INVESTIGATION ON SLURRY TRANSPORTATION PERFORMANCE OF COAL-WATER MIXTURE AT HIGH CONCENTRATIONS

Thesis submitted in partial fulfilment of the requirements for the award of the degree of

MASTER OF ENGINEERING

IN

THERMAL ENGINEERING

Submitted by:

ARUNANSHU CHAKRAVARTY
Registration no.: 801183005

Under the Guidance of

Mr. Satish Kumar **Assistant Professor** **Mechanical Engineering Department** **Thapar University, Patiala.**	**Dr. S.K. Mohapatra** **DOAA & Senior Professor** **Mechanical Engineering Department** **Thapar University, Patiala.**

MECHANICAL ENGINEERING DEPARTMENT
THAPAR UNIVERSITY
PATIALA-147004, INDIA.
July 2013

DECLARATION

I hereby declare that the work which is being presented in the dissertation entitled, **"INVESTIGATION ON SLURRY TRANSPORTATION PERFORMANCE OF COAL-WATER MIXTURE AT HIGH CONCENTRATIONS"** in partial fulfilment of the requirements for the award of the 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 Dr. S.K. Mohapatra. The work refers other researchers' works which are duly listed in the references section.

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

(Arunanshu Chakravarty)

Date: 9.07.2013
Place: Patiala

This is to certify that the above statement made by the candidate is correct and true to the best of our knowledge.

Supervisors:
Mr. Satish Kumar
Assistant Professor,
Thapar University, Patiala

Dr. S.K. Mohapatra
DOAA & Senior Professor
Thapar University, Patiala

Countersigned by

Dr. Ajay Batish
Professor & Head of Department
Mechanical Engineering Department
Thapar University, Patiala

Dr. S.K. Mohapatra
Dean of Academic Affairs
Thapar University, Patiala

ACKNOWLEDGEMENT

It gives me immense pleasure to record my deep sense of gratitude to work under the esteemed guidance of my research supervisor, Mr. Satish Kumar, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala. Words are inadequate to describe the great care and interest shown by him at all times during the course of the present work.

I would like to express my deepest respect towards my co-supervisor, Dr. S.K. Mohapatra, Senior Professor & Dean of Academic Affairs, Thapar University, Patiala for guiding and inspiring me in the course of the research work. The fruitful discussions with him throughout the research work were a great help for the successful completion of the present work.

I acknowledge my sincere thanks to all my friends and classmates for providing the companionship and making my stay at Thapar University, Patiala pleasant and joyful.

My heartfelt thanks are due to all the Faculty and staff members of the Mechanical Engineering Department, Thapar University, Patiala for providing the necessary instrumentation facility for carrying out the research work.

Last but not the least; I would like to express my love and affection towards my parents and younger brother for their constant moral support and encouragement throughout my life.

Arunanshu Chakravarty

ABSTRACT

The present study on the coal-water slurry rheology and its transportation performance was conducted at the Mechanical Engineering Department, Thapar University, Patiala. The rheological behaviour of five Indian coal samples were investigated by using Anton Paar RheolabQC rheometer to generate extensive rheological data with a perspective to study the effect of solids concentration, particle size distribution, fraction of coal fines and use of a natural additive as dispersant on the slurry rheology. The rheological data so obtained were utilized to numerically evaluate the pressure drop characteristics of coal water slurry flowing in straight pipe and 90^o pipe bend using ANSYS FLUENT 14.0 computational fluid dynamics code. The rheological results revealed that the coal water slurry exhibited non-Newtonian behaviour at solids loading greater than 30 % by weight. The coal water slurry flow behaviour was described by the Power-Law and Herschel-Bulkley models. The apparent viscosities of coal water slurry increased with solids loading. The Particle Size Distribution affected the slurry rheology which was investigated by correlating Rosin-Rammler distribution modulus with the apparent viscosities. The coal water slurry showed a decrease in apparent viscosity values by adding fraction of finer coal particles in a relatively coarse size range until an optimum coarse/fine ratio was reached. The dispersant chosen was Shikakai powder; a natural product available in India. The dispersant was effective in reducing the apparent viscosity of slurry with a dosage of 0.5 % by weight. The pressure drop predictions were obtained by utilizing the rheological data and the results revealed that in both straight pipe and 90^o pipe bend, with increase in solids loading and mean flow velocities, the pressure drop increased. However, by utilizing additive ar a dosage of 0.5 % by weight the pressure drop decreased for the same solids concentration.

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NOTATIONS

C_w : Weight concentration of slurry (wt. %)
D : Pipe diameter (mm)
d_{50} : Mass median particle diameter (microns)
f : Friction factor
g : Acceleration due to gravity
K : Flow consistency coefficient in Power law model
n : Flow behaviour index in Power law model
Δp : Pressure drop per metre (kPa/m)
R_e : Reynolds number
R^2 : Coefficient of determination
V : Mean flow velocity (m/sec)
ε : Absolute pipe roughness (mm)
γ : Shear rate
μ : Dynamic viscosity
η : Apparent viscosity
τ : Shear stress (Pa)
τ_y : Yield stress (Pa)

CHAPTER 1 INTRODUCTION

One of the most significant scientific challenges in the world today is to efficiently utilize a fuel to generate power at the most economic level. For this purpose various types of techniques of utilizing fuel in solid form (e.g. pulverized coal), liquid form (e.g. petroleum), and gaseous form (e.g. Compressed Natural Gas) have been utilized from the very beginning. A relatively new technique of utilizing solid fuel is to suspend fuel in a carrier liquid to form slurry and use this fuel slurry in atomized form for direct combustion in furnaces. However, when this fuel in a finely powdered form is mixed with a carrier liquid, the obtained slurry flow behaviour generally gets altered depending on the concentration of fuel powder (i.e. solid loading) and the interfacial properties in the carrier liquid. One such slurry that is widely recognized as a possible alternative to conventional furnace fuel is coal water slurry (CWS), which is a mixture of powdered coal and water. The efficient utilization of coal water slurry is possible only when the slurry is prepared such that it permits maximum coal loading with appreciable viscosity and maintains a uniform concentration. Therefore, to study whether a particular coal water slurry is suitable to be inducted as a fuel, rheological studies are often conducted to determine the rheological parameters like viscosity, shear stress etc. by applying a rate of shear on the slurry and the rheograms (flow curves) and viscosity curves obtained thus are then fitted to the different rheological models that best describes the category of fluid in which the slurry in investigation falls in. The present scope of study lies in to investigate the rheological behaviour of coal water slurry prepared from five grades of Indian coal from different locations across India and to determine the effect of particle size distribution, fraction of coal fines in a relatively coarse sample, ash content of coal and natural additive on the flow behaviour of the slurry. The rheological data generated were fitted to the rheological models by regression analyses and best fit were obtained. A numerical investigation was also undertaken for the coal water slurry flow in straight pipeline and 90^o pipe bend of 53 mm diameter by utilizing the rheological data obtained from the rheological measurements and the effect of solid concentrations, mean flow velocities on the pressure drop characteristics of coal water slurries were analyzed using computational fluid dynamics code ANSYS FLUENT 14.0.

1.1 COAL

Coal is a **fossil fuel** formed from the remains of plants that lived and died about 100 to 400 million years ago when parts of the Earth were covered with forests. Coal is classified as a **non-renewable** energy source because it takes millions of years to form. It is the most important and abundant fossil fuel in India. It accounts for 55% of the country's total energy need. (Anon, 2013)

Commercial primary energy consumption in India has grown by about 700% in the last forty years. The current per capita commercial primary energy consumption in India is about 350 kgoe/year (as of July, 2013), which is well below that of developed nations. Due to the rise in population, expansion of economy and a zeal for improved standard of living, energy usage in India is expected to rise in the near future. Considering the limited reserve potentiality of petroleum & natural gas, restriction on hydel project and pessimistic perception towards nuclear power, coal will continue to occupy centre-stage of India's energy scenario.

1.2 TYPES OF COAL

Indian coals are mainly classified as coking and non-coking coals depending on the ash content and Useful Heat Value (UHV) of the coal. The Coking coals are metallurgical coals that are generally employed in steel industries whereas Non-coking coals are thermal coals utilized in thermal power plants for power generation purposes. The coking and non-coking coals are further classified according to their grades. The Coking coals are classified as Steel Grade I and II with the ash content up to 18 % and Washery Grade I, II, III and IV for the ash content up to 35 %. The Non-Coking coals are classified as A, B, C, D, E, F, and G for the total of ash and moisture content ranging from 19.5 to 55 %.

1.3 COAL-WATER SLURRY

Coal-Water Slurry is a mixture of powdered coal and water which maintains a stable state over a long period when a small amount of chemical additive is also added. The coal-water slurry can be used as a liquid fuel for boilers (CWSF) and can replace petroleum for energy conversion.

Coal-Water Slurries that are utilized as fuels have high solid loadings in the range of 50–75 wt. % , which leads to high energy densities per unit mass. Possible applications include gas turbines, diesel engines, fluid bed combustors, blast furnaces, and gasification systems. Coal water slurries with a lower coal loading of 50 wt. % may be used for the internal combustion engines.

For maximum efficiency as a fuel, the coal concentration in coal-water slurry should be as high as possible, maintaining its viscosity at a minimum level so that it will be suitable for storage and transport via pipelines.

The primary factors that are responsible for the optimum preparation of coal-water slurry depend on the physicochemical properties of coal, such as its (i) surface hydrophobicity, (ii) particle size distribution, (iii) oxygen content, (iv) zeta potential, (v) pH sensitiveness, (vi) shear rate-shear stress relation, (vii) temperature sensitiveness of the viscosity of the coal-water slurry, and (viii) surface chemistry of coal etc.

Most of these factors are governed by the interfacial characteristics of coal in a carrier liquid. Coal, being a heterogeneous mixture of carbonaceous and mineral matter, has a surface which is mostly hydrophobic and, therefore, agglomerates to form clusters, reducing the stability of the coal-water suspension. For stable suspension, interparticle interaction of the coal particles has to be mutually repulsive. Surfactants and polymers adsorb strongly on solid/liquid interface, making the surface hydrophilic or hydrophobic. Depending on the charge of the head groups and size of both hydrophilic group and hydrophobic chain, they provide electrostatic/steric hindrance for the particle-particle association. Many commercially available surfactants and polymers, on being adsorbed to coal-water interface, have improved the stability of coal-water slurry as well as increased concentration of coal in the coal-water slurry.

1.4 UTILIZATION AREAS OF COAL-WATER SLURRY

In the present global scenario where the cost of petroleum products are increasing day by day, there is a surge among the researchers to develop new fuels that can replace the conventional fuels without compromising the thermal efficiency and other performance parameters. However this approach has been limited by various constraints. Therefore, utilizing a conventional fuel in some economic way that can provide cost reduction with better burning capability has caused the development of coal water slurry technology. The different utilization areas of coal-water slurries are described in Table 1.1.

Table 1.1: Utilization areas of coal-water slurries

Utilization Areas	Required properties of Coal Water Slurry
Thermal Power plants	Efficient combustion
Coal Gasification	High loading of coal
Diesel engine fuel	Good combustion properties
Industrial Heating	Stability during storage.

1.5 ADVANTAGES OF COAL-WATER SLURRY

Coal water slurry offers a good alternative for replacing conventional fuels if it satisfies the conditions of optimum slurry which permits maximum coal loading simultaneously possessing appreciable fluidity and stability.

The use of coal water slurry in various applications has yielded appreciable results and some of the benefits in utilizing coal water slurry are enumerated below:

1. Environmental protection

a) The coal for CWS is usually a cleaned coal – low in ash and sulphur content.

b) CWS burning temperature is 100 – 200^o C lower than oil or pulverized coal. It can effectively reduce No_x and SO_2 emissions.

2. Energy saving effect is remarkable

a) CWS has high combustion efficiency (above 95-98 %).

b) CWS combustion is easy to control

3. Providing new manner of coal transportation

CWS can be transported through pipelines and stored in storage tanks:

a) Less construction investment in railway and highways and rolling stocks.

b) Less environmental pollution.

4. Other benefits

Other benefits of utilizing Coal-Water slurry includes ease in handling and operation, low running costs and high reliability, replacing diesel oil through special processing.

1.6 RECENT DEVELOPMENTS IN COAL-WATER SLURRY TECHNOLOGY

Coal-water slurry fuels have received the most process development attention recently. Coal slurry facilities have been built in Australia, Canada, China, Italy, Japan, Russia, Sweden, and the U.S.

The most active countries have been Japan, China, and Russia. China has built several slurry production facilities and boiler units. Japan has done considerable research and technological development on slurry processes and has converted several boilers. Russia has built several pipelines, production facilities, and boilers. Currently, some new techniques, such as microwave irradiation, exposure to ultrasonic radiation, use of organic solvents in place of water, modification of the surface chemistry of coal through newly developed additives are being researched to obtain a coal -water slurry with good fluidity and stability.

1.7 RHEOLOGY

The word “Rheology” originates from the Greek word “reo”, meaning flow. Rheology is the study of the deformation and flow of materials. Typically, rheology studies the deformation of those materials whose behaviour falls between solids and fluids (viscoelastic materials). The study of rheological properties attempts to determine the intrinsic fluid properties; mainly viscosity, which is necessary to determine the relationships between the flow rate (shear rate) and the pressure gradient (shear stress) that causes the movement of a fluid. The science of rheology is useful for studying various aspects regarding the fluid behaviour. Some of the application areas where rheology provides immense help are enumerated below:

1) To control the quality of a raw material by measuring its rheological properties. The acceptance or rejection of a product can be determined based on rheological results.
2) To determine the mix ability and pump ability of a slurry and to effectively design slurry transportation systems by utilizing rheological data.
3) To determine the frictional pressure drop when a slurry flows in pipes.
4) To evaluate the capability of a slurry or paste to transport large particles.
5) To evaluate how the surrounding temperature profile affects the slurry flow behaviour.
6) To design a processing equipment such as selecting the appropriate pump to provide sufficient power for a material to flow over a certain distance in pipelines. The relationship between the pump and flow in pipelines is governed by the rheological properties of the material.

1.8 FLUID AND ITS TYPES

A fluid is a substance that undergoes continuous displacement as long as shearing forces are acting on it. Viscosity is a measure of the resistance of a fluid to deform under shear stress. Viscosity describes a fluid's internal resistance to flow and is a material property relating the shear stress (τ) and the time rate of shear strain (γ) in a moving fluid. Equation 1.1 below shows the relationship for these parameters in a Newtonian fluid.

$$\tau = \mu \gamma \tag{1.1}$$

For Newtonian fluids, the dynamic viscosity can be used to relate the shear stress to the applied rate of shear strain. For Newtonian fluids the viscosity is independent of both τ and γ. The shear stress is a linear function of the shear rate, with the slope of the curve being equal to the viscosity of the fluid.

Equation 1.2 represents the basic equation relating the time rate of deformation of a fluid to an applied shear stress.

$$\tau = \eta \gamma \tag{1.2}$$

In Equation 1.2, η is the apparent viscosity of the fluid. For Newtonian mixtures, the apparent viscosity is equal to the fluid viscosity ($\eta = \mu$). This is not the case for non-Newtonian fluids where η is a function of multiple rheological parameters as well as τ and γ.

In contrast to the Newtonian fluids, for non-Newtonian fluids, more than a single parameter is required to relate the shear stress to the applied rate of shear strain. The different non-Newtonian fluids are Power-Law, Herschel-Bulkley, Bingham, Casson etc. depending on the complexities involved in their constitutive equations. The constitutive model equations for selected non-Newtonian fluids are shown in Table 1.2:

Table 1.2: Constitutive equations of non-Newtonian fluids

Type of non-Newtonian Fluid	Constitutive equation	Parameter
Power-Law	$\tau = K\gamma^n$	Two parameter
Bingham	$\tau = \tau_y + \mu_P\gamma$	Two parameter
Herschel-Bulkley	$\tau = \tau_y + K\gamma^n$	Three parameter
Casson	$\tau^{1/2} = \tau_C^{1/2} + (\mu_C\gamma)^{1/2}$	Two parameter

Figure 1.1 shows a graphical representation of the shear stress versus time rate of shear strain behaviour plotted as a rheogram for a number of different continuum fluid models.

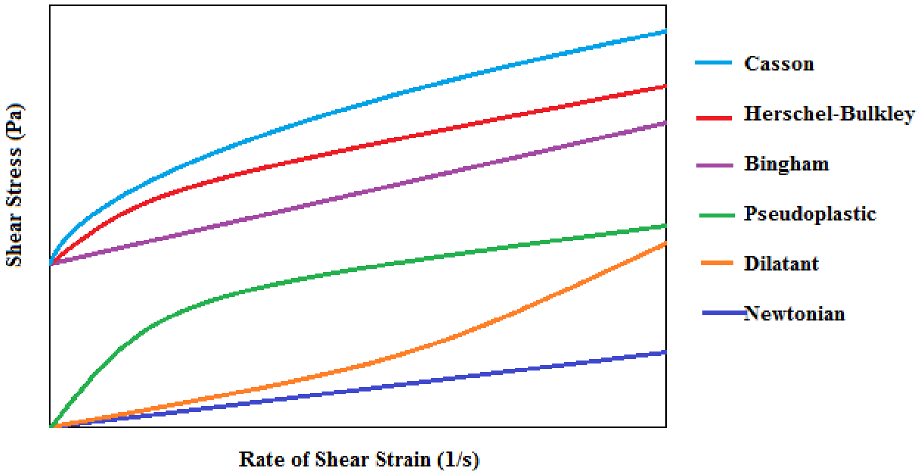

Fig.1.1: Rheogram of different fluid models

Power-Law fluids are those fluids that do not contain the yield stress and they can be pseudoplastic (shear-thinning) or dilatants (shear thickening) depending on the flow behaviour index, n. The Bingham, Herschel-Bulkley and Casson fluids show the inclusion of a yield stress term. In order for the fluid to flow, the applied shear stress must exceed this yield stress. Once the applied shear stress exceeds this yield stress, the rate of deformation of the fluid is determined by the difference between the applied stress and the yield stress. In the present study, slurries that exhibited a yield stress were represented with the Herschel-Bulkley rheological model.

Non-Newtonian slurries also displays time dependent behaviour. For slurries exhibiting time dependent behaviour the shear stress is a function of time at a constant shear rate. For a rheopectic fluid the shear stress increases with time at a constant shear rate; for a thixotropic fluid the shear stress decreases with time at a constant shear rate.

1.9 FLOW OF SOLID-LIQUID MIXTURE

Solid-Liquid mixtures (slurries) can generally be classified into two categories: homogeneous and heterogeneous. Due to non availability of a clear cut distinction between homogeneous and heterogeneous slurries, the flows in which the mean particle diameter is greater than 50 μm generally display heterogeneous properties. However, this might not be applicable for slurries of varying compositions, concentrations and flow conditions.

The fine particle slurries consisting of mean diameter less than 50 μm typically exhibit homogeneous fluid behaviour. Although the mixture consists of two distinct phases, the mixture is treated as a continuum possessing the density of the mixture. These types of slurries generally deviate from Newtonian behaviour and exhibit non-Newtonian characteristics. Many continuum models (i.e. Power-Law, Bingham, and Casson) have been developed for predicting their behaviour in laminar as well as turbulent flow regimes.

Heterogeneous slurries have more complicated flow behaviour than homogeneous slurries. These slurries are typically a mixture of coarser particles in a homogeneous carrier fluid. Due to the submerged weight and effects of gravity on the coarse particles, sedimentation occurs within the flow. As a result, concentration and velocity profiles across the flow domain are non-uniform.

1.10 RELEVANCE OF VISCOSITY MEASUREMENT

Viscosity of a Newtonian fluid is determined from the slope of the shear stress-rate of strain curve and is independent to the rate of strain. However, Coal water slurries at concentrations above 30 % by weight generally exhibit non-Newtonian behaviour with viscosity varying with a change in rate of strain. Therefore, the rheological tests are performed to evaluate the viscosity profile so that while designing the transportation system for these non-Newtonian coal water slurries, appropriate measures relating to the type of slurry pumps (input power) and use of dispersant (to reduce the viscosity of slurry), etc. could be taken.

1.11 MOTIVATION FOR THE PRESENT STUDY

The transportation of coal water slurries through pipeline is achieved by designing slurry transportation components that promotes an economic transport with a minimum pressure drop. At low solid concentrations of coal, the slurry behaviour is often Newtonian and the flow in the pipelines maintains a constant viscosity at the different shear rate ranges that are usually encountered in practical situations. However, the present commercial needs require the coal solid loading in the carrier fluid to be higher for the sake of saving the energy required in pumping slurries and also to conserve precious water. Also, in coal water slurry burners, highly concentrated slurry is required in atomized form that is subjected to very high shear rates. These highly concentrated coal water slurries typically exhibit non-Newtonian flow behaviour with apparent viscosities varying with the rate of shear. Thus, before designing a slurry transportation system, it is of paramount importance to determine the rheological behaviour of concentrated coal water slurries beforehand to know the various parameters like the apparent viscosities at different shear rates, the flow behaviour, the pressure drop predictions that are determined theoretically (by using empirical correlations), experimentally (by pipeline loop tests) and numerically (using computational fluid dynamics).

The present study was conducted to generate extensive rheological data for coal samples of different locations in India and determine the coal water slurry rheological behaviour that best describes the coal samples at varying solid concentrations, particle size distributions, coal fines and additives. The additive chosen was a natural product that is produced from Acacia concinna plant saponin. The rheological data obtained were fitted to the rheological models and the model parameters were calculated by regression analyses. The pressure drop for coal water slurries flowing in straight pipelines were also calculated by numerical simulation techniques.

1.12 ORGANIZATION OF THESIS

The first Chapter dealt with a brief overview of coal water slurry technology which is a promising alternative as a fuel technology for near future. A review of published works that are related to the present study are presented in Chapter 2. The results of characterisation studies on the coal samples are described in Chapter 3. Chapter 4 is devoted to the rheological results that were obtained by conducting the experimentation. It describes the effect of particle size distribution, coal fines, ash content and additive on the rheological behaviour of coal water slurries. The numerical simulation results for predicting pressure drops in straight pipe and 90^o pipe bend are presented in Chapter 5. The conclusions drawn from the present study and the future scope are mentioned in Chapter 6. At the end, the cited published works are mentioned in the References section and the Appendix contains the experimental data obtained in undertaking the present investigation.

CHAPTER 2 LITERATURE REVIEW

There is a considerable research work that has been done in the past to evaluate the coal water slurry rheology from different perspectives. Various factors that contribute in altering the coal water slurry rheology have been investigated by numerous researchers and an optimum value that promotes an economic slurry transport with an appreciable viscosity in a particular shear rate range has been found. Majority of research done in the past is focused on the use of chemical additive to reduce slurry viscosity. However, a gap in study reveals that there is still a lot of work to be done in finding a suitable natural and eco friendly product as an additive to the coal water slurry. In the present study, prior to the research work, an extensive review of the published works in the field of coal-water slurry technology with an emphasis on the effects of different factors like particle size distribution, packing characteristics, coal properties, solid loading, use of chemical additives, etc. that affects the rheological behaviour of concentrated coal-water suspensions were undertaken and a review of published works are presented in this chapter.

2.1 RHEOLOGY OF COAL SLURRIES

Castillo C et al. (1979) have investigated the rheological behaviour of highly concentrated coal suspensions made in suspension media of Aroclor 1254 (a chlorinated biphenyl) and glycerine. The coal used was an Illinois coal with particle size distribution of less than 62 µm. Viscosity was measured with a Weissenberg Rheogoniometer R-17, operating in a cone-and-plate mode. They found that the coal slurry exhibited Newtonian character at concentration less than 20 % and the settling did not occur as the density of the suspending media was close to that of coal. Also, they found that the viscosity generally exceeded the predictions of correlations and theory established for spherical particles.

Papachristodoulou G et al. (1984) examined the rheological properties of coal-oil mixtures. The coal oil mixture was prepared using a bituminous coal in four different grades of oil. These grades were grade 2, grade 4, light grade 6 and heavy grade 6. The rheological behaviour of coal oil mixture was obtained by varying coal concentration, coal particle size, and temperature effects. The rheological measurements were carried out using Ferranti-Shirley cone and plate viscometer. They found that the coal-oil mixtures showed Newtonian behaviour for concentrations up to 30 % by weight and above them exhibited Bingham plastic behaviour. Also, they observed that as the median particle size got higher and the slope of the particle size distribution became lower, the viscosity and the yield stress decreased.

Wildemuth C.R et al. (1985) conducted experiments on Illinois coal to determine the rheological behaviour of coal suspension in non aqueous media. They chose glycerin, bromonapthalene, Aroclor as suspending fluids. The Particle size distribution was obtained by Leeds and Northrup Microtrac Analyser. Viscosity was measured with a Weissenberg Rheogoniometer R-17, operating in a cone-and-plate mode. They developed a new model correlating the viscosity and yield stress by utilizing the rheological data obtained by the experimentation.

Hasan A.R et al. (1986) investigated the rheological behaviour of coal water slurry prepared from Sarpy Creek sub-bituminous coal. The viscosity was obtained at different solid loadings by using Brookfield viscometer with particle size varying from 0.044 mm to 0.223 mm. They found that at all concentrations, the coal water slurry showed pseudoplastic behaviour. The model fitted to the data was Power law and the parameters were calculated. They found that the coal water slurry prepared by hot water drying had better fluidity as compared to the slurry prepared from as received coal.

Sengun M.Z et al. (1989) studied the effect of bimodal particle size distribution on the slurryability of coal water slurries. Illinois coal was used for testing and the average diameter was 2-3 µm and different samples were prepared at different coarse to fine coal ratios. Brookfield LVT viscometer was used for viscosity measurements. They found that the shear rate exerted on the colloidal fraction was higher than that applied by the viscometer as a result of hydrodynamic interactions between the coarse particles, and that it was this effective higher shear rate which was applied in the correlations.

Leong Y.K et al. (1993) conducted experiments to study the rheology of brown coal suspensions at higher concentrations without the use of additives. Two types of coal were used i.e. Loy Yang and Yallourn coal. The Particle size distribution was obtained and classified into two size ranges of coarse and fine fractions. They used a capillary viscometer for viscosity measurements and they concluded that control of the material properties i.e., porosity, swelling and wetting of solids in a suspension allows considerable increase in making highly concentrated slurries with minimum viscosities.

Reddy G.V et al. (1994) investigated the rheological properties of coal oil mixtures and determined the effect of coal properties i.e. moisture and ash contents on the slurry behaviour. The particle size distribution data were fitted into the Rosin Rammler model. The viscosities of the coal oil mixture were measured using Brookfield synchroectric viscometer. (Model RVT). They found that coal oil mixtures with high ash content were less viscous and the viscosity decreased as the moisture content of the coal decreased.

Roh N.S et al. (1994) investigated the effects of coal type, loading and particle size on the rheological behaviour of coal water mixtures. Seven bituminous coals were used in the study with particle size distribution obtained by sieving for particle greater than 38 µm and Coulter counter for particles less than 38 µm. Rheological tests were conducted using Haake RV-12 viscometer. They found that all the slurries exhibited pseudoplastic behaviour. The blending with coarse coal fraction was useful in reducing the viscosity and the static stability measurement by rod penetration test revealed that the stability was maximum when the same optimum coarse fine ratio was utilized.

Tadros T F et al. (1995) investigated the addition of a Polyelectrolyte and Nonionic polymers on the rheology of coal water suspensions. The polyelectrolyte was sodium lignosulfonate. Polish coal was used for testing purposes. The electrophoretic mobility was measured using Malvern Zeta sizer 3. Rheological measurements were carried out Bohlin Rheometer both in oscillatory and steady state. Rheological investigations revealed that polyelectrolytes were able to produce colloidally stable coal water suspensions. Nonionic dispersants were found to produce either flocculated or relatively well dispersed suspensions, depending on both their concentration and their molecular weight. The flocculated systems showed relatively weak structures that are broken up under shear.

Vitolo S et al. (1995) studied the influence of adding petroleum coke in micronized fraction to the coal-water mixtures and hence the rheological behaviour of these slurries. Two types of coal were used with similar median diameters. A bimodal particle size distribution was made by blending coarse coal with micronized petroleum coke. The dispersant used was an anionic additive (an organic sodium sulfonate) in quantities varying from 0.3 to 0.9 wt. % of the dry solids. The rheological behaviour of CWM was studied with a HAAKE RV2 rotational viscometer. They observed that at room temperatures, the addition of micronized petroleum coke to the coal water mixtures yielded a good rheological behaviour due to the lower oxygen content and hence low hydrophillicity of the blended slurry.

Logos C et al. (1996) studied the effect of particle size on the flow properties of a South Australian coal water slurry. The coal used for the preparation of coal water slurry was a low rank Lochiel coal from South Australia. The particle size distribution was varied by introducing coarser fraction of coal to the finer fraction in different proportions. The rheological parameters were evaluated using concentric cylinder viscometer (HAAKE, Model RVI00). The solid loadings were in the range of 23 % to 50 % by weight. They found that the slurries prepared from only finer fraction i.e. under 45 µm were more viscous than the coal water slurries prepared from a mixture of coarse and fine particles with coarse particles varying from 208-279 µm. The optimum coarse to fine ratio was 40:60 that showed the least apparent viscosities with a Newtonian behaviour of the slurry.

Nguyen et al. (1997) determined the rheological properties of coal-water slurries and studied the effects of the size distribution of coal particles on the rheological behaviour of coal-water slurry. The coal studied were two raw lignites, Lochiel and Bowmans coal obtained from Southern Australia. The rheological properties were measured using HAAKE RV-100 viscometer. The coal-water slurry prepared consisted of 23 to 50 wt. % for Lochiel coal and 40 wt. % for Bowmans coal. They found that the solid concentration affected the nature of the slurry with 23 wt. % as Newtonian and at higher concentration as shear thinning. Above 40 wt% the slurry showed viscoplastic behaviour with the presence of a yield stress .They found that addition of a coarser coal fraction to a suspension lowers the viscosity substantially. They did not use additives.

Pawlik M et al. (1997) studied the effect of Humic acids and coal surface properties on rheology of coal-water slurries. Three types of bituminous coal were taken for the experimentation. The zeta potential was measured using Zeta-Meter System 3.0 by varying the pH and Humic acid concentration. Rheological measurements were conducted using a Haake Rotovisco RV20 viscometer with the M5 measuring system. They found that coal-water slurries prepared from hydrophobic coals in distilled water exhibited high values of yield stress and also higher apparent viscosity. In contrast, CWS's prepared from a hydrophilic coal in distilled water exhibited much lower yield stresses, and it was possible to achieve higher loading for these coals.

Yavuz R et al. (1998) investigated the effect of particle size distribution on the rheology of lignite-water slurries. They optimized the particle size distribution for lignite particles having size less than 125µm. Rheological properties of lignite water slurries were obtained using a Contraves, Rheomat-15 rotational rheometer with measuring systems MS-B and MS-C. Shear rate was increased at a constant rate from 0 to 100 s^{-1} over a period of 3 min, held constant for 1 min, then steadily decreased to 0 in 3 min. The apparent viscosities were higher for monodispersed suspensions and an optimum particle size distribution was found that showed least values of apparent viscosities at higher coal loadings.

Mishra S.K et al. (2002) investigated the rheological behaviour of coal water slurry made from Indian coal. The effect of solid concentration, ash content, pH and temperature on the rheology of coal water slurry was evaluated. The coal was obtained from Talcher coal field, Orissa, India. Rheological studies of the CWS were carried out in a HAAKE rotational viscometer RV30 using sensor MV1 and measuring system M5 which was connected to a personal computer. A thermostatic temperature bath was used to maintain the temperature with the accuracy of ±0.1°C of the slurry in the cup. They found that the coal water slurry exhibited pseudoplastic behaviour with apparent viscosity decreasing with an increasing shear rate. Also, the apparent viscosity values for higher coal loading were greater than for lower coal loading at the same shear rate. The viscosity also increased as the ash content of coal increased. The apparent viscosities were lower for higher pH values and with the increase in temperature the viscosity decreased.

Atesok G et al. (2002) investigated the effect of coal properties on the viscosity of coal-water slurries. Two Turkish coals of different ranks and one Siberian bituminous coal was used to prepare the coal water slurries. PSS (sodium polystyrene sulfonate) was used as the dispersing agent and CMC-Na was used as a stabilizer for the preparation of coal-water mixtures. Rheological measurements were carried out using RVD2-Brookfield rotating type viscometer. The apparent viscosities were measured using coal samples having mean particle sizes of 19, 35 and 50 µm. The solid loading varied from 42 to 63 % by weight. They found that the low rank Turkish coal showed less solid loading capacity than the Siberian coals due to presence of higher porosity than Siberian coal.

Lorenzi et al. (2002) studied the influence of coal particle size distribution on the rheological behaviour of coal-water slurry fuel and quantified the rheological behaviour of slurry as a function of different fine/coarse coal ratios and different total solid contents. The coal chosen for study were obtained from Iran and Venezuela. The particle size distribution was obtained by the method of laser diffraction. The surfactant employed was a block copolymer of ethylene and propylene oxides with a concentration of 0.7 wt. %. The xanthan gum with a concentration of 0.05 wt. % was used as a thickener to prevent particles settling. The rheological measurements were obtained from HAAKE VT 550 rheometer. They found that the optimum fine/coarse particle ratio was 55 % of fine coal with a minimum viscosity and also concluded that due to the addition of surfactant the air gets entrapped which causes a change in the viscosity of the slurry on the day following their preparation.

Tiwari K et al. (2003) investigated the performance of two newly developed anionic additives towards the coal loading and viscosity of coal-water slurry. The material consisted of the samples of coal obtained from Makum field of Assam called Ledo coal and from North Karanpura field of Jharkhand called Sirka coal. The characteristics of coal were first determined by the proximate and ultimate analysis. The additives chosen for the study were naphthalene based (P) and naphthalene-toluene based (R) and their concentration was held constant at 1 wt. % in each case with the coal loading varied from a minimum of 56 % to a maximum of 70 % loading. The rheological properties of CWS were measured by a HAAKE RV-12 Rotoviscometer using MVIP profiled sensor system and M500 measuring head. The shear rate was varied from 0 to 512 s^{-1} and the apparent viscosity of the slurries was determined at 128 s^{-1}. They found that with (P) as an additive the maximum coal loading was 70 % and with (R) as additive the maximum loading was around 69 %. The optimum concentration of additives for high coal concentration (65-70%) was found to be 0.8 % for naphthalene based and 0.9 % for naphthalene-toluene based. It was also suggested that the highly loaded coal-water slurry can be formulated by wet grinding the coal by ball milling to obtain the required particle size distribution.

Yuchi W et al. (2005) determined the effects of coal characteristics on the properties of coal water slurry. Sixteen Chinese coals of different ranks from lignite to anthracite were used in the study. Sodium naphthalene sulfonate formaldehyde condensate was selected as a dispersant. The apparent viscosity was measured by a NXS-11 rotation viscometer (Chongqing Analytical Instrument Factory, China). The shear rate was varied from 3.18 to 113.5 s^{-1} at 25^{o}C. They found that the slurryability decreased with an increase in solid loading.

Gurses A et al. (2006) studied the effects of coal loading, initial pH, addition of electrolytes, surfactants and temperature on the viscosity and rheological parameters of coal-water slurry. The apparent viscosity was measured with a RV8-Brookfield rotating type viscometer. The additives used were $AlCl_3$ and K_2HPO_4 as the electrolytes and Cetyltrimethyl Ammonium Bromide (CTAB), Sodium Dodecyl Sulphate (SDS) and Borrosperse NA-3A as the surfactants. They found that the most effective additives, in terms of the viscosity reduction, were CTAB and K_2HPO_4, and that the coal-water slurry which had coal concentrations up to 50 % (based on the weight of dry coal) could be prepared by using each additives. Also they concluded that the viscosities of coal-water mixture with increasing temperature were found to increase at low speed, and decrease at high speed.

Das D et al. (2009) investigated the formulation, rheology and stabilization of the highly concentrated coal-water slurry using a natural additive, saponin of the Acacia concinna plant commonly called *Shikakai*. The coal samples were obtained from Talcher coal fields, Orissa. The rheological measurements were carried out using HAAKE RV 30 model rotational viscometer. The slurry prepared had a coal loading in the range of 55-65 wt. % and they found that the reduction in apparent viscosity was appreciable when the additive concentration was less than 0.8 %.

Gao et al. (2010) studied the influence of the amount of dispersants and slurry content on the slurryability of coal pitch water slurry. Two types of particle size distribution were obtained and were named as gradation 1 and gradation 2. The dispersant employed was JL-CO1, a cationic type surfactant and the rheological measurements were carried out with NXS-4C viscometer at a shear rate of 100 s^{-1}. They found that gradation 2 kind of slurry had more slurryability for the same dosages of dispersant and slurry content.

Zhou et al. (2010) investigated the rheological properties of concentrated coal-water slurry by applying the Herschel-Bulkley model. The rheograms were obtained from HAAKE rheometer with shear rate range of 0 s^{-1}- 200 s^{-1}. The slurry was dispersed with lignin-based dispersant (MSL). Two slurries were prepared with coal concentration of 64.0 wt. % and dispersant dosage of 0.7 wt. % and 1.5 wt. %. They found that when the dispersant dosage was 0.7 wt. %, the slurry showed shear-thinning characteristic and for 1.5 wt. % dosage it showed shear-thickening characteristic. The affecting factors such as solid content of CWS and dispersant dosage on rheological property of CWS were also studied, and the results showed that the CWS tend to pseudoplastic characteristic with increasing coal concentration, while tend to dilatant flow characteristic with increasing dispersant dosage.

Buranasrisak P et al. (2012) studied the effects of particle size distribution and packing characteristics on the rheological behaviour of coal-water slurry. A sub-bituminous coal of Indonesian origin was used to prepare the samples. The samples were classified into six particle size ranges. Naphthalene Sulfonate formaldehyde (NSF) and Na-CMC were utilized as the dispersing agent and stabilizer respectively. The viscosities of coal water slurries were measured using MV-2000 series II Cannon® Rotary Viscometer at different solid loadings ranging between 60 to 65 % by weight. The different packing characteristics of the coal samples were defined by making monomodal, bimodal and multimodal distributions at different coarse to fine ratios. They observed that maximum coal loading was possible when coal water slurry was made from bimodal particle size distribution.

2.2 USE OF DISPERSANTS AND STABILIZERS

Usui et al. (1997) studied the sedimentation stability of coal-water slurry of a deashed coal with and without a stabilizer. Three coal-water mixtures were prepared that had equal apparent viscosities by controlling the coal concentrations. Polymethacrylate (PMA) with a 0.3 wt. % was used as a dispersing additive. Rhamsan gum was used as a stabilizing additive. The rod penetration test was conducted by using a stainless steel rod with a small disc attached to the tip of it. The rod had a diameter of 3 mm and the disc had a diameter of 10 mm with thickness of 1 mm. Both the Hard Pack Depth (HPD) and Soft Pack Depth (SPD) were calculated for the sedimentation layer. They found that very small additions of rhamsan gum were good enough to prevent the sedimentation of coal particles.

Takao S et al. (1997) studied the effect of high speed agitation on the rheological behaviour of coal water mixtures by using a laboratory-scale agitator. Mount Thorley coal was used for preparing coal water mixture samples. Sodium polystyrene sulfonate was used as a dispersant. Particle size distributions ranging from 0.1 µm to 600 µm were measured using a laser light scattering granulometer, (CILAS, model HR 850B). The rheological measurements were determined by using HAAKE Rotovisco RV-20 viscometer. The static stability was found by the ratio of the residual weight of the sediment to the sample weight. They concluded from the results obtained that the static stability and the flowability of the coal water mixture increased by performing high speed agitation.

Saeki et al. (1999) investigated the effect of eight commercially available surfactants, five newly synthesized surfactants and four stabilizers. The coal-water slurry was prepared from Indonesian coal with 60.0 wt. % coal loading. The dispersing additive concentration was set to 0.03 wt. % and stabilizing additive was set to 0.005 wt. %. They found that NSF-Na+ was the most effective additive to reduce the apparent viscosity of the coal-water slurry. The most effective stabilizer was found to be bio-polysaccharide (S-194).

Harmadi E et al. (2002) studied the effects of particle size distribution of pulverized coal on the rheology and stability of Coal Water Mixture (CWM). Sub bituminous low rank coal from Kalimantan Island was used with Carboxy Methyl Cellulose (CMC) and Triton X-100 as stabilizer and dispersing agent respectively. The results showed that maximum solid concentration increase with decreasing particle size. The maximum concentration of coal added in preparation of CWM as liquid fuel was 66.0 % by wt. of 270/325 to 325/400 mesh particle size with concentrations of stabilizer and dispersing agent were 0.03-0.05 % by wt. At the maximum concentration, the maximum stability of CWM, indicated by hard pack layer of thickness of 10 mm after eleven weeks, was achieved for particle size of 0.05 % by wt.

Dincer H et al. (2003) conducted experimentation on the rheology of bituminous Turkish coal water slurries by using chemical additives. The additives chosen for the study were polyisoprene sulphonic acid soda (Dynaflow-K), naphthalenesulfonate–formaldehyde condensate (NSF) as dispersing agents and sodium salt of carboxymethyl cellulose (CMC-Na) as the stabilizer. The coal sample of Zonguldak region was used to prepare the samples after obtaining the particle size distribution. The viscosity measurements were carried out using RVD2-Brookfield rotating type viscometer. It was found that the coal water slurry showed appreciable viscosity of 1000cp at dispersing agent concentration of 0.13 % by weight. Also, they found that by the addition of CMC-Na at a concentration of 0.01 % by weight, the stability of the coal water mixture increased.

Boylu F et al. (2005) investigated the stabilization properties of coal water slurry using carboxymethyl cellulose (CMC). The material chosen were two Turkish brown coals from Soma and Istanbul and a bituminous coal from Zonguldak. The coal particles were ground to less than 63 microns and the mixture prepared was 61, 55 and 52 %. The stability was measured using rod penetration test method. The effect of changing the CMC concentration on penetration after 7 days was studied. They found that there was a negligible effect on changing the concentration of CMC on the stability of coal from Soma and Istanbul as the penetration remained the same after days and hydrophilic nature of lignite coals were attributed to this but they found that varying the concentration of CMC has a profound effect as a stabilizer on the bituminous coal-water slurry increasing the stability with penetration possible to 100 % from 60 % due to the hydrophobic nature of bituminous coal and the optimum concentration of CMC was found to be of 0.01 %.

Senapati P.K et al. (2008) studied the rheological behaviour of coal water slurry using a natural additive. Two types of coal having different ash contents were obtained from Talcher Coal Field, Orissa, India. The rheological measurements were carried out employing HAAKE RV 30 rotational viscometer. The coal water slurries were prepared with concentration by weight ranging between 55-63.7 %. The additive concentrations for coal water slurries were varied from 0.4–1.2 % by weight. The static stability was measured using rod penetration test. They found that the coal water slurry in the presence of natural additive exhibited bingham plastic behaviour. The static stability of the coal water slurries were found to be 3 to 4 weeks by employing the natural additive.

Das D et al. (2008) developed a natural additive using saponin from the fruit of the Sapindous laurifolia plant. They investigated the rheological characteristics of coal-water slurry as a function of coal loading, ash content of coal, pH, temperature, and amount of saponin. The coal samples collected were from Talcher coal fields, Orissa. The rheological measurements were performed using HAAKE (Model RV 30) rotational viscometer. The slurry prepared had weight concentrations ranging from 55 to 64 wt. % with distilled water. The additive concentrations were varied from 0.4-1.2 wt. %. They found that in the presence of 0.8 % of saponin, coal-water slurry containing 64 % weight fraction of coal could be achieved. The slurry was stable for a period of as long as 1 month in contrast to 4-5 h in the case of bare coal-water slurry.

Umar D.F et al. (2009) investigated the effect of dispersing and stabilizing additives on upgraded coal water mixtures by the up gradation of a low rank coal by UBC (Upgraded Brown Coal) process. The coal water mixture was prepared for coal concentrations of 50, 55 and 60 wt. %. The dispersing additives used were NSF, PMA and PSS with a concentration of 0.3 wt. % and the stabilizing additives used were CMC, S-194 and S-40 with a concentration of 0.01 wt. % . A coal water mixture without the addition of dispersing and stabilizing additive was also prepared for the reference purpose. The flow characteristics of coal water mixture were measured by a stress control type rheometer (Rheometric Scientific Co. Ltd., SR-5) in steady shear mode using a para-plate system. The UBCWM (Upgraded Brown Coal Water Mixture) was prepared at an apparent viscosity of 1.0 Pa.s at shearing rate of 100 s^{-1} . They found that the addition of dispersing additives reduced the viscosity of the coal water mixture with NSF producing the lowest apparent viscosity for coal concentrations greater than 55 wt. % also they found that the stability additives when added caused an increase in apparent viscosity that was supposed to prevent the sedimentation and the fluid behaviour obtained from the rheogram conveyed the non-Newtonian bingham plastic with yield stress. They suggested that the UBCWM containing 0.3 wt. % NSF with stabilizer 0.01 wt. % S-194 as the effective coal water mixture with good slurryablity and stability.

Das D et al. (2010) reported the effect of starch xanthate, starch xanthide and starch phosphate as additives on the stabilization of coal-water slurry. The coal-water slurry was prepared from Indian coal with coal loading varying from 58-65 wt. %. The rheological measurements were obtained from HAAKE RV-30 rotational viscometer. The pH was kept in the range of 4.5-5.0 and the zeta potential was measured using Zeta probe 24 V (52-60 Hz) T3A. The static stability was measured using rod penetration method. They found that the stability increased by the addition of additives with starch xanthide as the most effective of the three additives in reducing the apparent viscosity.

Ongsirimongkol. N et al. (2012) studied the rheological characteristics and static stability of highly loaded coal-water slurry. The coal chosen for the study was a sub-bituminous coal of Indonesian origin. The coal was pulverized and was classified in two ranges 180-250 microns and 75-90 microns or the bimodal distribution. The dispersion additive chosen was Napthalene Sulfonate Formaldehyde and the three stabilizers chosen were CMC-Na, Guar Gum and Arabic Gum. The coal water slurry was prepared for the coal loadings of 62 and 65 wt. %. The apparent viscosities of the highly loaded coal-water slurry were measured by MV-2000 series II Cannon Rotary Viscometer. They found that in all slurries the apparent viscosity increased with increasing concentration of stabilizing agent regardless of the type. However, they also found that when the concentration of chemical additives were fixed with. 0.5 wt. % NSF and 0.05 wt. %, the HLCWS showed a decrease in the apparent viscosity with increasing shear rates.

CHAPTER 3 CHARACTERISATION STUDIES ON COAL SAMPLES

Five different Indian coals in pulverized form, each varying in their respective ash contents were procured from different sources. The different sources of procurement of coal samples were Thermal power plants and coal traders. The coal samples were Bathinda coal, Assam non-Steam coal, Panipat coal, Dhanbad coal and Assam Steam coal. Bathinda coal and Panipat coal samples were obtained from Bathinda Thermal power plant and Panipat Thermal power plant, respectively. Assam non Steam, Dhanbad and Assam Steam coal samples were obtained from coal traders. Throughout this thesis, the five coal samples are labeled as S-I, S-II, S-III, S-IV and S-V for Bathinda, Assam non-Steam, Panipat, Dhanbad and Assam Steam coals, respectively. The characterization studies were done on the five coal samples to determine the ash contents of coal, their particle size distribution, static stability in water without stabilizer and the values of slurry pH at different solids concentrations.

3.1 PROXIMATE ANALYSIS OF COAL

The proximate analysis of coal was done to determine the percentages of ash, inherent moisture, volatile matter and fixed carbon present in the particular sample. The proximate analysis of the five coal samples were conducted as per the prescribed testing method of IS: 1350 and the results of the proximate analysis are shown in Table 3.1.

Table 3.1: Proximate analysis of coal

Parameters	S-I	S-II	S-III	S-IV	S-V
Ash %	28.75	14.99	38.97	34.63	8.60
Total Moisture %	5.43	2.53	2.2	1.32	0.36
Volatile Matter %	25.89	35.53	21.83	25.88	41.44
Fixed Carbon %	39.93	46.95	37.0	38.17	49.60

The Proximate analysis of the coal samples revealed that all the five coal samples had different ash content with coal samples S-II and S-V having lesser ash content in comparison to the other three coal samples viz. S-I, S-III and S-IV. Also, coal S-V was having the least moisture in comparison to the other coal samples

3.2 PARTICLE SIZE DISTRIBUTION OF COAL SAMPLES

The variation in the size of the particles in the solid sample and the percent of particles present in different size ranges were determined to obtain the particle size distribution. A known weight of sample of coal particles was taken and washed over a B.S. 200 mesh. The coal particulates were then sieved through a set of British Standard sieves. The sample retained on each sieve was collected and the percentage retained on each sieve was calculated using the standard procedure to obtain the Particle Size Distribution curves.

The Particle Size Distribution (PSD) curves of the five coal samples S-I, S-II, S-III, S-IV and S-V are shown in Fig. 3.1.

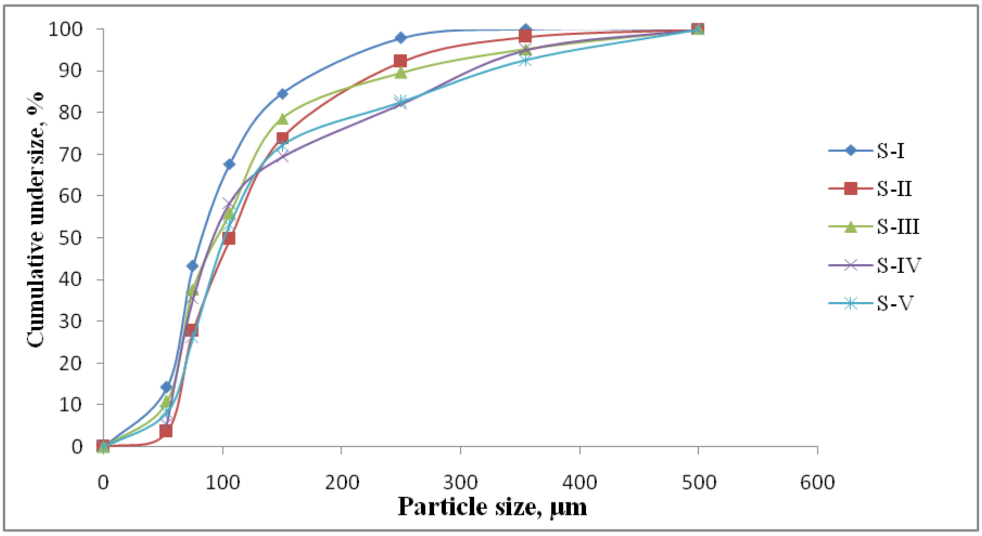

Fig. 3.1: Particle Size Distribution of coal samples

The PSD curves obtained indicated a continuous distribution with spread varying for each coal sample. The mass median diameters (d_{50}) of the five coal samples were calculated from the PSD curves and are shown in Table 3.2.

Table 3.2: Mass Median diameter of coal samples

Coal Sample	S-I	S-II	S-III	S-IV	S-V
d_{50} (µm)	80	100	105	110	112

3.3 MORPHOLOGICAL CHARACTERISTICS OF COAL SAMPLES

The morphological studies on coal samples were done by Scanning Electron Microscopy (SEM) technique. SEM enables the investigation of specimens with resolution down to the nanometer scale. The SEM technique produces images of a sample by scanning it with a focussed beam of electrons. The electrons interact with the atoms in the sample, producing various signals that can be detected and that contain information about the sample’s surface topography and composition.

The sample preparation was done before placing the sample for the visualization of the optical images obtained as an output on a visual display unit. The SEM micrographs that were obtained for five different coal samples are shown in Fig. 3.2 to 3.6.

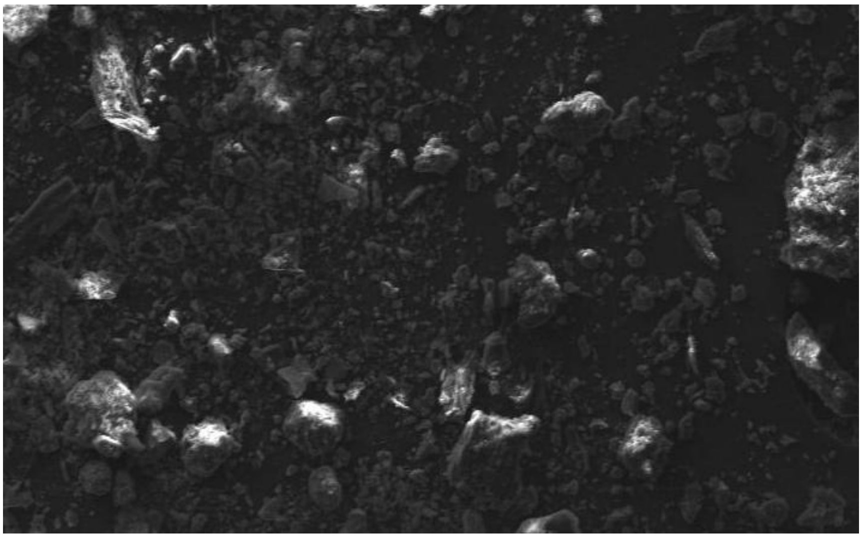

Fig. 3.2: SEM micrograph of S-I coal sample (d_{50}=80 µm)

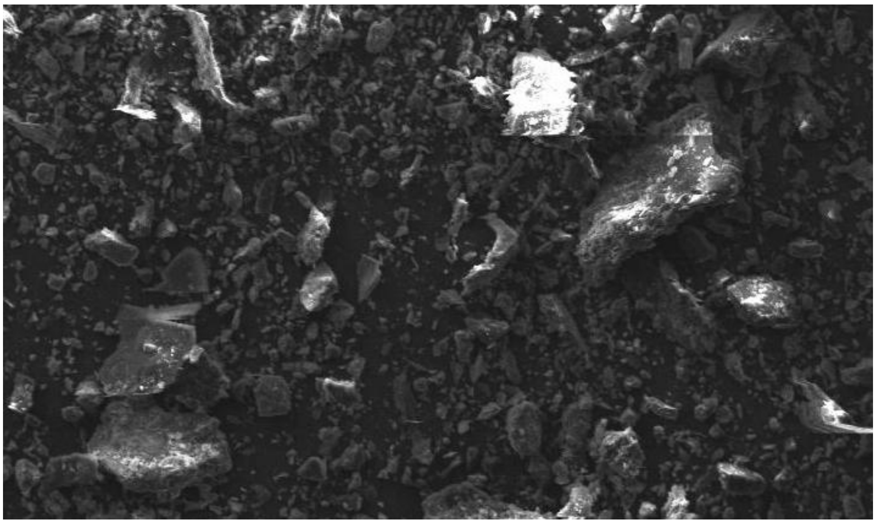

Fig. 3.3: SEM micrograph of S-II coal sample (d_{50}=100 µm)

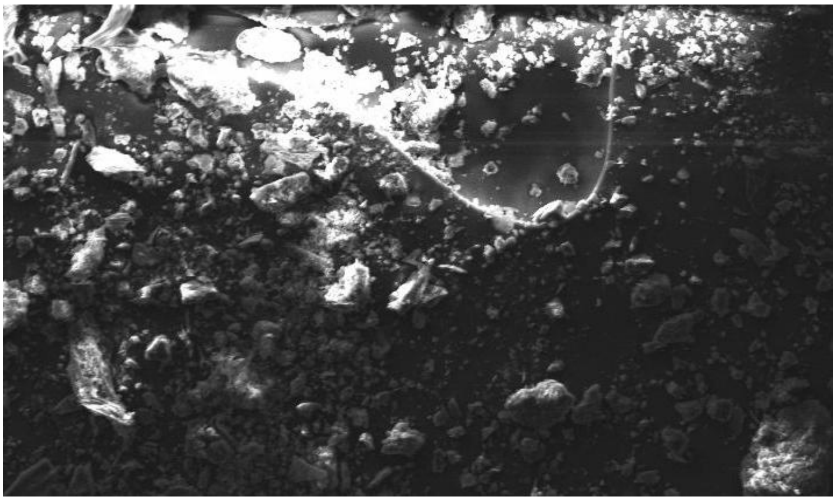

Fig. 3.4: SEM micrograph of S-III coal sample (d_{50}=105 μm)

Fig. 3.5: SEM micrograph of S-IV coal sample (d_{50}=110 μm)

Fig. 3.6: SEM micrograph of S-V coal sample (d_{50}=112 μm)

The observations from the morphological study conducted on the coal samples showed that the coal particles were mainly irregular in shape and there was a considerable difference in the distribution of coal particles of the five coal samples. The sample S-I contained more fines than any other coal sample. This was confirmed by the mass median diameter of 80 µm which was the lowest of the five coal samples. The micrograph of coal sample S-V depicted a mixture of coarse and fine particles. The SEM micrographs of S-II, S-III and S-IV exhibited coarser particles with a few fractions of fines.

3.4 SLURRY pH AT DIFFERENT SOLIDS CONCENTRATION

The pH of coal water slurries were determined to observe the effect of coal loading on the pH value of coal water slurries. The pH was measured by a digital pH meter shown in Fig. 3.7.

Fig. 3.7: Digital pH meter used for measuring slurry pH

The pH meter was first calibrated by dipping the electrode into the buffer solutions and then the electrode was cleaned with distilled water to ensure correct measurements.

The pH values at different solids concentration are shown in Table 3.3.

Table 3.3: pH values of coal samples

Concentration (% by wt.)	S-I	S-II	S-III	S-IV	S-V
30	6.12	6.18	6.21	6.23	6.29
40	6.08	6.13	6.13	6.19	6.27
50	6.05	6.07	6.08	6.15	6.23
60	5.97	5.99	6.01	6.10	6.18

The variation of pH with coal concentration is shown in Fig 3.8.

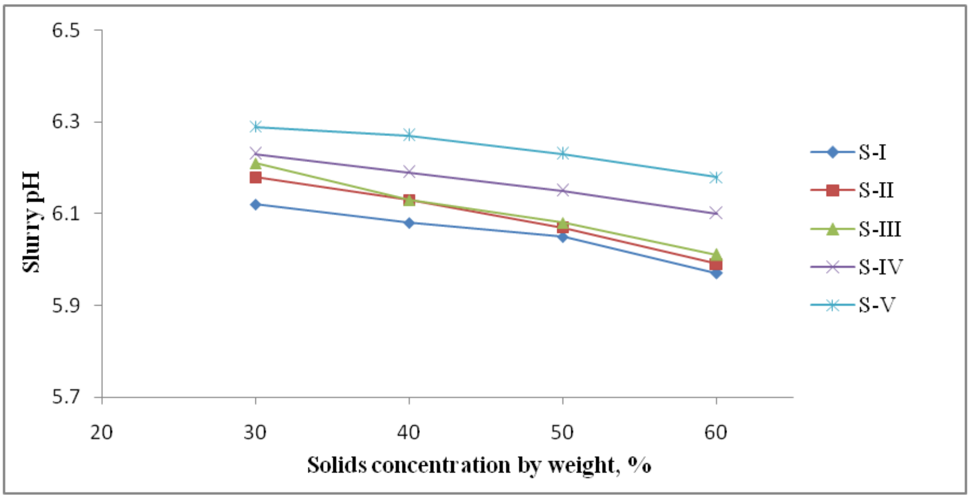

Fig. 3.8: Slurry pH at different solids loading (% by weight)

The pH value of the coal water slurries were found to decrease with an increase in the concentration of coal in the slurry. The decrease in slurry pH with an increase in coal loading can be attributed to the interaction of coal particulates with the carrier liquid and the interfacial properties of coal particulates in the carrier fluid.

3.5 STATIC STABILITY MEASUREMENTS

The storage of coal water slurries in storage tanks requires the slurry to be stable, resisting sedimentation of coal particles with storage time. The stability of slurry depends on various factors such as coal concentration, particle size distribution, type and amount of stabilizers. Static stability test on coal water slurries give the measure of their stability against sedimentation. To measure the static stability of coal water slurries the static stability test of five coal samples was carried out using rod penetration method as prescribed by Usui et al., (1997). There are two layers of sedimentation, soft layer determined as Soft Pack Depth (SPD) and hard layer determined as Hard Pack Depth (HPD). The soft sedimentation can be removed by mild stirring of the slurry whereas the hard sediment layer deposited at the bottom is detected to calculate the stability of coal water slurries.

In the present study, the hard sedimentation layer deposited at the bottom of the beaker when it was kept for predetermined time periods and covered with plastic pouches to avoid vaporization of slurry was detected by a steel rod (shown in Fig. 3.9) of 3 mm diameter with a small disc (10 mm diameter and 1 mm thick) attached at the tip of the rod.

Fig. 3.9: Static stability measuring rod

The total weight of the rod was 30 g. The rod was first penetrated into the slurry just after making it to calculate the maximum rod travel distance (d_t). Then after regular intervals of time, the rod was penetrated to calculate the rod travel (d) distance. When the tip of the rod touched the hard sedimentation layer, it was removed and the depth of penetration was noted.

The percent penetration was measured as:

$$\% \text{ penetration} = d/d_t \times 100 \tag{3.1}$$

where d = distance of rod travel (mm)

d_t = maximum distance of rod travel (mm)

The plots of percent penetration with time of storage for two coal concentrations of 40 % and 50 % by weight are shown in Fig. 3.10 and 3.11.

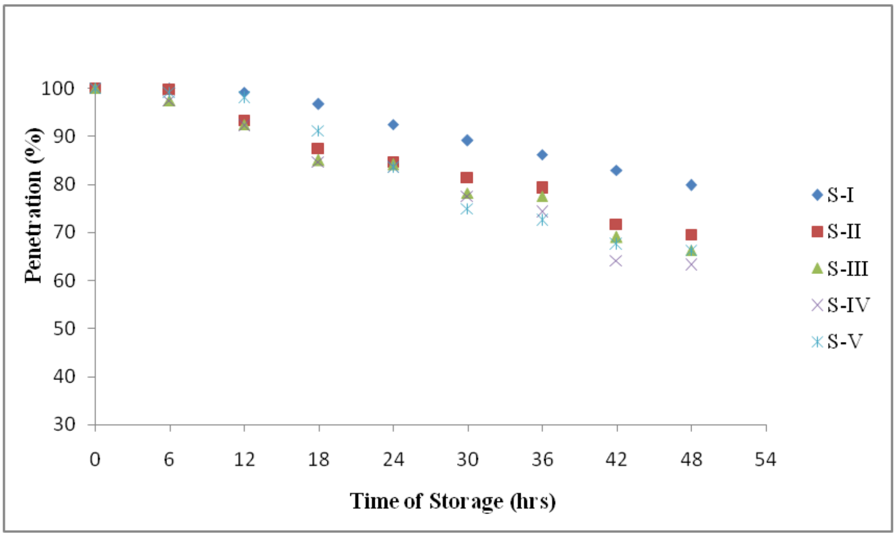

Fig. 3.10: Static stability of coal samples at C_w = 40%

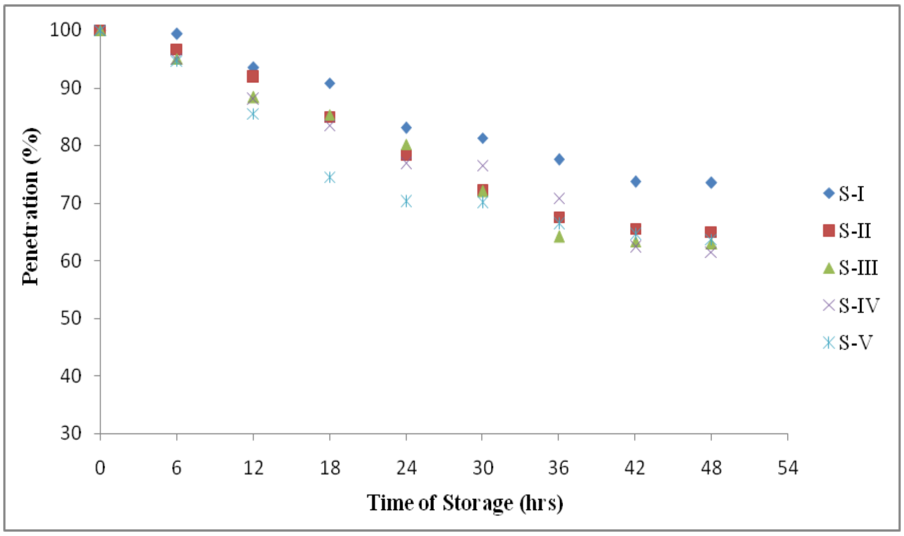

Fig. 3.11: Static stability of coal samples at $C_w = 50\%$

It was observed from the static stability test that the coal sample S-I ($d_{50} = 80$ µm) was having the maximum stability at both solids concentration of 40 % and 50 % by weight, with penetrations of 75 % after 48 hours of storage. The least stable was S-IV ($d_{50} = 110$ µm) at 40 % solids concentration and S-III ($d_{50} = 105$ µm) at 50 % solids concentration. The investigation was done without using stabilizers and it was observed that the hard sediment layer depth reached 10 mm after 30 hours in case of 40 % solids concentration and after 24 hours in case of 50 % solids concentration by weight.

3.6 ROSIN-RAMMLER MATHEMATICAL MODEL

Rosin-Rammler model is a mathematical model used to describe the Particle Size Distribution of finely ground powders. The advantage of using RR model is that by plotting the data into this model, it expands the fine and coarse particle size range (<25 % and >75 %) and compresses the mid range (30-60 %). The Rosin-Rammler distribution is expressed as:

$$R = 100 \exp\left[-\left(\frac{\varphi}{K}\right)^{n}\right] \tag{3.2}$$

where R = cumulative mass % retained on mesh size φ.

K = size modulus, and

n = distribution modulus

Rearranging and taking double logarithm of Eq. (3.2) gives:

$$ln\left(ln\left[\frac{100}{R}\right]\right) = nln\varphi + CONSTANT \tag{3.3}$$

A plot of $ln\left(ln\left[\frac{100}{R}\right]\right)$ versus $ln\varphi$ gives a straight line. The parameters of the Rosin-Rammler distribution, n and K are obtained by the regression analysis with slope of the fit giving distribution modulus, n and the horizontal intercept at R = 36.79 as size modulus, K.

The Particle Size Distribution data of five coal samples were fitted into the Rosin-Rammler mathematical model. The RR model fit of the five coal samples are shown in Fig.3.12 to 3.16.

The Rosin-Rammler model parameters i.e. n (distribution modulus) and K (size modulus) were calculated using linear Regression analysis.

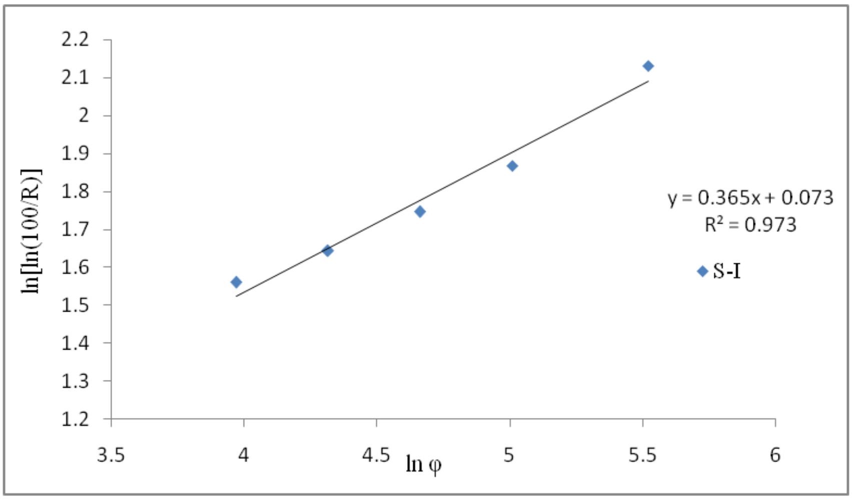

Fig. 3.12: RR model fit for coal sample S-I

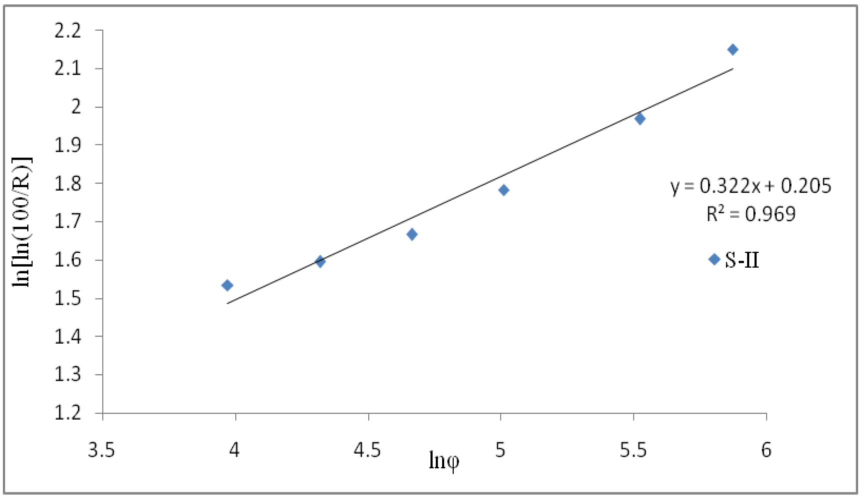

Fig. 3.13: RR model fit for coal sample S-II

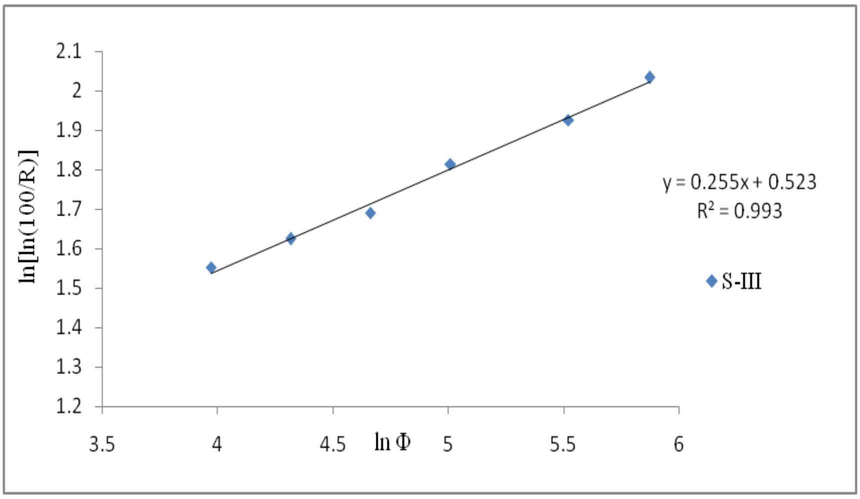

Fig. 3.14: RR model fit for coal sample S-III

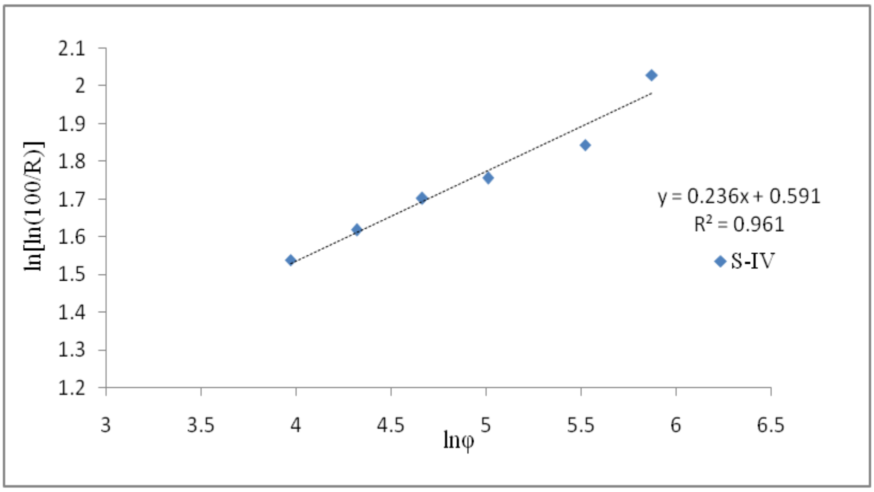

Fig. 3.15: RR model fit for coal sample S-IV

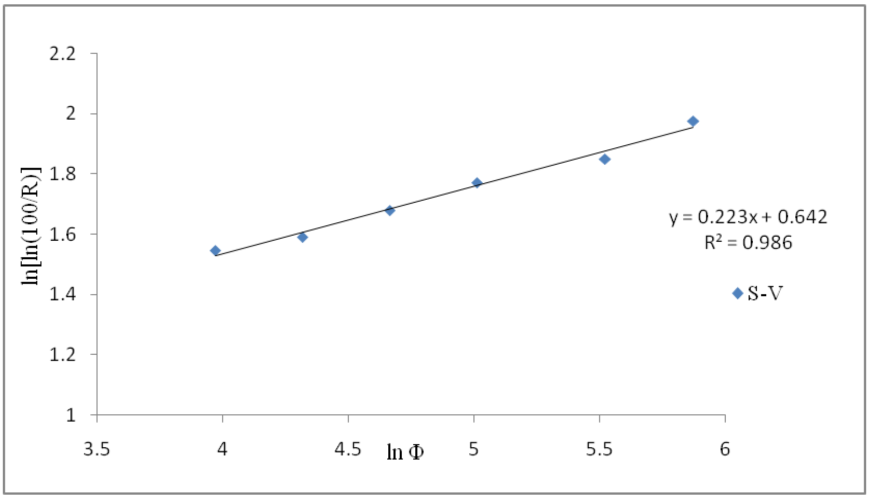

Fig. 3.16: RR model fit for coal sample S-V

The values of the RR model parameters for the five coal samples are shown in Table 3.4 with the respective R^2 values of the fit.

Table 3.4: Rosin-Rammler model parameters of coal samples

Coal sample	**n**	**K**	**R^2**
S-I	0.36	110	0.97
S-II	0.32	130	0.96
S-III	0.25	110	0.99
S-IV	0.23	105	0.96
S-V	0.22	125	0.98

It was found that coal sample S-I was the narrowest of the five coal samples as its value of distribution modulus was the highest and S-V as the broadest coal sample with the least value of distribution modulus with the width of samples increasing from S-I to S-V.

The resulting distribution functions obtained by the application of RR model are shown in Table 3.5.

Table 3.5: Rosin-Rammler distribution function

Coal Sample	RR model distribution function
S-I	$(\frac{R}{100}) = \exp[-(\frac{\varphi}{110})^{0.36}]$
S-II	$(\frac{R}{100}) = \exp[-(\frac{\varphi}{130})^{0.32}]$
S-III	$(\frac{R}{100}) = \exp[-(\frac{\varphi}{110})^{0.25}]$
S-IV	$(\frac{R}{100}) = \exp[-(\frac{\varphi}{105})^{0.23}]$
S-V	$(\frac{R}{100}) = \exp[-(\frac{\varphi}{125})^{0.22}]$

By using these equations, the cumulative percent retained on a known size of mesh screen can be determined.

CHAPTER 4 RHEOLOGICAL STUDIES ON COAL WATER SLURRY

During the transportation of solid particles through pipelines, the estimation of energy required for pumping depends on the viscosity of the slurry. The presence of solid particulates in the carrier fluid alters the viscosity of carrier fluid depending on the concentration of solids present, their particle size distribution, etc. The rheological studies are very useful for determining the viscous characteristics of slurry with respect to the material properties and slurry concentration. In the present study, the rheological experimentation was carried out on coal water slurries made from five different coals (S-I, S-II, S-III, S-IV and S-V) varying in their respective ash contents. The rheological data was generated using an Anton Paar RheolabQC rheometer.

4.1 DESCRIPTION OF THE EQUIPMENT

The Anton Paar (Model: RheolabQC) rheometer used for the rheological study was supplied by Anton Paar, Germany. A pictorial view of the Anton Paar (RheolabQC) rheometer installed in the Mechanical Engineering Department of Thapar University, Patiala is shown in Fig. 4.1. It is a rotational rheometer consisting of a high precision encoder and a highly dynamic EC motor. The measurements can be obtained by selecting either controlled shear rates or controlled shear stress test settings. It has wide speed and torque ranges and very short motor response time. The measuring systems can be detected automatically by the inbuilt Toolmaster™ system that ensures the exact measuring data to be used with more precision.

Two different measuring systems can be utilized as per need of the study. These systems are DG42/SS/QC-LTD (for lower concentrations) and CC27/QC-LTD (for higher concentrations). The rheometer component consists of concentric bob and cup with a small annular gap in between them. The coal water slurry is prepared for each measurement and is filled up to the mark in the measuring cup. The measuring cup is then inserted into the measuring cylinder and the system is coupled to the rotating spindle by pushing down the flanged coupling.

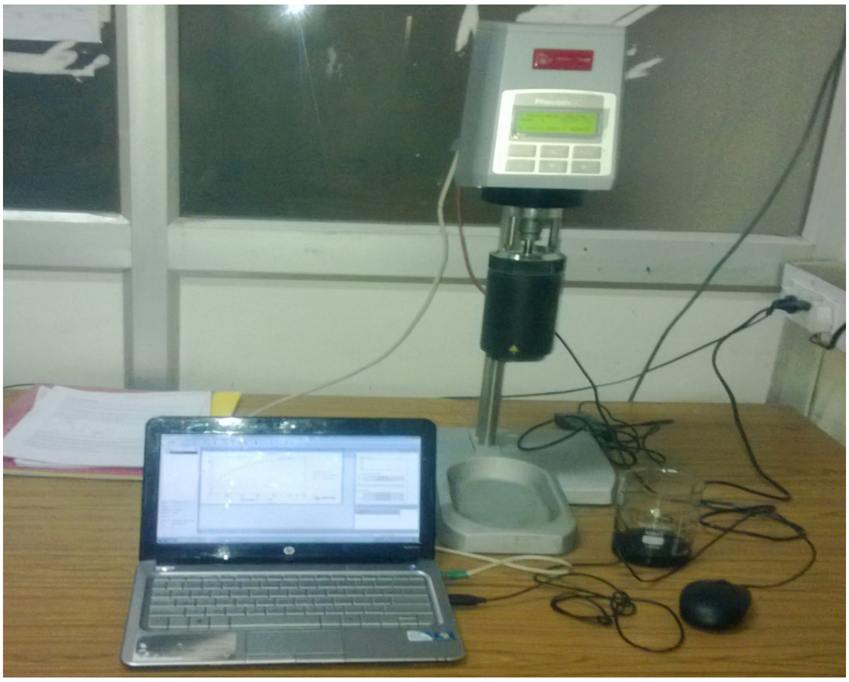

Fig. 4.1: Anton Paar RheolabQC rheometer

The slurry is subjected to shearing action in between the annular gap between the measuring cup and bob, and hence shear stress is measured as a function of shear rate. The output results are obtained on the Rheoplus software installed on a computer which is connected to the rheometer by LAN connection.

4.2 EXPERIMENTAL PROCEDURE

The rheological experiments were carried out using Anton Paar Rheolab QC rheometer. Two measuring systems DG42/SS/QC-LTD and CC27/QC-LTD were chosen for the rheological measurements. They were thoroughly cleaned and dried. The five coal samples S-I, S-II, S-III, S-IV and S-V were used for the rheological experiments.

For the preparation of coal water slurry samples, a known amount of coal particles was added to a known amount of solution depending on the solid concentration required by weight. The slurry was continuously stirred by a glass rod. The time of stirring varied between 5 and 10 minutes and a proper care was taken to avoid attrition and spillage of coal water slurry.

About 100 ml of coal water slurry was prepared by mixing coal with water. The required amount of coal was weighed in a single pan electronic balance (least count ±0.1 mg) for each of the five coal samples and the rheological results were generated at solids weight concentration of 30 %, 40 %, 50 % and 60 % by wt. The corresponding volume concentrations (vol. %) of the slurry samples were computed as 20 %, 28 %, 37 % and 46 % respectively. The shear rate was applied from 0 to 512 s^{-1} for a period of 2 minutes to measure the corresponding apparent viscosity and shear stress under controlled shear rate. The temperature was within the limit of 30 ± 0.1^{o} C. The rheological results were obtained on a computer screen.

The rheological investigation was conducted to determine the effect of solids concentration, ash content of coal, particle size distribution, fraction of coal fines and natural dispersing agent on the slurry rheology.

4.3 RESULTS AND DISCUSSION

The slurry concentration for the determination of apparent viscosity was varied from 30 % to 60 % (by weight) concentration. The flow characteristics of five coal samples having different mass median diameters and different particle size distributions were determined by the rheological study. The flow behaviour obtained for the five coal samples at different solids concentration (by weight) are presented in the rheograms (flow curve of shear stress vs. shear rate) in Fig. 4.2-4.6.

4.4 EFFECT OF SOLIDS CONCENTRATION ON SLURRY RHEOLOGY

The flow curves obtained by the rheological experimentation revealed that the rheological behaviour of coal water slurry is immensely affected by the variation in concentration of solids in the slurry.

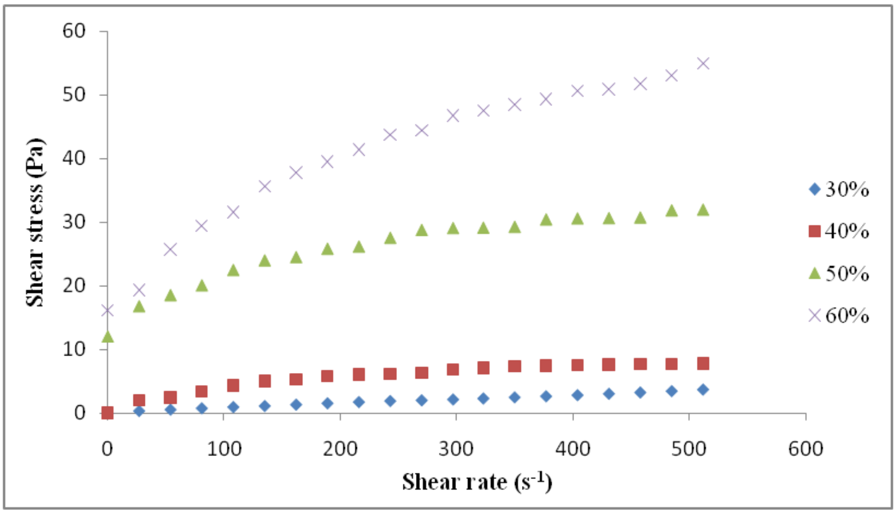

Fig. 4.2: Rheogram of coal water slurry (S-I), d_{50} = 80 µm

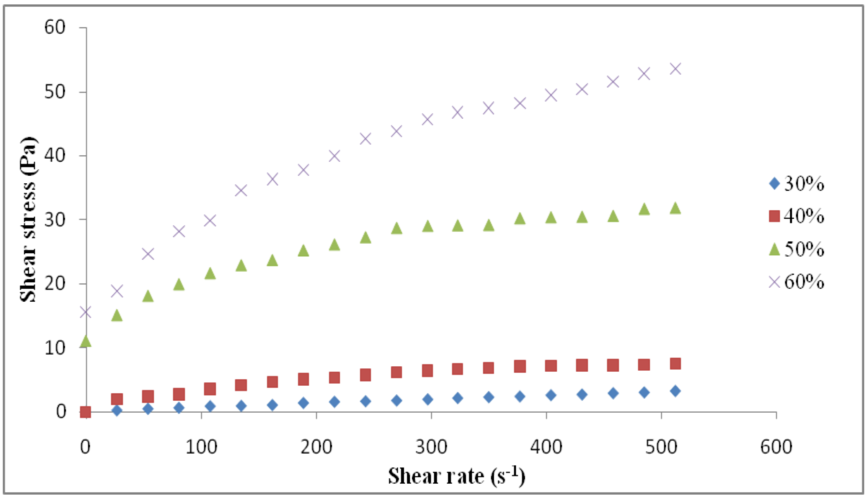

Fig. 4.3: Rheogram of coal water slurry (S-II), d_{50} = 100 µm

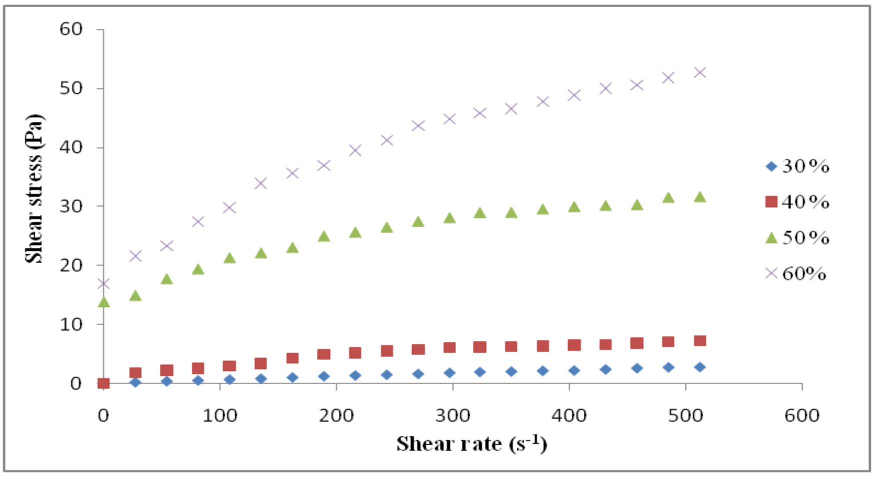

Fig. 4.4: Rheogram of coal water slurry (S-III), d_{50} = 105 µm

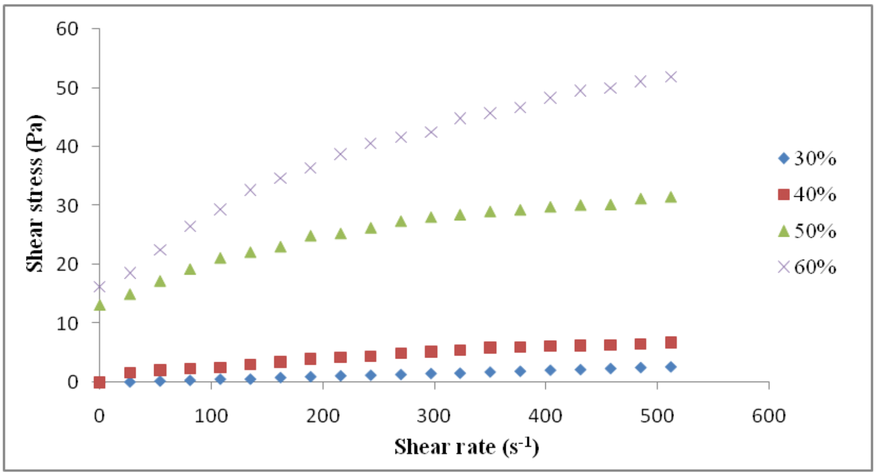

Fig. 4.5: Rheogram of coal water slurry (S-IV), d_{50} = 110 µm

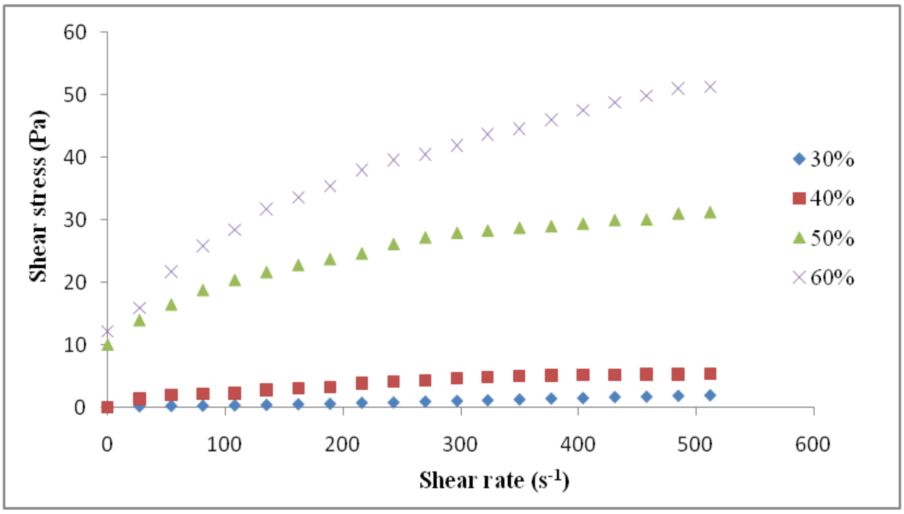

Fig. 4.6: Rheogram of coal water slurry (S-V), d_{50} = 112 µm

The coal water slurry showed an increase in the apparent viscosity values as the solids concentration increased. Similar results were obtained by Mishra S.K. et al. (2002) and Nguyen et al. (1997). The coal water slurry behaviour at 30 % (by weight) solids concentration for each of the five coal samples showed a Newtonian behaviour with viscosity independent of the shear rate. However, as the concentration of solid particulates were increased above 30 % (by weight), the slurry showed non-Newtonian behaviour for each of the coal samples. Further, it was observed from the rheograms that as the solid loading increased from 30 % (by weight), all the five coal samples showed pseudoplastic i.e. (shear thinning) behaviour with viscosity decreasing with an increase in the shear rate. Also, for each coal sample and at solid concentrations of 50 % and 60 % (by weight), the coal water slurry included a yield value at zero shear rate. This yield must be overcome before the slurry flow could take place.

The apparent viscosity as a function of shear rate for the five coal samples at solids concentration of 30 %, 40 %, 50% and 60 % by weight is shown for the five coal samples in Figs. 4.7-4.11.

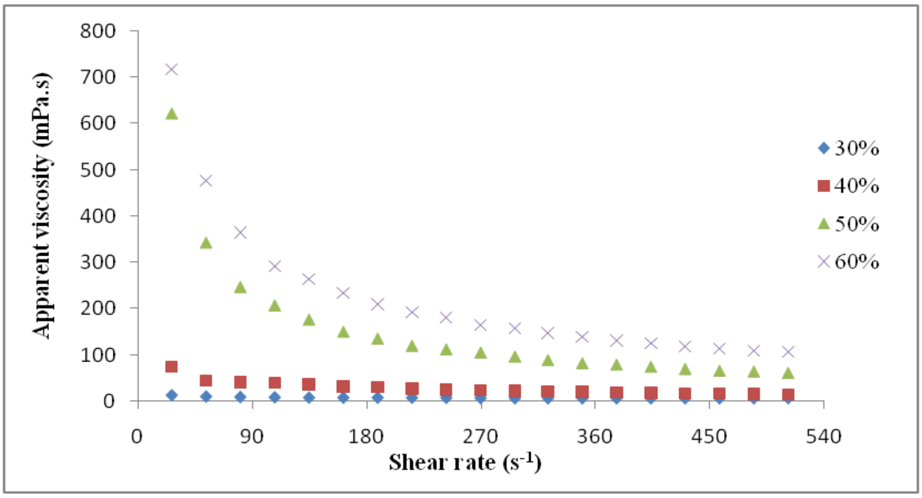

Fig. 4.7: Variation of apparent viscosity of coal water slurry (S-I) with shear rate

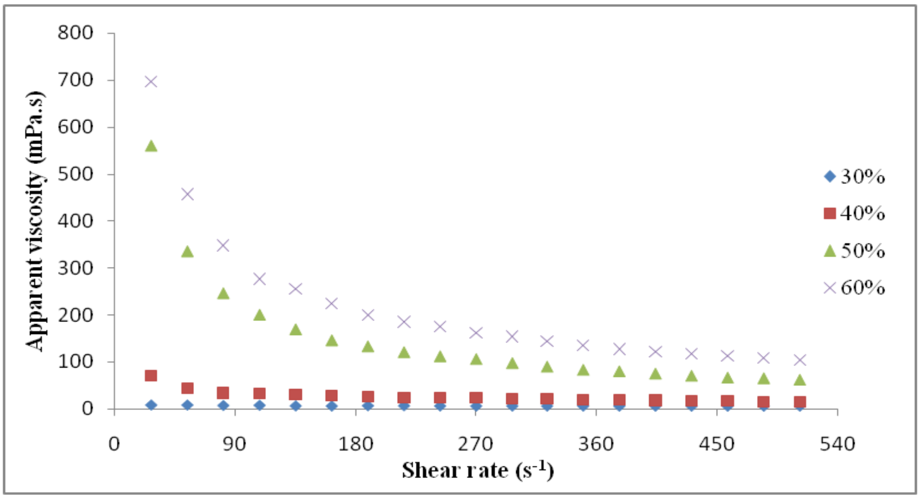

Fig. 4.8: Variation of apparent viscosity of coal water slurry (S-II) with shear rate

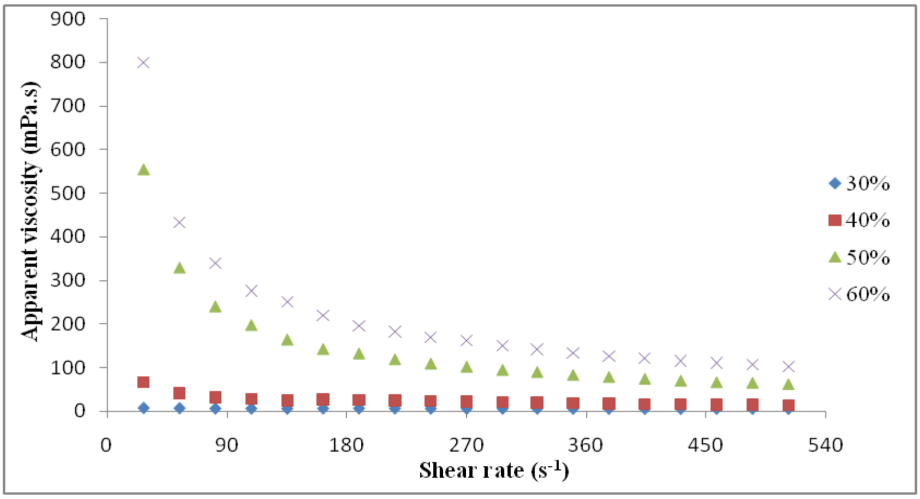

Fig. 4.9: Variation of apparent viscosity of coal water slurry (S-III) with shear rate

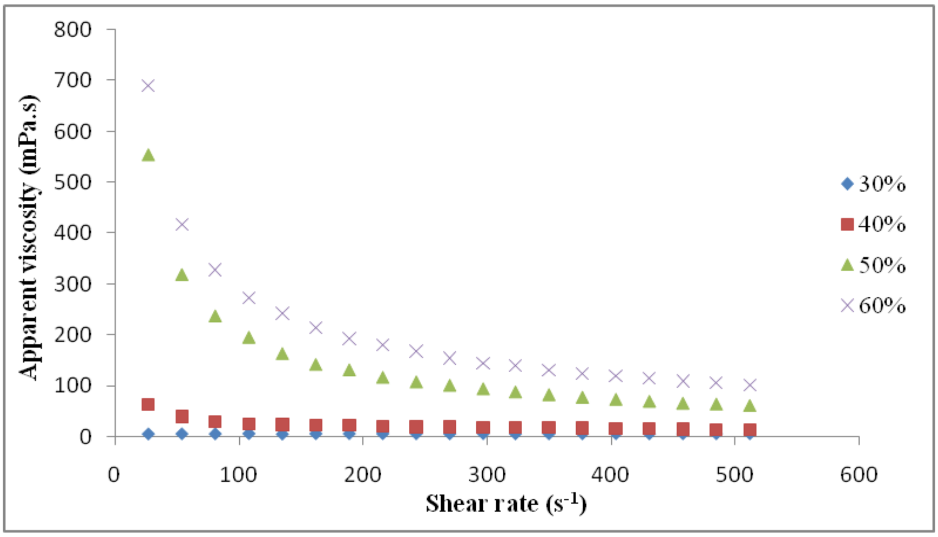

Fig. 4.10: Variation of apparent viscosity of coal water slurry (S-IV) with shear rate

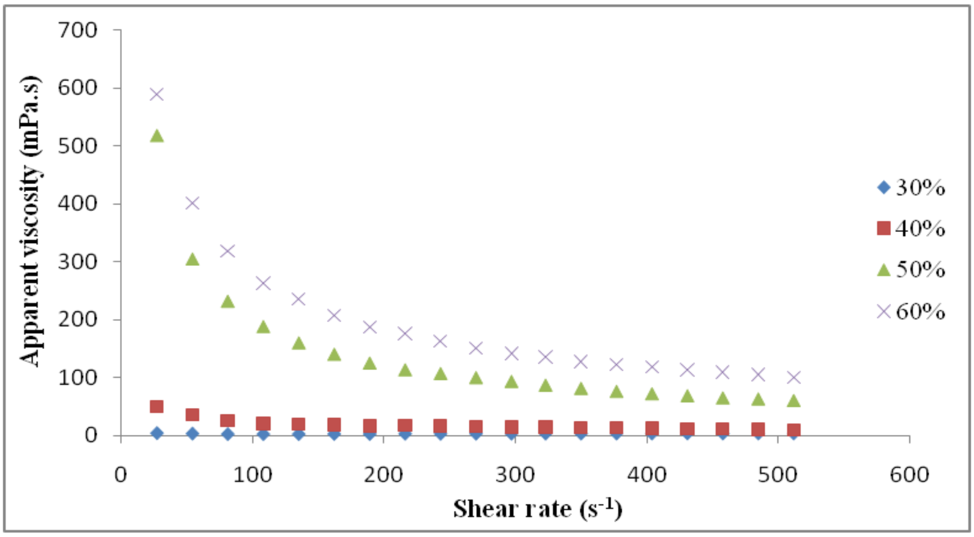

Fig. 4.11: Variation of apparent viscosity of coal water slurry (S-V) with shear rate

The pseudoplastic behaviour of coal water slurries indicated by the rheograms and viscosity curves of coal water slurries at higher solids concentration (i.e. above 30 % by weight) can be attributed to the viscous forces that dominate at higher shear rates and causes a breakdown of the slurry structure which causes a decrease in the slurry viscosity with an increasing shear rate. Also, the increase in solid loading causes an increase in the viscosity and shear stress of coal water slurry as the interparticle interaction among the coal particulates highly increases and the effective area under shear also increases. The result of both of these is to cause a steep rise in viscosity and shear stress.

4.5 RHEOLOGICAL MODEL FITS

The rheological data obtained from the experimentation was fitted into rheological models to calculate the model parameters. The coal water slurries at 40 % solids loading (by weight) exhibited a pseudoplastic fluid behaviour and hence Power-Law model was chosen. The constitutive relation for Power-Law fluid is:

$$\tau = K\gamma^{n} \tag{4.1}$$

where τ = shear stress

γ = shear rate

K = consistency coefficient and

n = flow behaviour index

The value of n for pseudoplastic (shear thinning) fluid is less than 1, for Newtonian fluid equals 1 and for dilatants (shear thickening) fluids is greater than 1. The Power-Law model parameters, n and K, for the five coal samples were calculated by linear regression analysis.

The regression equation was:

$$ln\,\tau = ln\,\mathrm{K} + n\,ln\gamma \qquad (4.2)$$

A linear regression of $ln\,\tau$ as a function of $ln\,\gamma$ was fitted to estimate the model parameters n and K. The rheogram with Power-Law fit for the five coal samples at 40 % solids concentration (by weight) is shown in Fig.4.12.

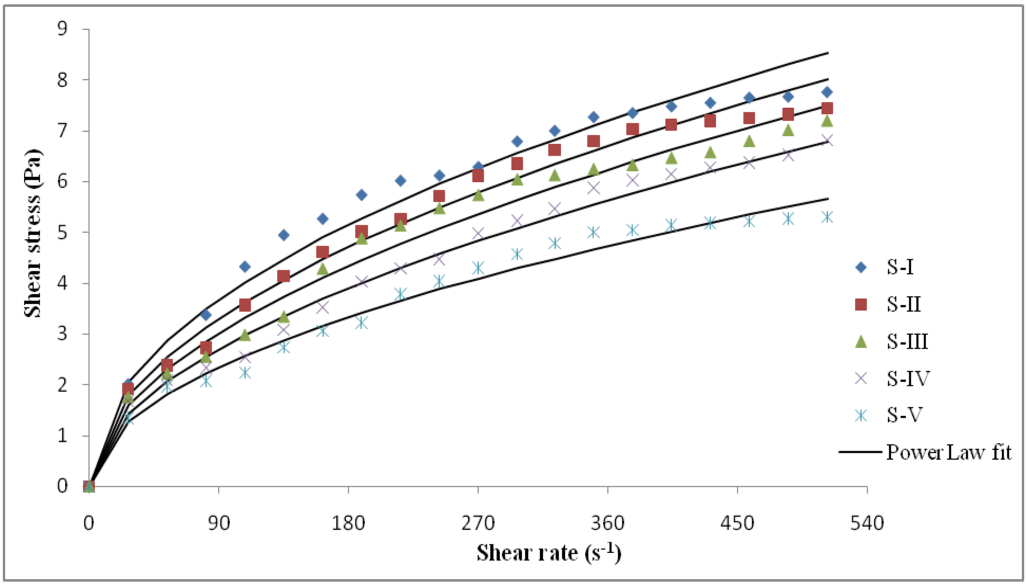

Fig. 4.12: Rheogram with Power-Law model fit for coal samples at C_w = 40 % (by weight)

The Power-Law parameters with the respective coefficient of determination (R^2) values of the model fit for the five coal samples are presented in Table 4.1.

Table 4.1: Power-Law model parameters for coal samples at C_w = 40 % by weight

Coal sample	**Distribution modulus (n)**	**Consistency Coefficient (K, Pa.s^n)**	**Coefficient of determination, R^2**
S-I	0.48	23-e02	0.96
S-II	0.50	25-e02	0.99
S-III	0.52	28-e02	0.98
S-IV	0.52	33-e02	0.98
S-V	0.50	41-e02	0.98

It was found that the consistency coefficient, K increased as the mass median diameter (D_{50}) of the coal sample increased.

In contrast to the Power-Law fluid behaviour at 40 % solids concentration (by weight), the coal water slurry rheological behaviour at solids concentration of 50 % and 60 % (by weight) fitted well into the Herschel-Bulkley fluid model with a measurable yield associated with them. The constitutive relation for Herschel-Bulkley model is:

$$\tau = \tau_y + K\gamma^n \tag{4.3}$$

where τ = shear stress

γ = shear rate

τ_y = yield stress

K = consistency coefficient and

n = flow behaviour index.

The Herschel-Bulkley is a three parameter model in which the model parameters are calculated by regression analysis. In the present study, the Herschel-Bulkley model parameters were calculated by first plotting the rheological data between the shear stress and shear rate. The ordinate was shear stress and the abscissa was shear rate. The yield stress at the ordinate axis for zero shear rate was visually estimated. Then, the Herschel-Bulkley model was reduced to a two parameter model and was linearized by taking the yield stress at the left hand side of Equation 4.3 and taking logarithms on both sides. The regression model equation was:

$$ln\ (\tau - \tau_{y)} = ln\ K + n\ ln\gamma \qquad (4.4)$$

Finally a linear regression of $ln\ (\tau - \tau_{y)}$ as a function of $ln\ \gamma$ was fitted to estimate K and n. The rheograms with Herschel-Bulkley model fit for five coal samples at 50 % and 60 % solids concentration (by weight) are shown in Fig. 4.13 and 4.14 respectively.

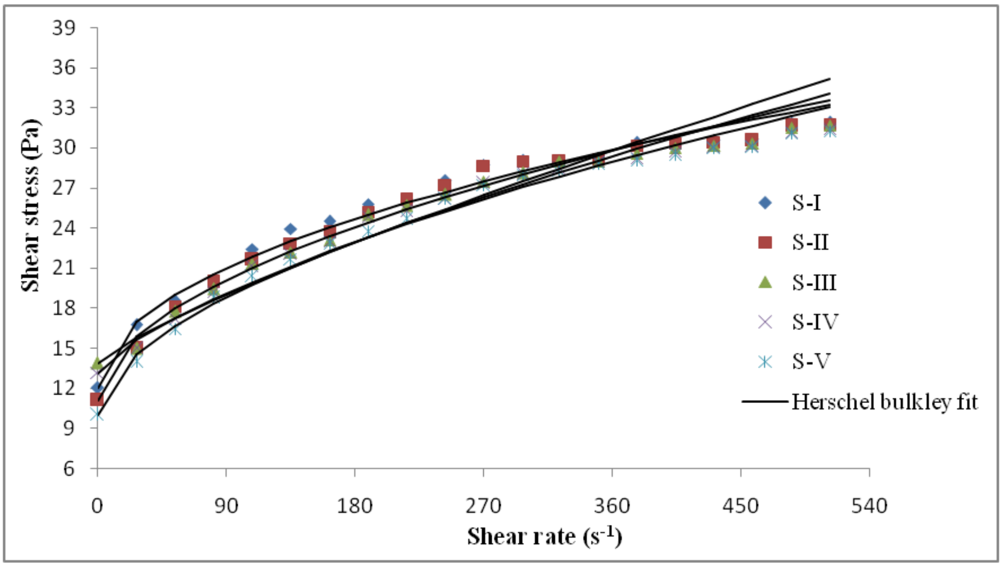

Fig. 4.13: Rheogram with Herschel-Bulkley model fit for coal samples at C_w = 50 % (by weight)

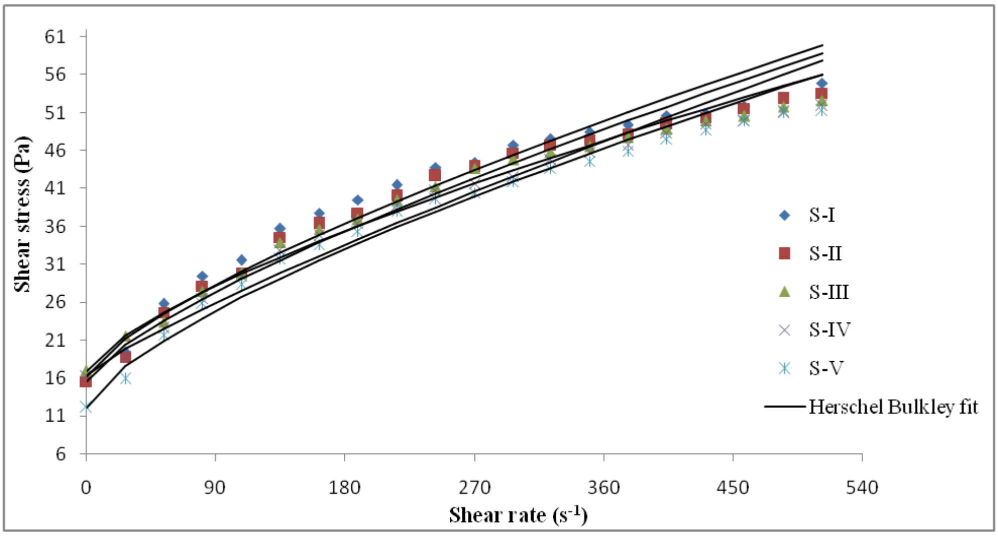

Fig. 4.14: Rheogram with Herschel-Bulkley model fit for coal samples at C_w = 60 % (by weight)

The Herschel-Bulkley model parameters with the respective coefficient of determination (R^2) values of the model fit for the five coal samples are presented in Table 4.2 and 4.3.

Table 4.2: Herschel-Bulkley model parameters for coal samples at C_w = 50 % by weight

Coal sample	Yield stress (τ_y, Pa)	Distribution modulus (n)	Consistency Coefficient (K, Pa.s^n)	Coefficient of determination, R^2
S-I	12.03	0.49	97-e02	0.99
S-II	11.12	0.52	83-e02	0.98
S-III	13.88	0.81	12-e02	0.92
S-IV	13.16	0.72	23-e02	0.96
S-V	10.03	0.55	73-e02	0.98

Table 4.3: Herschel-Bulkley model parameters for coal samples at C_w = 60 % by weight

Coal sample	Yield stress (τ_y)	Distribution modulus (n)	Consistency Coefficient (K, Pa.s^n)	Coefficient of determination, R^2
S-I	16.23	0.73	43-e02	0.93
S-II	15.56	0.74	41-e02	0.95
S-III	16.92	0.71	44-e02	0.98
S-IV	16.34	0.84	21-e02	0.95
S-V	12.12	0.71	51-e02	0.95

4.6 EFFECT OF ASH CONTENT OF COAL

A careful examination of the rheograms of the five coal samples revealed that the ash content of the coal influenced the yield stress i.e. the wall shear stress at zero shear rates. As the five coal samples had different ash contents, as discerned from the proximate analyses of coal done and described in chapter 3, the yield stress value increased as the ash content of the coal increased. The same behaviour was observed by Swain P. et al. (1996). The yield of the coal samples was found to be greatest for coal sample S-III i.e.13.88 (Pa) and 16.92 (Pa) at 50 % and 60 % solids concentration by weight respectively with an order of S-III>S-IV>S-I>S-II>S-V.

4.7 EFFECT OF PARTICLE SIZE AND SIZE DISTRIBUTION ON SLURRY RHEOLOGY

The particle size distributions of the five coal samples were having different median diameters and different values of Rosin-Rammler distribution modulus (n). The variation of apparent viscosities of coal water slurry at solids concentration of 50 % and 60 % by weight (at a shear rate of 100 s^{-1}) at varying values of RR model distribution modulus of coal sample is shown in Fig. 4.15.

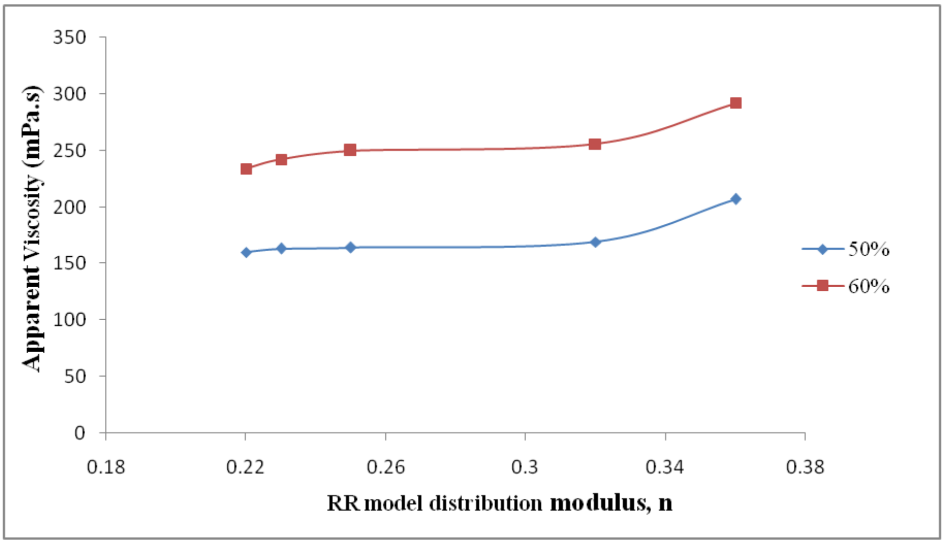

Fig. 4.15: Apparent viscosity for different values of distribution modulus at 50 and 60 % solid loading by weight at 100 s^{-1} shear rate

It was observed that as the Rosin-Rammler distribution modulus (n) of five coal samples under consideration decreased the apparent viscosity values also decreased. Similar trend was observed by Reddy G.V et al. (1994). This can be attributed to the broader particle size distribution for lower values of distribution modulus. The small coal particles fill the voids in between relatively coarser coal particles and hence, the effective surface area under shear decreases and hence the apparent viscosity decreases.

Also, it was found that the mass median diameter of the five coal samples influenced the apparent viscosities of coal water slurry. The coal water slurry prepared from Bathinda coal (S-I) with mass median diameter (d_{50}) of 80 µm showed the maximum apparent viscosities at all solids concentration by weight whereas Assam Steam coal with the mass median diameter of 112 µm showed least values of apparent viscosities at all solids concentration by weight. Similar findings were reported by Papachristodoulou G et al. (1984) for coal-oil mixtures. This is due to the fact that higher values of particle size (i.e. higher values of mass median diameter) have more voids that can be filled up by water and enhances the fluidity of coal water slurry. However, the coal water slurry prepared from lower particles size (i.e. lower values of mass median diameter) have less voids and poses a greater surface for shear and hence the apparent viscosity of coal water slurry increases.

4.8 EFFECT OF FRACTION OF FINES ON SLURRY RHEOLOGY

It is reported by many authors that the viscosity of the coal water slurries could be reduced by blending the coal samples with a fraction of fines and hence making a bimodal particle size distribution. The two coal samples i.e. S-I and S-V were first sieved to obtain a monodisperse size range of 150-250 µm and then blended with coal fines of size range 53-75 µm in different ratios of coarse and fine fraction. The resulting values of apparent viscosities at a shear rate of 100 s^{-1} for different coarse to fine ratios are shown in Fig. 4.16.

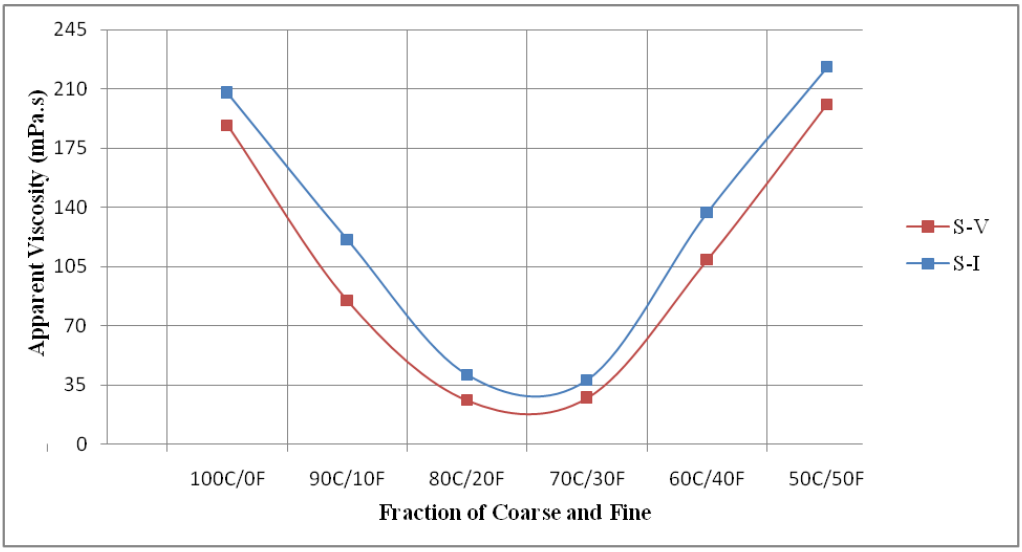

Fig. 4.16: Effect of fraction of fines on the apparent viscosity of S-I and S-V

By blending the coal samples with different ratios of coarse and fine fractions, it was found that as the fines were gradually added, the apparent viscosities decreased for both coal samples and as the blending ratio reached 70C/30F (i.e. 70 % Coarse and 30 % Fine), the apparent viscosities were a minimum. By adding further fraction of fines, the coal water slurry viscosity started to increase. Hence, the optimum coarse to fine ratio for the two coal samples i.e. S-I and S-V were found to be 70C/30F. The similar results were obtained by Roh N.S et al. (1994), Logos C et al. (1996) and Lorenzi et al. (2002). The reduction in apparent viscosities was due to the fact that the fine particles fill the voids of coarser particles and hence increases the fluidity at same volume fraction. Therefore, it is possible to reduce the apparent viscosities of coal samples by suitable blending of coarse particles with fines.

4.9 EFFECT OF DISPERSING AGENT ON SLURRY RHEOLOGY

The dispersing agents are added to the coal water slurry to reduce the apparent viscosities. There are numerous chemical additives that have been utilized so far and reported by many researchers. A majority of these additives are formed chemically and thus poses a threat to the environment. In the present study, the focus was to obtain an additive that is friendly to the environment and is obtained naturally. One such dispersant that satisfies these conditions is Shikakai Powder which is a natural product that is prepared from the saponin of Acacia concinna plant.

The Shikakai powder is also used as a common natural hair conditioner in India. The Shikakai powder was chosen as the dispersant.

The additive was used in the dosages of 0.5, 0.8 and 1 % by weight. The two coal samples were chosen to find the effect of additive on the rheological behaviour of coal water slurry. They were S-I and S-IV with solid concentration of 50 % by weight. The amount of coal required with the inclusion of additive was calculated and then mixed with water to obtain the coal water slurry of 50 % solids concentration by weight.

Fig. 4.17 and 4.18 presents the rheograms of coal water slurries of S-I and S-IV at different dosages of Shikakai powder.

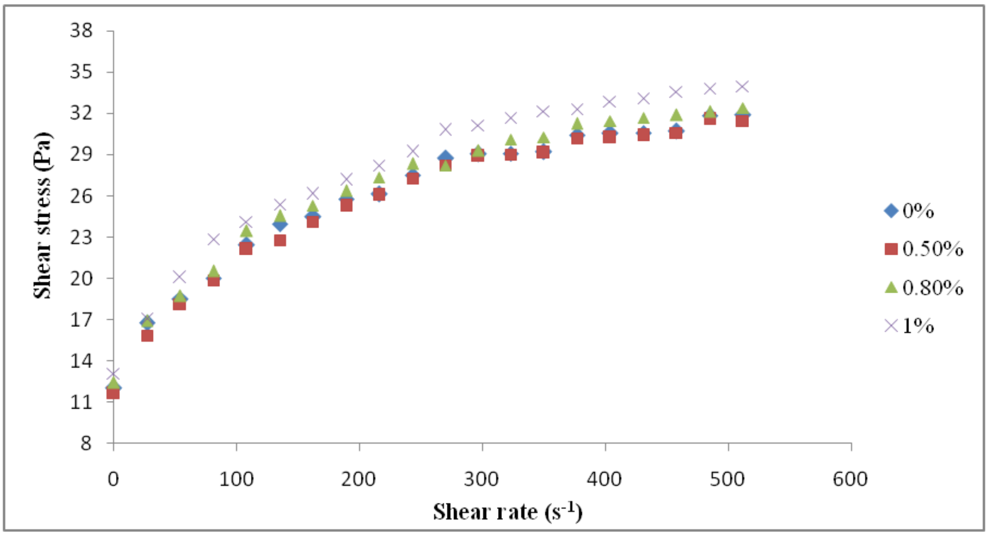

Fig. 4.17: Rheogram of S-I at additive concentrations of 0.5, 0.8 and 1 % by wt.

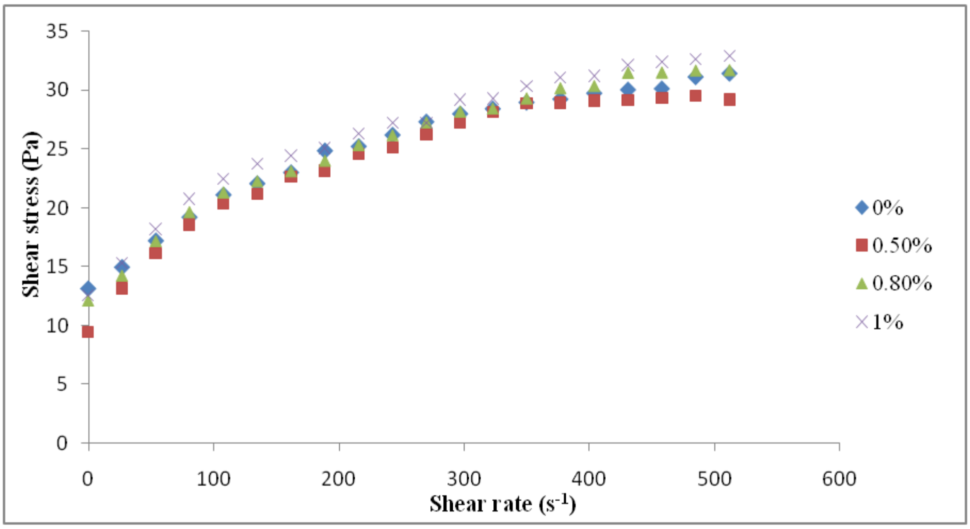

Fig. 4.18: Rheogram of S-IV at additive concentrations of 0.5, 0.8 and 1 % by wt.

It was found that the coal water slurry rheological behavior after the addition of Shikakai powder was pseudoplastic with a certain yield stress associated with it. The coal water slurry at additive dosage of 0.5 % by weight had lower values of apparent viscosities than the values of apparent viscosities obtained without the additive at the same solids concentration of 50 % by weight.

Figure 4.19 and Figure 4.20 describes the variation of apparent viscosities (at shear rate of 323 s^{-1}) with the addition of additive (Shikakai powder) in different amounts of 0.5 %, 0.8 % and 1 % by weight for coal sample S-I and S-IV. The solids concentration of the coal water slurry was fixed at 50 % by weight.

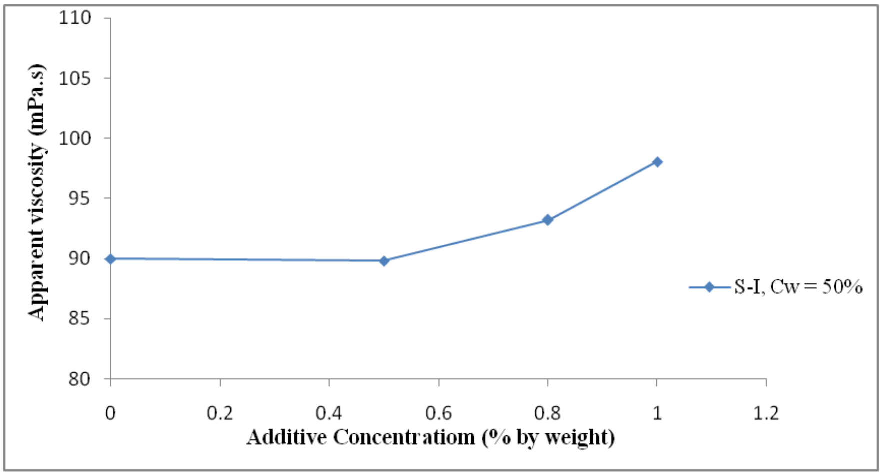

Fig. 4.19: Apparent viscosity at additive dosages of 0.5, 0.8 and 1 % by wt. for S-I

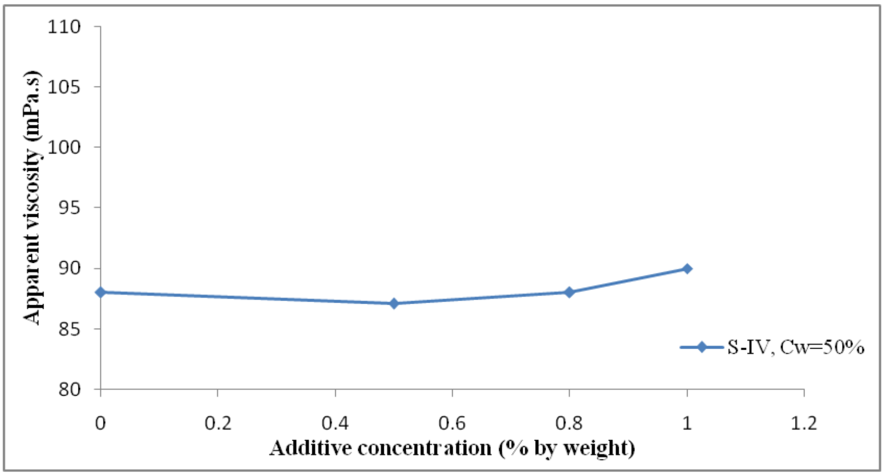

Fig. 4.20: Apparent viscosity at additive dosages of 0.5, 0.8 and 1 % by wt. for S-IV

It was found that at additive (Shikakai powder) dosage of 0.5 % by wt., the apparent viscosity values were the lowest for 50 % solids concentration by weight. However, as the additive dosage was increased to 0.8 and 1 % by weight, the apparent viscosity values were higher than those obtained without the additive.

Hence the optimum dosage of additive for 50 % solids concentration by weight was 0.5 % by wt. for both coal samples S-I and S-IV. The increase in the value of apparent viscosity at additive dosage of 0.8 % and 1 % by weight can be attributed to the interparticle friction between the additive particles at higher dosages. Therefore, the coal water slurry of optimum rheological behaviour can be prepared from coal samples S-I and S-IV by using Shikakai powder as an additive with a dosage of 0.5 % by weight.

4.10 CONCLUSION

The rheological behaviour of five different coal samples with varying ash content and median particle sizes (d_{50}) has been investigated. A pseudoplastic (shear thinning behaviour) is observed for all the five coal samples at solids concentration of 40 %, 50 % and 60 % by weight. The present study on the five coal samples showcased that the rheological behaviour of coal water slurry depends upon the solids concentration, the particle size and size distribution, the ash content, the fraction of coal fines in coarser coal particles and the amount of additive in the coal water slurry. The results obtained are useful for obtaining the flow behaviour of coal water slurries in pipelines.

CHAPTER 5 NUMERICAL STUDY ON PIPE FLOW CHARACTERISTICS

The design of slurry pipeline is a complex process and requires that the design should be optimised that permits highly concentrated slurry transport with minimum pressure drop and wear. The rheological study done on five coal samples was useful in generating the slurry viscosity data that can be utilized to determine the pressure drop in coal water slurry pipelines. In the present study, pressure drop characteristics of 53 mm diameter slurry pipeline were numerically evaluated using ANSYS FLUENT 14.0 code. The evaluation was done on straight pipe and a 90^o bend of a 53 mm diameter pipe and 2.65 m length.

5.1 NUMERICAL EVALUATION

Numerical evaluation for pipeline of different geometries for pressure drop characteristics was carried out by computational fluid dynamics (CFD). CFD is the analysis of systems involving fluid flow, heat transfer and associated phenomena by means of computer-based simulations. Computational power is used to perform the calculations required to simulate the interaction of fluid with object surfaces defined by proper boundary conditions.

5.2 MODELLING OF STRAIGHT PIPE AND 90^O PIPE BEND

The pipeline was modelled using Design Modeler available in ANSYS 14.0 workbench. The diameter and length of both straight pipe and 90^o pipe bend was kept same i.e. 53 mm and 2.65 m. The length was chosen to be 50 times the diameter for the fully developed flow condition. The radius of the bend was 0.0525 m. Fig. 5.1 and 5.2 presents the pictorial view of straight pipe and 90^o pipe bend modelled in Design Modeler of ANSYS 14.0 code.

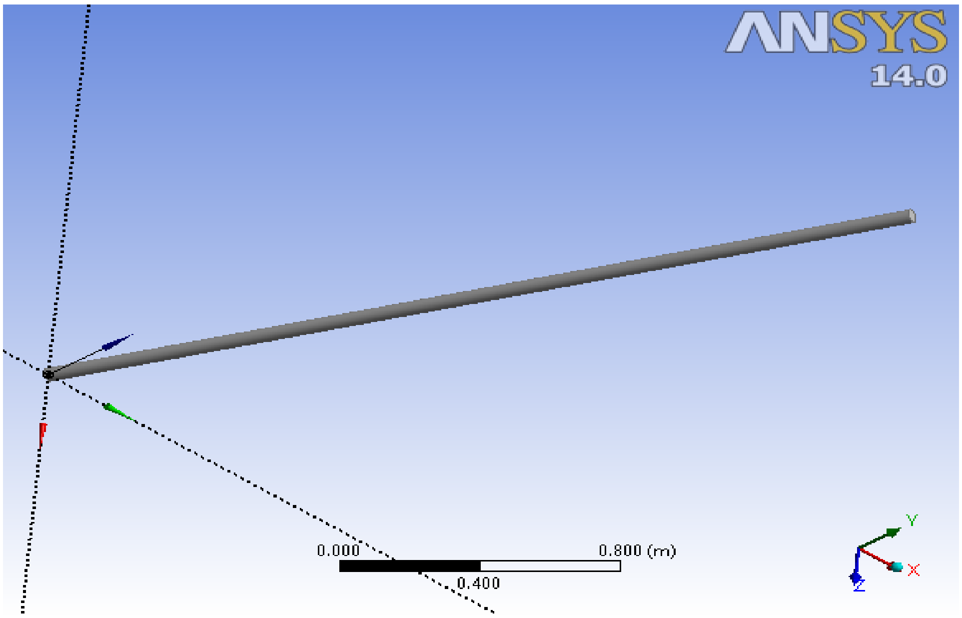

Fig. 5.1: Design of straight pipe of 53 mm diameter

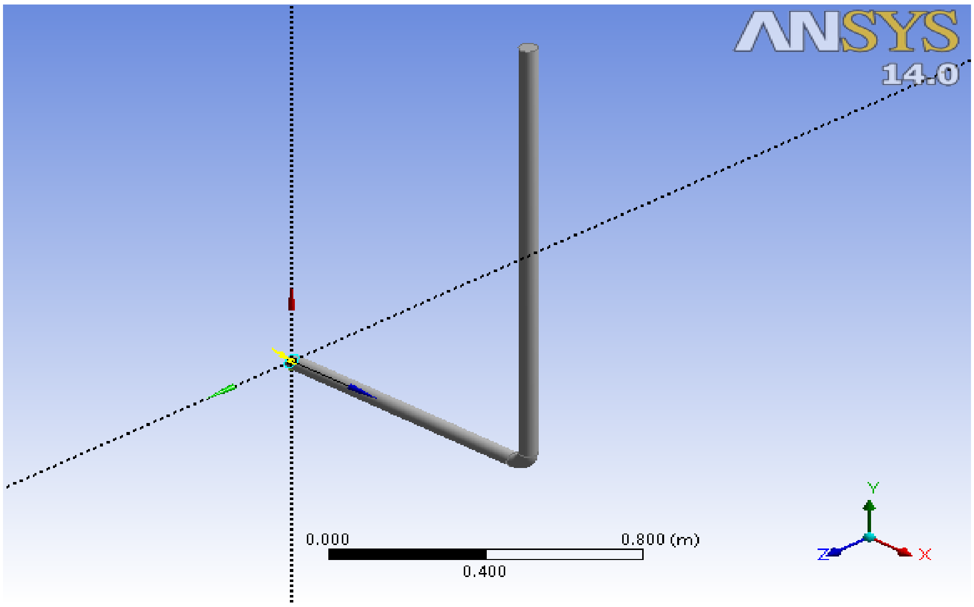

Fig. 5.2: Design of 90^o pipe bend of 53 mm diameter

5.3 MESH GENERATION OF STRAIGHT PIPE AND 90^{O} PIPE BEND

The model generated for the straight pipe and 90^{o} pipe bend was meshed using the Meshing function available in ANSYS 14.0 workbench. Tedrahedron mesh was generated with inflation provided on the pipe walls to get more elements generated on the pipe wall. Fig.5.3 and 5.4 describes the mesh generated for the straight ppe and 90^{o} pipe bend respectively.

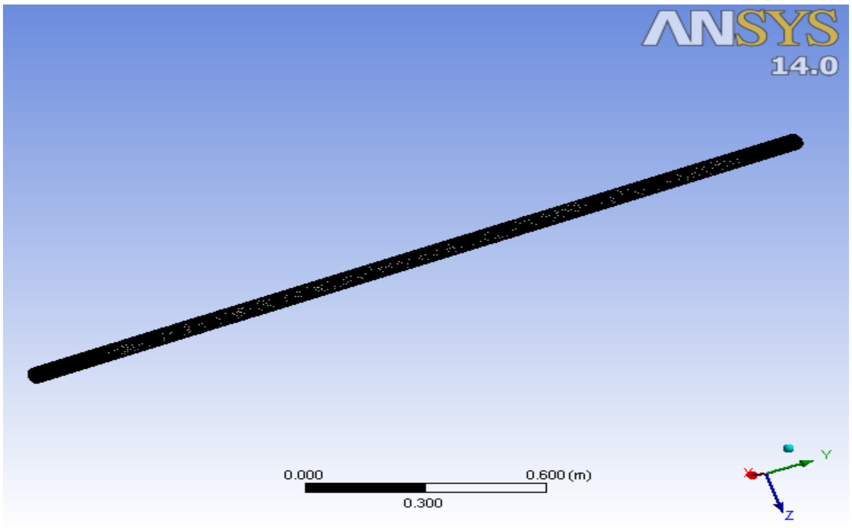

Fig. 5.3: Mesh generated for straight pipe of 53 mm diameter

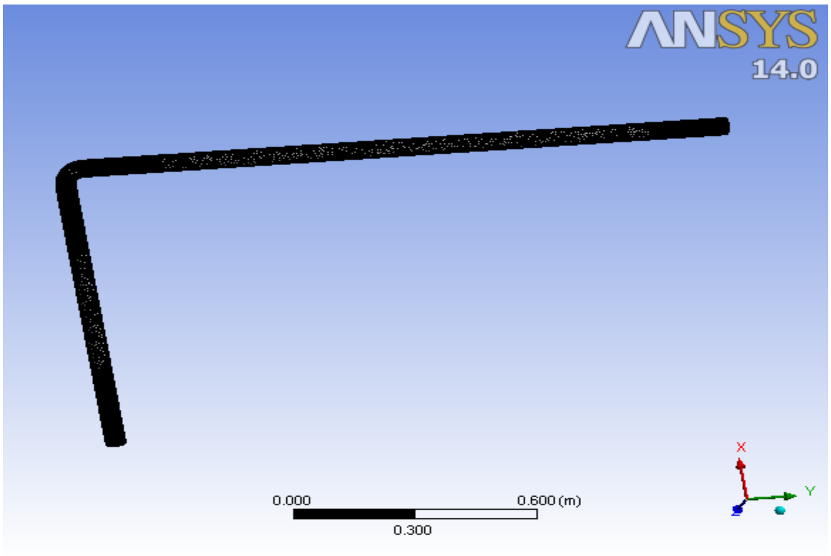

Fig. 5.4: Mesh generated for 90^{o} pipe bend of 53 mm diameter

A grid independence test was conducted for both straight pipe and 90^o pipe bend to choose the most suitable grid size. Different numbers of elements were obtained for different grid sizes and the simulation results for pressure drop of coal water slurry flow at fixed solids concentration of 50 % by weight and flow velocity of 2.5 m/s for both straight pipe and 90^o pipe bend were compared.

Before obtaining the grid test results for coal water slurry flow, the pressure drop was theoretically calculated at mean flow velocity of 2.5 m/s for water flowing in straight pipe by using Darcy-Weisbach equation. The Darcy-Weisbach equation is expressed as:

$$h_L = f \, \frac{l}{D} \frac{V^2}{2g} \tag{5.1}$$

where h_L is the head loss in pipeline, f is the friction factor, V is the mean flow velocity, D is the pipe diameter and g is the acceleration due to gravity. The pressure drop, Δp is given by the expression:

$$\Delta \mathrm{p} = \ h_L \ \times \ \gamma \tag{5.2}$$

where Δp is the pressure drop, h_L is the head loss and γ is the specific weight of the fluid. The theoretical calculations using Darcy-Weisbach equation for water flowing in the pipelines are summarized in the Table 5.1. The friction factor (f) was calculated from the Moody’s diagram.

Table 5.1: Pressure drop for water at mean flow velocity of 2.5 m/s

Pressure drop (kPa/m) calculation by Darcy-Weisbach equation.	Pressure drop (kPa/m) by simulation in ANSYS FLUENT 14.0	
Reynolds no. (Re) = 1.3×10^4 Pipe roughness (ε) = 0.004 mm Relative roughness $\left(\frac{\varepsilon}{D}\right) = 1.5 \times 10^{-3}$ Friction factor (f) = 0.02 Pressure drop (kPa/m) = 1.134	Grid size	Pressure drop (kPa/m)
	1.5	1.134
	2.0	1.029
	2.5	0.879
	3.0	0.792

The theoretical results of pressure drop for water flowing in straight pipe were validated with the simulated results at different grid sizes of 1.5, 2, 2.5 and 3.0. It was found that the pressure drop obtained by simulation in ANSYS FLUENT 14.0 with grid size of 1.5 was the same as obtained by Darcy-Weisbach equation.

Hence, it was ensured that the pressure drop obtained by simulating the flow of water in pipeline at grid size of 1.5 was the same as obtained theoretically. After conducting these tests, the coal water slurry flow was simulated and a grid independence test was performed to choose the most accurate grid size.

It was found that the grid size of 1.5 was appropriate for the present study. The grid independence test results are shown in Table 5.2.

Table 5.2: Grid independence test

Straight Pipe			90^o Pipe bend		
Grid size	Number of elements	Pressure drop (kPa/m)	Grid size	Number of elements	Pressure drop (kPa/m)
1.5	303946	10.9620	1.5	365743	18.8328
2.0	276536	10.9601	2.0	312090	18.7986
2.5	232378	9.8921	2.5	257895	17.1210
3.0	201248	8.5653	3.0	211289	16.5219

5.4 PROBLEM SETUP

There were three faces bounding the calculation domain, the inlet, the pipe wall and the outlet. In ANSYS FLUENT 14.0 code, the mixture model was chosen for the study of coal water slurry flow which is a multiphase flow. Phase 1 was considered as the carrier liquid which was water and Phase 2 was considered as coal powder. The rheological data obtained earlier were used to compute the pressure drop in the slurry pipeline.

k-ε turbulence model was chosen as the turbulence model. The pressure-velocity coupling was achieved by utilizing Coupled SIMPLE algorithm that caters to the need of multiphase flows. The boundary conditions were given as velocity inlet (inlet condition) and pressure outlet (outlet condition) with pipe wall as the wall domain.

5.5 COMPUTATIONAL RESULTS

The pressure drop measurements were predicted at different mean flow velocities of 1.5 m/s, 2.0 m/s, 2.5 m/s and 3 m/s for 30 %, 40 %, 50 % and 60 % solid concentration (by weight) of coal water slurry prepared from coal sample S-I.

Fig. 5.5 and 5.6 shows the plot of pressure drop with varying velocities for the flow of coal water slurry in a straight pipe and 90° pipe bend at different solids concentration by weight.

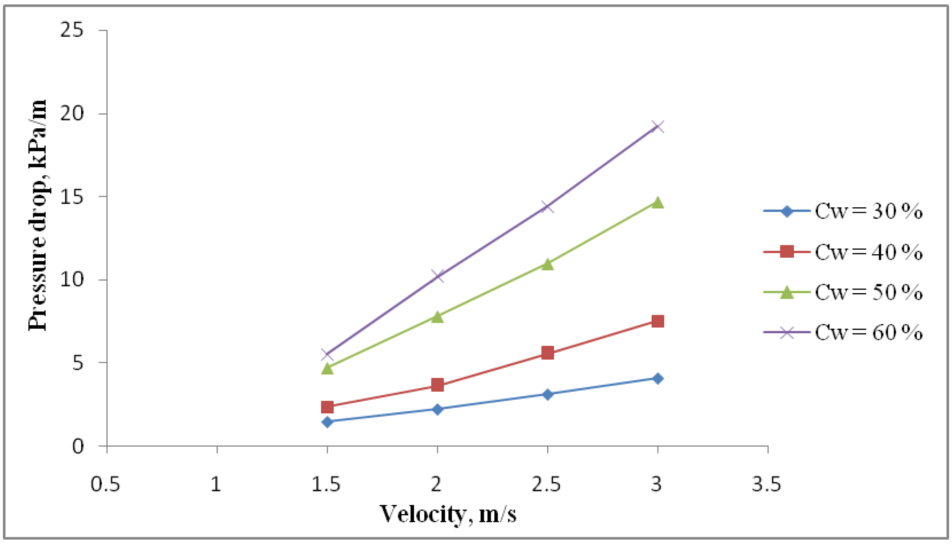

Fig. 5.5: Pressure drop at different solids concentration of coal sample S-I for straight pipe

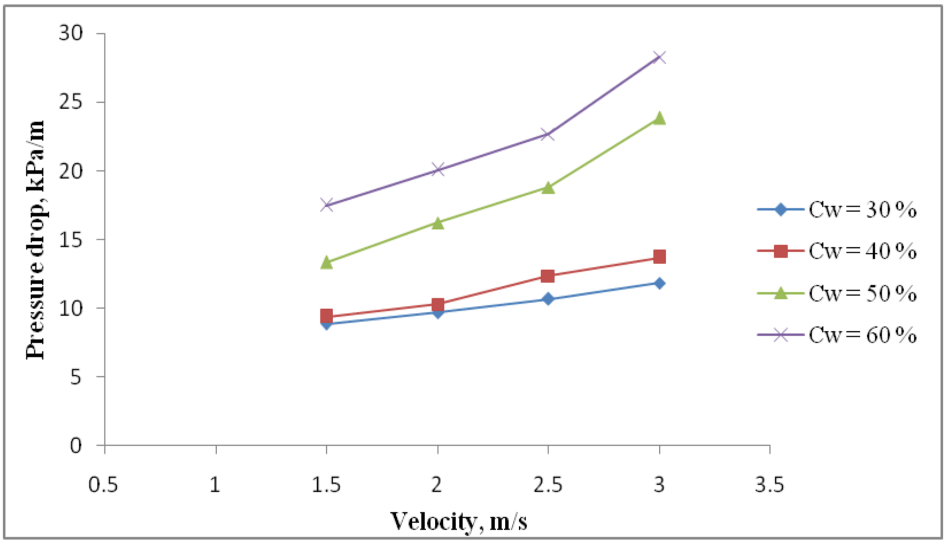

Fig. 5.6: Pressure drop at different solids concentration of coal sample S-I for 90° pipe bend

It was observed that the pressure drop in both straight pipe and 90^o pipe bend increased as the mean flow velocity increased. The pressure drop also increased with an increase in solids concentration of coal water slurry which was due to the increase in apparent viscosity of coal water slurry at increasing solids concentration by weight. Also, the pressure drop was greater for 90^o pipe bend than the straight pipe at same flow velocities and solids concentration. This was due to minor losses occurring in the bend. Hence, the rheological data was utilized to predict the pressure drop of coal water slurry at different solids concentration (by weight).

The static pressure contours for coal water slurry flow of coal sample S-I at 30 %, 40 %, 50 % and 60 % solids concentration and 2.5 m/s flow velocity for straight and pipe bend are shown in Fig.5.7-5.14

Fig. 5.7: Static Pressure contour at C_w = 30 %, Velocity = 2.5 m/s for straight pipe

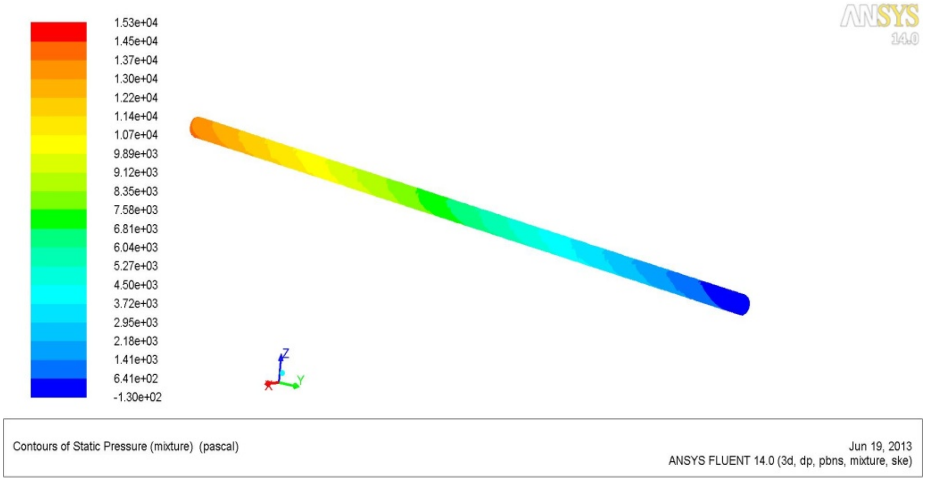

Fig. 5.8: Static Pressure contour at C_w = 40 %, Velocity = 2.5 m/s for straight pipe

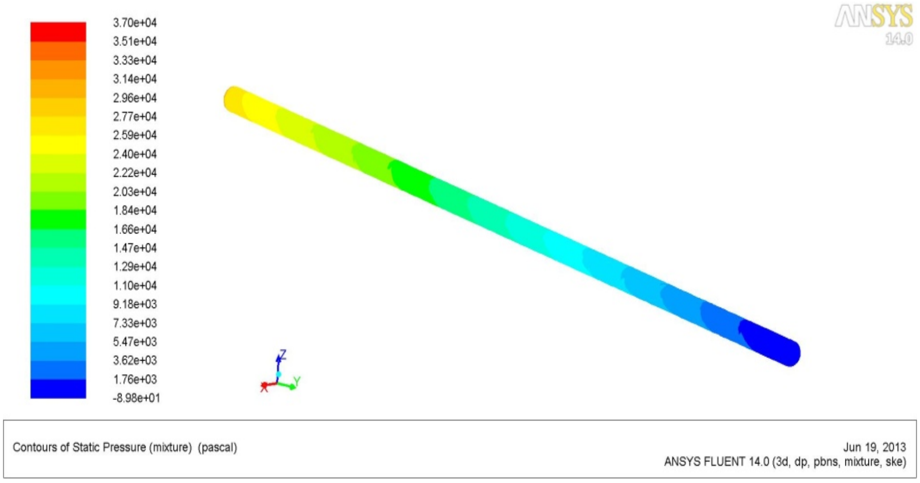

Fig. 5.9: Static Pressure contour at C_w = 50 %, Velocity = 2.5 m/s for straight pipe

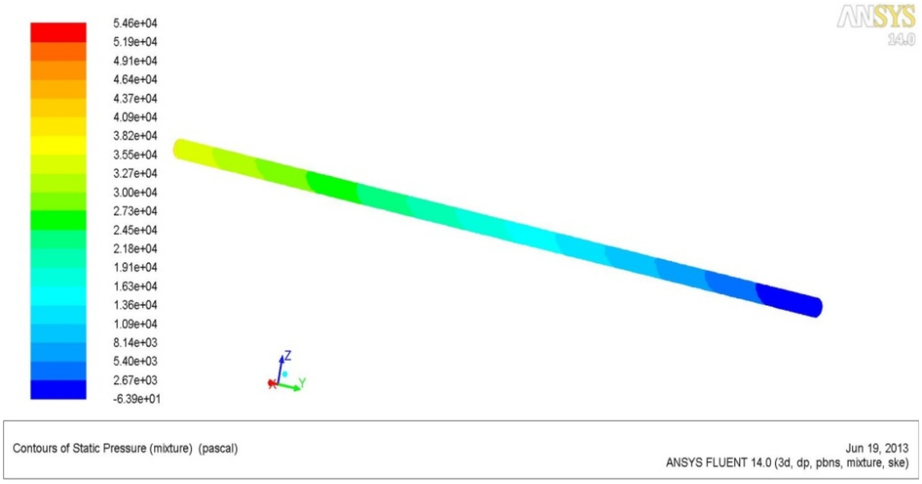

Fig. 5.10: Static Pressure contour at C_w = 60 %, Velocity = 2.5 m/s for straight pipe

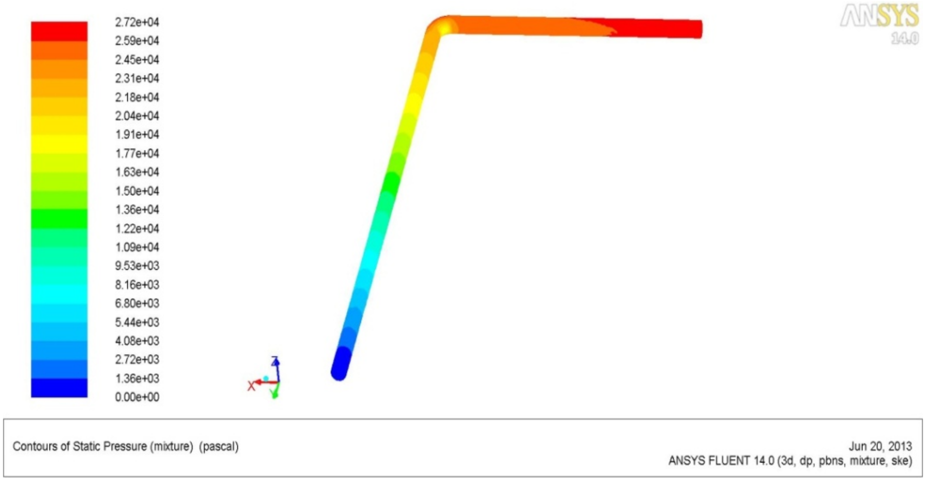

Fig. 5.11: Static Pressure contour at C_w = 30 %, Velocity = 2.5 m/s for 90^o pipe bend

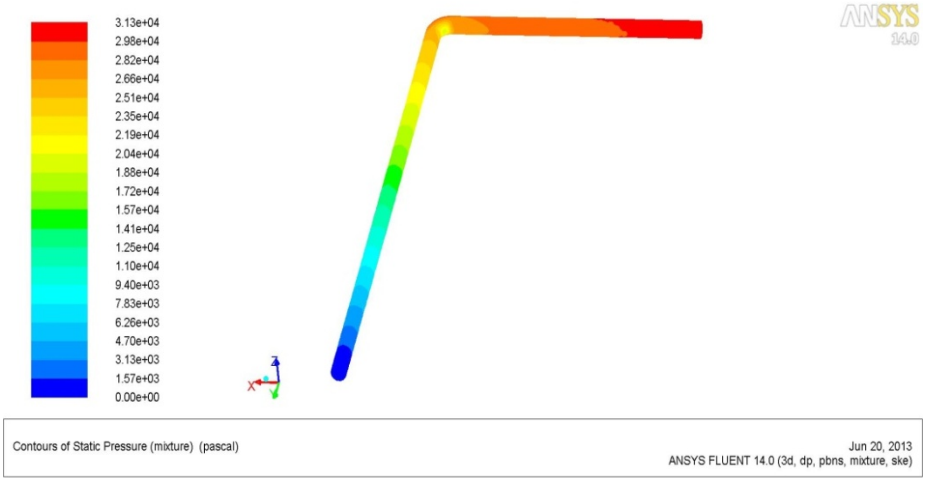

Fig. 5.12: Static Pressure contour at C_w = 40 %, Velocity = 2.5 m/s for 90^o pipe bend

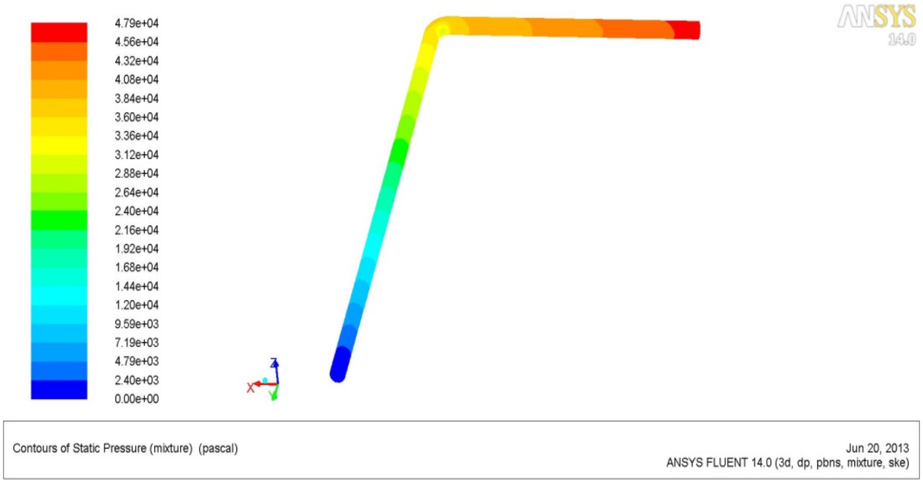

Fig. 5.13: Static Pressure contour at C_w = 50 %, Velocity = 2.5 m/s for 90^o pipe bend

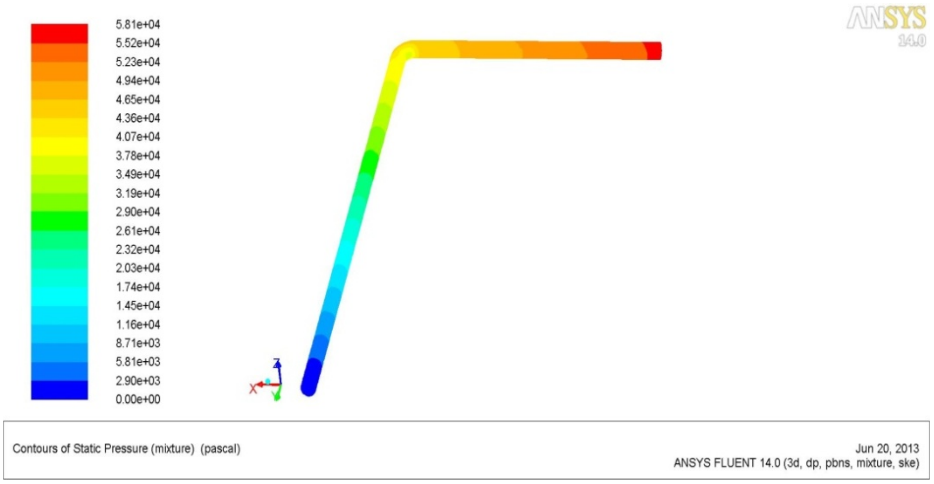

Fig. 5.14: Static Pressure contour at C_w = 60 %, Velocity = 2.5 m/s for 90^o pipe bend

It was observed from the static pressure contours that there was a greater pressure drop at higher solids concentration by weight. The volume fraction contours for phase 1 (water) and phase 2 (coal powder) of coal water slurry prepared from coal sample S-I at 60 % solids concentration for both straight pipe and 90^o pipe bend are shown in Figure 5.15-5.18.

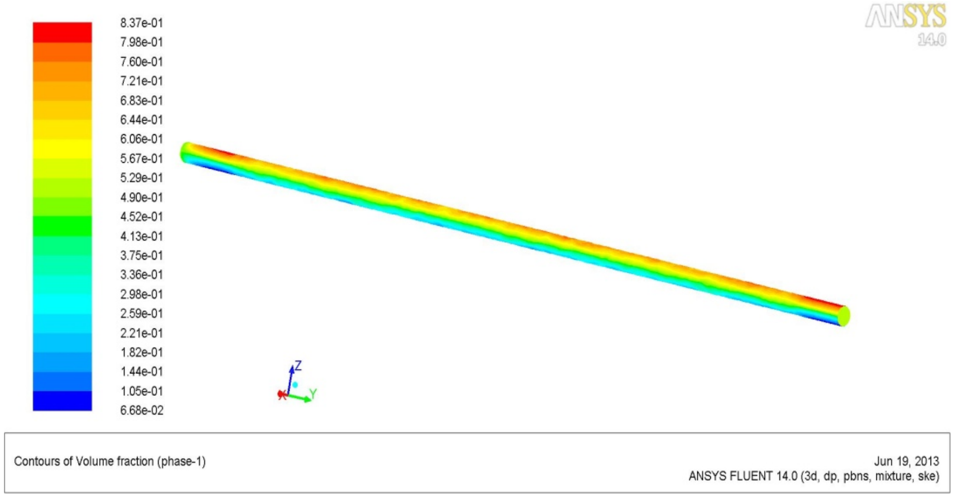

Fig. 5.15: Volume fraction contour of Phase 1 (water) at C_w = 60 %, Velocity = 2.5 m/s for Straight pipe

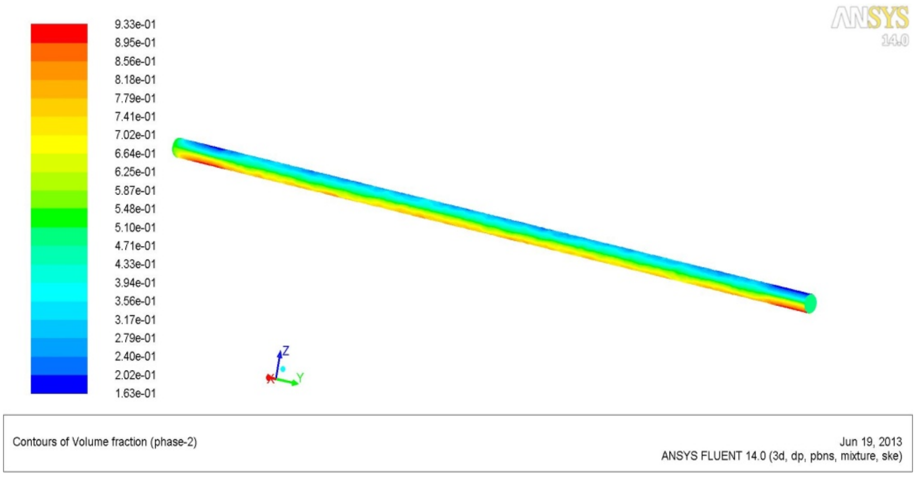

Fig. 5.16: Volume fraction contour of Phase 2 (coal powder) at C_w = 60 %,

Velocity = 2.5 m/s for Straight pipe

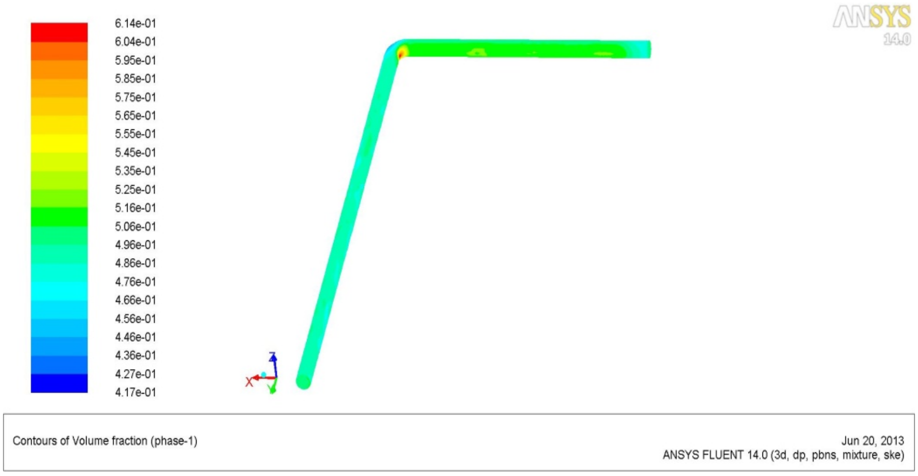

Fig. 5.17: Volume fraction contour of Phase 1 (water) at C_w = 60 %,

Velocity = 2.5 m/s for 90^o pipe bend

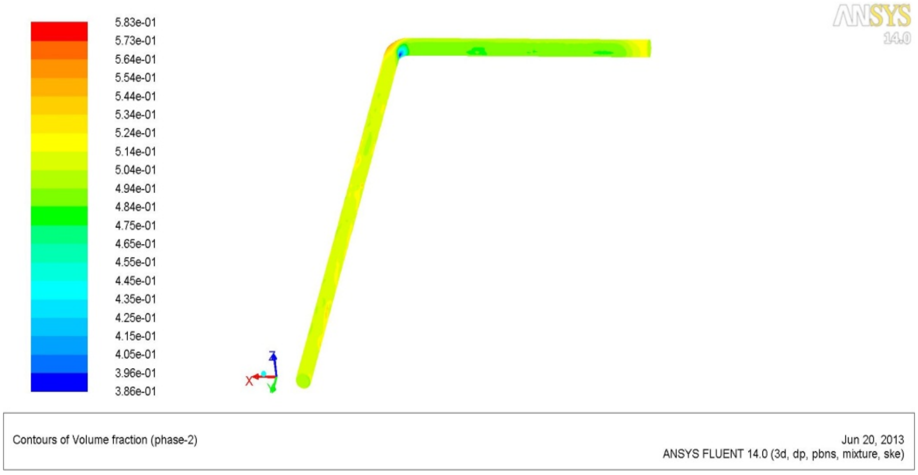

Fig. 5.18: Volume fraction contour of Phase 2 (coal powder) at C_w = 60 %,

Velocity = 2.5 m/s for 90^o pipe bend

It was observed from the volume fraction contours of coal water slurry flow at 60 % solids concentration (by weight) that incase of straight pipe, the flow of phase 2 (coal powder) in phase 1 (water) had a higher concentration towards the bottom of the pipe. This was attributed to the higher density of coal particles than water. Further, in coal water slurry flow through 90° pipe bend, the coal particles being heavier than water had higher concentration at the outer edge of the bend as they were unable to change the direction abruptly whereas the water changed the direction with the flow being lighter than coal particles.

The pressure drop was also calculated with Shikakai powder as an additive with a dosage of 0.5 % (by weight) at 50 % solids concentration (by weight) for coal sample S-I. The effect of additive (Shikakai powder, 0.5 % by weight) on the pressure drop characteristics of coal water slurry at 50 % solids concentration (by weight) was computed for straight pipe and 90° pipe bend. Fig.5.19 and 5.20 shows the effect of addition of Shikakai powder on the pressure drop characteristics of coal water slurry flow in straight pipe and 90° pipe bend.

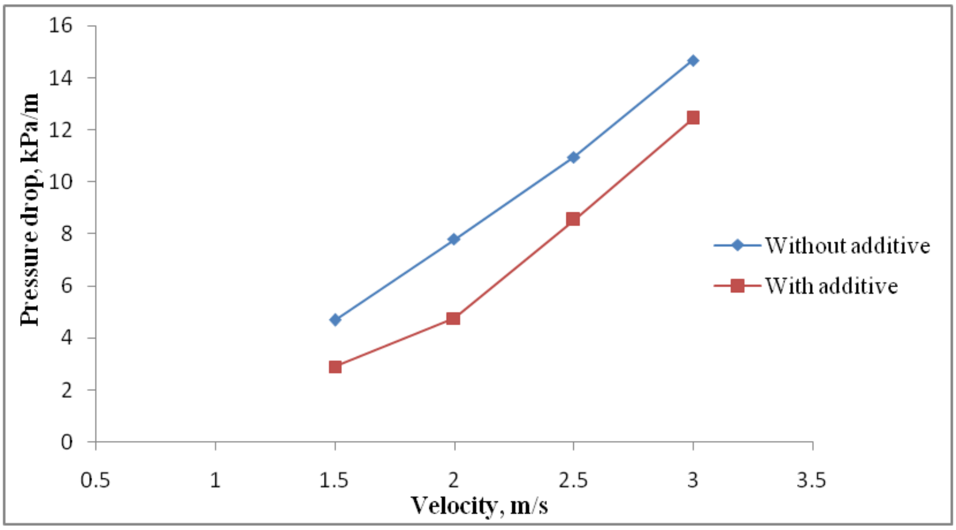

Fig. 5.19: Effect of additive on Pressure drop of coal water slurry at C_w = 50 % (S-I) in case of Straight pipe

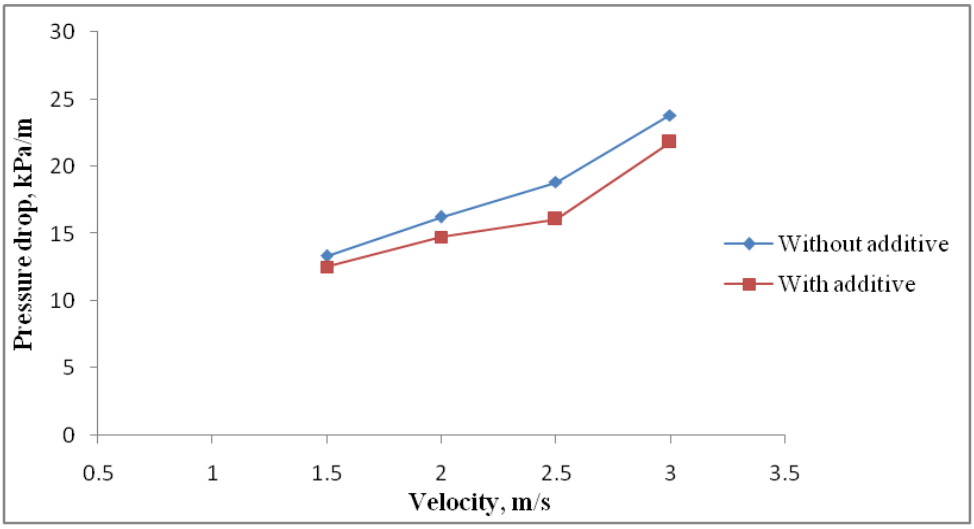

Fig. 5.20: Effect of additive on Pressure drop of coal water slurry at C_w = 50 % (S-I) in case of 90^o pipe bend

It was found that by adding Shikakai powder as an additive the pressure drop was reduced in both the straight pipe and the 90^o pipe bend. This was due to the reduced viscosities obtained by adding Shikakai powder at 50 % solids concentration (by weight).

CHAPTER 6 CONCLUSION AND FURTHER SCOPE

6.1 SUMMARY AND CONCLUSION

The present research work entitled “Investigation on Slurry Transportation Performance of Coal-Water Mixture at High Concentrations” was carried out using five different coal samples of Indian origin having different ash contents and mass median diameters. The characterization studies were done prior to the rheological study to determine the ash content, particle size distribution, morphology, coal-water mixture pH and static stability of coal-water mixture. The five coal samples showed different particle size distributions. The mass median diameter (in µm) for the five coal samples were 80, 100, 105, 110 and 112 for coal samples S-I, S-II, S-III, S-IV and S-V respectively. The morphological behaviour was also found to be different for each of the five coal samples with S-I containing maximum percentage of fine coal particles. The pH of coal water slurry was found to decrease with an increase in solids concentration. The stability measurements showed that the coal water slurry prepared from S-I coal sample had maximum stability. Further, the static stability in the absence of stabilizer was 30 hours for 40 % solids concentration (by weight) and 24 hours for 50 % solids concentration (by weight) for all the five coal samples.

The Particle Size Distribution data were fitted into the well known Rosin-Rammler mathematical model to characterize the size distribution of coal samples and the model parameters n (distribution modulus) and K (size modulus) were calculated using Regression analysis. After the characterization studies, the rheological data were generated for the five coal samples to determine the coal water slurry flow behaviour. The slurry flow behaviour was found to be shear thinning above 30 % solids concentration (by weight) with viscosity decreasing with an increasing shear rate. The shear stress-strain rate data were fitted into the rheological models to calculate the model parameters for Power-Law fluid and Herschel-Bulkley fluid. The rheological study was conducted to investigate the effect of solids concentration, ash content of coal, particle size distribution, fraction of coal fines and dispersing agent on the slurry rheological behaviour. It was found that the slurry viscosity increased with an increase in solids concentration. The yield stress obtained at 50 % and 60 % solids loading was found to increase with the increasing ash content of coal samples. The effect of particle size distribution on slurry rheology was studied by correlating the Rosin-Rammler model parameter n (distribution modulus) with the slurry viscosity. It was found that as the value of distribution modulus decreased, the slurry viscosity also decreased (due to a broader particle size distribution).

The coal fines were also added to relatively coarser coal particles to determine the effect of addition of fraction of coal fines and it was observed that the slurry viscosity decreased with the addition of coal fines until an optimum ratio of coarse and fine particles was reached. An increase in slurry viscosity was found at coarse/fine ratio greater than the optimum coarse/fine ratio. A natural additive, Shikakai Powder was tested as a dispersing agent in coal water slurries prepared from S-I and S-IV. The dosage of 0.5 % by weight was found as the optimum dosage for both coal samples.

The rheological data generated were utilized in evaluating the pipeline flow characteristics of coal water slurry using numerical techniques. Two pipeline geometries i.e. straight pipe and 90^o pipe bend were modelled using ANSYS Design Modeler package. The mesh generation was done in ANSYS meshing tool with the analysis performed using ANSYS FLUENT 14.0. It was found that for coal water slurries flowing in both straight pipe and 90^o pipe bend, the pressure drop increased as the solids concentration and flow velocity increased. The present work was undertaken to gain insight into the coal water slurry technology with a perspective towards its rheological behaviour and its transportation characteristics.

6.2 FURTHER SCOPE IN COAL WATER SLURRY TECHNOLOGY

The present research work was aimed at generating the rheological and pressure drop data for characterizing the coal water slurry rheological behaviour and utilizing the data to evaluate the transportation performance by predicting pressure drop in slurry pipelines by using computational fluid dynamics code. The various works that can augment the present study are:

1. Validation of results by computing slurry flow behaviour and pressure drop characteristics in an experimental pipeline loop setup.
2. Erosion wear studies of slurry pipelines for different solids weight concentration of coal water slurries.
3. Effect of surrounding temperature on the coal water slurry rheological behaviour.

There is still a large scope for further research work that lies in the field of coal water slurry technology for its efficient utilization and transport.

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APPENDIX

A1: Particle Size Distribution (% finer by weight)

Table A1: PSD results for five coal samples

Size (µm)	500	355	250	150	106	75	53
S-I	100	100	97.82	84.54	67.74	43.26	14.26
S-II	100	98.13	92.20	73.89	49.69	27.68	3.58
S-III	100	95.20	89.60	78.52	55.94	37.65	10.82
S-IV	100	95.05	82.12	69.35	58.37	35.48	5.58
S-V	100	92.60	82.62	72.12	53.18	26.20	8.32

B1: Static Stability test result for C_w = 40 % by weight

Table B1.1: Static stability result for S-I

Time (hrs)	d_t (mm)	d (mm)	% Penetration
0	60	60	100
6	60	60	100
12	60	59.5	99.16
18	60	58	96.66
24	60	55.5	92.5
30	60	53.5	89.16
36	60	51.7	86.15
42	60	49.78	82.96
48	60	47.9	79.83

Table B1.2: Static stability result for S-II

Time (hrs)	d_t (mm)	d (mm)	% Penetration
0	60	60	100
6	60	59.9	99.83
12	60	56	93.33
18	60	52.5	87.5
24	60	50.8	84.66
30	60	48.9	81.5
36	60	47.5	79.16
42	60	43	71.66
48	60	41.7	69.5

Table B1.3: Static stability result for S-III

Time (hrs)	d_t (mm)	d (mm)	% Penetration
0	60	60	100
6	60	58.5	97.5
12	60	55.5	92.5
18	60	51	85
24	60	50.5	84.16
30	60	46.9	78.16
36	60	46.5	77.5
42	60	41.4	69
48	60	39.8	66.33

Table B1.4: Static stability result for S-IV

Time (hrs)	**d_t (mm)**	**d (mm)**	**% Penetration**
0	60	60	100
6	60	58.5	97.5
12	60	55.3	92.16
18	60	50.8	84.66
24	60	50.1	83.5
30	60	46.5	77.5
36	60	44.5	74.16
42	60	38.5	64.16
48	60	37.9	63.166

Table B1.5: Static stability result for S-V

Time (hrs)	**d_t (mm)**	**d (mm)**	**% Penetration**
0	60	60	100
6	60	59.5	99.16
12	60	58.8	98
18	60	54.7	91.16
24	60	50.2	83.66
30	60	45	75
36	60	43.5	72.5
42	60	40.5	67.5
48	60	39.8	66.33

B2: Static Stability test result for C_w = 50 % by weight

Table B2.1: Static stability result for S-I

Time (hrs)	d_t (mm)	d (mm)	% Penetration
0	60	60	100
6	60	59.6	99.33
12	60	56.1	93.5
18	60	54.5	90.83
24	60	49.8	83
30	60	48.8	81.33
36	60	46.5	77.5
42	60	44.2	73.66
48	60	44.1	73.5

Table B2.2: Static stability result for S-II

Time (hrs)	d_t (mm)	d (mm)	% Penetration
0	60	60	100
6	60	58	96.66
12	60	55.1	91.83
18	60	51	85
24	60	47	78.33
30	60	43.2	72
36	60	40.5	67.5
42	60	39.3	65.5
48	60	39	65

Table B2.3: Static stability result for S-III

Time (hrs)	d_t (mm)	d (mm)	% Penetration
0	60	60	100
6	60	57	95
12	60	53	88.33
18	60	51.2	85.33
24	60	48.1	80.16
30	60	43.2	72
36	60	38.5	64.16
42	60	38	63.33
48	60	37.8	63

Table B2.4: Static stability result for S-IV

Time (hrs)	d_t (mm)	d (mm)	% Penetration
0	60	60	100
6	60	57	95
12	60	52.8	88
18	60	50.1	83.5
24	60	46.1	76.83
30	60	45.9	76.5
36	60	42.5	70.83
42	60	37.4	62.33
48	60	36.9	61.5

Table B2.5: Static stability result for S-V

Time (hrs)	d_t (mm)	d (mm)	% Penetration
0	60	60	100
6	60	56.8	94.66
12	60	51.3	85.5
18	60	44.7	74.5
24	60	42.1	70.16
30	60	42	70
36	60	39.8	66.33
42	60	38.7	64.5
48	60	38.2	63.66

C1: Rheology of coal-water slurry at C_w = 30 % by weight.

Table C1.1: Rheology of coal water slurry for S-I

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	0	####
27	0.359	13
54	0.573	10
80.9	0.782	9
108	0.978	9
135	1.14	8
162	1.35	8
189	1.57	8
216	1.76	8
243	1.93	7
270	2.03	7
297	2.17	7
323	2.32	7
350	2.5	7
377	2.67	7
404	2.85	7
431	3.06	7
458	3.27	7
485	3.48	7
512	3.72	7

Table C1.2: Rheology of coal water slurry for S-II

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	0	####
27	0.237	8
54	0.471	8
80.9	0.621	7
108	0.877	8
135	0.922	6
162	1.05	6
189	1.37	7
216	1.54	7
243	1.63	6
270	1.74	6
297	1.92	6
323	2.12	6
350	2.26	6
377	2.37	6
404	2.56	6
431	2.67	6
458	2.87	6
485	2.99	6
512	3.21	6

Table C1.3: Rheology of coal water slurry for S-III

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	0	####
27	0.197	7
54	0.371	6
80.9	0.504	6
108	0.669	6
135	0.814	6
162	1.03	6
189	1.23	6
216	1.37	6
243	1.49	6
270	1.63	6
297	1.82	6
323	1.97	6
350	2.05	5
377	2.17	5
404	2.22	5
431	2.42	5
458	2.63	5
485	2.78	5
512	2.82	5

Table C1.4: **Rheology of coal water slurry for S-IV**

Shear Rate (s^{-1})	**Shear stress (Pa)**	**Apparent Viscosity (mPa.s)**
0	0	####
27	0.132	4
54	0.275	5
80.9	0.407	5
108	0.604	5
135	0.612	4
162	0.877	5
189	1.02	5
216	1.17	5
243	1.27	5
270	1.39	5
297	1.56	5
323	1.62	5
350	1.81	5
377	1.94	5
404	2.12	5
431	2.22	5
458	2.4	5
485	2.56	5
512	2.68	5

Table C1.5: Rheology of coal water slurry for S-V

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	0	####
27	0.113	4
54	0.185	3
80.9	0.212	2
108	0.279	2
135	0.344	2
162	0.451	2
189	0.522	2
216	0.68	3
243	0.74	3
270	0.88	3
297	0.98	3
323	1.08	3
350	1.21	3
377	1.35	3
404	1.43	3
431	1.59	3
458	1.65	3
485	1.79	3
512	1.87	3

C2: Rheology of coal-water slurry at C_w = 40 % by weight.

Table C2.1: Rheology of coal water slurry for S-I

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	0	####
27	2.01	74
54	2.42	44
80.9	3.37	41
108	4.32	40
135	4.94	36
162	5.26	32
189	5.73	30
216	6.01	27
243	6.11	25
270	6.28	23
297	6.78	22
323	6.99	21
350	7.26	20
377	7.34	19
404	7.47	18
431	7.54	17
458	7.64	16
485	7.66	15
512	7.75	15

Table C2.2: **Rheology of coal water slurry for S-II**

Shear rate (s^{-1})	**Shear stress (Pa)**	**Apparent Viscosity (mPa.s)**
0	0	####
27	1.92	71
54	2.38	44
80.9	2.72	33
108	3.56	32
135	4.14	30
162	4.61	28
189	5.01	26
216	5.26	24
243	5.71	23
270	6.11	22
297	6.35	21
323	6.62	20
350	6.79	19
377	7.02	18
404	7.11	17
431	7.19	16
458	7.24	15
485	7.32	15
512	7.43	14

Table C2.3: **Rheology of coal water slurry for S-III**

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	0	####
27	1.76	65
54	2.22	41
80.9	2.55	31
108	2.98	27
135	3.34	24
162	4.28	26
189	4.88	25
216	5.13	23
243	5.47	22
270	5.73	21
297	6.04	20
323	6.12	18
350	6.24	17
377	6.32	16
404	6.46	15
431	6.57	15
458	6.79	14
485	7.01	14
512	7.19	14

Table C2.4: **Rheology of coal water slurry for S-IV**

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	0	####
27	1.68	62
54	2.09	38
80.9	2.34	28
108	2.54	23
135	3.08	22
162	3.52	21
189	4.03	21
216	4.29	19
243	4.47	18
270	4.98	18
297	5.23	17
323	5.47	16
350	5.88	16
377	6.03	15
404	6.14	15
431	6.28	14
458	6.37	13
485	6.52	13
512	6.81	13

Table C2.5: Rheology of coal water slurry for S-V

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	0	####
27	1.34	49
54	1.97	36
80.9	2.07	25
108	2.23	20
135	2.73	20
162	3.05	18
189	3.22	17
216	3.78	17
243	4.03	16
270	4.29	15
297	4.56	15
323	4.78	14
350	4.99	14
377	5.04	13
404	5.13	12
431	5.18	12
458	5.21	11
485	5.26	10
512	5.29	10

C3: Rheology of coal-water slurry at C_w = 50 % by weight.

Table C3.1: Rheology of coal water slurry for S-I

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	12.03	####
27	16.77	621
54	18.52	342
80.9	20.04	247
108	22.45	207
135	23.96	177
162	24.48	151
189	25.79	136
216	26.12	120
243	27.51	113
270	28.73	106
297	29.03	97
323	29.09	90
350	29.22	83
377	30.38	80
404	30.53	75
431	30.58	70
458	30.68	66
485	31.81	65
512	31.91	62

Table C3.2: Rheology of coal water slurry for S-II

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	11.12	####
27	15.13	560
54	18.12	335
80.9	19.94	246
108	21.65	200
135	22.87	169
162	23.67	146
189	25.19	133
216	26.1	120
243	27.22	112
270	28.66	106
297	28.98	97
323	29.07	90
350	29.14	83
377	30.18	80
404	30.34	75
431	30.41	70
458	30.54	66
485	31.65	65
512	31.78	62

Table C3.3: Rheology of coal water slurry for S-III

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	13.88	####
27	14.98	554
54	17.78	329
80.9	19.44	240
108	21.35	197
135	22.17	164
162	23.1	142
189	25.01	132
216	25.67	118
243	26.52	109
270	27.5	101
297	28.12	94
323	28.99	89
350	29.02	82
377	29.59	78
404	30.02	74
431	30.19	70
458	30.34	66
485	31.54	65
512	31.67	61

Table C3.4: Rheology of coal water slurry for S-IV

Shear rate (s^{-1})	**Shear stress (Pa)**	**Apparent Viscosity (mPa.s)**
0	13.16	####
27	14.98	554
54	17.23	319
80.9	19.23	237
108	21.13	195
135	22.09	163
162	23.03	142
189	24.88	131
216	25.25	116
243	26.22	107
270	27.34	101
297	28.02	94
323	28.45	88
350	28.99	82
377	29.27	77
404	29.77	73
431	30.07	69
458	30.16	65
485	31.16	64
512	31.45	61

Table C3.5: Rheology of coal water slurry for S-V

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	10.03	####
27	13.97	517
54	16.46	304
80.9	18.78	232
108	20.38	188
135	21.67	160
162	22.82	140
189	23.76	125
216	24.66	114
243	26.18	107
270	27.23	100
297	27.98	94
323	28.32	87
350	28.78	82
377	29.03	77
404	29.45	72
431	30.02	69
458	30.11	65
485	31.08	64
512	31.29	61

C4: Rheology of coal-water slurry at C_w = 60 % by weight.

Table C4.1: Rheology of coal water slurry for S-I

Shear rate (s^{-1})	**Shear stress (Pa)**	**Apparent Viscosity (mPa.s)**
0	16.23	####
27	19.34	716
54	25.75	476
80.9	29.44	363
108	31.56	292
135	35.67	264
162	37.77	233
189	39.54	209
216	41.43	191
243	43.76	180
270	44.43	164
297	46.76	157
323	47.49	147
350	48.47	138
377	49.34	130
404	50.66	125
431	50.87	118
458	51.76	113
485	52.98	109
512	54.88	107

Table C4.2: Rheology of coal water slurry for S-II

Shear rate (s^{-1})	**Shear stress (Pa)**	**Apparent Viscosity (mPa.s)**
0	15.56	####
27	18.78	695
54	24.67	456
80.9	28.13	347
108	29.89	276
135	34.56	256
162	36.34	224
189	37.73	199
216	39.96	185
243	42.65	175
270	43.87	162
297	45.67	153
323	46.76	144
350	47.45	135
377	48.24	127
404	49.46	122
431	50.37	116
458	51.56	112
485	52.86	108
512	53.56	104

Table C4.3: Rheology of coal water slurry for S-III

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	16.92	####
27	21.56	798
54	23.34	432
80.9	27.45	339
108	29.79	275
135	33.87	250
162	35.66	220
189	36.89	195
216	39.45	182
243	41.24	169
270	43.66	161
297	44.79	150
323	45.82	141
350	46.53	132
377	47.76	126
404	48.87	120
431	49.98	115
458	50.56	110
485	51.78	106
512	52.67	102

Table C4.4: Rheology of coal water slurry for S-IV

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	16.34	####
27	18.66	691
54	22.56	417
80.9	26.54	328
108	29.45	272
135	32.73	242
162	34.74	214
189	36.45	192
216	38.77	179
243	40.67	167
270	41.66	154
297	42.56	143
323	44.87	138
350	45.78	130
377	46.68	123
404	48.34	119
431	49.56	114
458	49.98	109
485	51.12	105
512	51.89	101

Table C4.5: Rheology of coal water slurry for S-V

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	12.12	####
27	15.89	588
54	21.68	401
80.9	25.77	318
108	28.37	262
135	31.67	234
162	33.58	207
189	35.36	187
216	37.96	175
243	39.58	162
270	40.45	149
297	41.91	141
323	43.67	135
350	44.56	127
377	45.97	121
404	47.56	117
431	48.74	113
458	49.87	108
485	50.98	105
512	51.24	100

D1: Rheology of coal-water slurry at C_w = 50 % by weight with additive

Table D1.1: Rheology of coal water slurry for S-I, additive dosage of 0.5 %

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	11.65	####
27	15.86	587
54	18.12	335
80.9	19.85	245
108	22.11	204
135	22.8	168
162	24.1	148
189	25.26	133
216	26.03	120
243	27.25	112
270	28.19	104
297	28.89	97
323	29.01	89
350	29.12	83
377	30.18	80
404	30.23	74
431	30.37	70
458	30.56	66
485	31.55	65
512	31.45	61

Table D1.2: Rheology of coal water slurry for S-I, additive dosage of 0.8 %

Shear rate (s^{-1})	**Shear stress (Pa)**	**Apparent Viscosity (mPa.s)**
0	12.43	####
27	16.92	626
54	18.73	346
80.9	20.53	253
108	23.45	217
135	24.56	181
162	25.32	156
189	26.35	139
216	27.34	126
243	28.33	116
270	28.19	104
297	29.26	98
323	30.12	93
350	30.24	86
377	31.23	82
404	31.45	77
431	31.67	73
458	31.89	69
485	32.11	66
512	32.37	63

Table D1.3: Rheology of coal water slurry for S-I, additive dosage of 1.0 %

Shear rate (s^{-1})	**Shear stress (Pa)**	**Apparent Viscosity (mPa.s)**
0	13.11	####
27	17.11	633
54	20.05	371
80.9	22.87	282
108	24.12	223
135	25.37	187
162	26.11	161
189	27.16	143
216	28.22	130
243	29.18	120
270	30.77	113
297	31.12	104
323	31.67	98
350	32.14	91
377	32.29	85
404	32.87	81
431	33.11	76
458	33.56	73
485	33.79	69
512	33.98	66

Table D1.4: **Rheology of coal water slurry for S-IV, additive dosage of 0.5 %**

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	9.45	####
27	13.14	486
54	16.12	298
80.9	18.56	229
108	20.34	188
135	21.16	156
162	22.65	139
189	23.13	122
216	24.55	113
243	25.12	103
270	26.22	97
297	27.19	91
323	28.16	87
350	28.87	82
377	28.93	76
404	29.09	72
431	29.16	67
458	29.34	64
485	29.49	60
512	29.19	57

Table D1.5: Rheology of coal water slurry for S-IV, additive dosage of 0.8 %

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	12.12	####
27	14.23	527
54	17.17	317
80.9	19.64	242
108	21.31	197
135	22.26	164
162	23.12	142
189	24.01	127
216	25.34	117
243	26.18	107
270	27.27	101
297	28.18	94
323	28.45	88
350	29.31	83
377	30.18	80
404	30.36	75
431	31.49	73
458	31.51	68
485	31.68	65
512	31.71	61

Table D1.6: Rheology of coal water slurry for S-IV, additive dosage of 1.0 %

Shear rate (s^{-1})	Shear stress (Pa)	Apparent Viscosity (mPa.s)
0	12.59	####
27	15.32	567
54	18.22	337
80.9	20.76	256
108	22.44	207
135	23.76	176
162	24.43	150
189	25.09	132
216	26.32	121
243	27.21	111
270	27.22	100
297	29.21	98
323	29.29	90
350	30.35	86
377	31.09	82
404	31.22	77
431	32.13	74
458	32.41	70
485	32.63	67
512	32.89	64