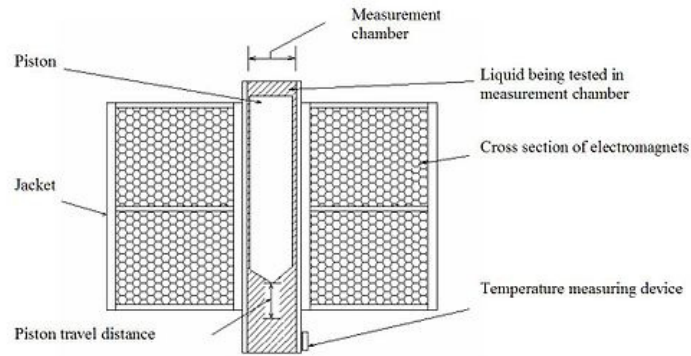


Figure.1.10 Piston Viscometer

## 1.4 RHEOLOGY MEASUREMENTS

**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.

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)

### Type of Rheometers

**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.

**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.



Fig 1.11: 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.

**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.

**Rheometer and Viscometer (A Comparison):** Viscometers, in comparison to rheometers, are usually relatively simple instruments. Their simplicity of design and operation can offer advantages for operator ease of use, particularly within a busy QC environment. Spindle movement in a viscometer is in one direction, which allows the measurement of viscosity. Rheometers can apply oscillatory and rapid step changes in stress and strain, and can therefore determine viscoelastic properties (providing information on the structural properties of the sample) as well as flow properties. Viscometers employ a mechanical bearing that limits the speed and torque capabilities of the instrument, whereas rheometers generally use a low friction air bearing. The residual friction from the mechanical bearing can make the measurement of low viscosity materials difficult. Rheometers, while generally more expensive than viscometers, are more versatile and have a much wider dynamic range for control and measurement parameters. In a typical stress and strain controlled rheometer a temperature control unit (TCU).

Rheometers function across a very wide range of shear rates enabling the simulation of real processes that occur over vastly different timescales, such as sedimentation and spraying.

Rheological measurements are essential for formulation, process and material control across all industries and applications. A viscometer is a low cost instrument that is simple to use and can offer portability for remote or field testing. It is highly suitable for quality control testing and for on-line process control. The rheometer represents a greater investment, but is essential for the true simulation of real processes and complete material characterization. The increased versatility and performance make it an excellent tool for research, product and process development, as well as quality control testing. Both instruments are complementary, and it is not uncommon within a single organization to find viscometers used for QC testing on products that have been developed using a rheometer.

## **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.

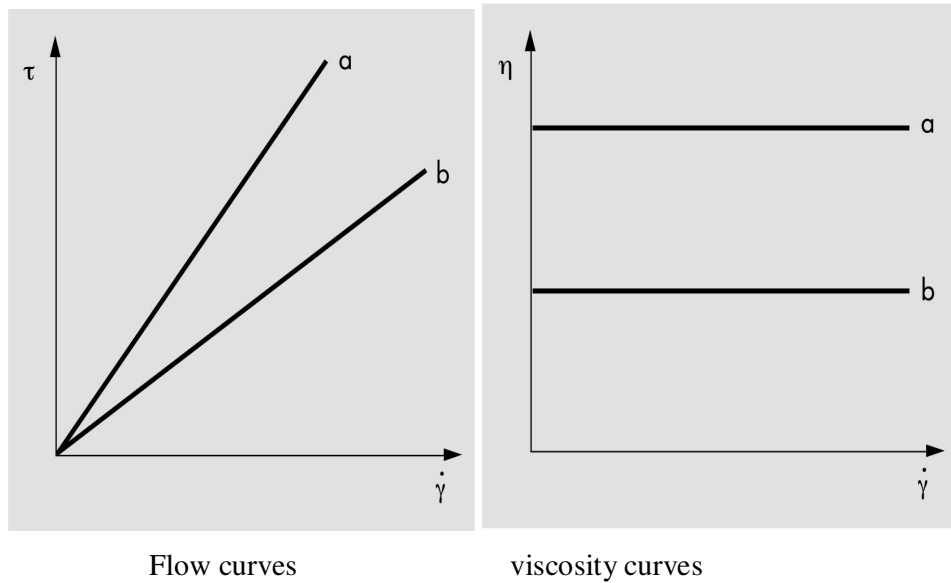


Figure 1.12: Newtonian flow behaviour

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.

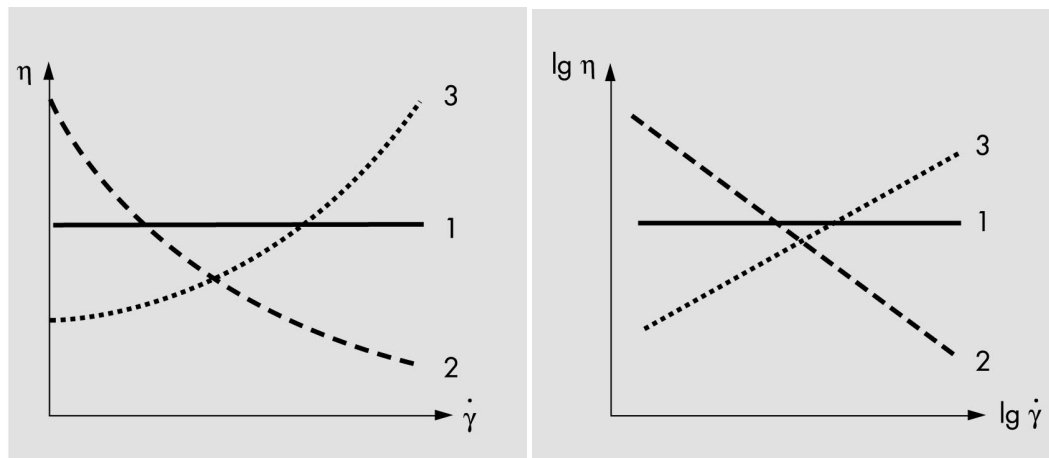


Figure 1.13: Flow and Viscosity Curves

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 is 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 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. 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 otherwise 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 COAL AND ITS TYPES**

**Coal** (from the old English term col, which has meant "mineral of fossilized carbon" since the 13th century) is a combustible black or brownish-black sedimentary rock usually occurring in rock strata in layers or veins called **coal beds** or **coal seams**. The harder forms, such as anthracite coal, can be regarded as metamorphic rock because of later exposure to elevated temperature and pressure. Coal is composed primarily of carbon along with variable quantities of other elements, chiefly hydrogen, sulfur, oxygen, and nitrogen.

Throughout history, coal has been a useful resource. It is primarily burned for the production of electricity and/or heat, and is also used for industrial purposes such as refining metals. A fossil fuel, coal forms when dead plant matter is converted into peat, which in turn is converted into lignite, then sub-bituminous coal, then bituminous coal, and lastly anthracite. This involves biological and geological processes that take place over a long period of time.

As geological processes apply pressure to dead biotic material over time, under suitable conditions it is transformed successively into:

- **Peat**, considered to be a precursor of coal, has industrial importance as a fuel in some regions, for example, Ireland and Finland. In its dehydrated form, peat is a highly effective absorbent for fuel and oil spills on land and water. It is also used as a conditioner for soil to make it more able to retain and slowly release water.

- **Lignite, or brown coal**, is the lowest rank of coal and used almost exclusively as fuel for electric power generation. Jet is a compact form of lignite that is sometimes polished and has been used as an ornamental stone since the Upper Palaeolithic.
- **Sub-bituminous coal**, whose properties range from those of lignite to those of bituminous coal, is used primarily as fuel for steam-electric power generation and is an important source of light aromatic hydrocarbons for the chemical synthesis industry.
- **Bituminous coal** is a dense sedimentary rock, usually black but sometimes dark brown often with well-defined bands of bright and dull material, used primarily as fuel in steam-electric power generation, with substantial quantities used for heat and power applications in manufacturing and to make coke.
- **Steam coal** is a grade between bituminous coal and anthracite, once widely used as a fuel for steam locomotives. In this specialized use it is sometimes known as sea-coal in the U.S. Small steam coal (dry small steam nuts or DSSN) was used as a fuel for domestic water heating.
- **Anthracite**, the highest rank of coal, is a harder, glossy black coal used primarily for residential and commercial space heating. It may be divided further into metamorphically altered bituminous coal and petrified oil, as from the deposits in Pennsylvania.
- **Graphite**, technically the highest rank, is difficult to ignite and is not commonly used as fuel — it is mostly used in pencils and, when powdered, as a lubricant.

## 1.7 COAL WATER SLURRY FUELS

Factors such as the continued rise in oil prices, the difficulties associated with a stable supply of crude oil, increased fuel consumption, and the limited oil reserves in recent years have increased interest in and research related to the use of coal, which is relatively cheaper, plentiful, and widely distributed across the globe. Therefore, many studies pertaining to coal water slurry (suspension of coal particles in water) as an alternative fuel replacing petroleum oil in the liquid state have been carried out. Coal slurry fuel can be divided into CWS (coal-water slurry), COS (coal-oil slurry), COWS (Coal-oil-water slurry), CMS (coal methanol slurry), and CMWS (coal-methanol-water slurry) depending on the type of liquid mixed with the solid coal. Among these different types, CWS fuel is considered by some to have the greatest economic feasibility as a fuel source and the greatest potential for commercialization.

The first oil crisis in 1973 turned all interests on coal converge technologies. From this time, extensive studies have been started particularly on coal gasification, liquefaction and combustion. In addition to these existing extensive studies, in recent years, research on coal–water mixtures CWM was commenced. The suspension contains 50%–75% coal. The coal content varies depending on particular requirements. CWM would produce less SO<sub>x</sub>, CO and NO<sub>x</sub> on combustion

than a coal–oil mixture COM. The emission of CO and NO<sub>x</sub> are much lower for a CWM than COM because of the slightly lower combustion flame temperature. Special storage and transportation are not required, therefore, loading and unloading costs are considerably reduced.

Beneficiated coal is important in CWM because the cleaned CWM could be burned in an oil-designed boiler without installing expensive particulate removal and flue gas desulfurisation of existing systems. At the same time, the cleaned CWM could improve boiler performance by reducing erosion, ash slugging and fouling.

One of the most important requirements to be met while preparing a coal water slurry is that coal concentration should be made as high as possible, but the viscosity is to be kept at a minimum level for ease of handling during preparation, storage, transfer through pipelines, and subsequent atomization. But the viscosity of coal water slurry (CWS) increases with solid concentration in the slurry and the stability of the suspension becomes poor if the viscosity is reduced. Another difficulty encountered in the preparation of HCCWS(Highly Concentrated Coal water Slurries)is the diversity of coals in their physical and chemical properties, which largely depends on the place where it is mined. A universal correlation for all coal samples is quite difficult. The flow behavior of CWS depends on many factors, such as (i) physico-chemical properties of coal, (ii) volume fraction of the suspension, (iii) particle size range and its distribution, (iv) temperature of the suspension, (v) pH, and (vi) presence of electrolytes and additives. Hence design of the operations encountered in preparation, transport, and utilization of HCCWS requires prior knowledge of its rheological behavior for the effective application and economic viability of these processes.

It has been reported that the proportion of the fine particles and mineral matter increased the viscosity due to the increase in interparticle interactions. The rheological behaviour of CWM, changed from a fluid exhibiting the properties of a low viscosity Newtonian fluid at low concentrations, to a fluid with the properties of a high viscosity pseudoplastic. Viscosity measurements show that surfactant addition to the suspension affected the rheology. This is presumed to be related to the adsorption of the reagent on the coal surface, which is dependent both on the nature of the surface and the reagent type and its concentration.

Coal particles are substances with an uneven structure. In general, ash is hydrophilic, whereas the surface of a pure coal particle is hydrophobic. Accordingly, coal particles have poor contact affinity with water, resulting in poor stability, so additives are used to make up for this. These additives increase the contact affinity between coal particles and water and decrease interfacial tension. Surfactants used as dispersants are classified into ionic and non-ionic surfactants. Ionic types of matter stick to coal particles; the hydrophilic group of the dispersant is ionized in water and electrically charges the particles, thereby causing electrostatic repulsion between the particles, increasing their dispersibility. With non-ionic substances, the high-molecular absorbent layer formed on the surface of the coal particle causes steric repulsion, thereby promoting dispersion.

## **1.8 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 SURVEY

Various studies on slurry rheology were carried out by many researchers in the past. Chapter reviews the previous published literatures, which lays foundation and basis for further work in this investigation. This helps to give a better understanding about the topic and also acts as a guideline for this thesis. The major focus of the following study is on the coal slurries and its applications in various areas. This section deals with literature review on rheology of coal slurries. The rheology of coal and coal ash slurries and their characterization has received attention in recent years because of widespread application in industry and academic interest. The focus of investigations has mostly been on viscosity of slurries and flow behaviour and taming them to meet certain requirements such as ease of transportation and handling etc. The viscosity of slurries is dependent on many parameters such as concentration, pH, particle size distribution, chemical composition, presence of chemicals etc<sup>1,3,6,8,17,25</sup>. The flow behaviour is newtonian at lower concentrations (upto 30%) for both coal ash and coal water slurries above which it deviates from newtonian behaviour to mostly shear thinning/pseudoplastic<sup>1,4,5</sup>. The coal slurries made of finer particles is more viscous as compared to those made of coarser ones. Mixing coarse particles with fine particles also helps in controlling viscosity. The wider particle size distributions show lower viscosities<sup>3,8,10</sup>. The flow behaviour and slurry characteristics are greatly influenced by the presence of surfactants/additives<sup>17-25</sup>. The presence of surfactants such as soap solution can cause reduction in pressure drop in slurry pipelines which can lead to substantial energy savings<sup>19,21</sup>. Addition of dispersant can successfully enhance the zeta potential of slurries keeping the particles water borne in transportation<sup>22-25</sup>. The flow behaviour can also be controlled by surfactant addition, it can induce newtonian behaviour or shear thinning at higher concentration with reduction in yield stress<sup>17,23</sup>.

#### **2.1 RHEOLOGY AND PIPELINE TRANSPORTATION STUDIES ON COAL AND COAL ASH SLURRIES:**

**Woskoboenko Fedir et al<sup>1</sup>[1986]** studied the rheology of victorian brown coal slurries. Aqueous suspensions of finely ground raw brown coal from Victoria, Australia, were tested in a Couette viscometer to evaluate their rheological properties. Shear rates covered the range 1-800 s-r and median particle sizes were 641 pm. They examined Concentrations up to 0.6 volume fraction. They found that results were well represented by two parameter Bingham model. They also observed that the degree of non-Newtonian behaviour, as measured by the yield stress, increased as the concentration was increased or the particle size decreased. The yield stress can be directly related to the volumetric solids concentration, particle size distribution and external specific area *via* a single,

physically meaningful parameter ~ the mean distance separating the particles. They found that the power law relationship between yield stress and inter-particle distance can be used to gauge the degree of flocculation of the system. The plastic viscosity of these suspensions was found to increase in a logarithmic fashion as the concentration increases but was independent of the absolute particle size.

**Gahlot V.K et al<sup>2</sup>[1988]** studied the rheological behavior of coal and zinc tailings slurries containing coarse size particles, which tend to settle during the experiments. They scalped the bigger size particles from the original sample and studied the rheological behavior using the residual finer size particulate suspension. They proposed a methodology to determine the viscosity of coarse particulate slurry using scalped samples.

**Reddy G.V et al<sup>3</sup>[1994]** studied the influence of particle size distribution on rheological properties of coal oil mixtures. The Rosin Rammer parameters and maximum packing fractions have been correlated with the viscosity of coal oil mixtures. It has been observed that coal oil mixtures with wider particle size distribution are less viscous.

**Parida A et al<sup>4</sup>[1996]** investigated the rheological behavior of fly ash samples. They found that viscosity of the fly ash slurry shows Newtonian nature up to a solids concentration of 50% (by weight). Above this concentration the behaviour is non-Newtonian. They used the pseudo-plastic model to estimate the head loss for the pipe flow and found that the transportation cost of fly ash slurry decreases drastically if it is transported at high concentrations instead of low concentrations.

**Panda D et al<sup>5</sup>[1996]** have established the pressure loss in horizontal pipes for transportation of fly ash up to 60% concentration (by weight) by correlating it with the rheological behavior of the slurry. They have also reported that the pressure loss could be estimated reasonably well using pressure loss models developed for Newtonian fluids in the range of 20-25% concentration by weight.

**Mishra S.K et al<sup>6</sup>[2010]** investigated the rheological behavior of Indian coal-water slurry (CWS) using a HAAKE RV30 viscometer. They studied effect of solid concentration, ash content, pH, and temperature on the rheology of CWS. The CWS was prepared on three coal samples with solids concentration varying from 50-55%. They found that all the samples exhibited shear thinning behaviour with increase in viscosity at higher concentration and ash content. pH was found to have a strong influence on the viscosity with highest around pH-6 and lowest around pH-8 for all slurry samples.

**Usui H et al<sup>7</sup> [2001]** have carried out experimental studies on rheology and pipeline transportation of dense fly ash water slurry. Simha's model is used to predict the maximum packing volume

fraction for non-spherical suspension and successfully used to predict the slurry viscosity under completely dispersed conditions. The model results in the estimation of inter particle bonding force between primary particles in a cluster and the power consumption and flow rate relationship in hydraulic slurry pipeline transportations system is predicted. A possible way to reduce the total cost of slurry pipeline system by means of periodical addition of stabilizer is proposed.

**Ghanta P et al<sup>8</sup> [2002]** 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. They concluded 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.

**Bournonville B et al<sup>9</sup>[2002]** studied the effect of concentration, yield stress and hydrodynamic interactions on Rheology of non-Newtonian suspensions of two different water-washed municipal solid waste (MSW) incinerator fly ashes. A shear-thinning and thixotropic behaviour is observed for aqueous suspensions of non-treated fly ashes. They concluded that the viscosity is sensitive to the concentration of solids.

**Kumar U et al<sup>10</sup>[2003]** studied the effect of particle gradation on flow characteristics of ash disposal pipelines and found that a slurry with a mix of fine and coarse particles requires less energy for transportation and at some optimum particle size distribution the energy required is even less than that required for the fine slurry. They observed that the pressure drop as well as the deposition velocity is affected considerably by the particle size distribution of the solid particles present in the slurry. They used modified two-layer model and the modified Karabelas model for pressure drop and solid distribution respectively have been found to predict the behaviour with reasonable accuracy. Their parametric study has revealed that the optimum particle size distribution for transport of fly ash-bottom ash mix is the one which corresponds to a solid phase having fly ash bottom ash ratio in the range 4:1 to 3:2.

**Kaushal D.R et al<sup>11</sup>[2005]** studied the effect of particle size distribution on pressure drop and concentration profile in pipeline flow of highly concentrated slurry. The experiments were conducted in 54.9 mm diameter horizontal pipe on two sizes of glass beads of which mean diameter and geometric standard deviation are 440  $\mu\text{m}$  & 1.2 and 125  $\mu\text{m}$  & 1.15, respectively, and a mixture of the two sizes in equal fraction by mass. Flow velocity was up to 5 m/s and overall concentration up to 50% by volume for each velocity. Pressure drop and concentration profiles were measured.

The profiles were obtained traversing isokinetic sampling probes in the horizontal, 45° inclined and vertical planes including the pipe axis. Slurry samples of the mixture collected in the vertical plane were analyzed for concentration profiles of each particle batch constituting the mixture. They found that the pressure drop is decreased for the mixture at high concentrations except 5 m/s and a distinct change of concentration profiles was observed for 440 μm particles indicating a sliding bed regime, while the profiles in the horizontal plane remains almost constant irrespective of flow velocity, overall concentration and slurry type.

They drew following conclusions: the particle concentration profile is measured for high concentration slurry transport where the maximum overall area-average concentration is 50% by volume employing coarse particles and higher flow velocities up to 5 m/s. Narrow grading particles tend to have high frictional losses while broad grading particles have low frictional losses at high concentrations. Concentration in the horizontal plane remains almost constant irrespective of flow velocity and overall concentration, A distinct change in the shape of concentration profiles was observed indicating the sliding bed regime for coarser particles at lower flow velocities.

**Knezevic D et al<sup>12</sup>[2008]** studied the influence of ash concentration on change of flow and pressure in slurry transportation. The results indicate that the transport should be accomplished with ash and bottom ash concentration below 50% but above 40% of solids. In this concentration range there is decrease of both flow (per volume) and pressure. However this decrease is considerably small regarding quantity of fly and bottom ash transported during the time limit

**Chandel S et al<sup>13</sup>[2009]** studied the deposition characteristics of coal ash slurries at higher concentrations. The results obtained from the experiments show that the cone angle depends on rheological properties like yield stress and bingham plastic viscosity which in turn depend on various properties like solid concentration, particle size distribution etc. Also, cone angle for fly ash slurry is higher than that for the mixture of FA and BA slurry at any given concentration. Further, it was also observed from the experiments that cone angle is higher for pervious bed as compared to impervious bed for both types of slurries.

**Branganca S.R et al<sup>14</sup>[2009]** investigated the rheological behavior of coal ash slurries at high concentration(68% by weight).They observed that viscosity depends on a number of factors such as chemical composition, particle size distribution, concentration of fine and medium particles.Paste fluidity was found to be best when water content ranged from 30% to 35% by weight.The viscosity of the pulps is reported to be high when they are motionless,but it diminishes under stirring (thixotropic behaviour) and becomes stable after a short period.It is claimed that it is technically feasible to transport coal ash slurries in the form of high concentration paste.

**Chandel S et al<sup>15</sup>[2010]** studied the Transportation of High Concentration Coal Ash Slurries through Pipelines the study reports the pressure drop and rheological characteristics of mixture of fly ash (FA) and bottom ash (BA) slurry (4:1) at high concentrations (above Cw 50% by weight). Pressure drops were measured at various flow velocities using a pilot plant test loop at various concentrations. Such measurements have been made for various concentrations in the range 50-70% by weight. Rheological studies are also carried out for mixture of fly ash (FA) and bottom ash (BA) slurry. The dependence of relative pressure drop on flow velocity at various concentrations has also been analyzed. Further, by using the rheological data, pressure drop has been predicted in a straight pipeline of 42 mm diameter at higher concentrations. They found that: The pressure drop for any given solid concentration increases with increase in velocity and at any given flow velocity pressure drop increases with increase in solid concentration, Relative pressure drop increases with increase in solid concentration, For a given efflux concentration relative pressure drop decreases with increase in flow velocity, The increase in pressure drop is much higher in the low velocity range compared to high velocity region for any efflux concentration, Mixture of FA and BA (4:1) slurries can be transported at higher concentrations, The prediction model proposed by Darby and Melson is suitable for the Bingham plastic fluid flow such as mixture of FA and BA (4:1) slurry at concentrations above 50% (by weight), Specific Energy Consumption decreases upto a concentration of 65% by weight and steeply increases beyond this value.

**Qihui He et al<sup>16</sup> [2011]** investigated the effect of particle size distribution of petroleum coke on the properties of petroleum coke–oil slurry of from four Chinese petroleum coke sample. They studied the effects of petroleum coke samples, the particle size distribution and the solid loading on the properties of petroleum coke–oil slurry. PCOS prepared with four different kinds of petroleum coke samples had similar apparent viscosity and stability. They also found that the petroleum coke loading of 30–35 wt.% and grinding time of 60 min are suitable. The prepared PCOS system exhibits shear-thinning or pseudo-plastic behavior and displays excellent stability and fluidity suitable for its handling in preparation, storage, transportation and combustion process.

## **2.2 RHEOLOGY AND PIPELINE TRANSPORTATION STUDIES OF COAL AND COAL ASH SLURRIES IN THE PRESENCE OF CHEMICALS/SURFACTANTS:**

**Aktas Z et al<sup>17</sup>[2000]** studied the effect of addition of surface active agent on the viscosity of a high concentration slurry of a low-rank British coal in water. They found that the viscosities of the slurries with low ash content were significantly reduced by the surfactant addition (Triton X-405 *p-tert*-octylphenoxy-polyethoxyethanol) which also altered the rheological characters of these slurries from non-Newtonian towards Newtonian fluids. However, they noted that the sample containing very fine particles with a high ash content 24.5%. It showed non-newtonian behaviour even in the presence of reagent.

**Verma A.K et al<sup>18</sup>[2006]** studied the rheological behavior of fly ash slurry with and without additives for different particle size distributions and concentrations of the solid-liquid mixture. They used sodium-hexa-metaphosphate at 0.1% concentration (by weight) as additive and also calculated the pressure drop in a straight pipeline of 75 mm diameter at high concentrations using the rheological data. The rheological behaviour of fly ash slurries above 60% solid concentrations (by weight) showed non-Newtonian behaviour and the Bingham model was used to fit for the data for these concentrations. Particle size distribution and concentration of solids affected more to the slurry rheology, above the solid concentration of 65% (by weight).

**Seshadri V et al<sup>19</sup>[2008]** studied the effect of additive (sodium hexametaphosphate) on head loss in the high concentration slurry disposal of fly ash, they took five slurry samples of fly ash having different highest particle size and particle size distribution (PSD) for determining the rheological behaviour at different concentrations. Then the effect of the additive they studied. Based on rheological data the pressure drop has been predicted at different concentrations with and without additive. They observed that the pressure drop for any concentration increases with the increasing Reynolds number for same particle size of fly ash slurry. With additive they noted that for given particle size and concentration at any selected velocity there is a significant reduction in pressure drop in comparison to original sample. It was also seen that pressure drop increases with increase in concentration. They further observed the pressure drop increases with increase in fineness of slurry.

**Mosa E.S et al<sup>20</sup>[2008]** examined the effect of chemical additives or reagents on rheological characteristics of coal water slurry (CWS). Apparent viscosity and flow properties of coal water slurry are sensitive to the use of chemical additives (dispersants and stabilizers). Among studied dispersing agents, sulphonic acid recorded the best performance in modification and reducing CWS viscosity. The best dosage of all tested dispersants was found to be as 0.75 % by wt of solids. With regard to studied stabilizers, Na- CMC recorded better performance than xanthan gum. The best dosage of investigated stabilizers was found to be as 0.1 % by wt. from total solids.

**Chandel S et al.<sup>21</sup>[2009]** described the effect of additive on pressure drop and rheological characteristics of fly ash slurry at high concentration (above CW=60 by weight). There is reduction in pressure drop when additive like soap solution is added to the fly ash slurry at higher concentrations. Slurries of fly ash at these concentrations show a Bingham fluid behavior. The Bingham viscosity and yield shear stress values increase with increase in concentration, the increase being more pronounced at higher concentrations. The addition of soap solution as additive to the fly ash slurries reduces the rheological parameters and result in substantial decrease in energy parameters.

**Dincer H et al<sup>22</sup> [2009]** studied the effect of chemicals on stability and viscosity of coal water slurries the effects of different chemicals that were used as dispersing agent and stabiliser on the stability and viscosity of coal–water slurries were investigated. In the experiments, anionic type of chemicals—polyisoprene sulphonic acid soda (Dynaflow-K), a derivative of carboxylic acid (AC 1320) and naphthalenesulfonate–formaldehyde condensate (NSF)—were used as dispersing agents and the stabiliser was the sodium salt of carboxymethyl cellulose (CMC-Na). The coal sample used was a bituminous coal (thermal code no. 434) of Turkish origin, with medium volatile matter. They found that polymeric anionic dispersing agents such as Dynaflow have much greater effect on the viscosity and the stability of coal water slurry.

**Naik H.K et al<sup>23</sup>[2009]** observed the effect of drag reducing additives on the rheological properties of fly ash water suspensions at varying temperature environment. The distinctive reduction of surface tension on colloidal disperse characteristics of the resulting slurry was observed in the presence of surfactants. Zeta potential measurements also confirmed that the additive has the capability to keep the fly ash particles water borne during its transportation in pipelines. All the treated slurries exhibited the shear thinning or / and Newtonian flow properties with zero yield stress.

**Das H.K et al<sup>24</sup>[2009]** They prepared highly concentrated coal-water slurry employing three different low-rank coals of Indian origin having variable ash content. The formulation, rheology, and stabilization of the slurry were investigated using saponin extracted from the seeds and pericarps (mods) of the Acacia concinna plant as a dispersant. The saponins extracted from both the seeds and pericarps of the plant are found to stabilize the slurry. They claim that the plant-based additive saponin from *A. concinna* (both pericarps and seeds) can be suitably substituted for a synthetic additive, such as SDS(Sodium Dodecyl Sulphate). A few pilot experiments with other commercially available additives, such as CMC and SDDBS, also yielded the same results.

**Naik H.K et al<sup>25</sup>[2011]** evaluated the flow characteristics of fly ash slurry at 40% concentration with and without additives. They collected six samples of fly ash from different power stations in south India. The main constituents of tested samples were fly ash, water, surfactant and counter ion. Detailed rheological properties were determined by using cylindrical coaxial rotational rheometer (Anton Parr rheometer model Physica MCR101), shear rates were varied from 100-1000s<sup>-1</sup>, temperature from 20-40<sup>0</sup>C. They observed that all slurries exhibited shear thinning behaviour in the presence of an additive and reduction in surface tension, both will manifest themselves as reduction in drag in case of transportation through pipelines. They concluded that in this way it is possible to design pipelines and pumping systems for transporting ash slurries at high concentrations.

## CHAPTER 3

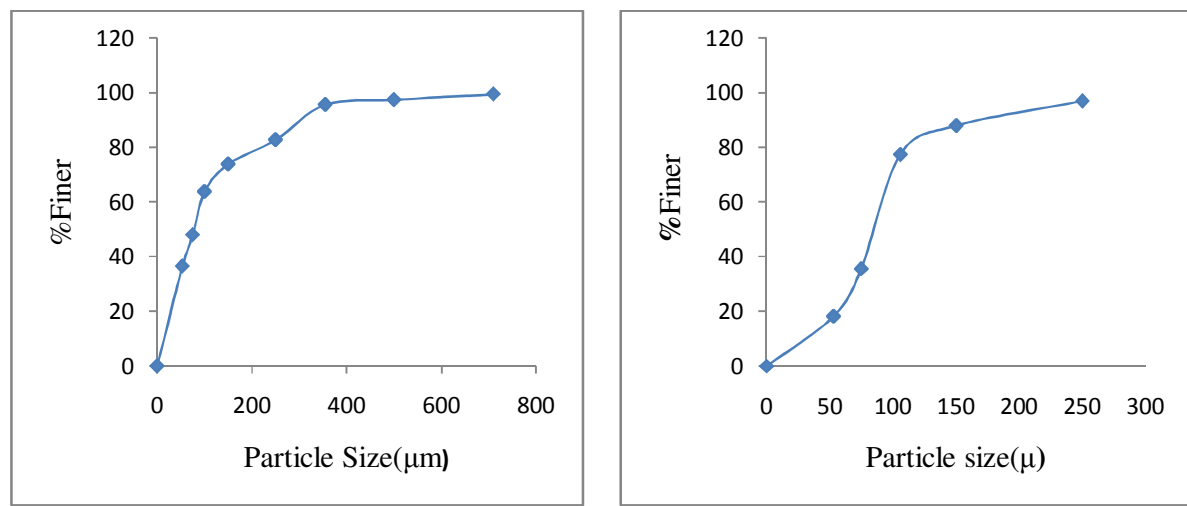
### STUDY ON PROPERTIES OF COAL AND COAL WATER SLURRY

Pulverized Coal samples were collected from Guru Nanak Dev Thermal Power Plant Bathinda, Punjab (sample A) and Panipath Thermal Power Plant, Haryana (B). Several tests such as Sieve Analysis for particle size distribution (PSD), pH analysis, Chemical composition, S.E.M (Scanning electron Microscope) was done prior to rheological measurements. The testing procedure and results are summarized below.

#### 3.1 PHYSICAL/CHEMICAL PROPERTIES OF COAL

**Particle Size Distribution (PSD):** A known weight of representative sample of solid particles is taken and washed over a B.S. 200 mesh (100  $\mu\text{m}$ ). 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 to obtain the sieve curve.



Particle Size Distribution For Coal A

Particle Size Distribution For Coal B

Figure 3.1

Figure 3.1 shows that for coal A almost all the particles are finer than 750  $\mu\text{m}$  while about 28% of the particles are finer than 53  $\mu\text{m}$ . For coal B almost all the particles are finer than 270  $\mu\text{m}$  while about 18% particles are finer than 53  $\mu\text{m}$ . Hence coal B is overall finer as compared to Coal A.

**pH 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 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 pH of sample A was between 6 to 5.8 for concentrations ( $C_w$ ) 10%-50% while the pH of sample B was between 6.5 to 7.1 for the same concentration range.

**Energy-dispersive X-ray spectroscopy (EDS or EDX) And Scanning Electron Microscope (S.E.M):** It is an analytical technique used for the elemental analysis or chemical characterization of a sample. It relies on the investigation of an interaction of some source of X-ray excitation and a sample. Its characterization capabilities are due in large part to the fundamental principle that each element has a unique atomic structure allowing unique set of peaks on its X-ray spectrum To stimulate the emission of characteristic X-rays from a specimen, a high-energy beam of charged particles such as electrons or protons, or a beam of X-rays, is focused into the sample being studied. At rest, an atom within the sample contains ground state (or unexcited) electrons in discrete energy levels or electron shells bound to the nucleus. The incident beam may excite an electron in an inner shell, ejecting it from the shell while creating an electron hole where the electron was. An electron from an outer, higher-energy shell then fills the hole, and the difference in energy between the higher-energy shell and the lower energy shell may be released in the form of an X-ray. The number and energy of the X-rays emitted from a specimen can be measured by an energy-dispersive spectrometer. As the energy of the X-rays are characteristic of the difference in energy between the two shells, and of the atomic structure of the element from which they were emitted, this allows the elemental composition of the specimen to be measured. It is often equipped with a scanning electron microscope(S.E.M) in which the sample in the instrument is bombarded by an electron beam in order to obtain a detailed topographical image of the surface of the sample from the ejected electrons.

The results of SEM/EDS on coal A and B are shown in figures 3.1-3.6.

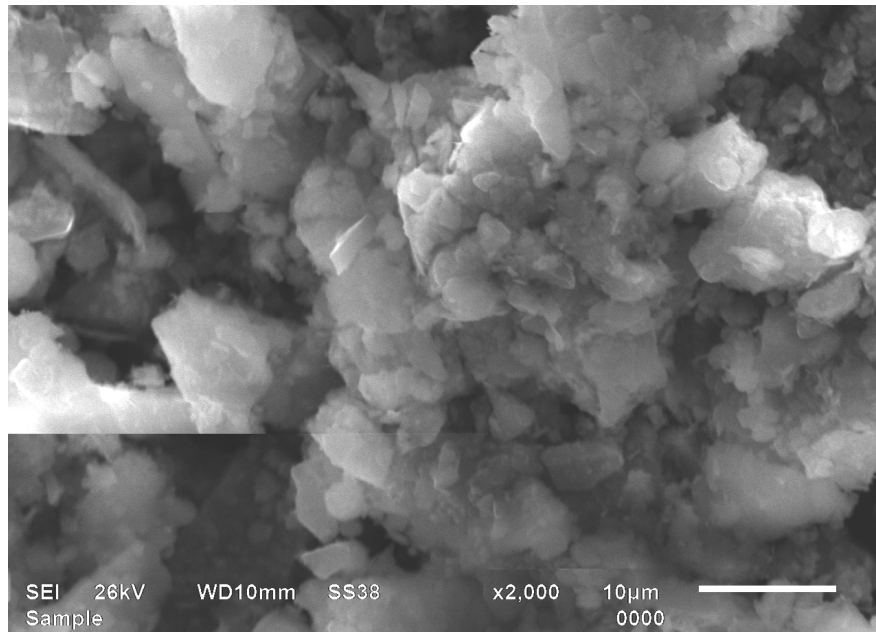


Fig. 3.2:S.E.M Image of Coal A

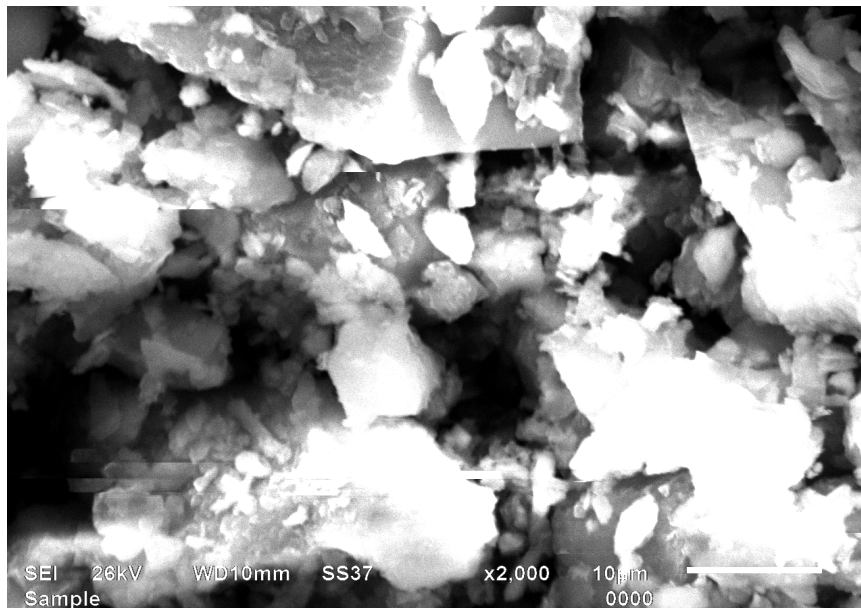


Fig 3.3:S.E.M Image of Coal B

The scanning electron microscope (S.E.M) images of coal A and B reveal that both coal samples have uneven/distorted particle shapes which might explain why they have much higher viscosity as compared to fly ash slurry at same  $C_w$  which have round shape providing ball bearing action manifesting as reduction in viscosity.

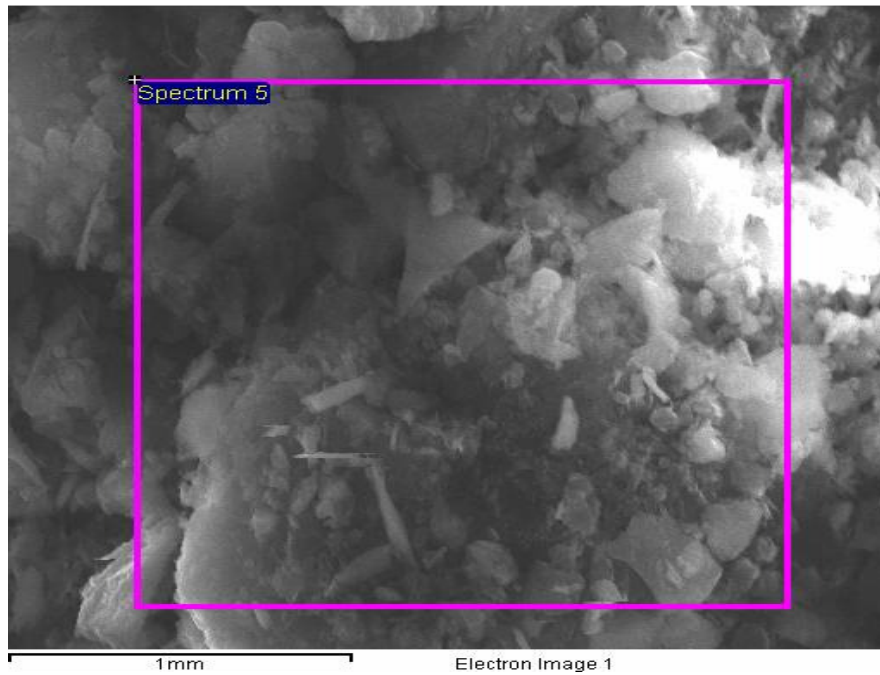


Fig 3.4:(Portion selected for EDS of Coal A)

Element	C	O	Al	Si	S	Cl	K	Ca	Ti	Fe	Cu	Zn
Weight%	50.26	38.51	3.53	4.51	0.54	0.11	0.31	0.24	0.42	0.80	0.42	0.36
Atomic%	60.20	34.62	1.88	2.31	0.24	0.04	0.11	0.09	0.13	0.21	0.09	0.08

Table 3.1 (Elemental composition for spectrum selected in fig 3.5 for Coal A)

The elements in table 3.1 are present in compound form as:  $\text{CaCO}_3$ ,  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$ ,  $\text{FeS}_2$ ,  $\text{KCl}$  where Ti(Titanium), Cu(Copper), Fe(iron), Zn(Zinc) are present in elemental form.

The results of the E.D.S analysis show that coal A is rich in carbon (more than 50% by weight) other major elements are Aluminum(3.5% by wt.) and silicon(4.5% by wt.) they are present in compound form  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$  respectively.

S(sulphur), K(potassium), Cl(chlorine), Ca(calcium), Ti(titanium), Fe(iron), Zn(zinc) and Cu(copper) are present in traces.

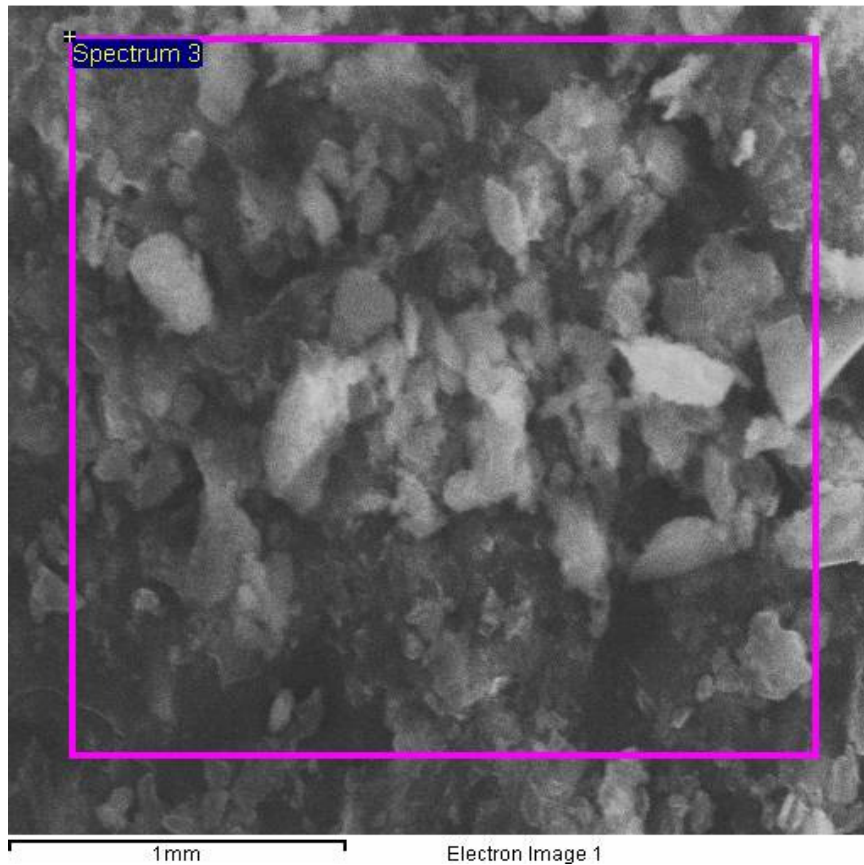


Fig 3.5: Portion selected for EDS analysis of coal B

Element	C	O	Al	Si	P	S	K	Ca	Ti	Fe	Cu	Zn
Weight%	39.85	34.83	8.09	11.67	0.31	0.37	0.84	0.89	0.99	0.43	1.03	0.70
Atomic%	52.41	34.39	4.73	6.56	0.16	0.18	0.34	0.35	0.33	0.12	0.26	0.17

Table 3.2: elemental analysis for Coal B

The table 3.2 shows the elemental composition of Coal B for spectrum selected in fig 3.5. These Elements are present in compound form as:  $\text{CaCO}_3$ ,  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$ ,  $\text{GaP}$ ,  $\text{FeS}_2$  and the remaining such as Ti(Titanium), Cu(Copper), Fe(iron), Zn(zinc) are present in elemental form.

Coal B contains about 40% carbon by weight, Al(aluminium) 8.09% by weight, Si(Silicon) 11.67% by weight. Aluminium and Silicon are present in compound form  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$  respectively. Trace elements include P(phosphorous), S(sulphur), K(potassium), Ca(Calcium), Ti(titanium), Cu(copper) Fe(iron) and Zn(zinc).

### 3.2 RHEOLOGICAL BEHAVIOUR OF COAL WATER SLURRIES

**TEST SETUP AND METHODOLOGY:** The RheolabQC (Make:AntonParr,Gurgaon) (fig 3.6) is used for carrying out all rheological measurements. It is a rotational rheometer which works according to the Searle principle. It consists of a high precision encoder and a highly dynamic EC motor, which is also used in the MCR rheometer series. We can select between controlled shear rates (CR) and controlled shear stress (shear stress) test settings. It has wide speed and torque ranges and very short motor responses time.

The coal samples A and B were each sieved in three particle size ranges i.e 53-75 microns,75-106 microns and 106-150 microns. Rheological measurements were carried for each particle size range at concentration range of 10-50% by weight. Shear Rate selected was in the range of 0-500/s for every measurement. The measuring system **DG42-SN22909** was used for lower concentrations (less than 40% by wt.). This geometry consists of a fixed cylinder (bob) and a rotating cylinder (cup) (Fig.3.7). The slurry placed between the annular space between the two cylinders and a torque applied on the rotating cylinder (cup).At higher concentration the measuring system used was **ST22-4V-40-SN23352**.

**SAMPLE PREPERATION:** For rheumatic tests, 50mL of the suspension is prepared by mixing the required quantity of coal with distilled water to obtain the desired concentration ( $C_w$ ).An electronic balance with a resolution of  $10^{-4}$  gm is 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 rheograms are shown from fig 3.8-fig 3.12



Fig 3.6:Rheometer(Anton Parr)



Fig 3.7:Cylindrical cup and rotating Bob

## RHEOGRAMS FOR COAL A AND B

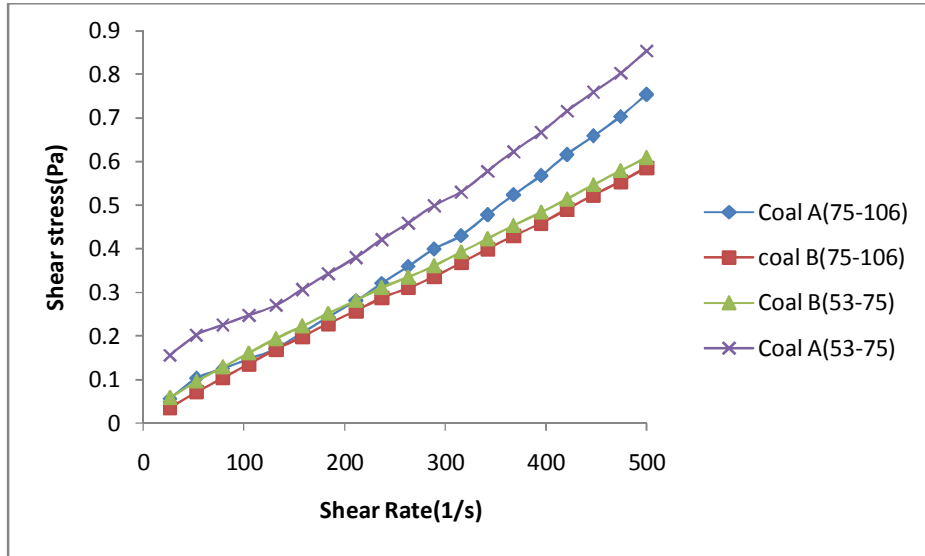


Fig 3.8: Coal A and B at 10% Cw for particle size 53-75 $\mu$ m and 75-106 $\mu$ m

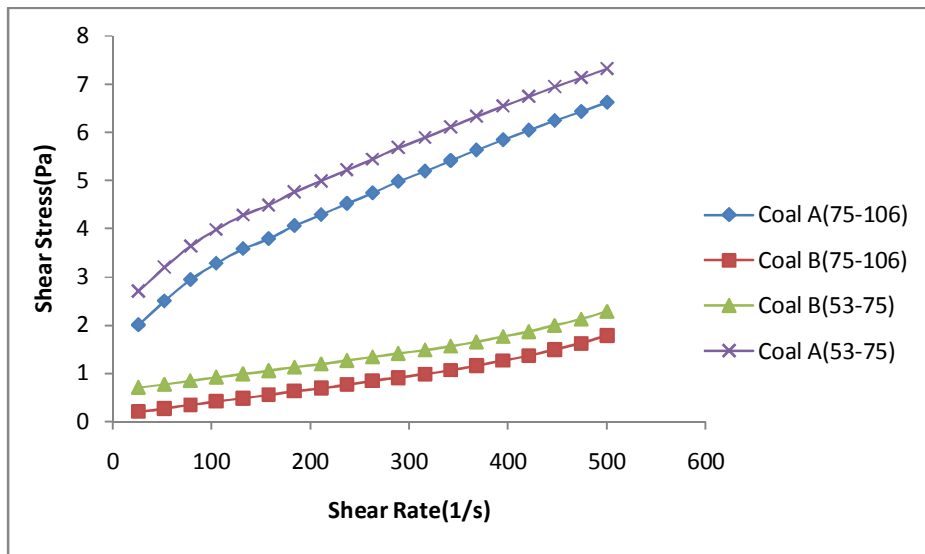


Fig 3.9: Coal A and B at 20% Cw for particle size 53-75 $\mu$ m and 75-106 $\mu$ m

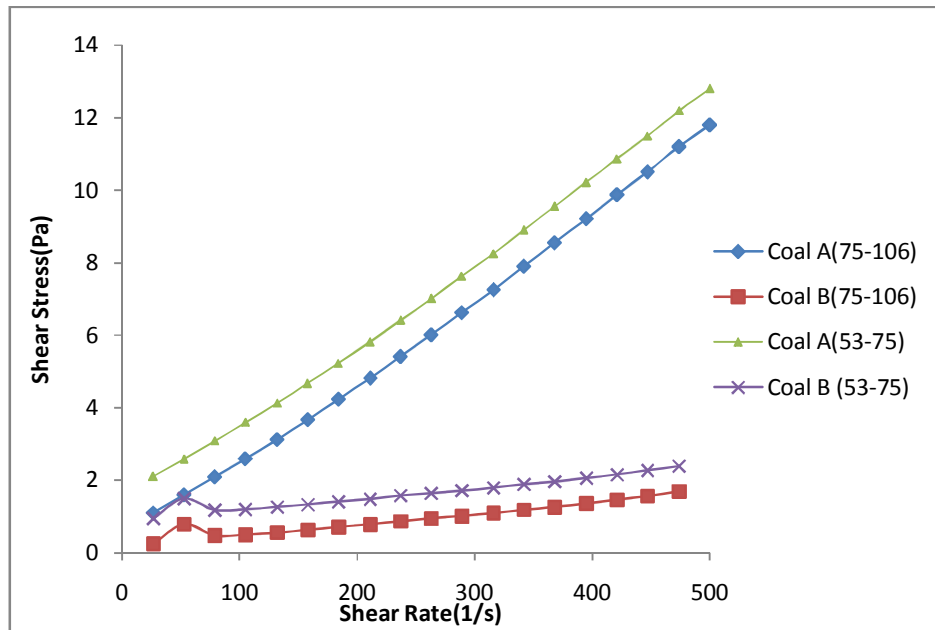


Fig 3.10: Coal A and B at 30% Cw for particle size 53-75 $\mu$ m and 75-106 $\mu$ m

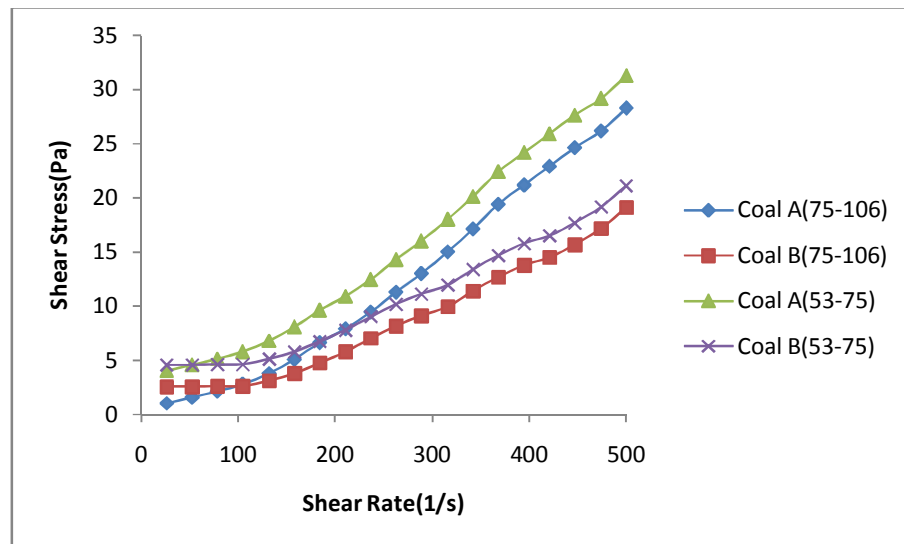


Fig 3.11: Coal A and B at 40% Cw for particle size 53-75 $\mu$ m and 75-106 $\mu$ m

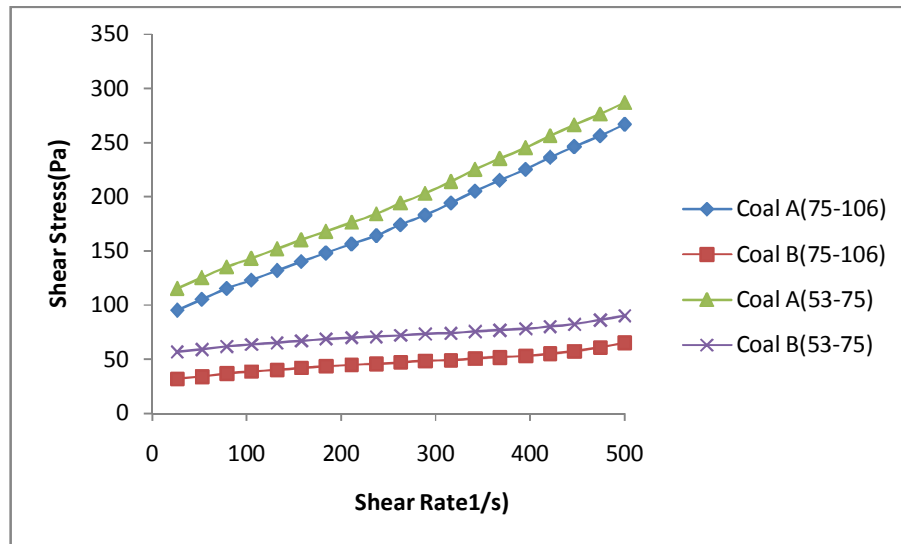


Fig 3.12: Coal A and B at 50% C<sub>w</sub> for particle size 53-75µm and 75-106µm

A close analysis of rheograms (fig 3.8-3.12) reveals several critical points

(1).The slurries show non-newtonian behavior for all concentrations except for 10% C<sub>w</sub> which can be modeled reasonably well with a Newtonian behavior. Between 20%-40% C<sub>w</sub> the behavior varies between shear thinning/thickening for all particle sizes for both coal samples. At 50% C<sub>w</sub> and above the slurry is consistently showing shear thinning behavior.

(2).The decrease in particle size increases the apparent viscosity for both samples. This could be due to the fact that with reduction in particle size the surface area per unit mass of coal increases providing greater frictional effects.

(3).The apparent viscosity of coal A is always greater than that of coal B at all coal concentrations at given particle size range. It can be because of different chemical/physical properties of coal samples A and B.

### CONCENTRATION VS VISCOSITY FOR COAL A AND COAL B

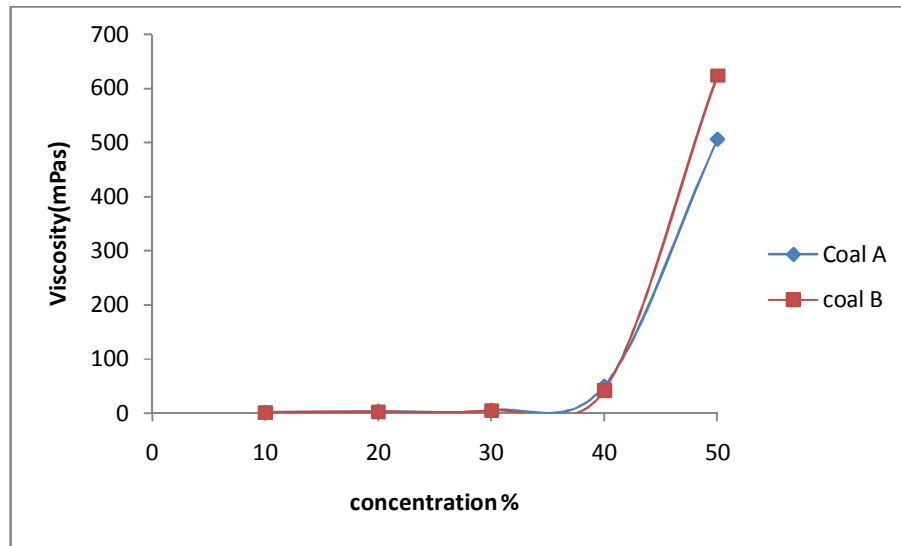


Fig 3.13: Viscosity Vs concentration (53-75 $\mu$ m)

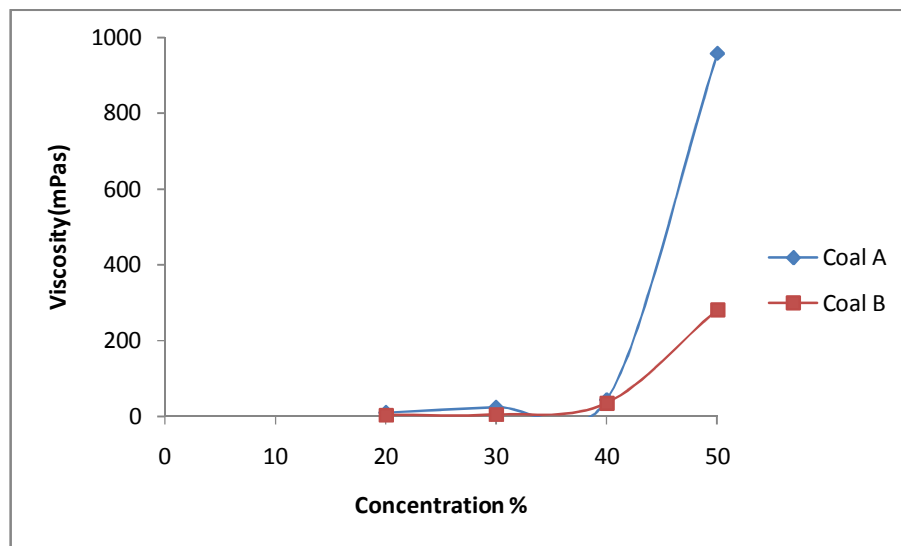


Fig 3.14: Viscosity Vs concentration (75-106 $\mu$ m)

From figures 3.13 and 3.14 seen that the apparent viscosity of coal water slurries is a strong function of concentration of solids for all particle size distributions and both coal samples. The viscosity first increases on an average about 2-4 times at lower concentrations (upto 30%) for every 10% rise in solids concentration by weight while it increases several folds (upto 8-9 times) for each

10% rise in concentrations at higher concentration of slurry(i.e above 30%).Hence we can say that rate at which the averaged apparent viscosity increases itself increases with concentration.

## CHAPTER 4

### RHEOLOGY STUDY OF COAL SLURRIES WITH ADDITIVE

#### 4.1 SURFACTANTS

The term surface – active agent or “surfactant” represents heterogeneous and chain molecules containing both hydrophilic and hydrophobic moieties.

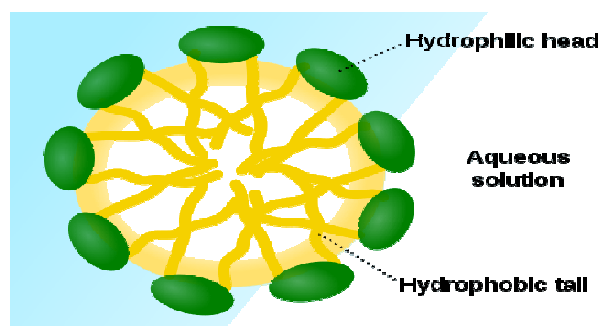


Fig: 4.1 Surface-Active Agents or Surfactant

A micelle is the lipophilic tail of the surfactant molecules remain on the inside of the micelle due to unfavorable interactions. The polar "heads" of the micelle, due to favorable interactions with water, form a hydrophilic outer layer that in effect protects the hydrophobic core of the micelle. The compounds that make up a micelle are typically amphiphilic in nature, meaning that micelles are soluble not only in protic solvents such as water but also in aprotic solvents as a reverse micelle.

#### **Classification of Surfactants:**

##### **According to the composition of their tail**

The tail of surfactants can be:

- **A hydrocarbon chain:** aromatic hydrocarbons (arenes), alkanes (alkyl), alkenes, cycloalkanes, alkyne-based
- **An alkyl ether chain:**
  - Ethoxylated surfactants: polyethylene oxides are inserted to increase the hydrophilic character of a surfactant
  - Propoxylated surfactants: polypropylene oxides are inserted to increase the lipophilic character of a surfactant
- **A fluorocarbon chain:** fluorosurfactants
- **A siloxane chain:** siloxane surfactants.

## According to the composition of their head

Surfactant classification according to the composition of their head: nonionic, anionic, cationic, amphoteric. A surfactant can be classified by the presence of formally charged groups in its head. A non-ionic surfactant has no charge groups in its head(ex.Triton X-100). The head of an ionic surfactant carries a net charge. If the charge is negative, the surfactant is more specifically called anionic(ex. : sodium lauryl sulfate,sodium laureth sulfate, Alkyl aryl ether phosphate, Fatty acid salts [soaps], dioctyl sodium sulfosuccinate.); if the charge is positive, it is called cationic (ex. cetyl trimethylammonium bromide (CTAB), Cetylpyridinium chloride (CPC) ,Benzalkonium chloride (BAC).). If a surfactant contains a head with two oppositely charged groups, it is termed zwitterionic(ex. Imino acids, cocamidopropyl hydroxysultaine).

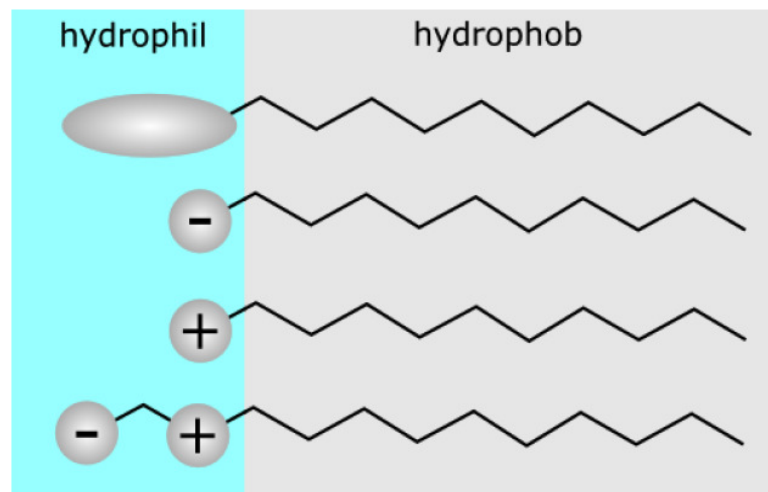


Fig4.2 Surfactant classification according to the head:-nonionic,anionic,cationic,amphoteric

The rheological behaviour of coal slurries is a strong function of the surface charge/characteristics of coal.This surface character can be altered by chemicals called surfactants.They usually prevent aggregation/flocculation by giving net charge on the surface of particles(in case of ionic surfactants) and by steric repulsion in case of non ionic surfactants. These changes often manifests in the form of altered

**Triton X-100** ( $C_{14}H_{22}O(C_2H_4O)_n$ ):It is a nonionic surfactant which has a hydrophilic polyethylene oxide chain (on average it has 9.5 ethylene oxide units) and an aromatic hydrocarbon lipophilic or hydrophobic group. The hydrocarbon group is a 4-(1,1,3,3-tetramethylbutyl)-phenyl group. It is related to the Pluronic range of detergents marketed by BASF.The pluronics are triblock copolymers of ethylene oxide and propylene oxide with the ethylene oxide segments being more hydrophilic than the propylene oxide. Triton X-100 is often warmed prior to use due to its high

viscosity at room temperature or favorable rheology of slurries. Fig 4.3 shows molecular structure of triton X-100.

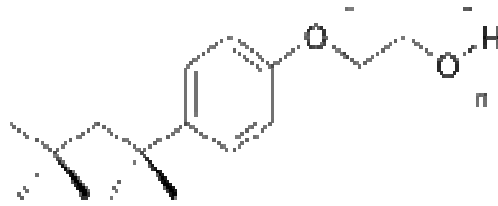


Fig 4.3: Triton X-100

**Uses:** Triton X-100 is a commonly used detergent in laboratories. Some applications include

- Permeabilizing unfixed (or lightly fixed) eukaryotic cell membranes.
- Solubilizing membrane proteins in their native state in conjunction with zwitterionic detergents such as CHAPS.
- Dispersion of carbon materials for soft composite materials.

Apart from laboratory use, Triton X-100 can be found in several types of cleaning compounds ranging from heavy-duty industrial products to gentle detergents. It is also a popular ingredient in homemade vinyl record cleaning fluids together with distilled water and isopropyl alcohol. Triton X-100 appears as a final ingredient in several yearly influenza vaccines worldwide.

## 4.2 EFFECT OF TRITON X-100 ON COAL WATER SLURRY RHEOLOGY

The non-ionic surfactant TRITON X-100 purchased from Loba Chemie Pvt.Ltd,Mumbai is used to analyze the effect of surfactants on the rheology of coal slurries. Its chemical name is iso-octyl phenoxy polyethanol. pH(5% aqueous solution ) is between 6-8.

The test setup and methodology is the same as in sec 3.2 except that only coal A(unsieved) is selected for rheological tests in the presence of additive. The results of tests in the presence of various dosages (by weight of slurry) of triton X-100 is given in fig 4.4-4.5.

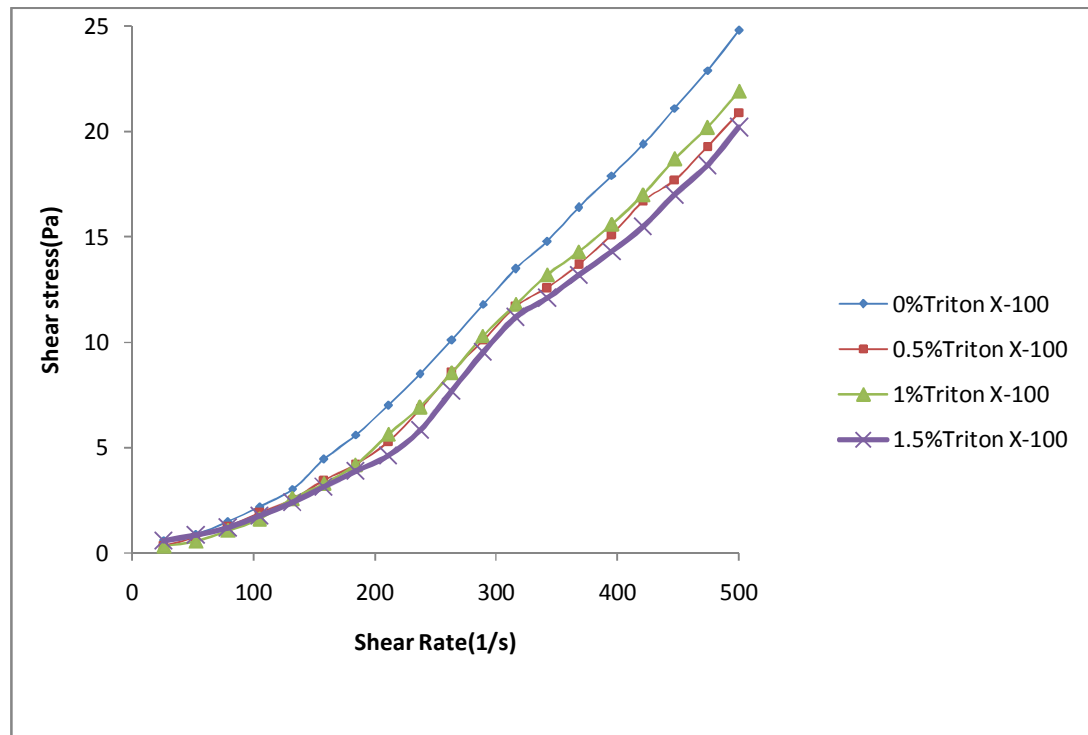


Fig 4.4: Coal A (40% C<sub>w</sub>) with Additive

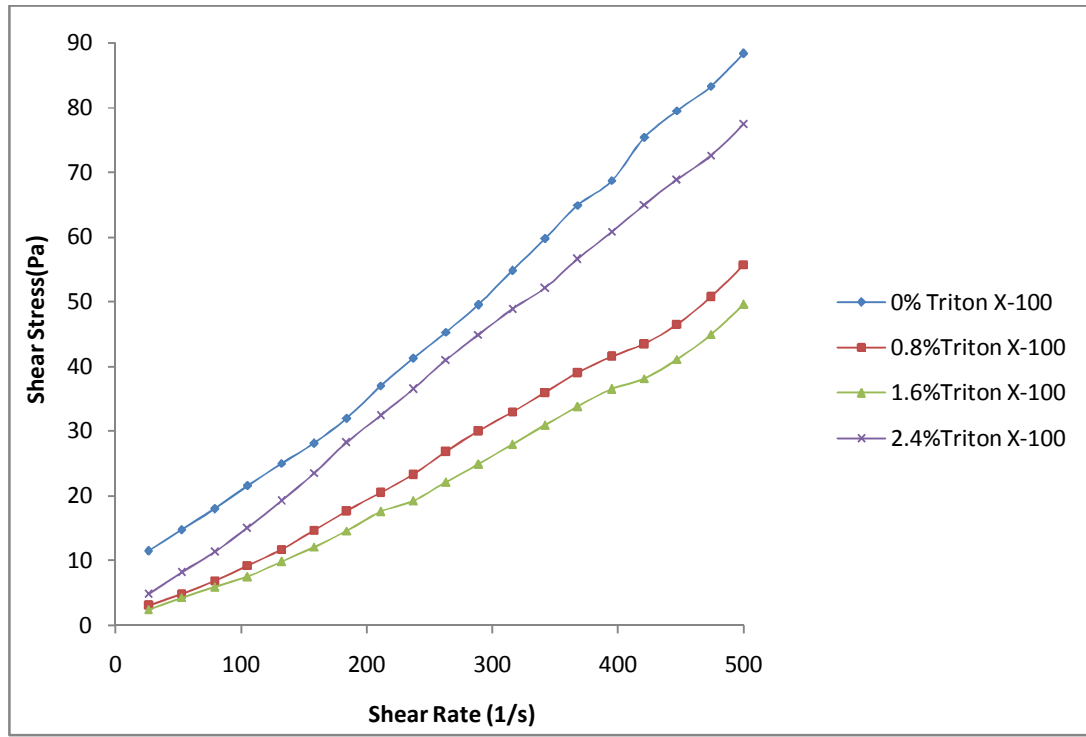


Fig 4.5: Coal A(50% C<sub>w</sub>)with Additive

The above two curves (fig 4.3 and 4.4) clearly show that triton X-100 has profoundly affected the rheology of coal water slurry obtained by coal A. The following points can be made.

- (1).The slurry shows lower viscosity for all tested dosages of additives.
- (2).The Additive is more effective at 50% C<sub>w</sub> where at 1.6% dosage the averaged viscosity is reduced by more than half (See Annexure 17)
- (3)At 40% C<sub>w</sub> of coal slurry the additive more vigorously reduces viscosity at low shear rates (less than 100/s) (See Annexure 11&12).This is highly desirable effect as it shows that it is easier to make the slurry flow from rest.
- (4).The increase in additive dosage does not guarantee a consistent decrease in viscosity. The optimal dosage is near 1.5 % by wt. of slurry.

## **CHAPTER 5**

### **CONCLUSION AND FUTURE SCOPE**

From the present work it is evident that the rheological properties of coal water slurries are dependent on several parameters such as pH, chemical composition, particle size distribution and the presence of additive. The slurry made of finer particles shows higher apparent viscosity as compared to slurry made of coarser particles for a given sample. This could be due to increase in surface area available for frictional effects. Both samples show an exponential increase in viscosity with concentration showing shear thickening/thinning behaviour at lower concentrations and shear thinning/pseudoplastic behaviour at higher concentrations (i.e. 50% Cw and above). The effect of additive (Triton X-100) on the rheology is profound, the additive lowers the yield stress and in the limiting case has reduced the averaged apparent viscosity by half at optimal dosage of around 1.5% concentration by weight of slurry. From the work on additive it can be concluded that additives might be used to tame the rheological behaviour of slurries in a way suited for storage and transportation.

A lot of work needs to be done in the present research area. It could be possible to suitably manipulate particle size distribution, pH to meet a given requirement. The effect of additive on the stability of slurries could be done and it might be possible to develop an additive which could simultaneously lower viscosity/yield stress and improve stability which is seemingly a difficult goal to achieve.

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## Annexure 1

**Table 3.1: Experimental results of particle size distribution for Coal A**

Sieve openings( $\mu\text{m}$ )	%Finer
710	99.38
500	97.31
355	95.56
250	82.71
150	73.82
100	63.77
75	48
53	36.48

**Table 3.2: Experimental results of particle size distribution for Coal B**

Sieve Openings( $\mu\text{m}$ )	%Finer
250	97
150	87.9
106	77.3
75	35.5
53	18.1

## Annexure 2

**Table 3.2: Rheology of coal A (75-106 $\mu$ m) at 20% Cw**

Meas.Pts.	Time[s]	Viscosity[mPa·s]	Shear Rate[1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	311,000	3.63E-05	0.0113	0.00499
2	12	76.2	26.3	2	0.885
3	18	47.6	52.6	2.5	1.11
4	24	37.2	79	2.94	1.3
5	30	31.1	105	3.28	1.45
6	36	27.2	132	3.58	1.58
7	42	24	158	3.79	1.67
8	48	22	184	4.06	1.79
9	54	20.4	211	4.29	1.89
10	60	19.1	237	4.52	1.99
11	66	18	263	4.74	2.09
12	72	17.2	289	4.98	2.2
13	78	16.4	316	5.19	2.29
14	84	15.8	342	5.41	2.39
15	90	15.3	368	5.63	2.49
16	96	14.8	395	5.84	2.58
17	102	14.3	421	6.04	2.67
18	108	13.9	447	6.24	2.75
19	114	13.6	474	6.43	2.84

### Annexure 3

**Table 3.3: Rheology of coal A for 20% Cw(75-106 $\mu$ m)**

Meas. Pts.	Time [s]	Viscosity[mPa·s]	Shear Rate [1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	-1.61E+06	-3.4E-05	0.0542	0.0239
2	12	7.75	26.3	0.204	0.09
3	18	5.11	52.6	0.269	0.119
4	24	4.36	78.9	0.344	0.152
5	30	3.95	105	0.416	0.184
6	36	3.67	132	0.483	0.213
7	42	3.49	158	0.551	0.243
8	48	3.4	184	0.626	0.276
9	54	3.27	211	0.688	0.304
10	60	3.22	237	0.763	0.337
11	66	3.19	263	0.839	0.37
12	72	3.14	289	0.908	0.401
13	78	3.1	316	0.98	0.432
14	84	3.11	342	1.06	0.469
15	90	3.12	368	1.15	0.508
16	96	3.19	395	1.26	0.555
17	102	3.23	421	1.36	0.601
18	108	3.33	447	1.49	0.658
19	114	3.43	474	1.62	0.717

## Annexure 4

**Table 3.4: Rheology of coal A for 30% Cw(75-106 $\mu$ m)**

Meas. Pts.	Time[s]	Viscosity[mPa·s]	Shear Rate[1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	332,000	-7.3E-05	-0.0242	-0.0107
2	12	41.8	26.3	1.1	0.485
3	18	30.2	52.6	1.59	0.701
4	24	26.4	78.9	2.09	0.921
5	30	24.7	105	2.6	1.15
6	36	23.8	132	3.13	1.38
7	42	23.2	158	3.67	1.62
8	48	23	184	4.23	1.87
9	54	22.9	211	4.82	2.13
10	60	22.8	237	5.41	2.39
11	66	22.9	263	6.01	2.65
12	72	22.9	289	6.63	2.93
13	78	23	316	7.25	3.2
14	84	23.1	342	7.9	3.48
15	90	23.2	368	8.55	3.77
16	96	23.3	395	9.21	4.06
17	102	23.4	421	9.87	4.35
18	108	23.5	447	10.5	4.65
19	114	23.6	474	11.2	4.94

## Annexure 5

**Table 3.5: Rheology of coal B for 30% Cw(75-106 $\mu$ m)**

Meas. Pts.	Time [s]	Viscosity[mPa·s]	Shear Rate[1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	332,000	-7.3E-05	-0.0242	-0.0107
2	12	41.8	26.3	1.1	0.485
3	18	30.2	52.6	1.59	0.701
4	24	26.4	78.9	2.09	0.921
5	30	24.7	105	2.6	1.15
6	36	23.8	132	3.13	1.38
7	42	23.2	158	3.67	1.62
8	48	23	184	4.23	1.87
9	54	22.9	211	4.82	2.13
10	60	22.8	237	5.41	2.39
11	66	22.9	263	6.01	2.65
12	72	22.9	289	6.63	2.93
13	78	23	316	7.25	3.2
14	84	23.1	342	7.9	3.48
15	90	23.2	368	8.55	3.77
16	96	23.3	395	9.21	4.06
17	102	23.4	421	9.87	4.35
18	108	23.5	447	10.5	4.65
19	114	23.6	474	11.2	4.94

## Annexure 6

**Table 3.6: Rheology of coal A for 40% Cw(75-106 $\mu$ m)**

Meas. Pts.	Time[s]	Viscosity[mPa·s]	Shear Rate[1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	2.01E+08	-9.4E-06	-1.89	-0.0202
2	12	39.4	26.3	1.04	0.0111
3	18	29.7	52.6	1.56	0.0167
4	24	27.3	78.9	2.15	0.0229
5	30	26.3	105	2.77	0.0295
6	36	29	132	3.82	0.0407
7	42	32.2	158	5.08	0.0541
8	48	35.9	184	6.61	0.0704
9	54	37.6	211	7.92	0.0844
10	60	40	237	9.47	0.101
11	66	43	263	11.3	0.121
12	72	44.9	289	13	0.139
13	78	47.6	316	15	0.16
14	84	50	342	17.1	0.182
15	90	52.6	368	19.4	0.207
16	96	53.7	395	21.2	0.226
17	102	54.5	421	22.9	0.244
18	108	55	447	24.6	0.262
19	114	55.3	474	26.2	0.279
20	120	56.6	500	28.3	0.302

## Annexure 7

**Table 3.7: Rheology of coal B for 40% Cw(75-106 $\mu$ m)**

Meas. Pts.	Time[s]	Viscosity[mPa·s]	Shear Rate[1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	2.13E+08	-2.8E-06	-0.597	-0.00637
2	12	97.4	26.3	2.56	0.0273
3	18	48.7	52.6	2.56	0.0273
4	24	33.1	78.9	2.61	0.0278
5	30	25	105	2.63	0.028
6	36	23.8	132	3.13	0.0333
7	42	23.9	158	3.77	0.0401
8	48	25.8	184	4.76	0.0507
9	54	27.4	211	5.78	0.0616
10	60	29.7	237	7.04	0.075
11	66	31	263	8.16	0.0869
12	72	31.6	289	9.14	0.0974
13	78	31.5	316	9.94	0.106
14	84	33.4	342	11.4	0.122
15	90	34.5	368	12.7	0.135
16	96	35	395	13.8	0.147
17	102	34.5	421	14.5	0.155
18	108	35.1	447	15.7	0.167
19	114	36.2	474	17.2	0.183
20	120	38.2	500	19.1	0.203

## Annexure 8

**Table 3.8: Rheology of coal A for 50% Cw(75-106 $\mu$ m)**

Meas. Pts.	Time[s]	Viscosity[mPa·s]	Shear Rate[1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	-1.66E+08	-1.9E-06	0.319	0.0034
2	12	3,610	26.3	95	1.01
3	18	2,000	52.6	105	1.12
4	24	1,450	78.9	115	1.22
5	30	1,170	105	123	1.31
6	36	1,000	132	132	1.4
7	42	886	158	140	1.49
8	48	802	184	148	1.57
9	54	740	211	156	1.66
10	60	694	237	164	1.75
11	66	660	263	174	1.85
12	72	632	289	183	1.95
13	78	614	316	194	2.07
14	84	599	342	205	2.18
15	90	583	368	215	2.29
16	96	569	395	225	2.39
17	102	560	421	236	2.51
18	108	549	447	246	2.62
19	114	540	474	256	2.73
20	120	534	500	267	2.84

## Annexure 8

**Table 3.8: Rheology of coal B for 50% Cw(75-106 $\mu$ m)**

Meas. Pts.	Time[s]	Viscosity[mPa·s]	Shear Rate[1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	-6.33E+08	-3.7E-06	2.33	0.0249
2	12	1,200	26.3	31.6	0.337
3	18	650	52.6	34.2	0.364
4	24	464	78.9	36.6	0.39
5	30	368	105	38.7	0.412
6	36	306	132	40.3	0.429
7	42	267	158	42.1	0.449
8	48	237	184	43.7	0.466
9	54	213	211	44.8	0.477
10	60	194	237	45.8	0.488
11	66	179	263	47.1	0.502
12	72	167	289	48.3	0.515
13	78	156	316	49.2	0.524
14	84	148	342	50.5	0.538
15	90	141	368	52	0.554
16	96	135	395	53.2	0.567
17	102	130	421	54.9	0.585
18	108	128	447	57.4	0.612
19	114	129	474	61	0.65
20	120	130	500	64.9	0.691

## Annexure 9

**Table 3.9: Rheology of coal B for 60% Cw(75-106µm)**

Meas. Pts.	Time[s]	Viscosity[mPa·s]	Shear Rate[1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	1.78E+09	1.36E-05	24.2	0.258
2	12	10,400	26.3	274	2.92
3	18	5,380	52.6	283	3.01
4	24	3,700	78.9	292	3.12
5	30	2,870	105	302	3.22
6	36	2,380	132	313	3.33
7	42	2,040	158	322	3.43
8	48	1,790	184	329	3.51
9	54	1,600	211	336	3.58
10	60	1,440	237	341	3.64
11	66	1,320	263	348	3.71
12	72	1,230	289	356	3.79
13	78	1,160	316	367	3.91
14	84	1,100	342	377	4.02
15	90	1,030	368	380	4.05
16	96	959	395	378	4.03
17	102	894	421	377	4.01
18	108	845	447	378	4.03
19	114	814	474	386	4.11
20	120	782	500	391	4.17

## Annexure 10

### 3.10: Concentration vs. Viscosity for coal A and B(53-75 $\mu$ m)

Concentration Cw%	Viscosity coal B(mPas)	Viscosity coal A(mPas)
10	1.21	1.47
20	3	3.37
30	5.19	5.59
40	42.2	50
50	624	506

### 3.10: Concentration vs. Viscosity for coal A and B(75-106 $\mu$ m)

Concentration Cw%	Viscosity Coal A(mPas)	Viscosity Coal B(mPas)
20	10	3.71
30	24	4.75
40	42.66	35.56
50	957	281

## Annexure 11

**Table 4.1: Rheology of coal B at 40% Cw without Additive**

Meas. Pts.	Time[s]	Viscosity[mPa·s]	Shear Rate[1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	-4.32E+08	2.68E-06	-1.16	-0.0124
2	12	23	26.3	0.606	0.00645
3	18	16.7	52.6	0.878	0.00935
4	24	18.8	78.9	1.48	0.0158
5	30	20.8	105	2.19	0.0233
6	36	23	132	3.03	0.0323
7	42	28.1	158	4.44	0.0473
8	48	30.4	184	5.6	0.0597
9	54	33.4	211	7.02	0.0748
10	60	35.9	237	8.51	0.0907
11	66	38.4	263	10.1	0.108
12	72	40.9	289	11.8	0.126
13	78	42.7	316	13.5	0.144
14	84	43.3	342	14.8	0.158
15	90	44.6	368	16.4	0.175
16	96	45.2	395	17.9	0.19
17	102	46.2	421	19.4	0.207
18	108	47.2	447	21.1	0.225
19	114	48.4	474	22.9	0.244
20	120	49.7	500	24.8	0.265

## Annexure 12

**Table 4.2: Rheology of coal B at 40% Cw with 0.5% Triton X-100**

Meas. Pts.	Time[s]	Viscosity[mPa·s]	Shear Rate[1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	7.91E+07	-3.5E-06	-0.276	-0.00294
2	12	12.9	26.3	0.339	0.00361
3	18	14.2	52.6	0.745	0.00794
4	24	15.8	78.9	1.25	0.0133
5	30	18.1	105	1.9	0.0203
6	36	19.4	132	2.55	0.0272
7	42	21.9	158	3.46	0.0369
8	48	22.7	184	4.19	0.0446
9	54	25.1	211	5.29	0.0563
10	60	28.8	237	6.82	0.0727
11	66	32.5	263	8.55	0.0911
12	72	35	289	10.1	0.108
13	78	37.1	316	11.7	0.125
14	84	36.8	342	12.6	0.134
15	90	37.1	368	13.7	0.146
16	96	38.3	395	15.1	0.161
17	102	39.6	421	16.7	0.177
18	108	39.5	447	17.7	0.188
19	114	40.7	474	19.3	0.205
20	120	41.8	500	20.9	0.223

## Annexure 13

**Table 4.3: Rheology of coal B at 40% Cw with 1% Triton X-100**

Meas. Pts.	Time[s]	Viscosity[mPa·s]	Shear Rate[1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	-2.09E+08	3.94E-06	-0.824	-0.00878
2	12	12.4	26.3	0.325	0.00347
3	18	10.3	52.6	0.542	0.00577
4	24	13.4	78.9	1.06	0.0112
5	30	15.3	105	1.61	0.0172
6	36	19.7	132	2.59	0.0276
7	42	20.8	158	3.29	0.035
8	48	22.8	184	4.19	0.0447
9	54	26.7	211	5.63	0.0599
10	60	29.3	237	6.93	0.0739
11	66	32.5	263	8.55	0.0911
12	72	35.5	289	10.3	0.109
13	78	37.3	316	11.8	0.126
14	84	38.5	342	13.2	0.14
15	90	38.7	368	14.3	0.152
16	96	39.6	395	15.6	0.166
17	102	40.5	421	17	0.182
18	108	41.8	447	18.7	0.199
19	114	42.7	474	20.2	0.216
20	120	43.8	500	21.9	0.233

## Annexure 14

**Table 4.4: Rheology of coal B at 40% Cw with 1.5% Triton X-100**

Meas. Pts.	Time[s]	Viscosity[mPa·s]	Shear Rate[1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	-2.28E+07	-5.1E-06	0.115	0.00123
2	12	21.4	26.3	0.562	0.00599
3	18	16.5	52.6	0.868	0.00925
4	24	15.4	78.9	1.21	0.0129
5	30	16.9	105	1.78	0.019
6	36	18.3	132	2.4	0.0256
7	42	19.8	158	3.13	0.0334
8	48	21.1	184	3.89	0.0415
9	54	21.9	211	4.62	0.0492
10	60	24.6	237	5.82	0.0621
11	66	29.2	263	7.68	0.0818
12	72	33	289	9.54	0.102
13	78	35.3	316	11.2	0.119
14	84	35.3	342	12.1	0.129
15	90	35.8	368	13.2	0.14
16	96	36.1	395	14.3	0.152
17	102	36.7	421	15.5	0.165
18	108	37.9	447	17	0.181
19	114	38.7	474	18.4	0.196
20	120	40.4	500	20.2	0.215

## Annexure 15

**Table 4.5: Rheology of coal B at 50% Cw without Additive**

Meas. Pts.	Time[s]	Viscosity[mPa·s]	Shear Rate[1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	-2.22E+09	-1E-06	2.23	0.0237
2	12	435	26.3	11.5	0.122
3	18	281	52.6	14.8	0.158
4	24	228	78.9	18	0.192
5	30	205	105	21.5	0.229
6	36	190	132	25	0.266
7	42	178	158	28.1	0.299
8	48	174	184	32	0.341
9	54	176	211	37	0.394
10	60	174	237	41.3	0.44
11	66	172	263	45.3	0.483
12	72	171	289	49.5	0.527
13	78	174	316	54.8	0.584
14	84	175	342	59.8	0.638
15	90	176	368	64.9	0.691
16	96	174	395	68.7	0.732
17	102	179	421	75.4	0.804
18	108	178	447	79.5	0.847
19	114	176	474	83.3	0.888
20	120	177	500	88.4	0.942

## Annexure 16

**Table 4.6: Rheology of coal B at 50% Cw with 0.8% Triton X-100**

Meas. Pts.	Time[s]	Viscosity[mPa·s]	Shear Rate[1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	-1.70E+08	-4.9E-06	0.827	0.00882
2	12	114	26.3	3	0.032
3	18	92.1	52.6	4.85	0.0516
4	24	87	78.9	6.87	0.0732
5	30	87.6	105	9.22	0.0983
6	36	89.2	132	11.7	0.125
7	42	92.9	158	14.7	0.156
8	48	95.4	184	17.6	0.187
9	54	97.4	211	20.5	0.218
10	60	98.3	237	23.3	0.248
11	66	102	263	26.8	0.285
12	72	103	289	30	0.319
13	78	104	316	33	0.352
14	84	105	342	36	0.384
15	90	106	368	39	0.416
16	96	105	395	41.5	0.442
17	102	103	421	43.5	0.464
18	108	104	447	46.5	0.496
19	114	107	474	50.7	0.54
20	120	111	500	55.7	0.594

## Annexure 17

**Table 4.7: Rheology of coal B at 50% Cw with 1.5% Triton X-100**

Meas. Pts.	Time[s]	Viscosity[mPa·s]	Shear Rate[1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	1.01E+08	-3.3E-06	-0.333	-0.00355
2	12	91.9	26.3	2.42	0.0258
3	18	80.8	52.6	4.25	0.0453
4	24	74.5	78.9	5.88	0.0627
5	30	71.3	105	7.5	0.08
6	36	74.6	132	9.82	0.105
7	42	76.4	158	12.1	0.129
8	48	79.1	184	14.6	0.155
9	54	83.1	211	17.5	0.186
10	60	81	237	19.2	0.204
11	66	83.9	263	22.1	0.235
12	72	86.1	289	24.9	0.265
13	78	88.7	316	28	0.298
14	84	90.4	342	30.9	0.33
15	90	91.7	368	33.8	0.36
16	96	92.4	395	36.5	0.389
17	102	90.4	421	38.1	0.406
18	108	91.9	447	41.1	0.438
19	114	94.8	474	44.9	0.478
20	120	99.2	500	49.6	0.529

## Annexure 18

**Table 4.8: Rheology of coal B at 50% Cw with 2.4% Triton X-100**

Meas. Pts.	Time[s]	Viscosity[mPa·s]	Shear Rate[1/s]	Shear Stress[Pa]	Torque[Nm]
1	6	-2.92E+08	1.77E-06	-0.516	-0.0055
2	12	181	26.3	4.76	0.0507
3	18	155	52.6	8.14	0.0868
4	24	144	78.9	11.3	0.121
5	30	143	105	15	0.16
6	36	146	132	19.2	0.205
7	42	149	158	23.5	0.251
8	48	153	184	28.2	0.3
9	54	154	211	32.4	0.345
10	60	154	237	36.5	0.389
11	66	156	263	41	0.437
12	72	155	289	44.9	0.479
13	78	155	316	48.9	0.521
14	84	152	342	52.1	0.555
15	90	154	368	56.6	0.603
16	96	154	395	60.8	0.648
17	102	154	421	65	0.693
18	108	154	447	68.9	0.734
19	114	153	474	72.6	0.774
20	120	155	500	77.4	0.825

