INVESTIGATION OF RHEOLOGICAL CHARACTERISTICS OF COAL-OIL MIXTURES

Thesis submitted in partial fulfillment of requirement for the award of the degree of

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THERMAL ENGINEERING

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DECLARATION

I hereby declare that thesis entitled **"Investigation of rheological characteristics of coal-oil mixtures"** is an authentic record of my study carried out as requirements for award of the degree of **M.E (Thermal Engineering)** at **Thapar University, Patiala,** under the supervision of **Dr. S.K. Mohapatra**, DOAA & Senior Professor, Department of Mechanical Engineering, Thapar University, Patiala. The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

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This is to certify that the above declaration made by the student concerned is correct to best of my knowledge and belief.

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Sandeep Singh

ABSTRACT

The present study on investigation of rheological characteristics of coal-oil mixtures was conducted at the Mechanical Engineering Department, Thapar University, Patiala. Three coal samples having different ash and moisture contents and furnace oil of grade MV2 were used for the preparation of coal-oil mixtures. Coal concentration was varied from 20 – 50 % by weight and temperature was varied from 25° - 45° C, in order to study the effect of solids concentration and temperature on the rheological properties of coal-oil mixtures. Rheological measurements were carried out using Anton Paar RheolabQC rheometer. It was observed that both apparent viscosity and yield stress of coal-oil mixture increased, with an increase in solids concentration and decreased, with an increase in temperature. The flow behavior of coal-oil mixtures was described by the Power-Law and Herschel-Bulkley models. The coal-oil mixtures up to 30 % solids concentration, behaved as a Newtonian fluid and with solids concentration more than 40 %, they behaved as a yield pseudo plastic fluid. Also the effect of various properties of coal like ash content, moisture content, particle size and particle size distribution on coal-oil mixture rheology was studied. It was found that both apparent viscosity and yield stress of coal-oil mixture decreased, with an increase in ash content of coal and increased, with an increase in moisture content of coal. As mass median diameter of coal particles increased, both apparent viscosity and yield stress of coal-oil mixture decreased. Also, with an increase in distribution modulus (n) of coal sample, both apparent viscosity and yield stress of coal-oil mixture increased.

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NOMENCLATURE

d_{50}	: Mass median particle diameter (microns)
C_w	: Weight concentration of mixture (wt. %)
τ	: Shear stress (Pa)
τ_y	: Yield stress (Pa)
γ	: Shear rate
R^2	: Coefficient of determination
n	: Distribution modulus
K	: Size modulus
$\dot{n}$	: Flow behaviour index
$\dot{K}$	: Consistency coefficient

CHAPTER 1 INTRODUCTION

In thermal power plants coal is used as a fuel in pulverized form. The other method of using coal as a fuel is in the form of coal-oil mixture in which fine coal is mixed with furnace oil. Coal-oil mixture should be prepared in such a manner that it has low viscosity and uniform concentration. In order to investigate that whether a particular coal-oil mixture is suitable to be used as a fuel, rheological studies are conducted to determine the various rheological parameters like viscosity, shear stress, flow behavior etc.

1.1 COAL

Coal is a combustible and organic rock, formed from plants which were consolidated beneath the rocky layers of Earth about 360 million to 270 million years ago. The remains of dead plants were then acted upon by intense heat and pressure over a long period of time resulting in formation of coal reserves. The energy that we receive from coal today is actually the solar energy that plants absorbed from the sun through photosynthesis millions of years ago. When dead plants were buried beneath the crust, this solar energy was trapped inside and was locked into the coal.

Coal is classified as a non-renewable source of energy because it can’t be replenished, once it is exhausted. It is the most utilized and abundant fuel in India. Coal primarily consists of Carbon along with variable quantities of other elements, such as Hydrogen, Oxygen, Sulfur and Nitrogen.

1.2 TYPES OF COAL

- **Lignite**: It is also known as brown coal and technically it is the lowest rank of coal because of its low heating value. It has a carbon content of about 30 %. Due to its high content of volatile matter it is used in liquid petroleum products. It is mostly used as a fuel in power plants.
- **Sub-bituminous coal**: It is a type of coal whose properties fall in between bituminous and lignite coals. These coals have a low value of sulfur content as a result of which they are mostly used as a fuel in power plants due to lower emissions. These coals also act as a source of hydrocarbons which are required in chemical industries.
- **Bituminous coal**: It is also known as black coal and has a carbon content of about 70 %. It is of higher rank than lignite but lower rank as compared to anthracite. It is mainly used in manufacturing industries and for electricity generation. It is also used to make coke.
- **Coking coal**: It is prepared by heating bituminous coal in the absence of oxygen, as a result of which moisture content and volatile matter is driven off. It is mainly used in manufacture of steel.
- **Steam coal**: It is a type of coal whose properties fall in between anthracite and bituminous coals. It was once extensively used as a fuel in steam locomotives.
- **Anthracite**: It has a high carbon content of about 95 %. Also it has the highest heating value when compared to other types of coal. It is mainly used for commercial and residential space heating purpose.

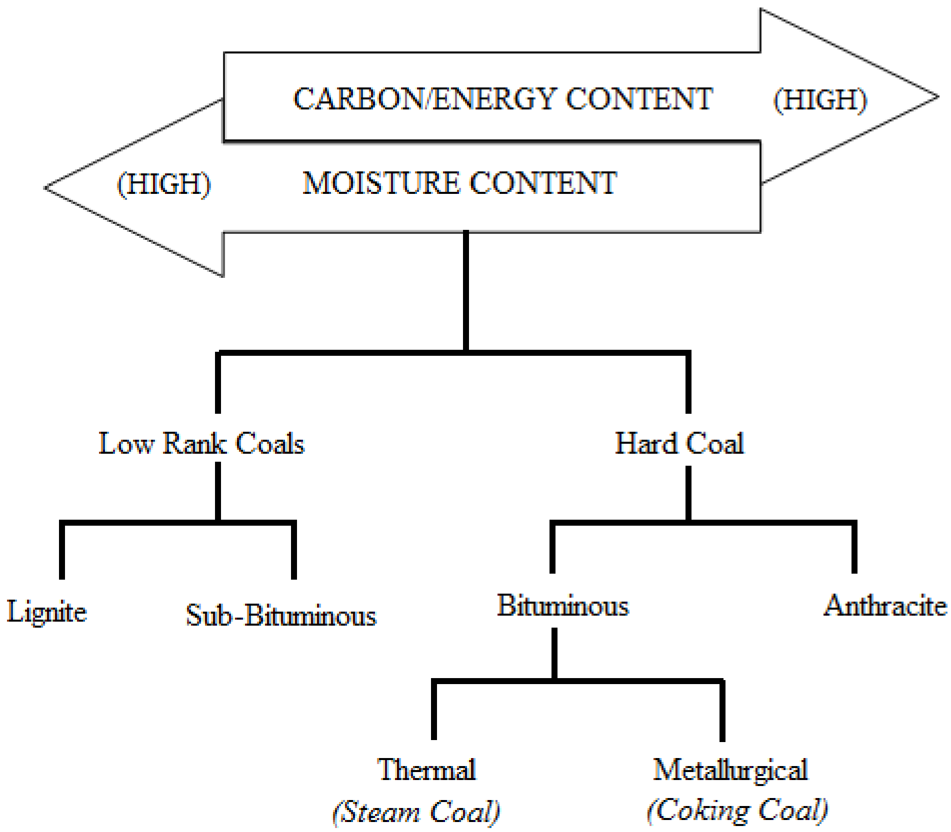

Fig. 1.1: Types of coal

From Fig. 1.1, it can be seen that the carbon content of different coals increases in the order of lignite < sub-bituminous < bituminous < anthracite. Also the moisture content of different coals decreases in the order of lignite > sub-bituminous > bituminous > anthracite.

1.3 COAL UTILIZATION

Coal has numerous vital uses globally. Most important applications of coal are in the field of power generation, cement industries, steel manufacturing and as a liquid fuel. Since 2000, the worldwide coal consumption has increased faster as compared to other fuels. The five largest coal users are USA, Russia, India, China and Japan who consume about 75 % of total coal reserves. Coal has a major share in power generation worldwide. Coal fired thermal power plants currently generate 42 % of global electricity. In India coal fired power plants contribute 68 % of total electricity generation.

In thermal power plants coal is first pulverized to a fine powder in bowl mills, as a result of which it's surface area increases and it further improves the combustion efficiency of coal. Then this pulverized coal is carried by hot air into the combustion chamber of a boiler where it is burnt at high temperatures. The combustion of coal produces tremendous heat energy that converts the feed water into high pressure and high temperature steam. This high pressure steam is then expanded in a turbine. As the steam glides over these blades, very high force is exerted on the blades due to change in momentum and this causes the turbine to rotate at very high speed. A generator is coupled at one end of the turbine shaft and it rotates at the same speed as that of turbine. The used steam is then condensed in condenser and cycle is repeated. Electricity is distributed through transmission lines for industrial and domestic use.

1.4 COAL-OIL MIXTURE TECHNOLOGY

The term "coal-oil" in general means any mixture of pulverized solid hydrocarbon, such as coal or lignite, in various hydrocarbons that are semi-liquid or liquid at ordinary atmospheric temperatures, such as petroleum fractions, furnace oil and heavy residues.

Coal-oil mixtures are prepared by homogeneously mixing pulverized coal in furnace oil, either in the presence of additives or without. A typical example of coal-oil mixture technology is shown in Fig. 1.2.

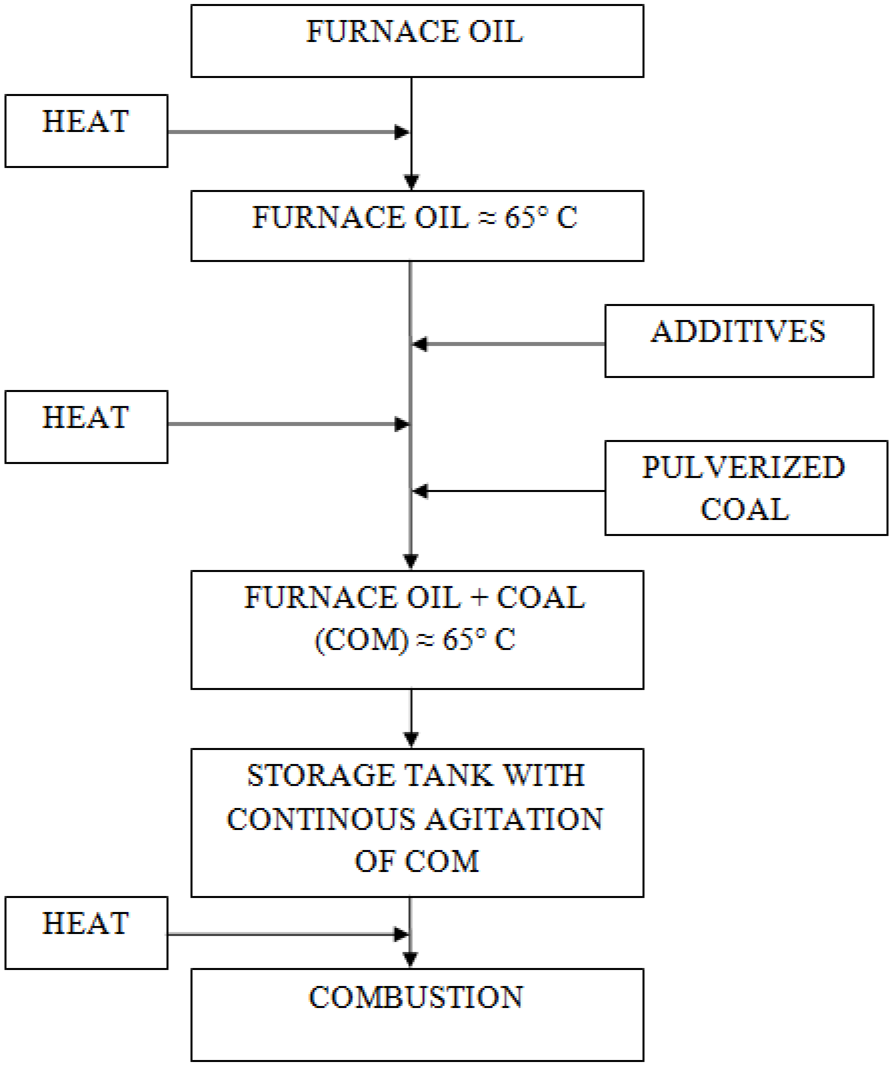

Fig. 1.2: Typical example of coal-oil mixture technology

Initially the furnace oil is heated to ≈ 65° C so that it can be brought to a flow able condition. Then the required additives are mixed to the furnace oil along with the required weight of coal in a mixing tank. The coal-oil mixture so prepared is then finally stored in a storage tank equipped with an agitator so that settling of coal particles can be avoided. The coal-oil mixture is heated during atomization and pumping before using it for combustion.

1.5 REQUIREMENT AND USES OF COAL-OIL MIXTURES

Requirements for coal-oil mixtures:

- Viscosity must be low to reduce pumping costs.
- Coal-oil mixture fuel must burn as pollution free as possible.
- Mixture must be stable for long periods.
- Problem of settling must not occur.
- Mixture must be non-abrasive and non- corroding.

Utilization areas for coal-oil mixtures:

- As an alternative fuel for oil fired boilers.
- As a fuel for industrial boilers.
- As a supplementary fuel in a coal fired boiler during peak load hours.
- As an alternative fuel in blast and utility furnaces.

1.6 TYPES OF FLUID

The flow behavior of any kind of fluid can be described as:

$$\tau = \tau_y + \dot{K}\,\gamma^{\dot{n}} \qquad (1.1)$$

When $\tau_y = 0$

- $\dot{n}<1$, the flow behavior of fluid is pseudo plastic
- $\dot{n}=1$, the flow behavior of fluid is Newtonian
- $\dot{n}>1$, the flow behavior of fluid is dilatant

When $\tau_y \neq 0$

- ṅ<1, the flow behavior of fluid is yielding pseudo plastic
- ṅ=1, the flow behavior of fluid is Bingham plastic
- ṅ>1, the flow behavior of fluid is dilatant plastic

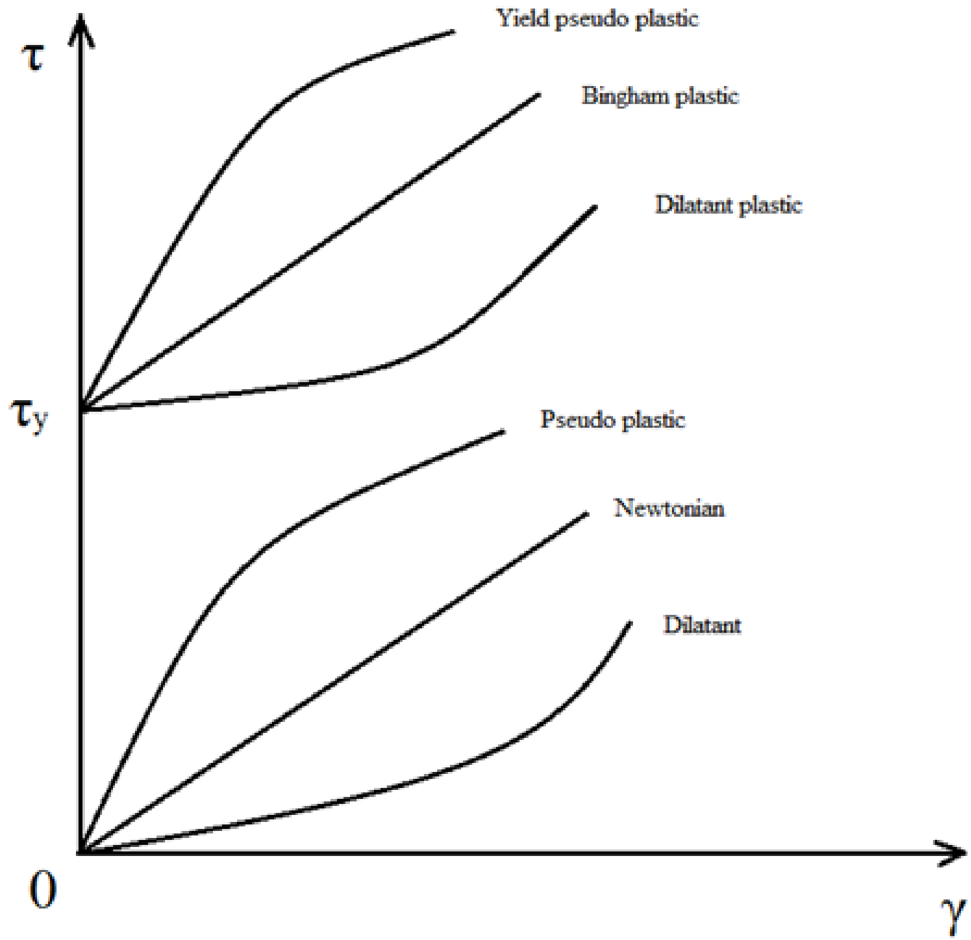

Fig. 1.3: Rheogram of different types of fluids

1.7 IMPORTANCE OF VISCOSITY MEASUREMENT

The viscosity of coal-oil mixture has a vital role regarding its combustion, transportation, atomization and storage. The viscosity of coal-oil mixture depends on coal and oil properties, and also on particle size distribution of coal.

The viscosity affects the overall pump ability of the fuel product. The viscosity of the fuel in the storage tank at a specified temperature should be such as to allow pumping at a rate to meet boiler output requirement. The storage temperature should be kept as low as possible consistent with pumping requirements to minimize settling. The viscosity just prior to injection has to be matched to the burner nozzle to allow adequate atomization of the fuel for efficient combustion.

Therefore, the rheological tests are performed to evaluate the viscosity profile so that while designing the transportation system for coal-oil mixtures, appropriate measures relating to the type of pump and input power, could be taken.

1.8 MOTIVATION FOR THE PRESENT STUDY

Viscosity of coal-oil mixture is one of the key factors which help in designing the transportation system (type of pump and input power) and design of the burner nozzle. At lower solids concentrations, coal-oil mixture behaves as a Newtonian fluid having constant viscosity. However, at higher solids concentrations, coal-oil mixture deviates from the Newtonian behavior and the viscosity is no more constant and changes with change in shear rates. Now if a transportation system is designed by keeping in view the Newtonian behavior of coal-oil mixture at lower solids concentrations, then this system might not work for higher solids concentrations because of change of viscosity. A similar phenomenon can occur with design of burner nozzle.

Therefore it becomes very vital to determine the rheological properties of coal-oil mixtures before designing burner nozzle and transportation system.

The present study was conducted for investigating rheological properties of coal-oil mixtures along with studying the effect of various key factors like solids concentration, temperature and coal properties on its rheology.

CHAPTER 2 LITERATURE REVIEW

A lot of research work has been done in the past to investigate the rheological behavior of coal-oil mixtures from different perspectives. Various factors that affect coal-oil mixture rheology have been investigated by researchers. However, a gap in study reveals that so far very limited work has been done on investigating rheological properties of coal-oil mixtures with variation in temperature and coal properties. In the present study, prior to the research work, an extensive review of the published works in the field of coal-oil mixture technology with an emphasis on the effects of different factors like solids concentration, temperature and coal properties, etc. that affects the rheological behaviour of coal-oil mixtures, were undertaken and a review of published works are presented in this chapter.

2.1 RHEOLOGY OF COAL-OIL MIXTURES

Castillo C et al. (1979) 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. Coal volume fraction was varied up to 0.6. Rheological measurements were made using Weissenberg Rheogoniometer R-17, which was operated in cone and plate mode and the temperature was kept constant at 20° ± 2°C by using a thermostat. They observed that the coal slurry exhibited Newtonian behavior at concentration less than 20 %. Furthermore there was no problem of settling as the density of the suspending media was close to that of coal. It was also observed that the viscosities were much higher in Aroclor as compared to glycerine.

Ghassemzadeh M.R et al. (1981) studied the rheological behavior of coal-oil mixtures. The solids concentration was varied from 30 - 50% by weight. Rheological measurements were made using Brookfield cone plate viscometer (model HB). The temperature was varied from 54° - 82° C and shear rate was varied from 2-385 s^{-1}. It was observed that coal-oil mixtures behaved as yield pseudo plastic fluids, i.e., the viscosity decreased as shear rate increased. It was observed that in the concentration range of 30–40% by weight, the coal-oil mixtures behaved as a Newtonian fluid. Also yield stress was observed for mixtures having coal concentration above 40 %. They also found that viscosity of coal-oil mixture increased, as coal concentration was increased. Also viscosity decreased, when temperature was increased.

Adiga K.C et al. (1983) studied rheological behavior of coal mixtures in no.2 fuel oil and ethanol with varying concentrations of water at ambient temperature. Rheological measurements were made using Brookfield cone plate viscometer. For calculation of viscosity the shear rate was varied from 1.15 - 230 s^{-1}. It was found that in the presence of water the mixtures had a tendency for incursion of yield stress and it was also observed that the presence of water increased the viscosity of the mixtures. For low coal concentration mixtures, it was observed that when the concentration of water increased, both viscosity and yield stress of mixture increased. The rheological parameters were calculated using the power law and Bingham plastic models. The mixtures behaved as dilatant, Newtonian or pseudoplastic, depending upon the concentration of water, at lower shear rates. At higher shear rates the mixtures depicted pseudoplastic behavior. It was also observed that mixtures having higher coal concentrations behaved as pseudoplastic fluid for every water concentration. At 10 % of water concentration, both viscosity and yield stress depicted a maximum value.

Papachristodoulou G et al. (1984) investigated the rheological properties of coal-oil mixtures. The coal-oil mixtures were prepared using bituminous coal in different grades of oil. These grades were grade 2, grade 4, light grade 6 and heavy grade 6. The coal concentration was varied from 0 - 60% by weight and temperature was varied from 25°C - 90°C. The rheological experimentation was done with 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, it was observed that as the particle size of coal particles got higher, the viscosity and the yield stress decreased and this decrease was more noticeable at higher concentrations. Also the yield stress increased, when coal concentration was increased.

Wildemuth C.R et al. (1985) examined the rheological behaviour of coal suspension in non aqueous media. Glycerin, bromonapthalene, and Aroclor were chosen as three suspending fluids. The Particle size distribution was obtained by Leeds and Northrup Microtrac Analyser. Rheological measurements were made using Weissenberg Rheogoniometer R-17, which was operated in cone and plate mode. Shear rate range varied from 10^{-3}- 10^{2} s^{-1} and coal volume fractions were varied up to 0.46. 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 sub-bituminous coal. Rheological tests were conducted using Brookfield viscometer with particle size varying from 0.044 mm to 0.223 mm. They observed that at all concentrations, the coal water slurry showed pseudoplastic behaviour. The data was fitted to the Power law model 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.

Adiga K.C et al. (1988) studied rheological behavior of coal mixtures in no.2 fuel oil and ethanol with varying concentrations of water at ambient temperature in the presence of surfactant. The surfactant used was TRS10-80 (petroleum sulfonate). Rheological measurements were made using Brookfield cone plate viscometer. For calculation of viscosity the shear rate was varied from 1.15 - 230 s^{-1}. It was found that in the presence of water the mixtures had a tendency for incursion of yield stress and maximum value of yield stress was found at 10 % water concentration. It was also observed that when surfactant was added to mixture there was a significant reduction in yield stress. The rheological parameters were calculated using the power law and Bingham plastic models. It was also observed that when concentration of surfactant was 0.25 %, the flow behavior of mixtures changed from yield pseudo plastic to Newtonian.

Reddy G.V et al. (1994) investigated the rheological behavior 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. Rheological measurements were made using Brookfield synchroectric viscometer (Model RVT). The coal loading in coal oil mixture was varied from 25-45 % by volume and the temperature was varied from 30°C - 45°C. It was 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 impacts of coal 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 measurements 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.

Vitolo S et al. (1995) studied the influence of adding petroleum coke on the rheological properties of coal water mixtures. Two types of coal were used and 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 measurements were made using HAAKE RV2 rotational viscometer. They found 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.

Skarvelakis C et al. (1996) examined the rheological properties of coal-water-fuel oil mixture. The rheological properties were measured with the help of tube viscometer having tube diameter of 12.6 mm. Shear rate was varied from 30 – 1000 s^{-1}. Temperature was kept constant at 20° C. It was also observed that fluid consistency coefficient K decreased as water concentration was increased. Furthermore as coal concentration increased, the value of fluid consistency coefficient K increased.

Fu X et al. (1996) examined the rheological properties of coal-water-light oil mixture. The coal used had a size less than 20 µm. The particle size distribution was calculated with the help of laser diffraction apparatus. The rheological measurements were made by using co-axial cylindrical viscometer. Temperature was kept constant at 25° C. It was observed that when water to oil ratio was decreased, the viscosity of the mixture increased sharply. The apparent viscosity of the mixture increased with increasing coal concentration. It was also observed that with the increase in coal concentration, the yield stress of mixture increased.

Guo D et al. (1997) examined the rheological properties of coal-water-heavy oil mixture. The rheological properties were measured with the help of a co-axial cylindrical viscometer (NXS-11). Temperature was kept constant at 25° C. It was observed that when water to oil ratio was decreased, the viscosity of the mixture increased sharply. It was found that with increase in dispersant content, the viscosity first decreased, then reached a minimum value at dispersant concentration of 0.50 % and further increased with enhancement in dispersant concentration. The viscosity of the slurry increased with increase in coal and oil concentration, which altered the slurry behavior from Newtonian to Bingham plastic fluid. It was also observed that with the increase in coal and oil concentration, the yield stress of mixture increased.

Guo D et al. (1998) examined the rheological properties of coal-water-residual oil triplex synfuel. The ratio of the components oil (O) to coal (C) to water (W) by weight was O:C:W = 4:2:4 for water-based synfuel, and O:C:W = 5:2:3 for oil-based synfuel. The rheological properties were measured with the help of a coaxial cylindrical viscometer (NXS-11). Temperature was kept constant at 25° C. It was found that the rheological behaviour of water-based synfuel followed the Herschel–Bulkley model, whereas that of oil-based synfuel followed the Bingham model. An investigation of temperature dependence of their viscosities showed that the viscosity–temperature characteristic of both synfuels followed Arrhenius equation at fixed shear rates.

Guo D et al. (1998) examined the rheological properties of oil based multiphase slurries consisting of coal-water-heavy oil. The impact of various factors like dispersant concentration and temperature on its rheological behavior was examined. The rheological properties were measured with the help of a coaxial cylindrical viscometer (NXS-11). Temperature was kept constant at 25° C. The rheological behavior of multiphase slurry was described by Herschel-Bulkley model. It was observed that the synfuel depicted pseudo plastic behavior with decrease in apparent viscosity as shear rate was increased. Also the apparent viscosity of synfuel decreased with increase in temperature. Furthermore the apparent viscosity of synfuel decreased with enhancement of dispersant concentration and this decrease in apparent viscosity was more sharp at low shear rates as compared to high shear rates.

Mishra S.K et al. (2002) observed the rheological properties of coal-water slurry made from Indian coal. The impact of various factors like temperature, pH, ash content, and solid concentration on the rheology of coal-water slurry was evaluated. Rheological measurements were made using HAAKE rotational viscometer RV30. A thermostatic temperature bath was used to maintain the temperature within the accuracy of ±0.1°C. They found that the coal water slurry exhibited pseudoplastic behaviour with decrease in apparent viscosity with an increasing shear rates. The apparent viscosity increased as the ash content of coal increased and decreased, as pH value was increased.

Nik W.B et al. (2005) examined the rheological properties of different bio-edible oils which included palm, coconut, canola, corn and sunflower oils. The rheological properties were measured with the help of a Brookfield rotational type viscometer. The temperature was varied from 40° C - 100° C and shear rate was varied from 3 - 100 rpm. Numerous rheological models such as Arrhenius, Carreau, Ostwald de-Waele and Herschel–Bulkley were used to determine the flow behavior of oils. It was found that both shear rate and temperature had a considerable effect on the variation of viscosity and it was also observed that temperature had more significant impact as compared to shear rate. Results from rheological model fit indicated that the bio-edible oils belonged to pseudo plastic category. Also the palm and sunflower oils were highly stable in terms of shear rate and temperature, respectively.

Shukla S.C et al. (2008) investigated the rheological properties of coal-water-oil mixtures having coal particles of different sizes. Three different particle sizes of 108 µm, 75.7 µm and 62.9 µm were used. The rheological properties were measured with the help of coaxial cylindrical viscometer. The solids concentration was varied from 10 -50 % by weight and shear rate was varied from 100 – 2500 rpm. Temperature was kept constant at 30° C. It was found that depending on the concentration of oil and water, the mixtures behaved as pseudo plastic, dilatants or Newtonian type of fluid. Also a general correlation was developed for the prediction of apparent viscosity of coal-water-oil mixtures. The different parameters that were incorporated in the correlation included particle diameter, coal concentration, torque and oil concentration. It was observed that the experimental data was in good agreement with the correlation.

Yong-gang W et al. (2009) investigated the rheological properties of Shengli lignite coal-solvent slurries. Three different types of solvent hydrogenated recycle solvent (REC), heavy oil (HAR) and tetralin (THN) were used in the study. The effect of various parameters like temperature, shear rate, particle diameter, coal to solvent ratio and type of solvent was studied. Rheological properties were measured with the help of a rotary viscometer (NXS-11A). Shear rate was varied from 0 – 1000 s^{-1} and temperature was varied from 30° C - 70° C. It was found that with the increase in temperature the behavior of coal-solvent slurries altered from pseudo plastic fluid to Newtonian fluid. It was also observed that when coal to solvent ratio was increased the behavior of coal-solvent slurries altered from Newtonian fluid to pseudo plastic fluid. These transformations occurred at 40° C, when REC was used as solvent and at 60° C, when HAR was used as solvent.

Li W et al. (2010) studied the impacts of adding sewage sludge on the rheological behavior of coal sludge slurry that consisted of coal, water and sewage sludge. The rheological properties were measured with the help of rotary type rheometer (model: Malvern Bohlin CVO). Shear rate was varied from 5 – 180 s^{-1}. Temperature was kept constant at 25° C. The rheological behavior and yield stress of the coal sludge slurry was examined and results were compared with coal water slurry. It was observed that the coal sludge slurry showed an incursion of yield stress when shear rate was varied from 5 – 10 s^{-1}. Naphthalene sodium formaldehyde was chosen as dispersant. It was observed that the yield stress of coal sludge slurry reached up to 23 Pa, when sludge to coal ratio was 1: 10. Rheological models were used for investigating the flow behavior of the coal sludge slurry. It was observed that the coal sludge slurry behaved as a shear thinning fluid having decrease in viscosity with increasing shear rates.

Anderson M. P et al. (2011) examined the rheological properties of alcohol-water char and bio char slurry fuels. The rheological properties were measured with the help of a Haake VT550 cone-and-plate viscometer. The slurries were prepared by mixing lignite in aqueous solution of ethanol. The concentration of ethanol in the slurries varied from 5 – 50 % by weight. Rheological models were used for investigating the flow behavior of slurries. It was observed that the slurries with high solids concentration exhibited dilatant behavior and the slurries with low solids concentration exhibited Newtonian behavior. An anionic dispersant D-102 was chosen to study its effect on the rheological behavior of the slurries prepared at 10 % and 50 % ethanol concentrations. It was found that even in the presence of ethanol, the dispersant was very helpful in increasing the solids concentration of the slurries, without having a considerable effect on its viscosity. It was also observed that by the addition of dispersant the stability of the slurries improved considerably. However it was found that the addition of dispersant had a very less effect at high ethanol concentrations.

He Q et al. (2011) studied the impact of particle size distribution of petroleum coke on the various properties like static stability, apparent viscosity and rheology of petroleum coke oil slurry. The rheological measurements were made by using a rotary viscometer (NXS-11A). Shear rate was varied from 0 – 100 s^{-1}. Temperature was kept constant at 100° C. Scanning electron microscopy and zeta potential techniques were applied for studying the size and morphological characteristics of coal particles with variation in grinding time. It was observed that coal concentration of 30 % – 35 % by weight and grinding time of about 1 hour were suitable for the petroleum coke oil slurry. Rheological models were used for investigating the flow behavior of the slurry and it was observed that the slurry exhibited pseudo plastic behavior having decrease in viscosity with increase in shear rate.

Chen R et al. (2011) investigated the rheological behavior of lignite char, bio-char and coal slurry fuels. Different solids like biomass char, sub-bituminous coals and a low rank coal were used for the preparation of slurries. These solids in pulverized form were mixed with water along with different additives which included polyacrylic acid, sucrose and co-polymers D-101 and D-102. The rheological properties of the slurries were measured by using Brookfield viscometer. HAAKE VT 550 cone and plate viscometer was also employed for measuring the rheological properties of the slurries at constant shear rates. The effect of various properties like particle size distribution, solids concentration, additives concentration and type of solid on rheological behavior of slurries was determined in terms of yield stress and apparent viscosity. It was observed that high concentration slurries with relatively lower values of yield stress and apparent viscosity could be prepared when additives D-101 and D-102 were used. Rheological models were used for investigating the flow behavior of the slurries and it was observed that the slurries made from low ash lignite, in the presence of these additives exhibited Newtonian and mild dilatant behavior at higher solids concentrations. It was also observed that the maximum solids concentration that can be used without having a considerable increase in apparent viscosity was found to be 40 % for biomass char, 55 - 62 % for sub-bituminous coals and 65 % for lignite coal.

Ren Y et al. (2011) studied the viscosity variations of coal-oil slurry (COSL) under high temperature and high pressure during heating process. Three kinds of coal, which were Yanzhou coal (middle rank and caking), Shenhua coal (low rank and non-caking) and Shengli coal (brown coal), were mixed with anthracene oil to prepare the COSL. The rheological properties were measured with the help of a rotary viscometer.The COSL from Yanzhou, Shenhua and Shengli at the same experimental conditions showed different viscosity variations under high hydrogen pressure during heating. Yanzhou COSL had a higher viscosity peak, while Shenhua COSL had two small viscosity peaks and in the case of Shengli COSL, no viscosity peak was present under a high hydrogen pressure during the whole heating process. It was found that the coal nature was an important factor for viscosity variations of COSL. It was observed that higher was the coal rank, the more caking coal was present, and more were the viscosity variations of the COSL.

Tangsathitkulchai C et al. (2012) investigated the rheological behavior of slurries of char and bio-oil. Three bio-oil samples, namely, raw bio-oil from pyrolysis of cassava pulp residue (CPR), separated oil phase and aqueous phase of bio-oil from pyrolysis of palm shell (PS), were used as suspending media for preparing slurries of bio-oil and the co-product char. The rheological properties were measured with the help of a Haake VT550 concentric cylinder viscometer. Shear rate was varied from 0.712 – 690 s^{-1} and temperature was varied from 15° C - 45° C. Rheologies of all tested slurries exhibited pseudoplasticity with yield stress and the degree of this non-Newtonian behavior depended on parameters such as slurry type, solid concentration, particle size and slurry temperature. Also wider size distribution or larger mean size of char particles gave higher shear stress and apparent viscosity at a given shear rate, but showed a decrease of yield stress and consistency index. It was observed that there was a tendency for both shear stress and slurry viscosity to decrease with increase in slurry temperature.

Wang R et al. (2012) investigated the rheological behavior of petroleum coke–sludge slurry (PCSS). The various properties of PCSS like slurryability, rheology, stability and fluidity were analyzed. The rheological properties were measured with the help of a rotational concentric cylinder viscometer (NXS-4C). Measurements were done at temperature of 20° ± 1°C. The results showed that the fixed-viscosity solid concentration (SC_{fv}) decreased obviously with increasing the sludge mixing proportion (SMP). The flow behavior of slurry was changed from shear-thickening to shear-thinning after adding petrochemical sludge, and the pseudoplastic behavior was enhanced with increasing either the solid content or SMP. The rheological characteristics fitted perfectly the Herschel–Bulkley model (R^2>0.998). Moreover, the sludge produced a significant effect to improve slurry stability.

Shao S et al. (2012) studied the rheological and stability properties of coal alcohol fermentation wastewater slurries. The rheological properties were measured with the help of a rotary viscometer (NXS-4C). Measurements were done at temperature of 25° ± 1°C. Shear rate was varied from 0 – 100 s^{-1}. Coal slurries with solid concentrations ranging from 45 to 65 wt% were prepared. The results showed that both coal maize and cassava alcohol fermentation wastewater slurries exhibited shear-thinning behavior. Also because of the oxygen-containing functional groups (carboxylic) with exchangeable cations in alcohol fermentation wastewater and its low pH value, coal maize and cassava alcohol fermentation wastewater slurries exhibited the higher apparent viscosities, the stronger shear-thinning behavior, and worse stabilities as compared with the coal water slurry.

Jianzhong L et al. (2014) investigated the rheological behavior of coal–wasteliquid slurry (CWLS). Three coal slurry samples were prepared using tap water, wasteliquid A, and wasteliquid B, and their respective names were CWS, CWLS-A, and CWLS-B, respectively. The coal used was bituminite. The rheological behavior of the coal slurry was examined with the help of a rotational viscometer (HAAKE VT 550). Rheological measurements were carried out at a constant temperature of 20° ±0.5° C. Shear rate was varied from 0 – 100 s^{-1}. CWLS had a relatively low viscosity of 278 and 221 mPa-s and depicted shear thinning pseudo plastic behavior without the use of any additive agent. In contrast, CWS required the use of an additive agent to achieve good fluidity, and its viscosity was 309 mPa-s. The maximum flame temperature of the two CWLSs (CWLS-A and CWLS-B) was 1309.0 and 1303.1°C, respectively, and their respective combustion efficiencies were 99.61 % and 99.42 %. The values of both these parameters were greater than those obtained in the case of CWS.

Xu M et al. (2014) investigated the rheological behavior of coal–oily-sludge slurry (COSS). Sodium sulfonate formaldehyde condensate (NSF) was used as a dispersant at a fixed ratio of 0.8 g/ 100 g dry fuel (oil and coal) in the preparation of COSS. The rheological properties were measured with the help of Malvern Bohlin CVO rheometer. Measurements were done at temperature of 25° ± 0.1°C. Shear rate was varied from 0 – 100 s^{-1}. The results showed that apparent viscosity of COSS decreases with increasing the ratio of oily sludge when oily sludge was firstly mixed with coal. As more oily sludge was added, the yield stress of COSS gradually decreased. The maximum solids loading of COSS increased from 62.2 wt% to 64.0 wt% when oily sludge was added in a ratio of 10.0 wt%.

CHAPTER 3 CHARACTERISATION OF COAL SAMPLES

Three different Indian coals in pulverized form, each varying in ash and moisture contents, were collected from different thermal power plants of Punjab. Throughout this thesis, the three coal samples are labeled as S-I, S-II and S-III, and they were collected from Bathinda thermal plant, Lehra Mohabat thermal plant and Ropar thermal plant, respectively. The various characterization studies that were done on the three coal samples included scanning electron microscopy (SEM) analysis, energy dispersive x-ray spectroscopy (EDS) analysis and proximate analysis. Also particle size distribution curves were generated for three coal samples in order to find the mass median diameter of coal samples. At the last, particle size distribution data was fitted into the well known Rosin-Rammler mathematical model for calculating the distribution modulus (n) for all the three coal samples.

3.1 SCANNING ELECTRON MICROSCOPY (SEM) ANALYSIS

The morphological and topographical studies on coal samples were done with the help of Scanning Electron Microscopy (SEM) technique. This technique is very powerful and can record images even at the nanometer scale. In this technique a high energy beam of electrons is made incident on the sample to be analyzed. These energetic electrons then interact with the atoms of the sample and produce different signals that are detected by the sensors. The equipment used was SEM-JSM-6510LV JEOL. The SEM images that were obtained for three different coal samples are shown in Fig. 3.1 - 3.6.

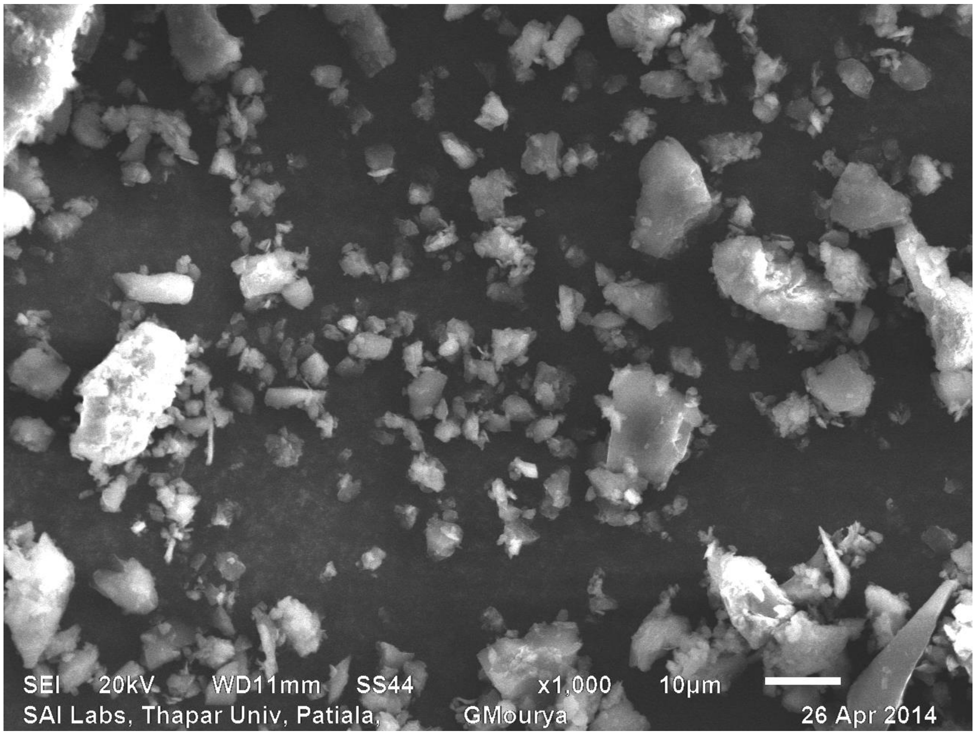

Fig. 3.1: SEM image of S-I coal sample at X1000

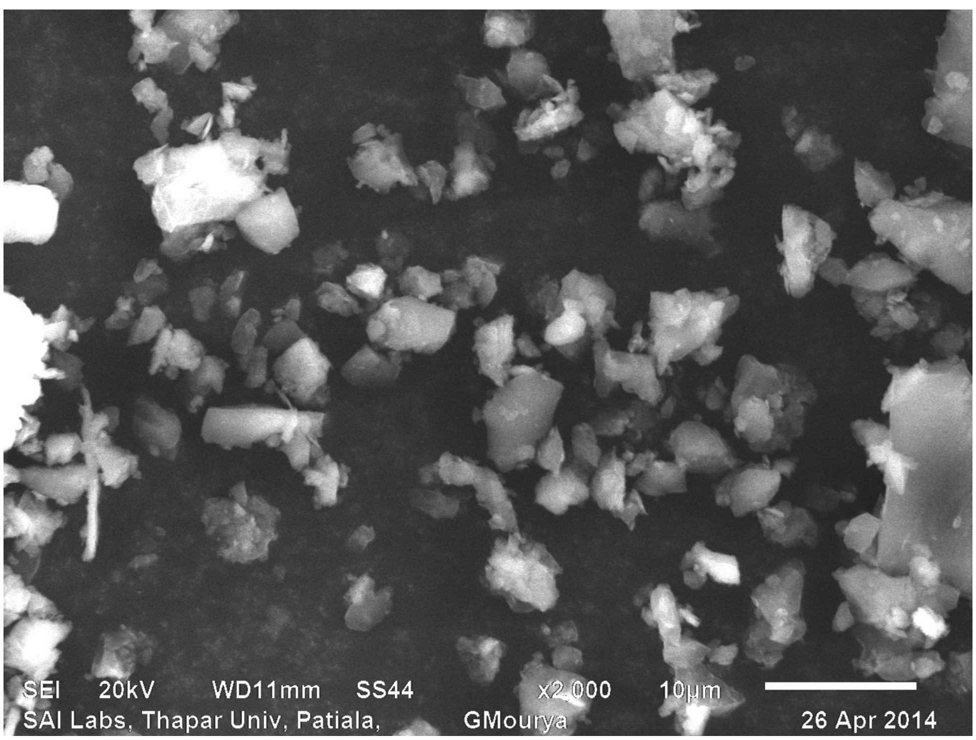

Fig. 3.2: SEM image of S-I coal sample at X2000

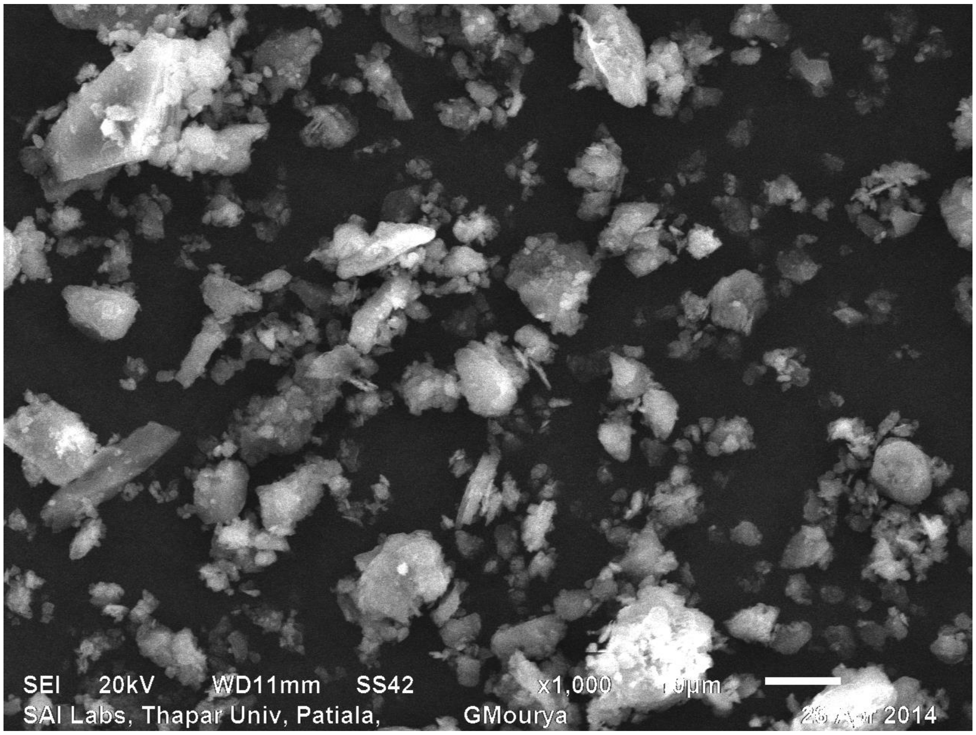

Fig. 3.3: SEM image of S-II coal sample at X1000

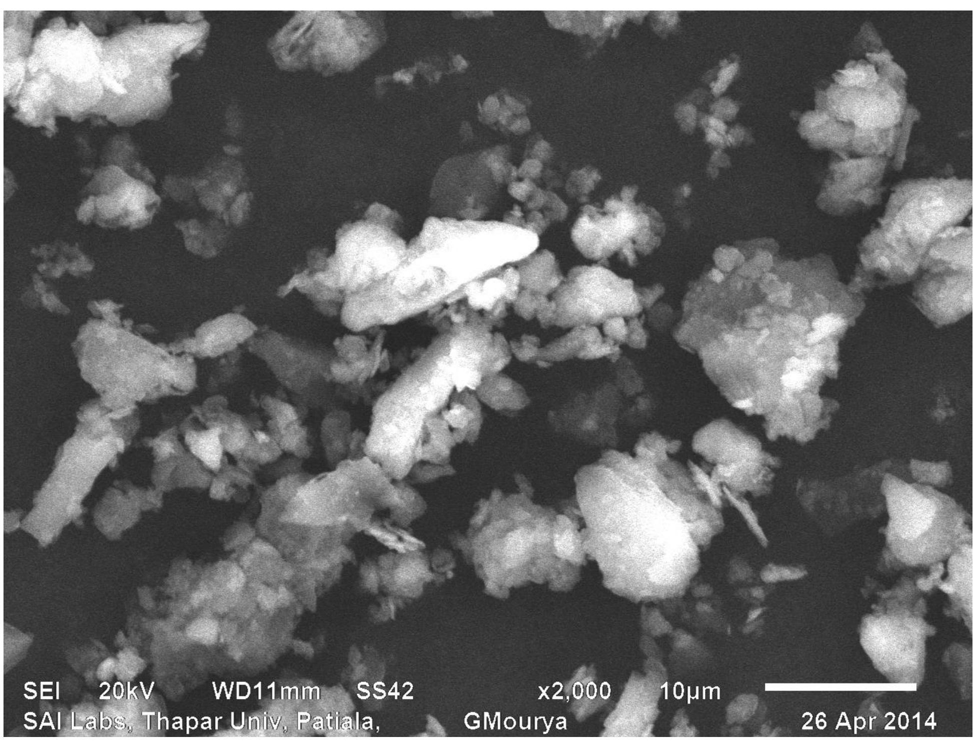

Fig. 3.4: SEM image of S-II coal sample at X2000

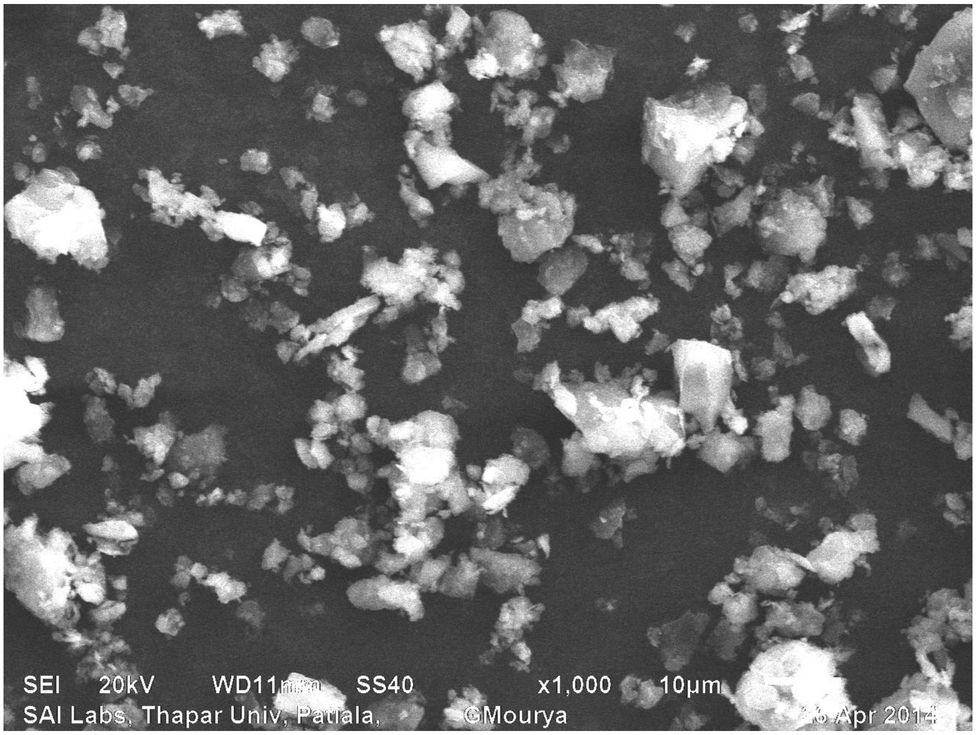

Fig. 3.5: SEM image of S-III coal sample at X1000

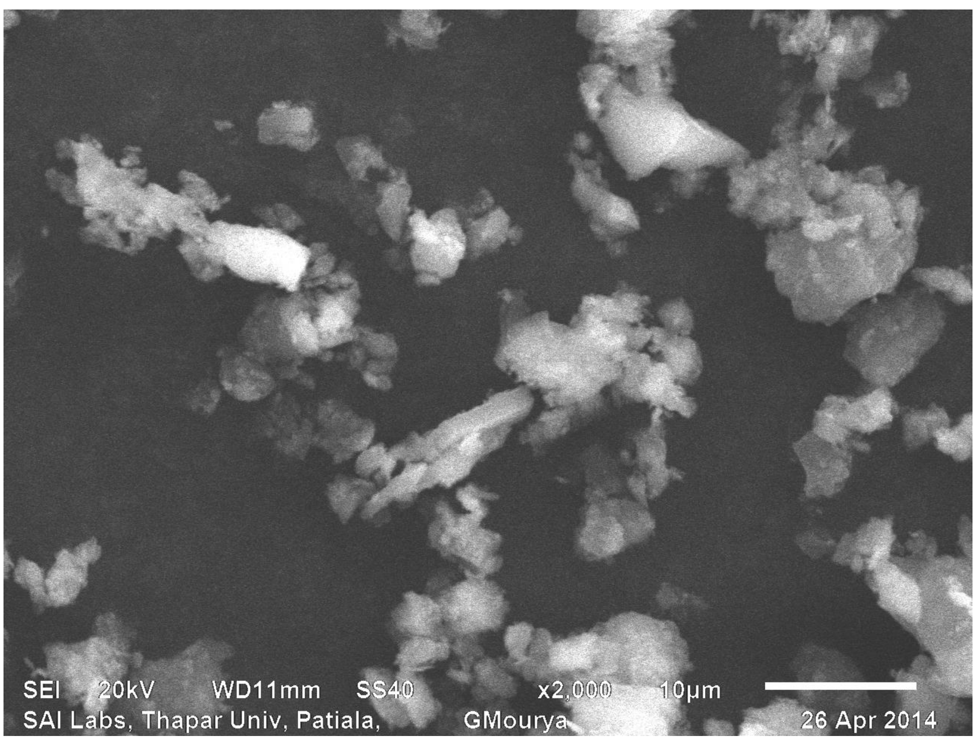

Fig. 3.6: SEM image of S-III coal sample at X2000

The observations from the SEM analysis 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 three coal samples. The coal sample S-II contained more fine particles than any other coal sample which was confirmed by the mass median diameter of 165 µm for coal sample S-II which was the lowest of the three coal samples. The micrographs of coal samples S-I and S-III depicted a mixture of coarse and fine particles.

3.2 ENERGY DISPERSIVE X-RAY SPECTROSCOPY (EDS) ANALYSIS

Energy dispersive x-ray spectroscopy is a nondestructive micro analytical technique which is used to calculate the composition of elements in a sample. Most often the EDS system is used in conjugation with scanning electron microscope (SEM). Initially an electron beam is made incident on the sample with the help of scanning electron microscope. This high energy incident beam of electrons then interacts with the atoms of the sample. The incident beam knocks out the electrons from the inner shells of an atom. Now, when an electron is knocked out from the inner shell, an empty hole is created in its original place. The electron from outer shell will now try to fill this empty hole and hence it jumps from outer high energy shell to inner low energy shell. This difference of energy between outer high energy shell and inner low energy shell is emitted in the form of x-ray. The emitted x-rays from atoms of the sample are unique in wavelength and energy to the element of parent atom from which they were emitted and hence this fact helps in finding out the composition of different elements in the sample. EDS spectrum is a graph having x-ray counts along ordinate and corresponding energy (in keV) along abscissa. The EDS spectrums that were obtained for three different coal samples are shown in Fig. 3.7 - 3.9.

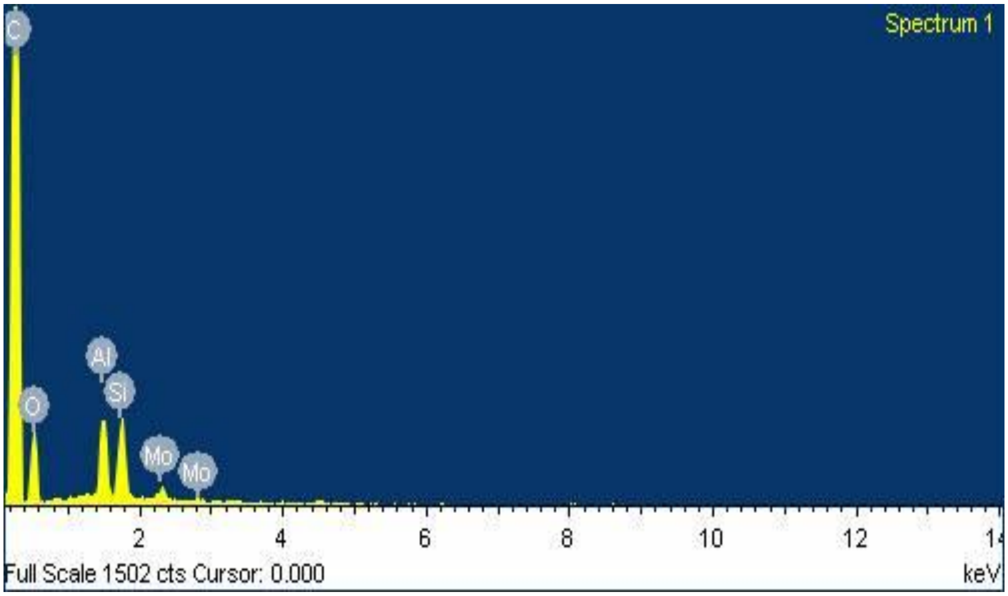

Fig. 3.7: EDS spectrum of S-I coal sample

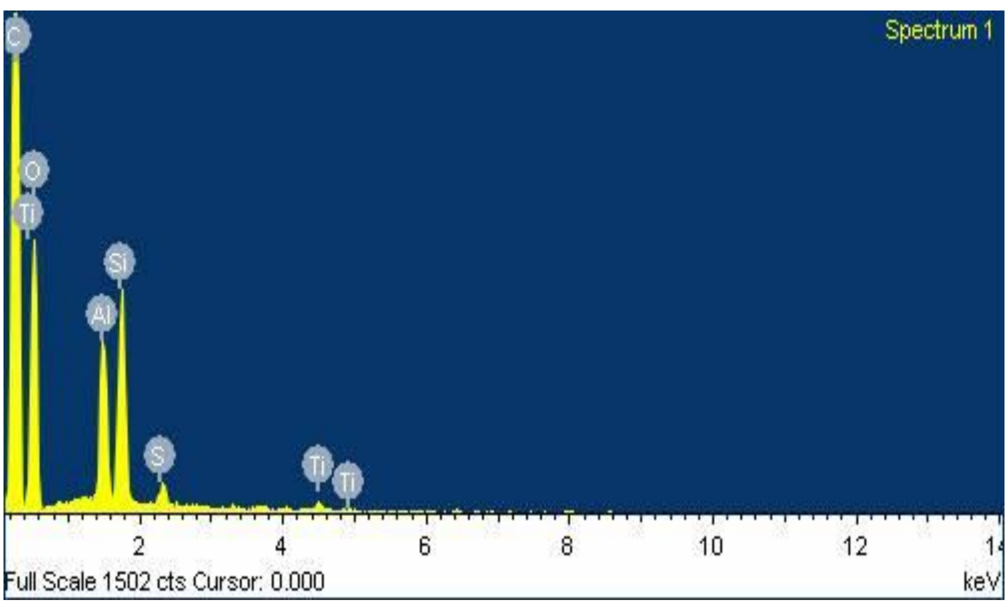

Fig. 3.8: EDS spectrum of S-II coal sample

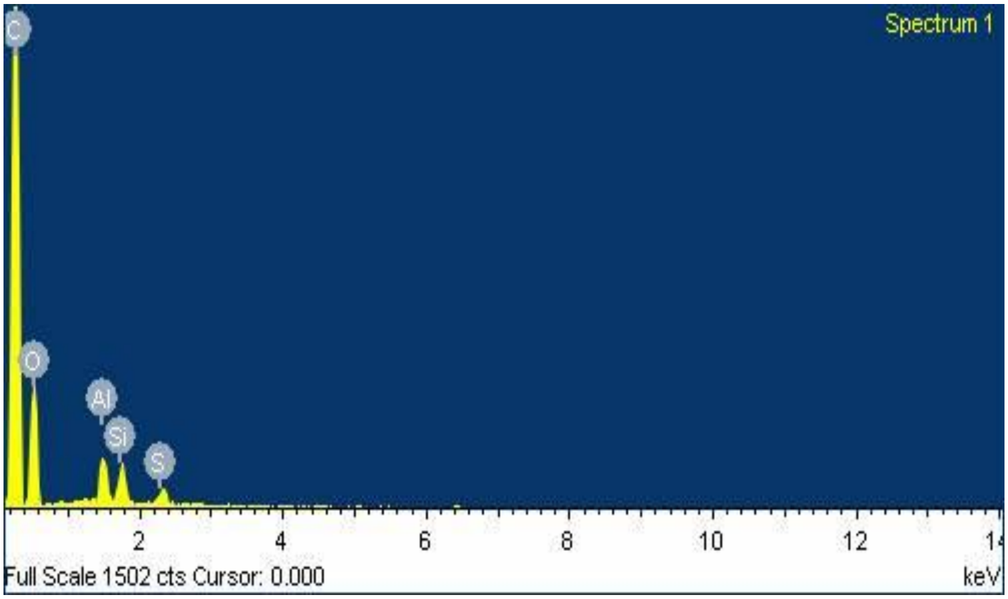

Fig. 3.9: EDS spectrum of S-III coal sample

From the Fig. 3.7 – 3.9, it was found that for all the three coal samples, the peaks in the EDS spectrum were corresponding to the elements Carbon and Oxygen. This indicated that in all the three coal samples, Carbon and Oxygen were present in major proportions. Apart from Carbon and Oxygen, the other elements those were present included Aluminum, Silicon, Sulphur and traces of Titanium and Molybdenum.

The composition of various elements in three coal samples is shown in Table 3.1-3.3.

Table 3.1: Composition of elements for coal sample S-I

Element	Weight %	Atomic %
Carbon(C)	78.76	84.57
Oxygen(O)	17.08	13.77
Aluminum(Al)	1.58	0.76
Silicon(Si)	1.70	0.78
Molybdenum(Mo)	0.88	0.12

Table 3.2: Composition of elements for coal sample S-II

Element	Weight %	Atomic %
Carbon(C)	61.78	69.69
Oxygen(O)	32.63	27.63
Aluminum(Al)	2.09	1.05
Silicon(Si)	2.93	1.41
Sulphur(S)	0.36	0.15
Titanium(Ti)	0.21	0.06

Table 3.3: Composition of elements for coal sample S-III

Element	Weight %	Atomic %
Carbon(C)	69.34	75.71
Oxygen(O)	28.29	23.19
Aluminum(Al)	1.03	0.50
Silicon(Si)	0.93	0.43
Sulphur(S)	0.41	0.17

From the Tables 3.1 - 3.3, it was found that in all the three coal samples, Carbon and Oxygen were present in major proportions. Apart from Carbon and Oxygen, the other elements those were present in minor proportions included Aluminum, Silicon, Sulphur and traces of Titanium and Molybdenum.

3.3 PROXIMATE ANALYSIS OF COAL SAMPLES

The proximate analysis of coal was performed to determine the percentages of ash, inherent moisture, fixed carbon and volatile matter present in a particular sample. The proximate analysis of the three coal samples was conducted as per the prescribed testing method of IS: 1350 and the results of the proximate analysis are shown in Table 3.4.

Table 3.4: Proximate analysis of coal samples

Parameters	S-I	S-II	S-III
Moisture %	0.52	8.22	7.23
Ash %	41.74	26.25	27.99
Volatile Matter %	16.60	23.24	27.65
Fixed Carbon %	41.14	37.29	37.13

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

3.4 PARTICLE SIZE DISTRIBUTION OF COAL SAMPLES

Particle size distribution was performed for all three coal samples in order to know the variations in particle size among three coal samples and also to calculate the percentage of particles that were present in different size ranges. Particle size distribution was calculated by the method of sieve analysis. The values of percentage finer corresponding to different particle size ranges were calculated using the standard procedure. This data was further used to create the particle size distribution curves.

The particle size distribution (PSD) curves of the three coal samples S-I, S-II and S-III are shown in Fig. 3.10.

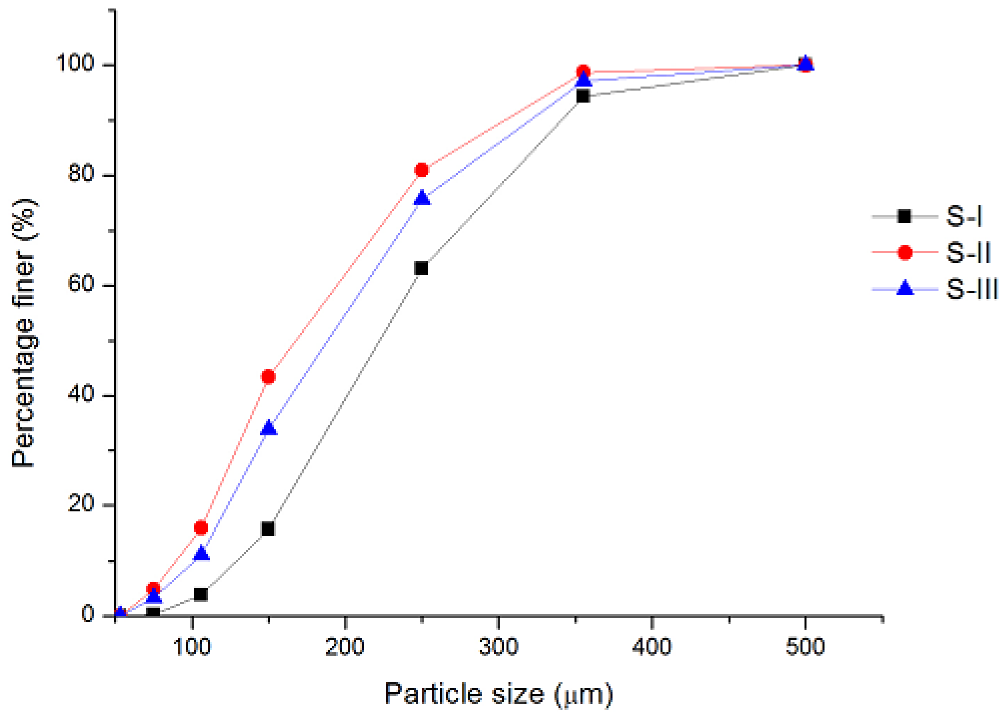

Fig. 3.10: Particle size distribution of coal samples

The mass median diameters (d_{50}) of the three coal samples were calculated from the PSD curves and are shown in Table 3.5.

Table 3.5: Mass median diameter of coal samples

Coal Sample	S-I	S-II	S-III
d_{50} (μm)	220	165	185

3.5 ROSIN-RAMMLER MATHEMATICAL MODEL

Rosin-Rammler model is a mathematical model which describes the particle size distribution of finely ground powders. The Rosin-Rammler distribution is expressed as:

$$R = 100 \exp\left[-\left(\frac{\emptyset}{K}\right)^{n}\right] \tag{3.1}$$

Where R = cumulative mass % retained on mesh size ∅

K = size modulus, and

n = distribution modulus

Rearranging and taking double logarithm of Eq. (3.1) gives:

$$ln\left(ln\left[\frac{100}{R}\right]\right) = nln\emptyset + CONSTANT \tag{3.2}$$

A plot of $ln\left(ln\left[\frac{100}{R}\right]\right)$ versus $ln\emptyset$ gives a straight line. The Rosin-Rammler model parameters i.e. n (distribution modulus) and K (size modulus) were calculated using linear Regression analysis of Eq. (3.2). The values of the distribution modulus (n) for the three coal samples are given in Table 3.6.

Table 3.6: Distribution modulus of coal samples

Coal sample	n
S-I	0.293
S-II	0.399
S-III	0.349

It was found that coal sample S-II was the narrowest of the three coal samples as its value of distribution modulus was the highest and S-I as the broadest coal sample with the least value of distribution modulus.

The RR model fit for the three coal samples is shown in Fig. 3.11-3.13.

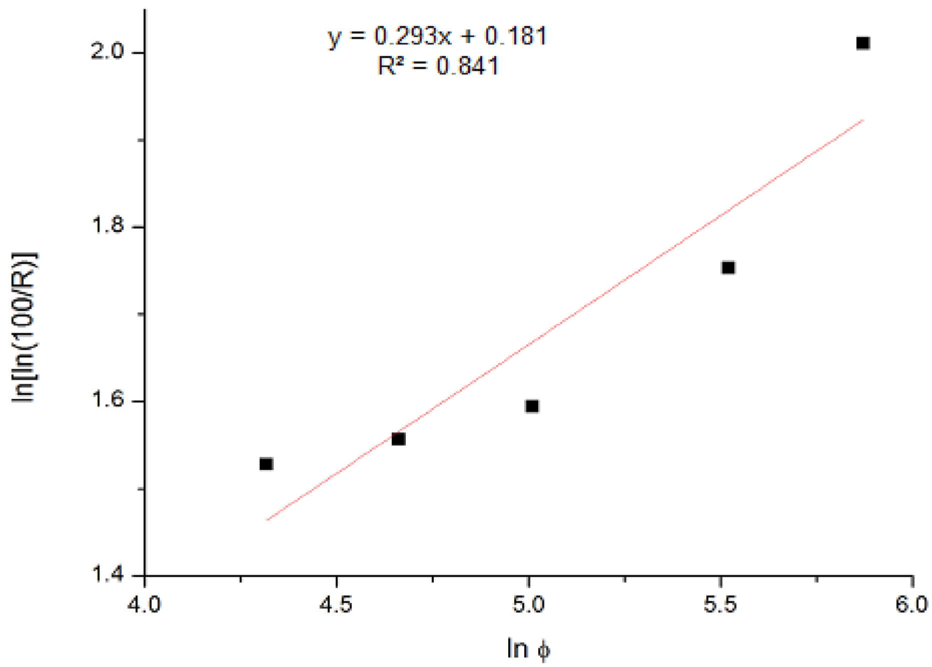

Fig. 3.11: RR model fit of S-I coal sample

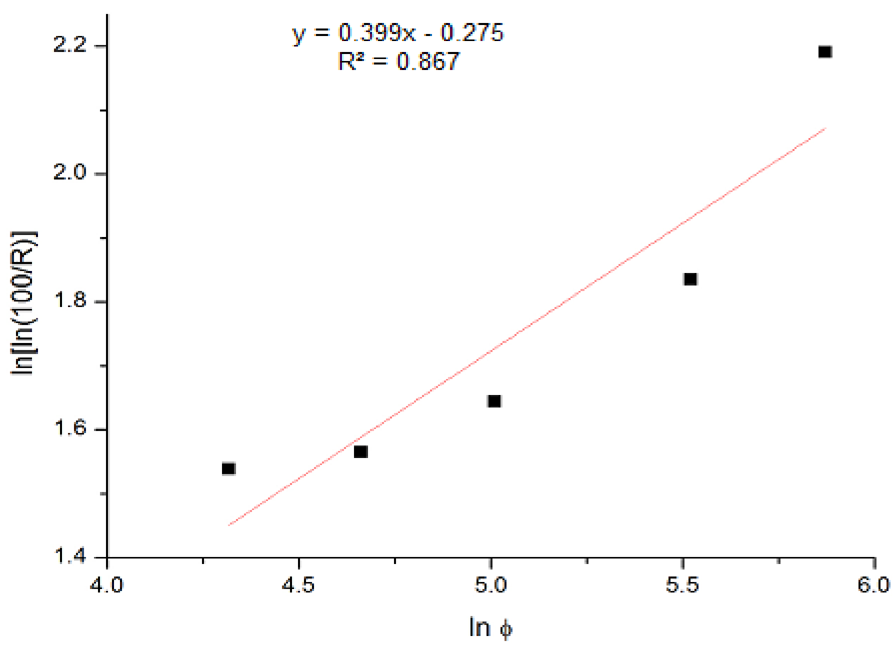

Fig. 3.12: RR model fit of S-II coal sample

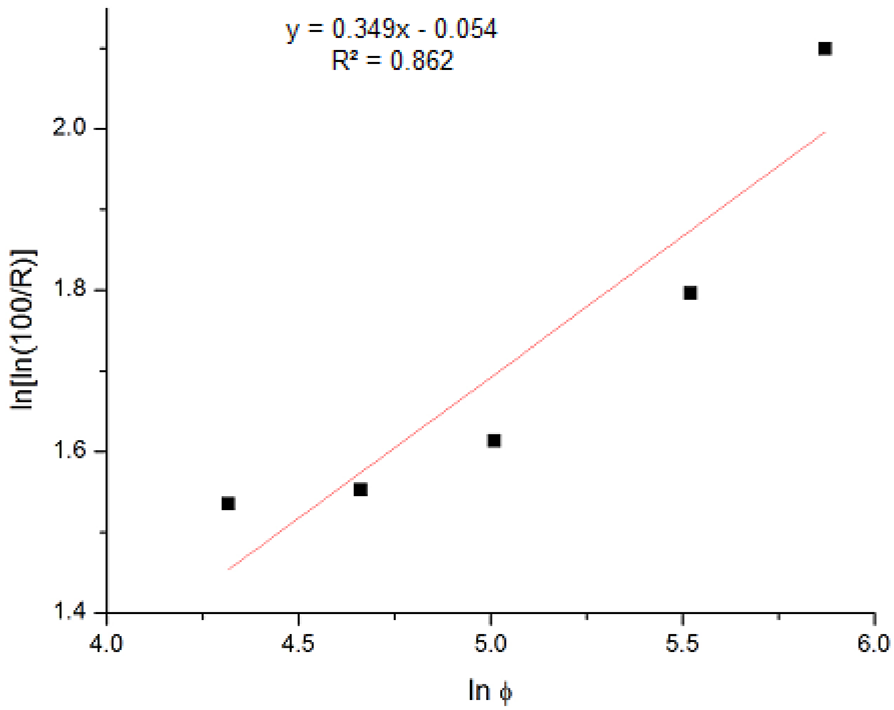

Fig. 3.13: RR model fit of S-III coal sample

CHAPTER 4 RHEOLOGICAL PROPERTIES OF COAL-OIL MIXTURES

During the transportation of coal-oil mixture through pipelines, the estimation of energy required for pumping depends on the viscosity of the mixture. Therefore rheological studies are very useful for determining the viscosity and also for studying the effect of various parameters like solids concentration, temperature, particle size distribution, and properties of coal like ash and moisture content. In the present study, the rheological experimentation was carried out on coal-oil mixtures made from three different coals (S-I, S-II and S-III) varying in their respective ash and moisture contents. The rheological measurements were made with the help of 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 are obtained by selecting controlled shear rate 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.

The measuring system consists of a spindle having bob and a cup with a small annular gap in between them. The coal-oil mixture 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 RheolabQC rheometer. Measuring system CC27/QC-LTD was chosen for the rheological measurements. It was thoroughly cleaned and dried before being used. The three coal samples S-I, S-II and S-III were used for the rheological experiments.

For the preparation of coal-oil mixture samples, a known amount of coal particles was added to a known amount of furnace oil, depending on the solid concentration required by weight. The furnace oil used was Grade MV2 and its specifications are given in Table 4.1.

Table 4.1: Specifications of furnace oil

Characteristics	**Requirements**
Specific gravity	0.98
Gross calorific value, (Cal/ gm)	≈ 10000
Kinematic viscosity, (centi Stokes) at 50°C	125-180
Sulphur, total % wt. Max	4.0
Water content, % v/v, Max	1.0
Ash, % wt. Max	0.1

Coal-oil mixture samples were prepared at 60° C so as to have a better mixing of coal in oil. The mixture was continuously stirred by a glass rod and the time of stirring varied between 5 and 10 minutes. Also proper care was taken to avoid spillage of coal-oil mixture.

The amount of coal required for coal-oil mixture, was weighed in a single pan electronic balance (least count ±0.1mg) for each of the three coal samples. The rheological measurements were made at solids weight concentration of 20 %, 30 %, 40 % and 50 % by weight and at temperature of 25° C, 30° C, 35° C, 40° C and 45° C . The shear rate was applied from 0 to 30

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 ± 0.5° C and was controlled by using a water bath system. The rheological results were obtained on a computer screen.

4.3 RHEOGRAM OF COAL-OIL MIXTURES

To study the effect of parameters like solids concentration and temperature on coal-oil mixture rheology, flow curves of shear stress vs. shear rate (rheograms) were generated for coal-oil mixtures at different solids concentration and temperature. Rheograms for coal-oil mixtures made from three coal samples S-I, S-II and S-III are shown in Fig. 4.2 - 4.7.

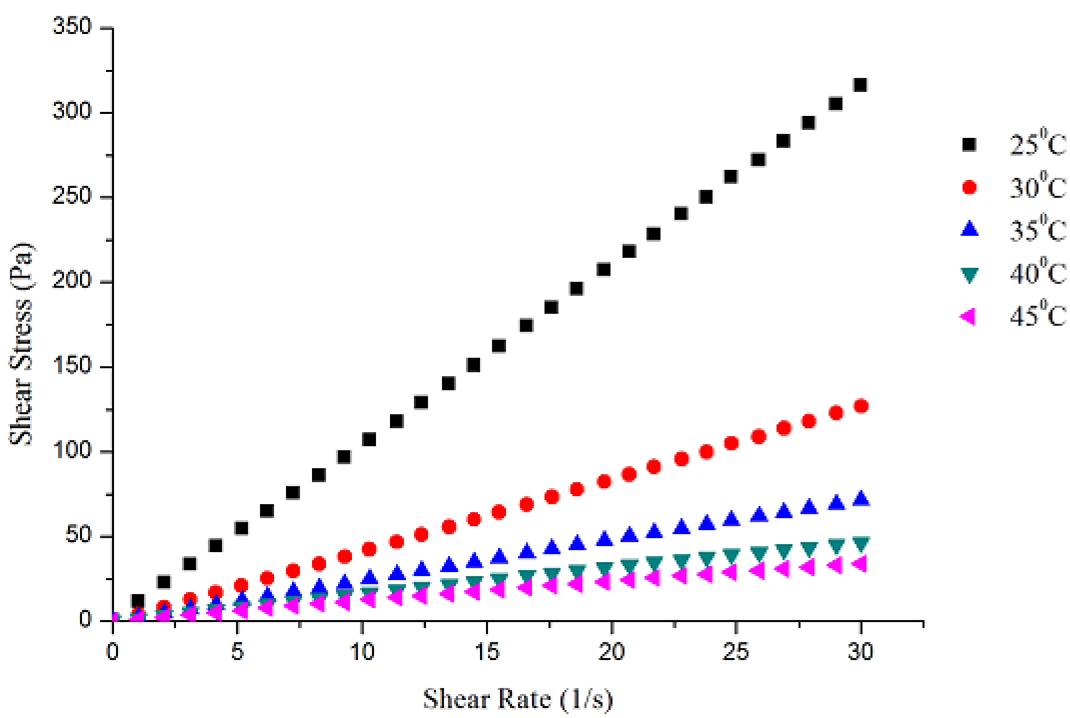

Fig. 4.2: Rheogram of coal-oil mixture (S-I) at C_w = 20 %

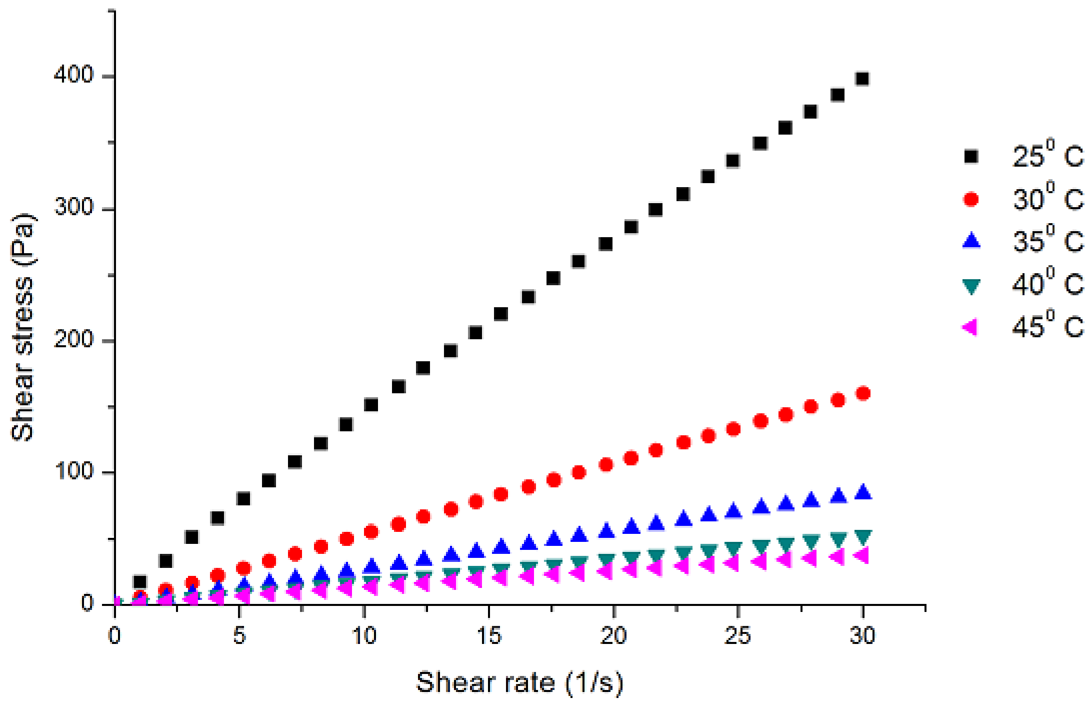

Fig. 4.3: Rheogram of coal-oil mixture (S-II) at C_w = 20 %

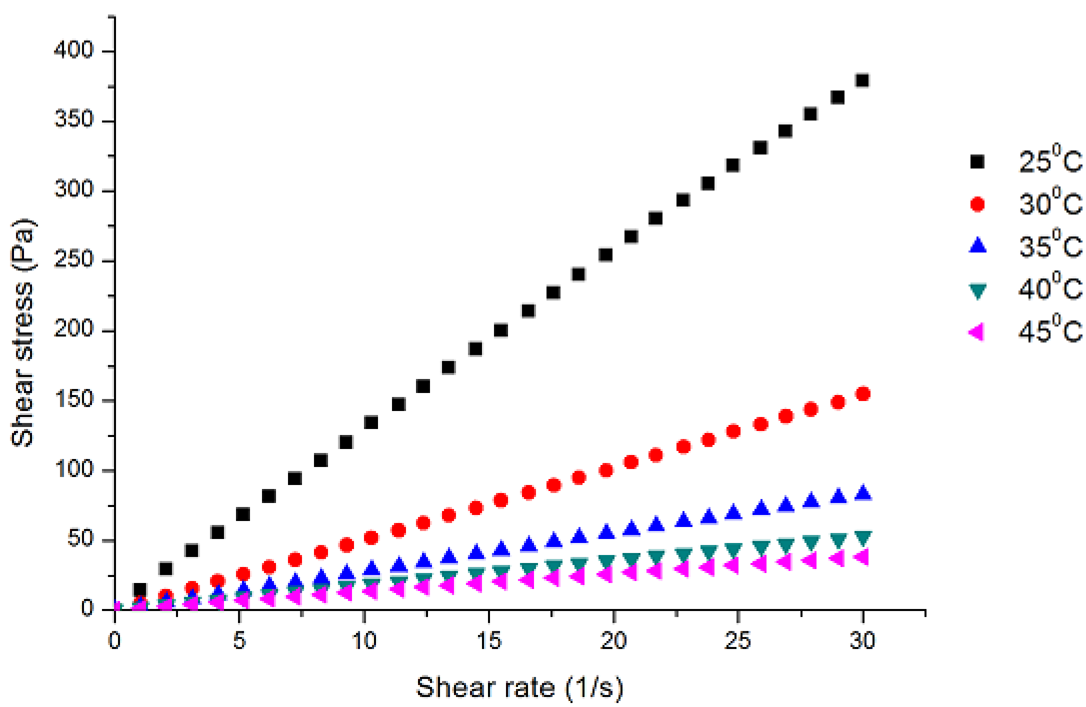

Fig. 4.4: Rheogram of coal-oil mixture (S-III) at C_w = 20 %

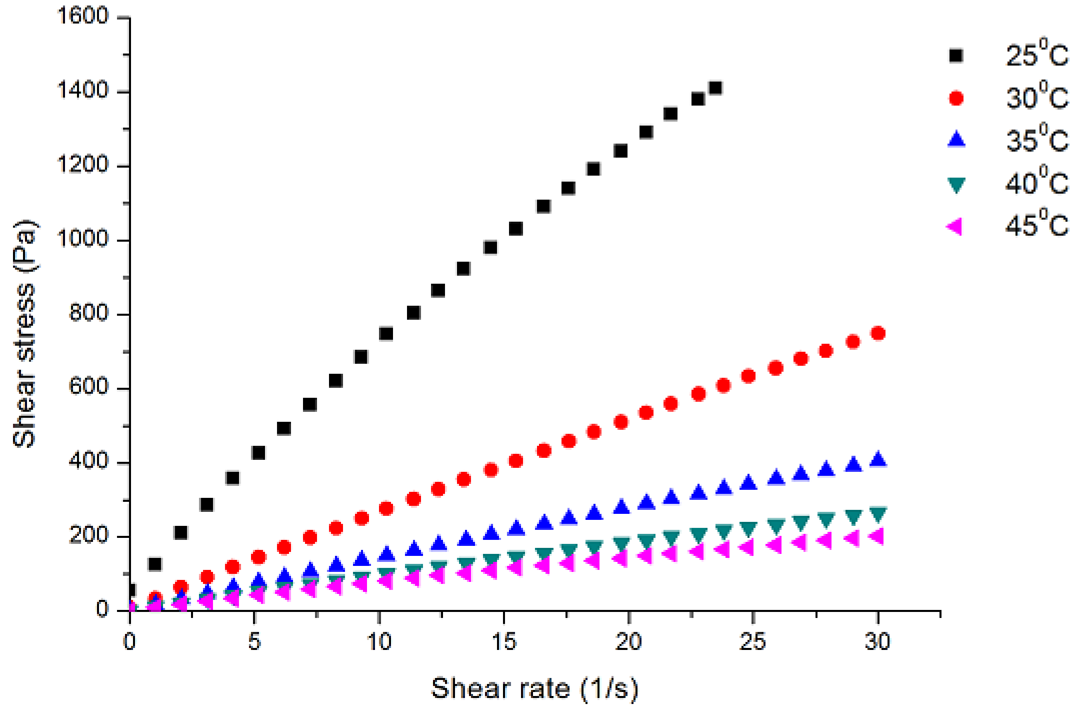

Fig. 4.5: Rheogram of coal-oil mixture (S-I) at C_w = 50 %

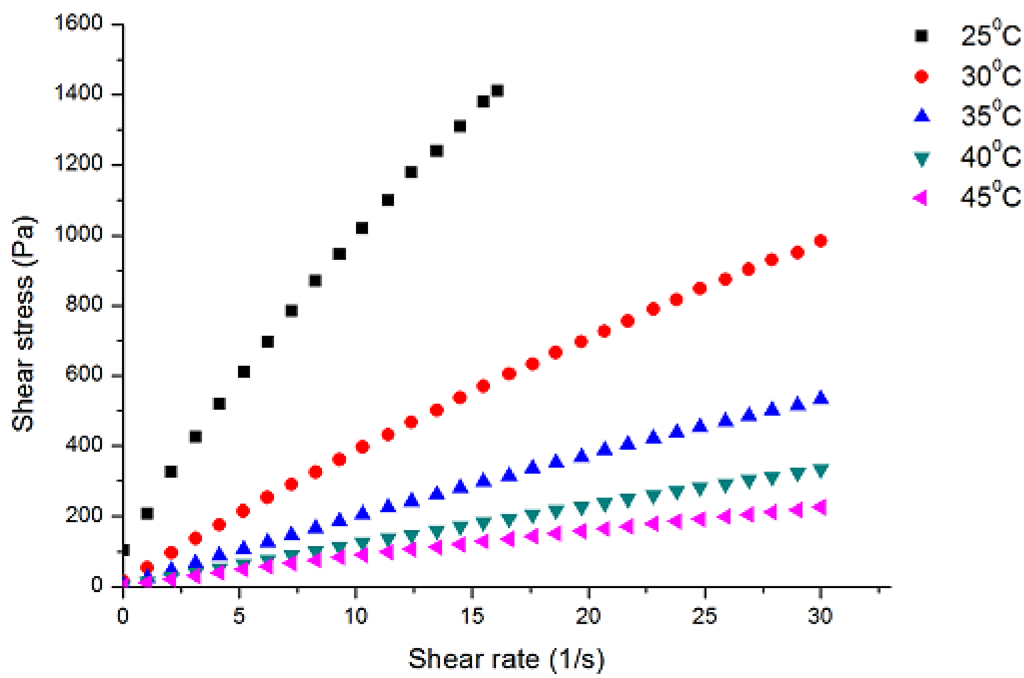

Fig. 4.6: Rheogram of coal-oil mixture (S-II) at C_w = 50 %

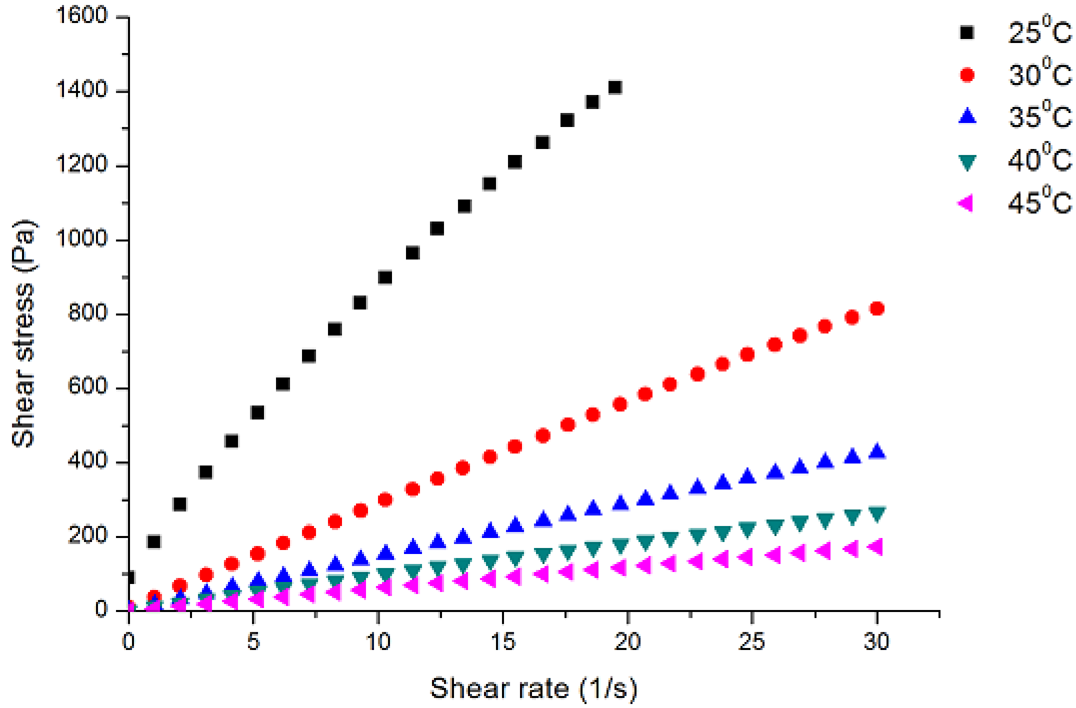

Fig. 4.7: Rheogram of coal-oil mixture (S-III) at C_w = 50 %

After studying Fig. 4.2 - 4.7, it was found that both temperature and solids concentration had a considerable effect on rheological behavior of coal-oil mixture. As temperature was increased, the slope of the curve decreased indicating that apparent viscosity decreased. The decrease in apparent viscosity with increase in temperature can be attributed to the fact that with increase in temperature, the kinetic energy of molecules increases. With increase in kinetic energy, the magnitude of attractive forces between molecules decreases and molecules can now move more freely with respect to one another, hence resulting in lesser viscosity. Also when solids concentration was increased, the apparent viscosity of coal-oil mixture increased. This can be attributed to the fact that when concentration increases, the density of coal particles in coal-oil mixture also increases, which means that there are now more coal particles in same amount of volume. As a result of which particle to particle shear interactions increases and hence viscosity increases. It was also observed that the yield stress of coal-oil mixture increased, with an increase in solids concentration and decrease in temperature. Similar observations were reported by Papachristodoulou G et al. (1984) for coal-oil mixtures. Also for mixtures with coal concentrations higher than 40%, a yield stress was observed. This yield stress must be overcome before the flow could take place. Similar results were found by Ghassemzadeh M.R et al. (1981) for coal-oil mixtures.

4.4 VARIATION OF APPARENT VISCOSITY WITH SHEAR RATE

Variation of apparent viscosity as a function of shear rate for coal-oil mixtures made from three coal samples S-I, S-II and S-III is shown in Fig. 4.8 - 4.13.

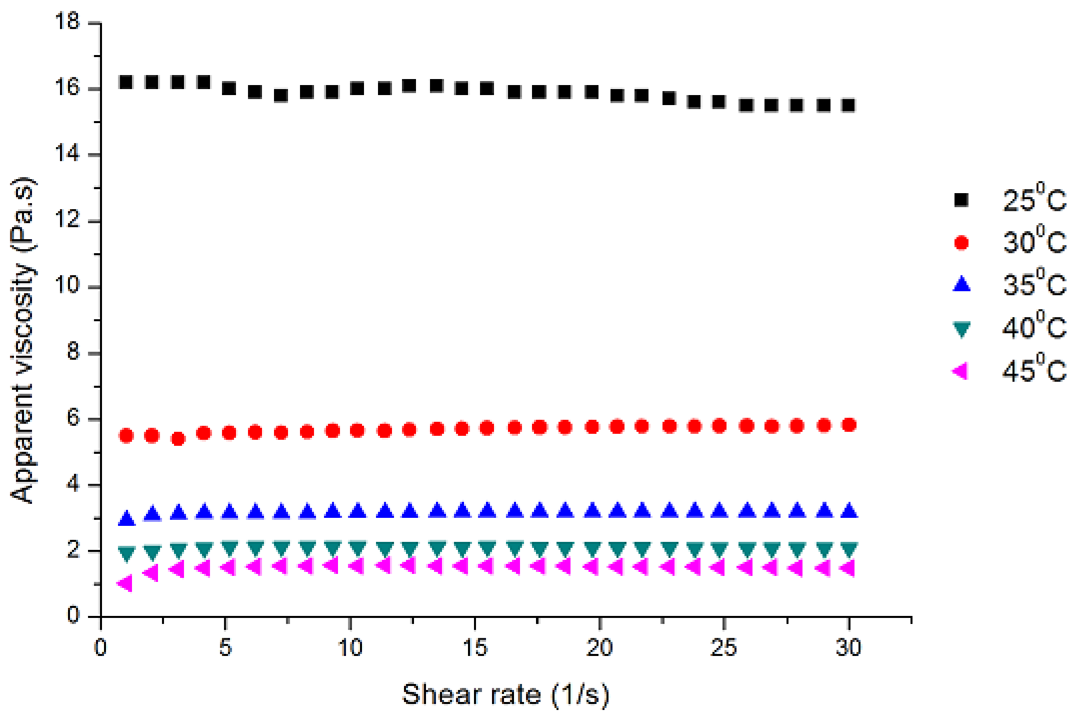

Fig. 4.8: Variation of apparent viscosity with shear rate for coal-oil mixture (S-I) at C_w = 30 %

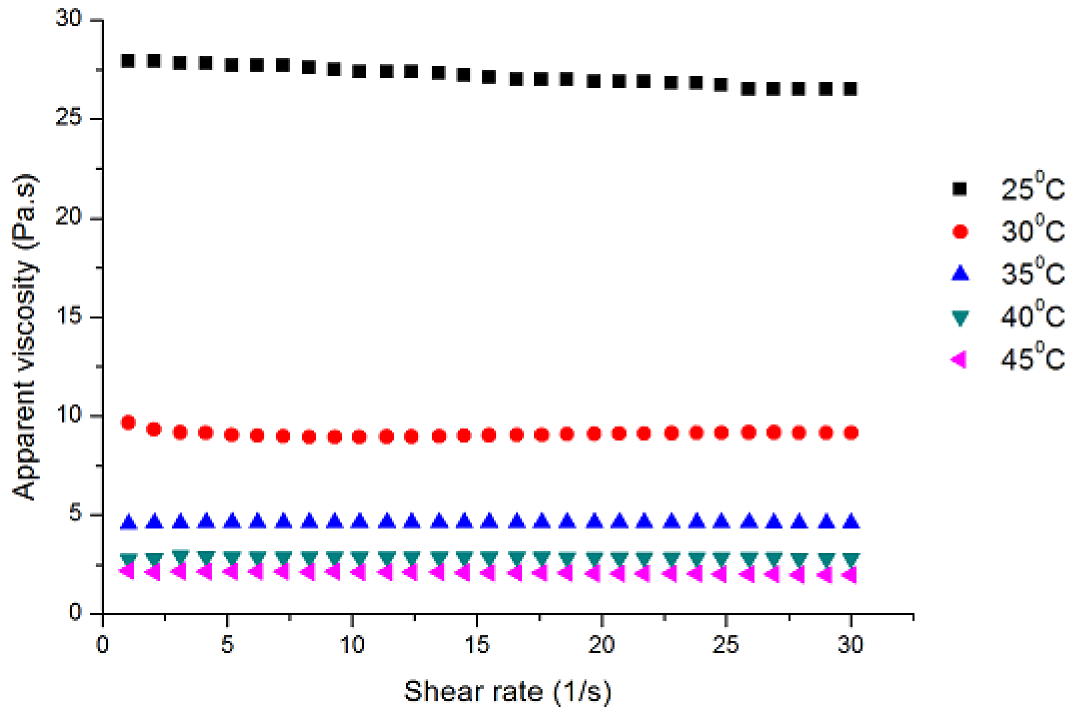

Fig. 4.9: Variation of apparent viscosity with shear rate for coal-oil mixture (S-II) at C_w = 30 %

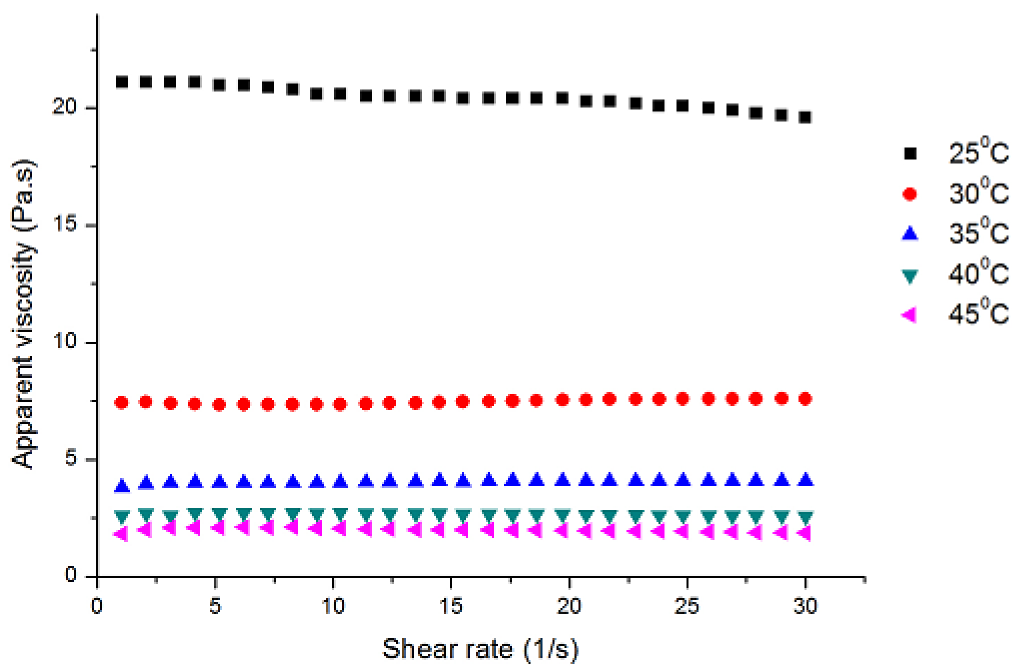

Fig. 4.10: Variation of apparent viscosity with shear rate for coal-oil mixture (S-III) at C_w = 30 %

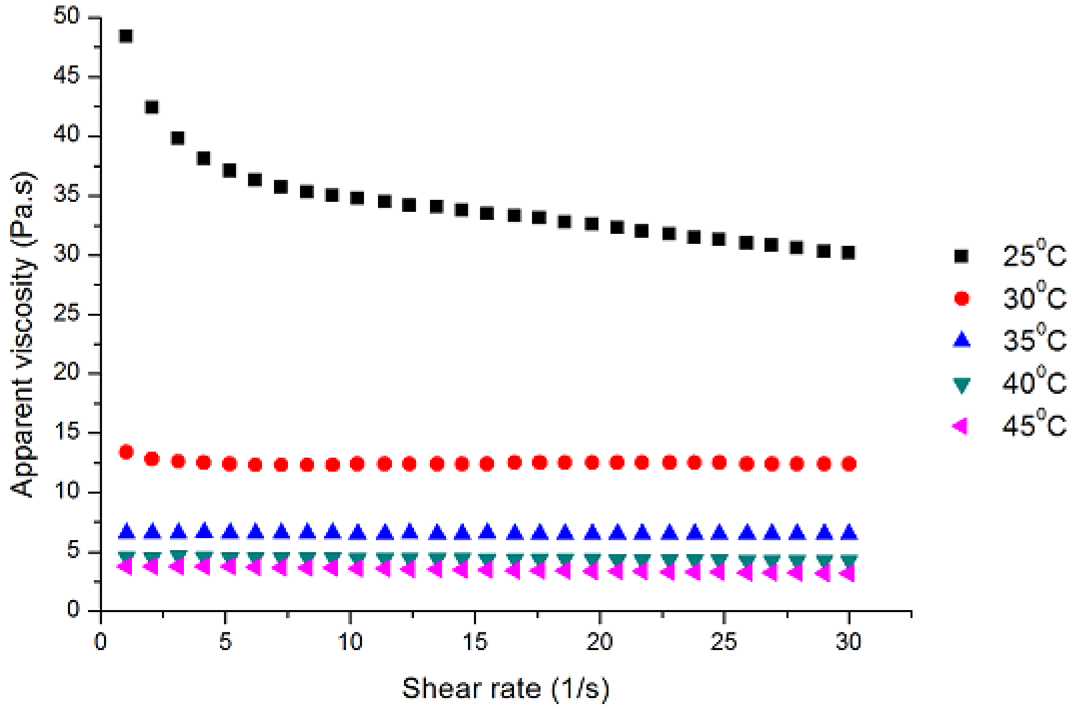

Fig. 4.11: Variation of apparent viscosity with shear rate for coal-oil mixture (S-I) at C_w = 40 %

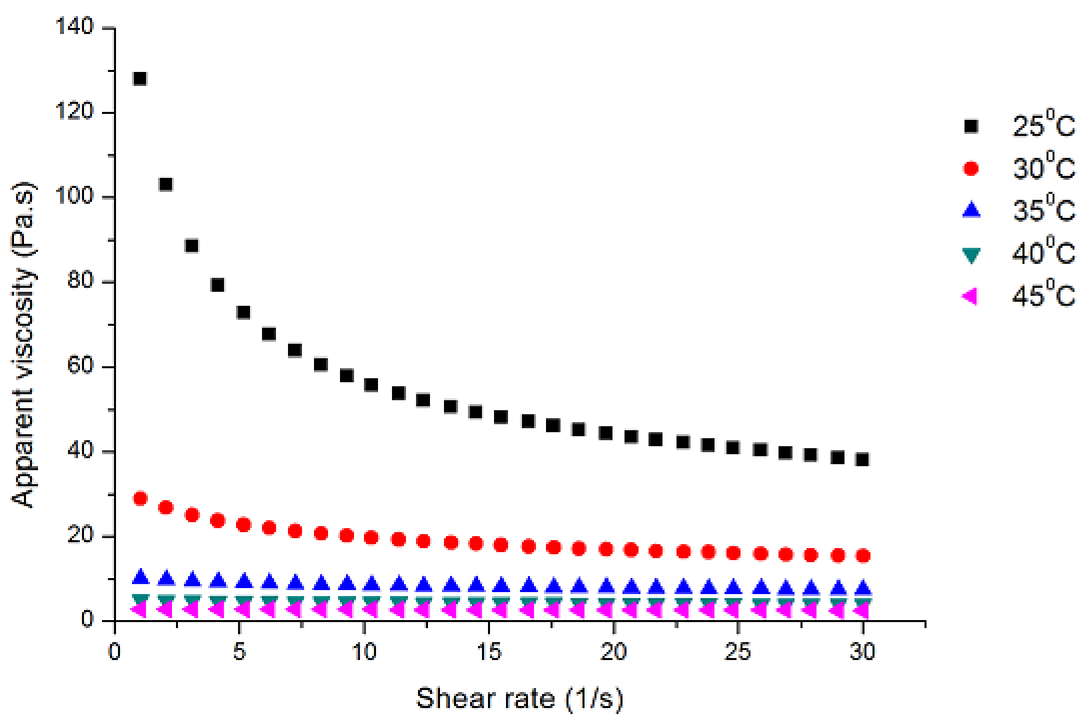

Fig. 4.12: Variation of apparent viscosity with shear rate for coal-oil mixture (S-II) at C_w = 40 %

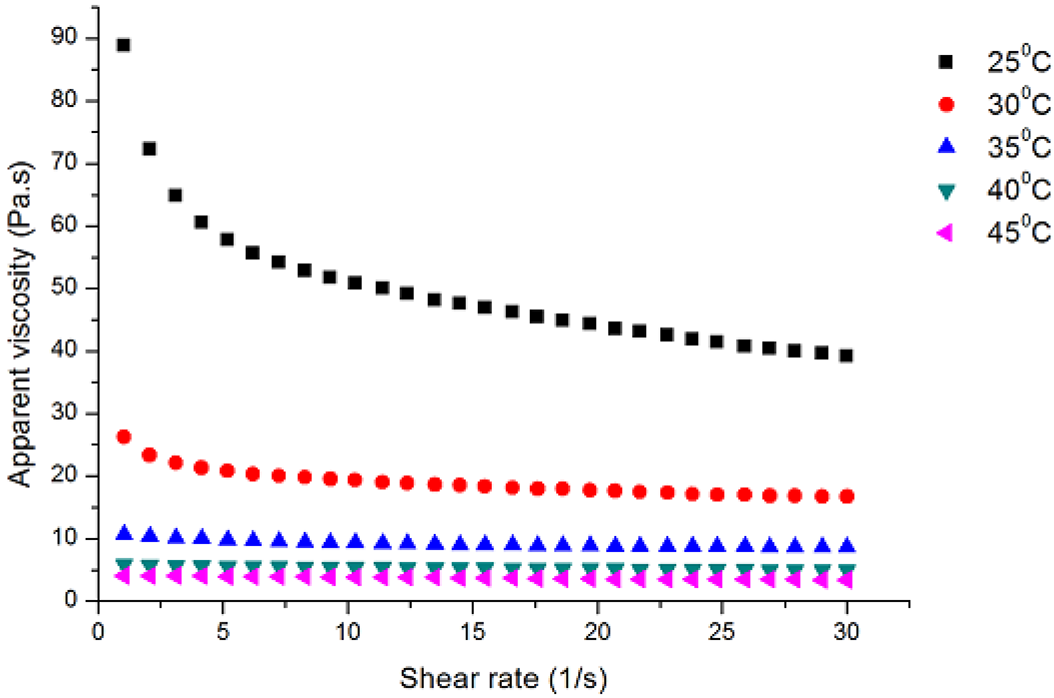

Fig. 4.13: Variation of apparent viscosity with shear rate for coal-oil mixture (S-III) at C_w = 40 %

From the Fig. 4.8 - 4.13, it was observed that up to 30 % solids concentration, coal-oil mixtures behaved as a Newtonian fluid having apparent viscosity independent of shear rate. Similar observations were reported by Papachristodoulou G et al. (1984) for coal-oil mixtures. It was also observed that above 40 % solids concentration, the coal-oil mixtures behaved as yield pseudo plastic fluid having a decrease in apparent viscosity with increase in shear rate.

4.5 EFFECT OF TEMPERATURE ON RHEOLOGY OF COAL-OIL MIXTURES

In order to study the effect of temperature on rheological properties of coal-oil mixtures, variation of apparent viscosity and yield stress with temperature at different solids concentration for coal-oil mixtures made from three coal samples S-I, S-II and S-III is shown in Fig. 4.14 - 4.19. The values of apparent viscosities used in these graphs were taken at a shear rate of 15.5 s^{-1}.

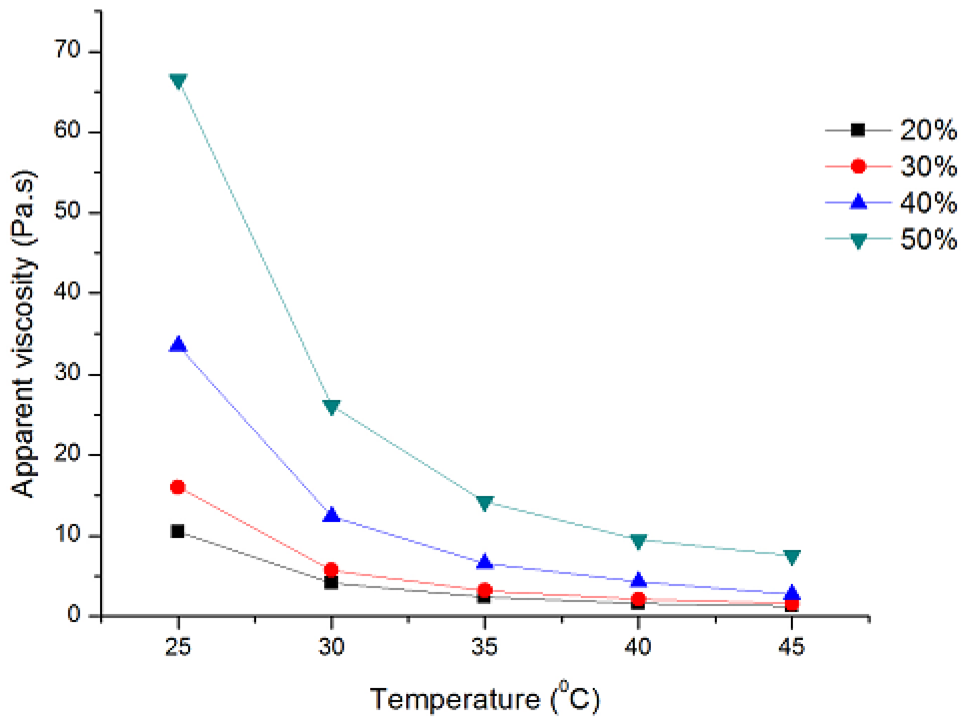

Fig. 4.14: Variation of apparent viscosity with temperature for coal-oil mixture (S-I)

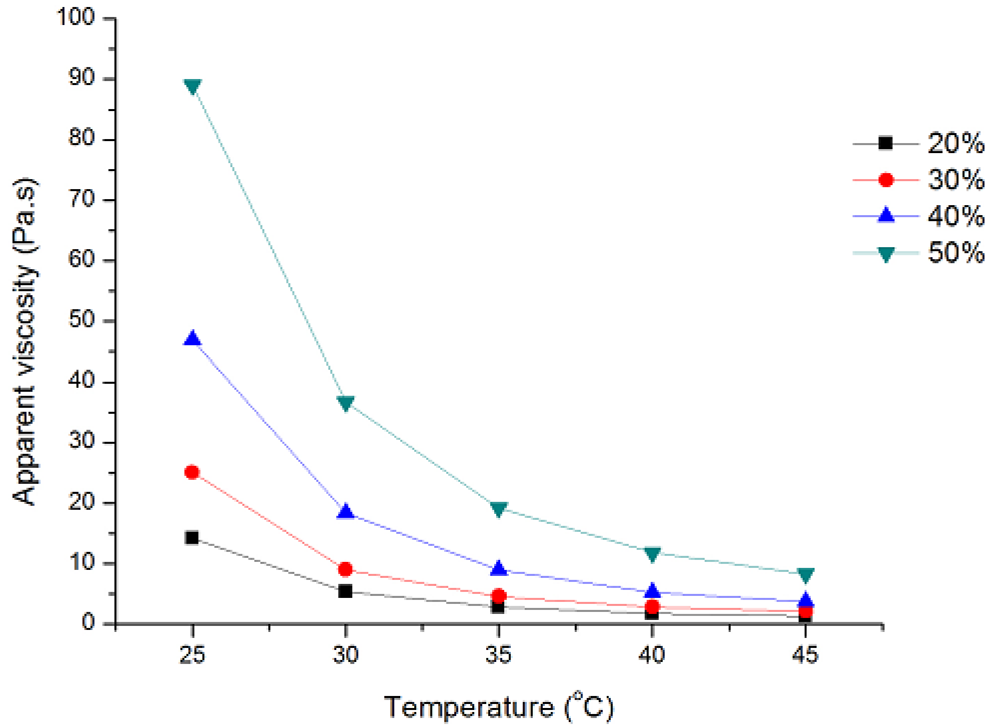

Fig. 4.15: Variation of apparent viscosity with temperature for coal-oil mixture (S-II)

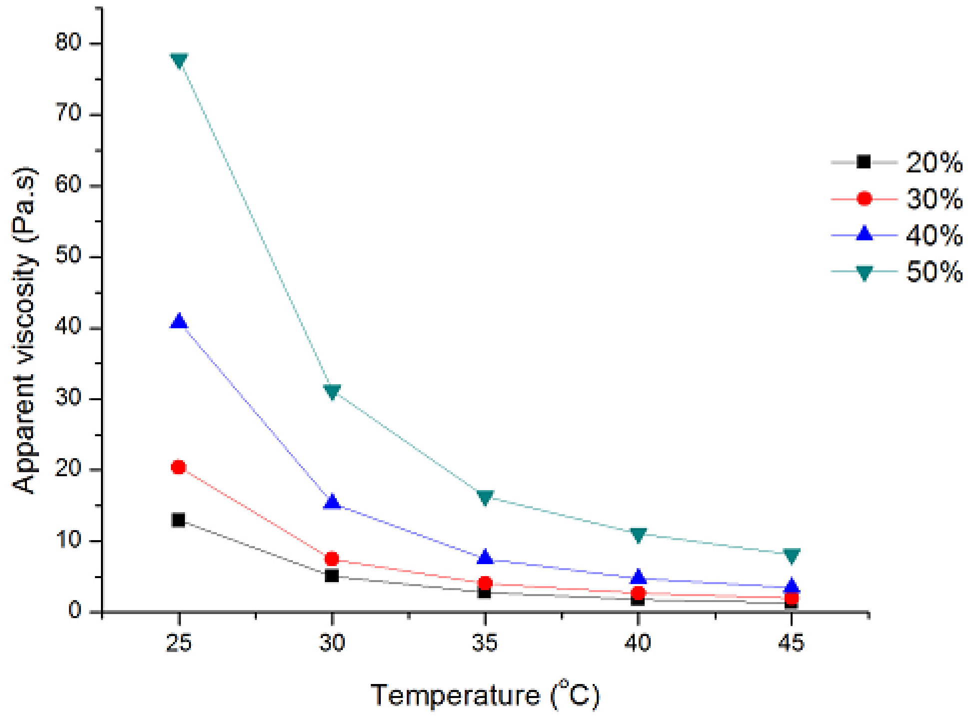

Fig. 4.16: Variation of apparent viscosity with temperature for coal-oil mixture (S-III)

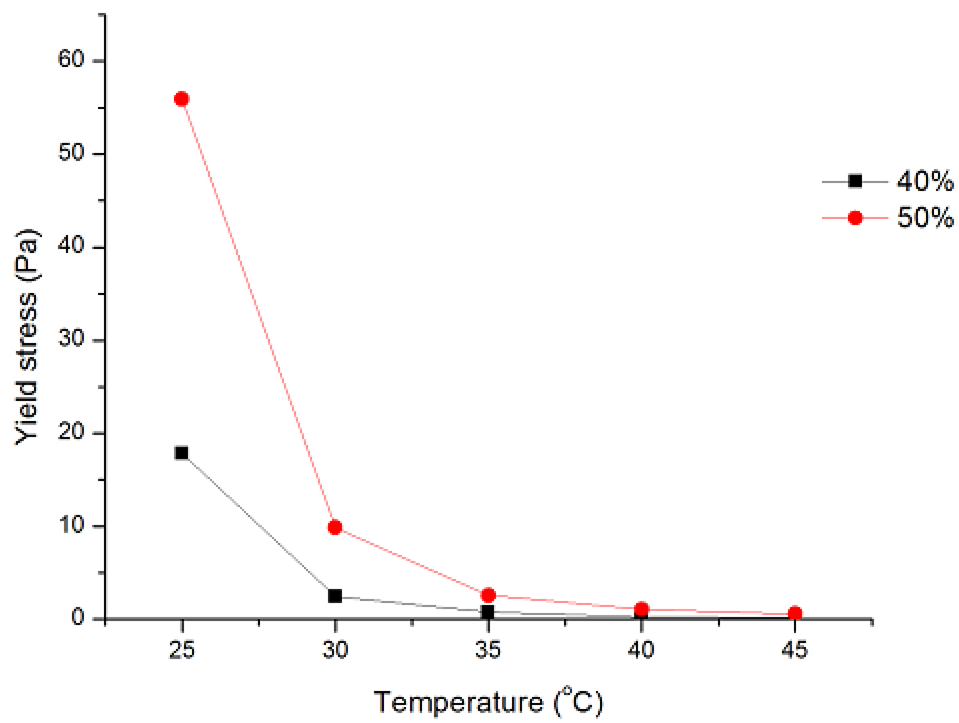

Fig. 4.17: Variation of yield stress with temperature for coal-oil mixture (S-I)

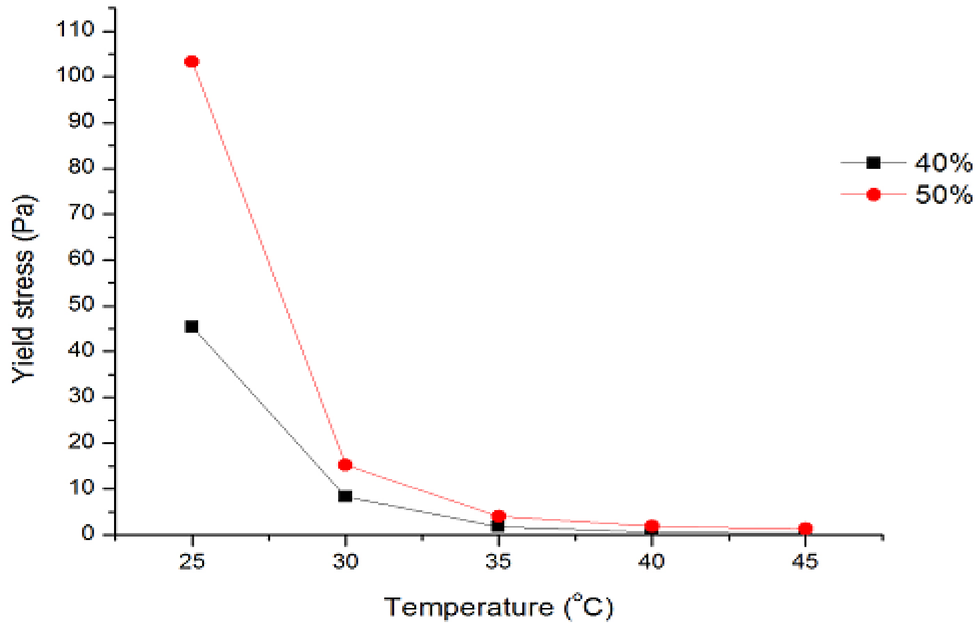

Fig. 4.18: Variation of yield stress with temperature for coal-oil mixture (S-II)

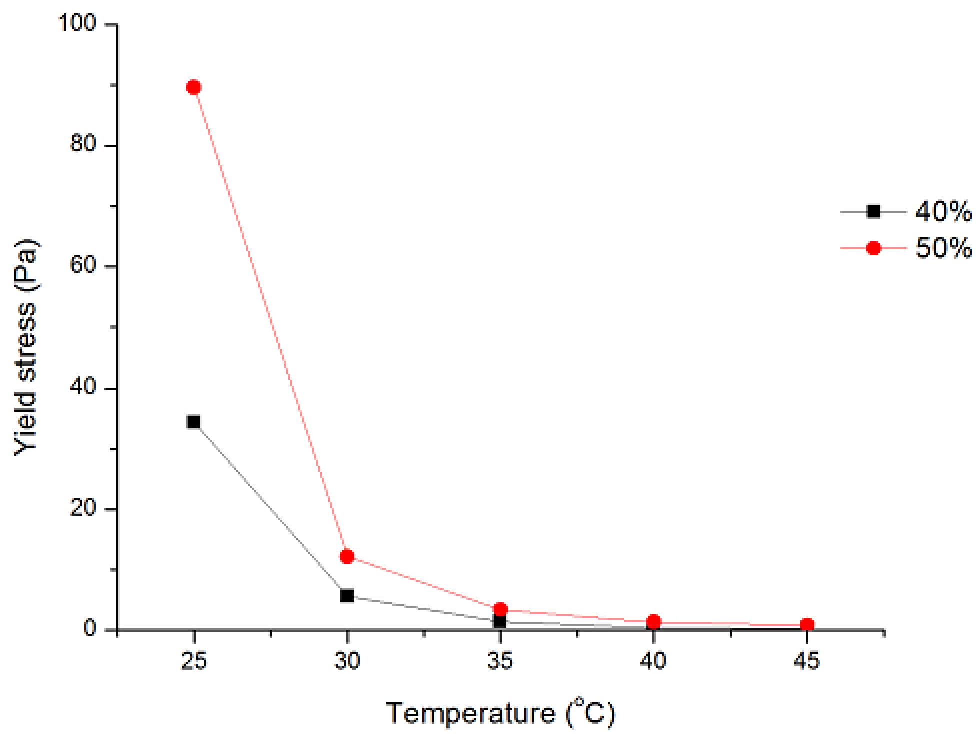

Fig. 4.19: Variation of yield stress with temperature for coal-oil mixture (S-III)

Variation of percentage decrease of apparent viscosity at different temperature ranges for three coal samples is shown in Fig. 4.20-4.23.

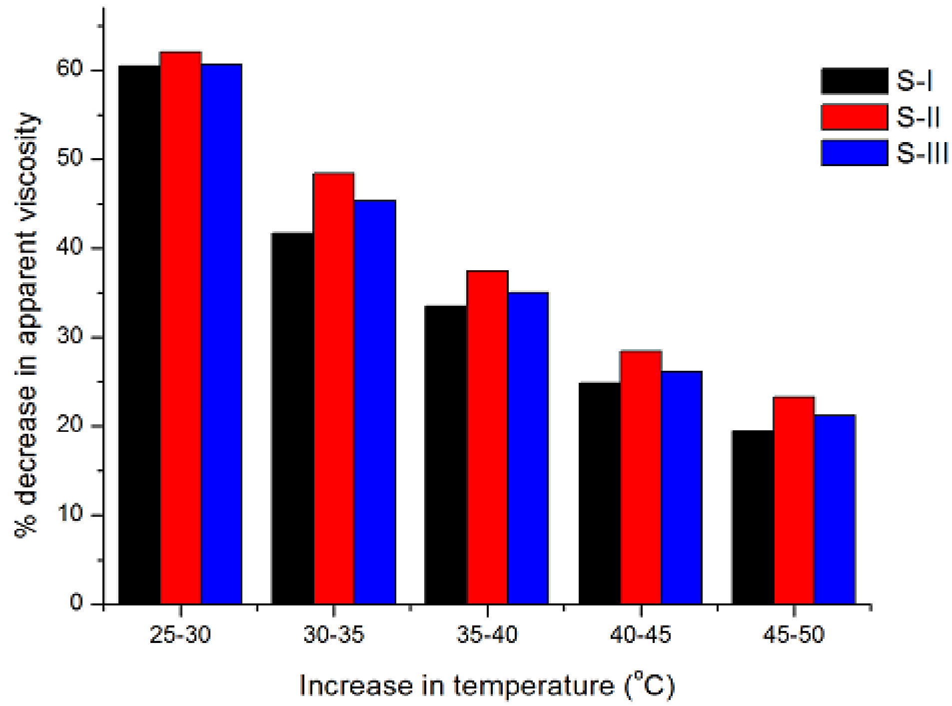

Fig. 4.20: Variation of % decrease in apparent viscosity with increase in temperature at C_w = 20 %

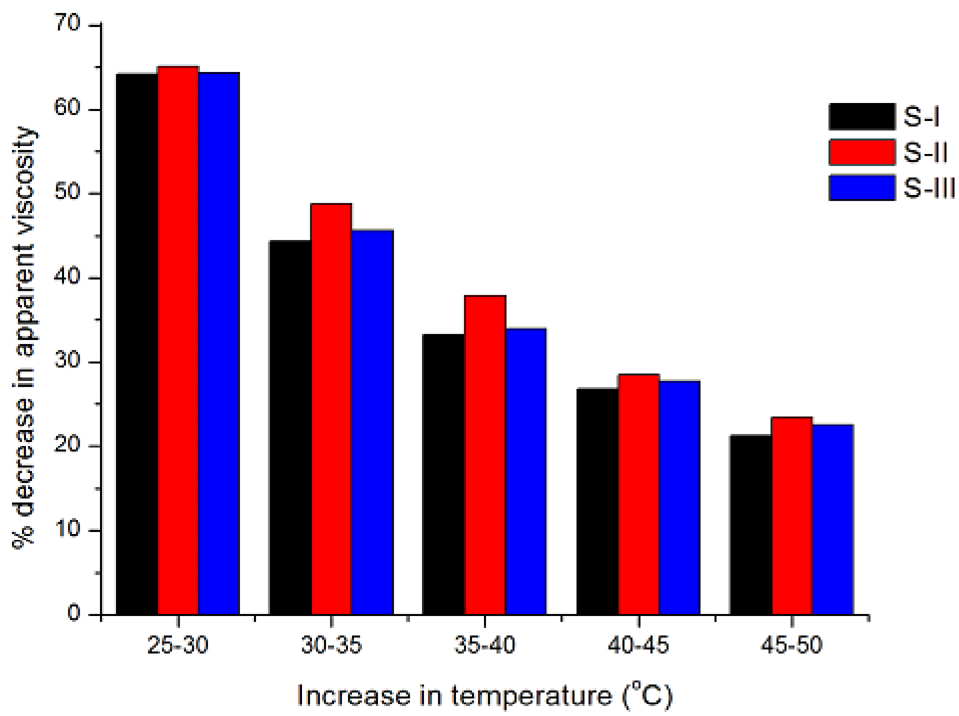

Fig. 4.21: Variation of % decrease in apparent viscosity with increase in temperature at C_w = 30 %

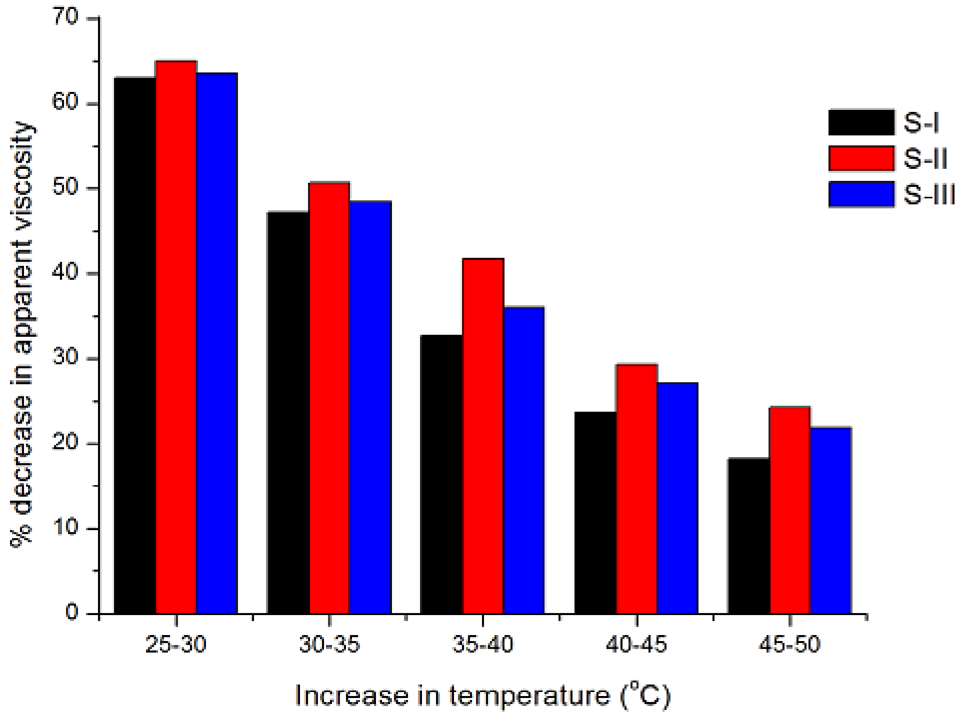

Fig. 4.22: Variation of % decrease in apparent viscosity with increase in temperature at C_w = 40 %

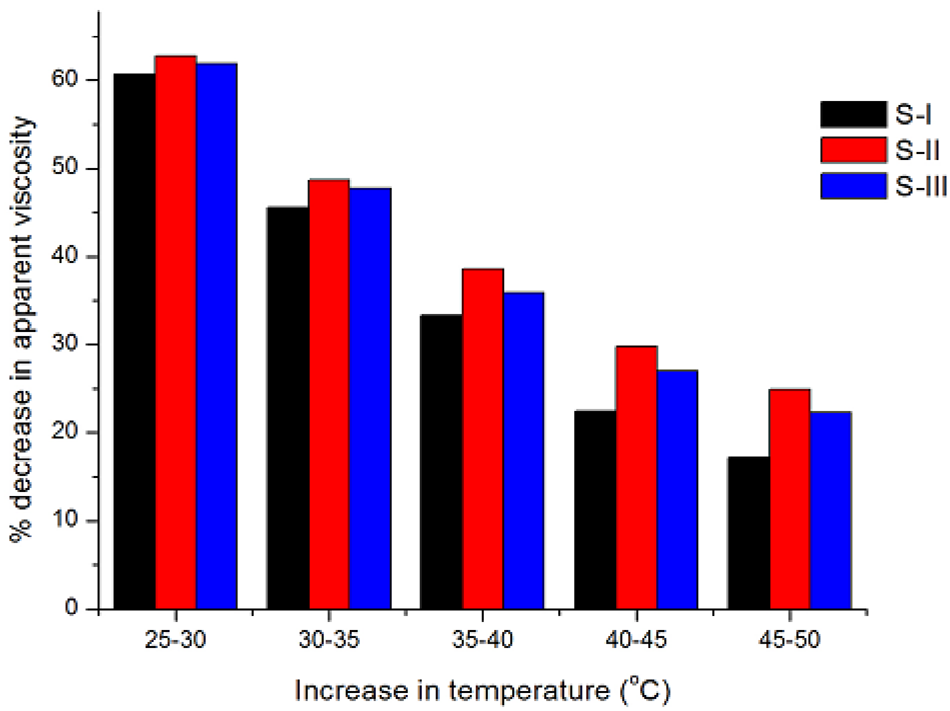

Fig. 4.23: Variation of % decrease in apparent viscosity with increase in temperature at C_w = 50 %

In Fig. 4.20 - 4.23, values of percentage decrease in apparent viscosity corresponding to 45° C - 50° C were found by curve fitting. After careful examination it was observed that there was very less difference in percentage decrease in apparent viscosity between temperature ranges of 40° C - 45° C and 45° C - 50° C as shown in Table 4.2.

Table 4.2: Comparison of percentage decrease in apparent viscosity above 45° C

Solids concentration	Temperature range	Percentage decrease in apparent viscosity		
		S-I	S-II	S-III
20 %	40° C - 45° C	24.84	28.41	26.11
	45° C - 50° C	19.46	23.27	21.16
50 %	40° C - 45° C	22.48	29.74	27.02
	45° C - 50° C	17.23	24.88	22.28

Therefore it can be concluded that an increase in temperature above 45° C results in a less decrease in apparent viscosity.

After careful examination of Fig. 4.14 - 4.16, it was observed that there was a sharp increase in apparent viscosity as solids concentration was increased from 40 % to 50 % and this increase was more noticeable at lower temperatures as compared to higher temperatures.

4.6 RESULTS OF COMPARISON OF THREE COAL SAMPLES

After careful examination of Fig. 4.20 - 4.23, it was found that the coal-oil mixture made from coal sample S-II was having the highest value of apparent viscosity and the one made from coal sample S-I, was having the lowest value of apparent viscosity at all temperatures and solids concentration. It was also found that the coal-oil mixture made from coal sample S-II depicted the highest value of yield stress and the one made from coal sample S-I, showed the lowest value of yield stress.

4.7 EFFECT OF COAL PROPERTIES ON RHEOLOGY OF COAL-OIL MIXTURES

4.7.1 EFFECT OF ASH CONTENT OF COAL

It was found that the apparent viscosity of coal-oil mixtures made from three coal samples S-I, S-II and S-III, decreased in order of S-II> S-III> S-I. Also the ash content in coal samples increased in order of S-II< S-III< S-I. Therefore it can be concluded that apparent viscosity of coal-oil mixture decreases with an increase in ash content of coal. Similar trend was observed by Reddy G.V et al. (1994) for coal-oil mixtures. Also the yield stress of coal-oil mixture decreases with an increase in ash content of coal.

4.7.2 EFFECT OF MOISTURE CONTENT OF COAL

It was found that the apparent viscosity of coal-oil mixtures made from three coal samples S-I, S-II and S-III, increased in order of S-I< S-III< S-II. Also the moisture content in coal samples increased in order of S-I< S-III< S-II. Therefore it can be concluded that apparent viscosity of coal-oil mixture increases with an increase in moisture content of coal. Similar trend was observed by Reddy G.V et al. (1994) for coal-oil mixtures. This is due to the fact that when coal is heated the moisture is driven off and empty pores are left. When oil is mixed with coal during preparation of coal-oil mixtures, these empty pores get collapsed due to pressure of oil. As a result of which the volume of coal particles will decrease and mobility of coal particles will increase. With increase in mobility the particle to particle interactions will be reduced thereby reducing the particle to particle shear stress and hence decreasing the apparent viscosity.

4.7.3 EFFECT OF PARTICLE SIZE OF COAL PARTICLES

The effect of particle size on rheology of coal-oil mixture was studied by correlating the mass median diameter (d_{50}) with apparent viscosities. It was found that the apparent viscosity of coal-oil mixtures made from three coal samples S-I, S-II and S-III, decreased in order of S-II> S-III> S-I. Also the mass median diameter (d_{50}) of coal samples increased in order of S-II< S-III< S-I. Therefore it can be concluded that apparent viscosity of coal-oil mixture decreases with an increase in mass median diameter of coal particles. Also the yield stress of coal-oil mixture decreases with an increase in mass median diameter of coal particles. Similar observations were reported by Papachristodoulou G et al. (1984) for coal-oil mixtures. This is due to the fact that lower particles size (i.e. lower values of mass median diameter) has less voids and poses a greater surface for shear and hence the apparent viscosity and yield stress of coal-oil mixture increases.

4.7.4 EFFECT OF PARTICLE SIZE DISTRIBUTION OF COAL SAMPLE

The effect of particle size distribution on rheology of coal-oil mixture was studied by correlating the Rosin-Rammler distribution modulus (n) with apparent viscosities. It was found that the apparent viscosity of coal-oil mixtures made from three coal samples S-I, S-II and S-III, increased in order of S-I< S-III< S-II. Also the distribution modulus (n) of coal samples increased in order of S-I< S-III< S-II. Therefore it can be concluded that apparent viscosity of coal-oil mixture increases with an increase in distribution modulus (n) of coal sample. Similar trend was observed by Reddy G.V et al. (1994) for coal-oil mixtures. The reason for low apparent viscosity for coal sample having broader particle size distribution may be attributed to the fact that in broader particle size distribution the small coal particles may enter the voids between relatively bigger particles and hence, the effective surface area under shear decreases and as a result apparent viscosity decreases. Also the small coal particles entering the voids may even act as lubricant resulting in decrease in apparent viscosity.

4.8 RHEOLOGICAL MODEL FITS

The rheological data obtained from the experimentation was fitted into rheological models to calculate the model parameters for determining the flow behavior of coal-oil mixtures at different concentrations and temperatures. Coal-oil mixtures without yield stress were analyzed with Power-Law model and those having yield stress were analyzed with Herschel-Bulkley model.

The relation for Power-Law model is:

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

Taking logarithm on both sides of Eq. (4.1) gives:

$$\ln\tau = \ln\dot{K} + \dot{n}\ln\gamma \tag{4.2}$$

A linear regression of $\ln\tau$ as a function of $\ln\gamma$ was performed to calculate the model parameters $\dot{n}$ and $\dot{K}$.

The relation for Herschel-Bulkley model is:

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

The Herschel-Bulkley is a three parameter model. The yield stress corresponding to zero shear rate was estimated by curve fitting. Then, the Herschel- Bulkley model was reduced to a two parameter model by taking the yield stress at the left hand side of Equation 4.3 and taking logarithms on both sides.

Rearranging and taking logarithm on both sides of Eq. (4.3) gives:

$$\ln(\tau - \tau_y) = \ln\dot{K} + \dot{n}\ln\gamma \tag{4.4}$$

A linear regression of $\ln(\tau - \tau_y)$ as a function of $\ln\gamma$ was performed to calculate the model parameters $\dot{n}$ and $\dot{K}$. The model parameters i.e Flow behaviour index ($\dot{n}$) and consistency coefficient ($\dot{K}$) are shown in Table 4.3 – 4.6.

Table 4.3: Rheological model parameters for coal samples at C_w = 20 %

Tempe-rature (°C)	Coal sample	Yield stress (Pa)	Rheological model used	Flow behaviour index (ṅ)	Consistency coefficient (K̇)	Fluid type
25	S-I	0	Power-Law	1	10.32	Newtonian
	S-II	0	Power-Law	1	14.68	Newtonian
	S-III	0	Power-Law	1	11.85	Newtonian
30	S-I	0	Power-Law	1	3.89	Newtonian
	S-II	0	Power-Law	1	5.2	Newtonian
	S-III	0	Power-Law	1	4.7	Newtonian
35	S-I	0	Power-Law	1	2.29	Newtonian
	S-II	0	Power-Law	1	2.62	Newtonian
	S-III	0	Power-Law	1	2.53	Newtonian
40	S-I	0	Power-Law	1	1.59	Newtonian
	S-II	0	Power-Law	1	1.7	Newtonian
	S-III	0	Power-Law	1	1.62	Newtonian
45	S-I	0	Power-Law	1	1.22	Newtonian
	S-II	0	Power-Law	1	1.35	Newtonian
	S-III	0	Power-Law	1	1.27	Newtonian

Table 4.4: Rheological model parameters for coal samples at C_w = 30 %

Tempe-rature (°C)	Coal sample	Yield stress (Pa)	Rheological model used	Flow behaviour index (ṅ)	Consistency coefficient (K̇)	Fluid type
25	S-I	0	Power-Law	1	15.45	Newtonian
	S-II	0	Power-Law	1	27.26	Newtonian
	S-III	0	Power-Law	1	18.33	Newtonian
30	S-I	0	Power-Law	1	4.95	Newtonian
	S-II	0	Power-Law	1	7.97	Newtonian
	S-III	0	Power-Law	1	6.46	Newtonian
35	S-I	0	Power-Law	1	3.03	Newtonian
	S-II	0	Power-Law	1	4.58	Newtonian
	S-III	0	Power-Law	1	3.9	Newtonian
40	S-I	0	Power-Law	1	2.03	Newtonian
	S-II	0	Power-Law	1	2.87	Newtonian
	S-III	0	Power-Law	1	2.7	Newtonian
45	S-I	0	Power-Law	1	1.29	Newtonian
	S-II	0	Power-Law	1	2.25	Newtonian
	S-III	0	Power-Law	1	2.07	Newtonian

Table 4.5: Rheological model parameters for coal samples at C_w = 40 %

Tempe-rature (°C)	Coal sample	Yield stress (Pa)	Rheological model used	Flow behaviour index (ṅ)	Consistency coefficient (K̇)	Fluid type
25	S-I	17.84	Herschel-Bulkley	0.94	34.83	Yield pseudo plastic
	S-II	45.41	Herschel-Bulkley	0.91	62.56	Yield pseudo plastic
	S-III	34.38	Herschel-Bulkley	0.93	54.25	Yield pseudo plastic
30	S-I	2.42	Herschel-Bulkley	0.96	11.32	Yield pseudo plastic
	S-II	8.26	Herschel-Bulkley	0.94	27.39	Yield pseudo plastic
	S-III	5.60	Herschel-Bulkley	0.96	20.26	Yield pseudo plastic
35	S-I	0.80	Herschel-Bulkley	0.97	6.1	Yield pseudo plastic
	S-II	1.77	Herschel-Bulkley	0.96	9.74	Yield pseudo plastic
	S-III	1.46	Herschel-Bulkley	0.93	9.61	Yield pseudo plastic
40	S-I	0.23	Herschel-Bulkley	0.98	4.53	Yield pseudo plastic
	S-II	0.62	Herschel-Bulkley	0.97	5.6	Yield pseudo plastic
	S-III	0.44	Herschel-Bulkley	0.94	4.92	Yield pseudo plastic
45	S-I	0.17	Herschel-Bulkley	0.94	2.96	Yield pseudo plastic
	S-II	0.46	Herschel-Bulkley	0.93	4.4	Yield pseudo plastic
	S-III	0.24	Herschel-Bulkley	0.96	4.07	Yield pseudo plastic

Table 4.6: Rheological model parameters for coal samples at C_w = 50 %

Tempe-rature (°C)	Coal sample	Yield stress (Pa)	Rheological model used	Flow behaviour index (ṅ)	Consistency coefficient (K̇)	Fluid type
25	S-I	55.91	Herschel-Bulkley	0.92	78.03	Yield pseudo plastic
	S-II	103.3	Herschel-Bulkley	0.89	111.82	Yield pseudo plastic
	S-III	89.63	Herschel-Bulkley	0.87	101.66	Yield pseudo plastic
30	S-I	9.85	Herschel-Bulkley	0.94	25.68	Yield pseudo plastic
	S-II	15.25	Herschel-Bulkley	0.90	41.24	Yield pseudo plastic
	S-III	12.15	Herschel-Bulkley	0.91	26.47	Yield pseudo plastic
35	S-I	2.56	Herschel-Bulkley	0.97	14.83	Yield pseudo plastic
	S-II	4.03	Herschel-Bulkley	0.95	21.23	Yield pseudo plastic
	S-III	3.42	Herschel-Bulkley	0.96	17.28	Yield pseudo plastic
40	S-I	1.07	Herschel-Bulkley	0.95	10.51	Yield pseudo plastic
	S-II	1.94	Herschel-Bulkley	0.96	12.78	Yield pseudo plastic
	S-III	1.37	Herschel-Bulkley	0.95	11.53	Yield pseudo plastic
45	S-I	0.59	Herschel-Bulkley	0.91	6.29	Yield pseudo plastic
	S-II	1.29	Herschel-Bulkley	0.91	10.3	Yield pseudo plastic
	S-III	0.85	Herschel-Bulkley	0.98	9.03	Yield pseudo plastic

CHAPTER 5 CONCLUSION AND FURTHER SCOPE

5.1 CONCLUSIONS

The rheological behavior of coal-oil mixture was investigated with the variation of solids concentration and temperature. The conclusions of the present study are as follows:

- It was found that an increase in temperature above 45° C had a less effect on decrease in apparent viscosity of coal-oil mixture.
- It was observed that there was a sharp increase in apparent viscosity as solids concentration was increased from 40 % to 50 % and this increase was more noticeable at lower temperatures as compared to higher temperatures.
- Up to 30 % solids concentration, all three coal-oil mixtures behaved as a Newtonian fluid having viscosity independent of shear rate.
- Above 40 % solids concentration, all three coal-oil mixtures behaved as yield pseudo plastic fluid having a decrease in apparent viscosity with increase in shear rate.
- Both apparent viscosity and yield stress of coal-oil mixture decreased, with an increase in ash content of coal.
- Both apparent viscosity and yield stress of coal-oil mixture increased, with an increase in moisture content of coal.

- With an increase in mass median diameter of coal particles, both apparent viscosity and yield stress of coal-oil mixture decreased.
- With an increase in distribution modulus (n) of coal sample, both apparent viscosity and yield stress of coal-oil mixture increased.

5.2 FURTHER SCOPE IN COAL-OIL MIXTURE TECHNOLOGY

The main aim of the present study was to investigate the rheological behavior of coal-oil mixtures at different solids concentration and temperatures and to study the effect of different coal properties like ash content, moisture content, particle size and particle size distribution on coal-oil mixture rheology. The various works that can augment the present study are:

1. Investigation of rheological behavior of coal-oil mixtures in the presence of additives.
2. Investigation of rheological behavior of coal-oil-water mixtures.
3. Investigation of rheological behavior of coal-oil mixtures with ethanol blends.

There is still a large scope for further research work in the field of coal-oil mixture technology for its efficient utilization.

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APPENDIX

A1: Particle Size Distribution (% finer by weight)

Table A1: PSD results for three coal samples

Particle Size (µm)	S-I	S-II	S-III
500	100	100	100
355	94.285	98.685	97.15
250	63.035	80.92	75.75
150	15.715	43.345	33.87
106	3.875	15.995	11.12
75	0.25	4.89	3.35
53	0	0	0

B1: Rheology of coal-oil mixtures at C_w = 20 % and temperature 25^o C

Table B1.1: Rheology of coal-oil mixture for S-I

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0
11.1	1.04	11.8
11.1	2.07	22.9
10.9	3.11	33.7
10.7	4.14	44.2
10.6	5.18	54.6
10.5	6.21	64.9
10.4	7.24	75.6
10.4	8.28	86
10.4	9.31	96.7
10.4	10.3	107
10.4	11.4	118
10.4	12.4	129
10.4	13.4	140
10.4	14.5	151
10.5	15.5	162
10.5	16.6	174
10.5	17.6	185
10.5	18.6	196
10.5	19.7	207
10.5	20.7	218
10.5	21.7	228
10.5	22.8	240
10.5	23.8	250
10.5	24.8	262
10.5	25.9	272
10.5	26.9	283
10.5	27.9	294
10.5	29	305
10.5	30	316

Table B1.2: Rheology of coal-oil mixture for S-II

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0
16.5	1.04	17.2
16.5	2.07	33.2
16.5	3.11	51.3
15.8	4.14	65.5
15.4	5.18	79.9
15.1	6.21	93.9
14.9	7.24	108
14.8	8.28	122
14.7	9.31	136
14.6	10.3	151
14.5	11.4	165
14.4	12.4	179
14.3	13.5	192
14.2	14.5	206
14.2	15.5	220
14.1	16.6	233
14	17.6	247
14	18.6	260
13.9	19.7	273
13.8	20.7	286
13.8	21.7	299
13.7	22.8	311
13.6	23.8	324
13.5	24.8	336
13.5	25.9	349
13.4	26.9	361
13.4	27.9	373
13.3	29	386
13.3	30	398

Table B1.3: Rheology of coal-oil mixture for S-III

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0
14.1	1.04	14.3
14.1	2.07	29.3
13.6	3.11	42.4
13.4	4.14	55.5
13.3	5.17	68.6
13.1	6.21	81.4
13	7.24	94.2
13	8.28	107
12.9	9.31	120
12.9	10.3	134
12.9	11.4	147
12.9	12.4	160
12.9	13.4	174
12.9	14.5	187
12.9	15.5	200
12.9	16.6	214
12.9	17.6	227
12.9	18.6	240
12.9	19.7	254
12.9	20.7	267
12.9	21.7	280
12.9	22.8	293
12.8	23.8	305
12.8	24.8	318
12.8	25.9	331
12.7	26.9	343
12.7	27.9	355
12.7	29	367
12.6	30	379

B2: Rheology of coal-oil mixtures at C_w = 20 % and temperature 30^o C

Table B2.1: Rheology of coal-oil mixture for S-I

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0
3.96	1.04	4.1
4.07	2.07	8.44
4.09	3.11	12.7
4.09	4.14	16.9
4.08	5.17	21.1
4.08	6.21	25.4
4.08	7.24	29.6
4.1	8.28	33.9
4.09	9.31	38.1
4.11	10.3	42.5
4.12	11.4	46.9
4.13	12.4	51.2
4.14	13.5	55.7
4.15	14.5	60.1
4.15	15.5	64.4
4.16	16.6	68.9
4.18	17.6	73.5
4.18	18.6	77.9
4.19	19.7	82.4
4.19	20.7	86.7
4.2	21.7	91.2
4.2	22.8	95.7
4.21	23.8	100
4.21	24.8	105
4.22	25.9	109
4.23	26.9	114
4.23	27.9	118
4.23	29	123
4.24	30	127

Table B2.2: Rheology of coal-oil mixture for S-II

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0
5.46	1.04	5.67
5.39	2.07	11.2
5.36	3.11	16.6
5.37	4.14	22.3
5.38	5.17	27.8
5.37	6.21	33.3
5.35	7.24	38.8
5.36	8.28	44.3
5.38	9.31	50.1
5.36	10.3	55.5
5.36	11.4	61
5.37	12.4	66.6
5.38	13.5	72.3
5.39	14.5	78
5.39	15.5	83.6
5.38	16.6	89.1
5.38	17.6	94.6
5.38	18.6	100
5.38	19.7	106
5.38	20.7	111
5.38	21.7	117
5.38	22.8	123
5.38	23.8	128
5.37	24.8	133
5.37	25.9	139
5.37	26.9	144
5.36	27.9	150
5.35	29	155
5.34	30	160

Table B2.3: Rheology of coal-oil mixture for S-III

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0
4.77	1.04	4.95
4.92	2.07	10.2
5.01	3.11	15.6
4.99	4.14	20.7
4.98	5.18	25.8
4.98	6.21	30.9
4.99	7.24	36.1
4.99	8.28	41.3
5.01	9.31	46.7
5.02	10.3	51.9
5.02	11.4	57.1
5.03	12.4	62.4
5.04	13.5	67.8
5.05	14.5	73.2
5.07	15.5	78.7
5.08	16.6	84.1
5.09	17.6	89.5
5.1	18.6	95
5.11	19.7	100
5.12	20.7	106
5.13	21.7	111
5.14	22.8	117
5.14	23.8	122
5.15	24.8	128
5.15	25.9	133
5.15	26.9	139
5.15	27.9	144
5.16	29	149
5.15	30	155

B3: Rheology of coal-oil mixtures at C_w = 20 % and temperature 35^o C

Table B3.1: Rheology of coal-oil mixture for S-I

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0
2.2	1.04	2.28
2.35	2.07	4.86
2.36	3.11	7.33
2.36	4.14	9.79
2.37	5.18	12.3
2.37	6.21	14.7
2.38	7.24	17.3
2.39	8.28	19.7
2.39	9.31	22.2
2.4	10.3	24.8
2.4	11.4	27.3
2.41	12.4	29.9
2.41	13.5	32.3
2.42	14.5	35
2.42	15.5	37.5
2.42	16.6	40.1
2.42	17.6	42.5
2.42	18.6	45
2.42	19.7	47.5
2.42	20.7	50
2.41	21.7	52.4
2.41	22.8	54.8
2.4	23.8	57.1
2.4	24.8	59.6
2.4	25.9	62
2.39	26.9	64.3
2.39	27.9	66.8
2.38	29	69
2.38	30	71.5

Table B3.2: Rheology of coal-oil mixture for S-II

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0
2.47	1.04	2.56
2.59	2.07	5.37
2.68	3.11	8.32
2.68	4.14	11.1
2.7	5.18	14
2.7	6.21	16.8
2.72	7.24	19.7
2.72	8.28	22.5
2.73	9.31	25.4
2.74	10.3	28.4
2.74	11.4	31.2
2.75	12.4	34.2
2.76	13.4	37.2
2.77	14.5	40.1
2.78	15.5	43.1
2.78	16.6	46
2.79	17.6	49
2.79	18.6	52
2.8	19.7	55
2.8	20.7	58
2.8	21.7	60.9
2.81	22.8	63.9
2.81	23.8	66.9
2.81	24.8	69.8
2.81	25.9	72.7
2.81	26.9	75.6
2.81	27.9	78.5
2.81	29	81.3
2.81	30	84.2

Table B3.3: Rheology of coal-oil mixture for S-III

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0
2.54	1.04	2.64
2.63	2.07	5.46
2.72	3.11	8.46
2.74	4.14	11.3
2.75	5.17	14.2
2.75	6.21	17.1
2.76	7.24	20
2.76	8.28	22.8
2.76	9.31	25.7
2.76	10.3	28.6
2.76	11.4	31.4
2.76	12.4	34.3
2.77	13.5	37.3
2.77	14.5	40.2
2.77	15.5	43
2.78	16.6	46
2.78	17.6	48.9
2.78	18.6	51.8
2.78	19.7	54.7
2.79	20.7	57.6
2.78	21.7	60.4
2.78	22.8	63.4
2.78	23.8	66.1
2.78	24.8	69
2.77	25.9	71.7
2.77	26.9	74.6
2.77	27.9	77.4
2.77	29	80.2
2.76	30	82.9

B4: Rheology of coal-oil mixtures at C_w = 20 % and temperature 40^{o} C

Table B4.1: Rheology of coal-oil mixture for S-I

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0
1.51	1.04	1.56
1.61	2.07	3.33
1.62	3.11	5.05
1.63	4.14	6.73
1.6	5.18	8.3
1.61	6.21	10
1.6	7.24	11.6
1.6	8.28	13.3
1.61	9.31	15
1.6	10.3	16.6
1.62	11.4	18.4
1.61	12.4	20
1.62	13.5	21.8
1.62	14.5	23.4
1.61	15.5	25.1
1.62	16.6	26.8
1.62	17.6	28.4
1.61	18.6	30
1.61	19.7	31.6
1.6	20.7	33.2
1.6	21.7	34.7
1.6	22.8	36.3
1.58	23.8	37.7
1.58	24.8	39.2
1.57	25.9	40.7
1.57	26.9	42.2
1.56	27.9	43.6
1.56	29	45.1
1.55	30	46.5

Table B4.2: Rheology of coal-oil mixture for S-II

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0
1.47	1.04	1.52
1.65	2.07	3.42
1.71	3.11	5.32
1.72	4.14	7.11
1.73	5.18	8.97
1.74	6.21	10.8
1.72	7.25	12.5
1.73	8.28	14.3
1.72	9.31	16.1
1.73	10.3	17.9
1.73	11.4	19.7
1.74	12.4	21.6
1.74	13.5	23.4
1.74	14.5	25.2
1.74	15.5	27.1
1.75	16.6	28.9
1.75	17.6	30.7
1.75	18.6	32.6
1.75	19.7	34.5
1.76	20.7	36.3
1.75	21.7	38
1.75	22.8	39.9
1.75	23.8	41.7
1.75	24.8	43.5
1.76	25.9	45.4
1.75	26.9	47.2
1.76	27.9	49.1
1.75	29	50.8
1.75	30	52.6

Table B4.3: Rheology of coal-oil mixture for S-III

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0
1.59	1.04	1.64
1.69	2.07	3.5
1.78	3.11	5.54
1.78	4.14	7.38
1.8	5.18	9.34
1.8	6.21	11.2
1.8	7.24	13
1.81	8.28	14.9
1.81	9.31	16.8
1.8	10.3	18.6
1.8	11.4	20.5
1.8	12.4	22.4
1.81	13.5	24.3
1.8	14.5	26.1
1.8	15.5	27.9
1.8	16.6	29.9
1.8	17.6	31.6
1.8	18.6	33.5
1.79	19.7	35.3
1.79	20.7	37
1.78	21.7	38.7
1.78	22.8	40.5
1.78	23.8	42.4
1.77	24.8	44
1.77	25.9	45.8
1.77	26.9	47.5
1.76	27.9	49.3
1.76	29	51
1.76	30	52.7

B5: Rheology of coal-oil mixtures at C_w = 20 % and temperature 45^o C

Table B5.1: Rheology of coal-oil mixture for S-I

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0
1.13	1.04	1.17
1.15	2.07	2.39
1.2	3.11	3.74
1.28	4.14	5.29
1.26	5.18	6.53
1.26	6.21	7.8
1.25	7.24	9.06
1.25	8.28	10.3
1.24	9.31	11.5
1.23	10.3	12.8
1.23	11.4	14
1.22	12.4	15.2
1.22	13.5	16.4
1.21	14.5	17.6
1.21	15.5	18.7
1.2	16.6	19.9
1.2	17.6	21.1
1.19	18.6	22.2
1.19	19.7	23.4
1.19	20.7	24.5
1.18	21.7	25.7
1.18	22.8	26.8
1.17	23.8	27.9
1.17	24.8	29.1
1.16	25.9	30.1
1.16	26.9	31.1
1.15	27.9	32.1
1.14	29	33.1
1.14	30	34.1

Table B5.2: Rheology of coal-oil mixture for S-II

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0
1.18	1.04	1.22
1.32	2.07	2.73
1.42	3.11	4.42
1.39	4.14	5.74
1.38	5.18	7.15
1.39	6.21	8.63
1.39	7.25	10.1
1.37	8.28	11.4
1.38	9.31	12.9
1.36	10.3	14.1
1.36	11.4	15.5
1.36	12.4	16.8
1.36	13.5	18.2
1.35	14.5	19.6
1.35	15.5	20.9
1.34	16.6	22.2
1.33	17.6	23.4
1.33	18.6	24.7
1.32	19.7	25.9
1.32	20.7	27.2
1.31	21.7	28.4
1.3	22.8	29.7
1.3	23.8	30.9
1.29	24.8	32.1
1.29	25.9	33.3
1.28	26.9	34.5
1.28	27.9	35.7
1.27	29	36.9
1.27	30	38

Table B5.3: Rheology of coal-oil mixture for S-III

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0
1.07	1.04	1.11
1.31	2.07	2.72
1.36	3.11	4.21
1.36	4.14	5.65
1.36	5.17	7.03
1.35	6.21	8.4
1.36	7.24	9.86
1.36	8.28	11.2
1.35	9.31	12.6
1.35	10.3	13.9
1.34	11.4	15.3
1.34	12.4	16.7
1.33	13.5	17.9
1.33	14.5	19.3
1.33	15.5	20.7
1.33	16.6	21.9
1.32	17.6	23.2
1.32	18.6	24.5
1.31	19.7	25.8
1.31	20.7	27.1
1.3	21.7	28.3
1.3	22.8	29.7
1.3	23.8	31
1.29	24.8	32.1
1.29	25.9	33.5
1.29	26.9	34.6
1.29	27.9	35.9
1.28	29	37.1
1.28	30	38.3

B6: Rheology of coal-oil mixtures at C_w = 50 % and temperature 25^o C

Table B6.1: Rheology of coal-oil mixture for S-I

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	55.91
122	1.04	126
102	2.07	211
92	3.11	286
86.4	4.14	358
82.3	5.18	426
79	6.21	491
76.6	7.25	555
74.9	8.28	620
73.6	9.31	685
72.2	10.3	747
70.6	11.4	803
69.5	12.4	863
68.7	13.4	923
67.5	14.5	978
66.5	15.5	1,030
65.8	16.6	1,090
64.8	17.6	1,140
64	18.6	1,190
63.2	19.7	1,240
62.3	20.7	1,290
61.5	21.7	1,340
60.7	22.8	1,380
60.1	23.5	1,410
59.8	23.6	1,410
59.5	23.7	1,410
59.7	23.7	1,410
59.1	23.9	1,410
59.5	23.7	1,410
59.6	23.7	1,410

Table B6.2: Rheology of coal-oil mixture for S-II

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	103.3
200	1.04	208
157	2.07	326
137	3.11	426
125	4.14	520
118	5.18	610
112	6.21	697
108	7.24	784
105	8.28	870
101	9.31	945
98.2	10.3	1,020
96.5	11.4	1,100
94.8	12.4	1,180
92	13.5	1,240
90.4	14.5	1,310
89	15.5	1,380
87.9	16.1	1,410
87.6	16.1	1,410
87.2	16.2	1,410
87	16.2	1,410
87	16.2	1,410
86.9	16.3	1,410
87	16.2	1,410
86.8	16.3	1,410
86.3	16.4	1,410
86.4	16.4	1,410
86.6	16.3	1,410
86.2	16.4	1,410
86.2	16.4	1,410
85.5	16.5	1,410

Table B6.3: Rheology of coal-oil mixture for S-III

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	89.63
178	1.04	185
138	2.07	286
120	3.11	373
110	4.14	455
103	5.18	534
98.4	6.21	611
94.7	7.25	686
91.6	8.28	758
89.1	9.31	829
86.7	10.3	898
84.7	11.4	964
82.8	12.4	1,030
80.9	13.5	1,090
79.3	14.5	1,150
77.8	15.5	1,210
76.3	16.6	1,260
74.8	17.6	1,320
73.5	18.6	1,370
72.3	19.5	1,410
71.8	19.7	1,410
71.4	19.8	1,410
71.1	19.9	1,410
70.8	20	1,410
70.5	20	1,410
70.2	20.1	1,410
69.9	20.2	1,410
69.6	20.3	1,410
69.4	20.4	1,410
69.1	20.4	1,410

B7: Rheology of coal-oil mixtures at C_w = 50 % and temperature 30^o C

Table B7.1: Rheology of coal-oil mixture for S-I

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	9.85
32.6	1.04	33.8
30.9	2.07	64
29.5	3.11	91.5
28.7	4.14	119
28	5.18	145
27.7	6.21	172
27.3	7.24	198
27.1	8.28	224
26.9	9.31	250
26.7	10.3	276
26.5	11.4	302
26.4	12.4	328
26.4	13.4	355
26.2	14.5	380
26.1	15.5	405
26.1	16.6	432
26	17.6	458
25.9	18.6	483
25.9	19.7	510
25.8	20.7	535
25.7	21.7	559
25.7	22.8	585
25.5	23.8	608
25.5	24.8	633
25.3	25.9	655
25.3	26.9	681
25.1	27.9	701
25.1	29	726
25	30	749

Table B7.2: Rheology of coal-oil mixture for S-II

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	15.25
51.4	1.04	53.5
46.4	2.07	96.1
44	3.11	137
42.4	4.14	176
41.6	5.17	215
40.7	6.21	253
40	7.24	290
39.3	8.28	325
38.7	9.31	360
38.3	10.3	396
37.9	11.4	431
37.6	12.4	467
37.3	13.5	501
37.1	14.5	537
36.7	15.5	570
36.5	16.6	605
36	17.6	633
35.8	18.6	666
35.4	19.7	697
35.1	20.7	726
34.8	21.7	756
34.7	22.8	790
34.3	23.8	816
34.2	24.8	848
33.8	25.9	874
33.6	26.9	903
33.3	27.9	930
32.8	29	951
32.8	30	984

Table B7.3: Rheology of coal-oil mixture for S-III

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	12.15
35.8	1.04	37.2
32.8	2.07	67.9
31.6	3.11	98
30.6	4.14	127
30	5.18	155
29.6	6.21	184
29.3	7.24	212
29.1	8.28	241
28.9	9.31	270
28.9	10.3	299
28.8	11.4	327
28.7	12.4	356
28.7	13.4	385
28.6	14.5	414
28.5	15.5	443
28.5	16.6	472
28.5	17.6	501
28.4	18.6	529
28.3	19.7	557
28.2	20.7	584
28.1	21.7	611
28	22.8	638
27.9	23.8	665
27.8	24.8	691
27.7	25.9	717
27.6	26.9	742
27.4	27.9	767
27.3	29	791
27.2	30	815

B8: Rheology of coal-oil mixtures at C_w = 50 % and temperature 35^o C

Table B8.1: Rheology of coal-oil mixture for S-I

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	2.56
16.3	1.04	16.9
15.9	2.07	32.9
15.6	3.11	48.4
15.2	4.14	63.1
15	5.17	77.5
14.8	6.21	92
14.7	7.24	107
14.7	8.28	121
14.6	9.31	136
14.5	10.3	150
14.4	11.4	164
14.3	12.4	178
14.3	13.5	192
14.3	14.5	207
14.2	15.5	220
14.1	16.6	234
14.1	17.6	248
14	18.6	262
14	19.7	276
14	20.7	289
13.9	21.7	302
13.9	22.8	316
13.8	23.8	329
13.8	24.8	342
13.7	25.9	355
13.7	26.9	368
13.6	27.9	379
13.5	29	392
13.5	30	405

Table B8.2: Rheology of coal-oil mixture for S-II

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	4.03
23.5	1.04	24.4
22.6	2.07	46.8
21.7	3.11	67.4
21.1	4.14	87.6
20.7	5.18	107
20.4	6.21	127
20.2	7.24	147
20.1	8.28	166
20	9.31	186
20	10.3	207
19.7	11.4	225
19.5	12.4	242
19.4	13.4	261
19.4	14.5	281
19.2	15.5	299
19	16.6	315
19	17.6	335
18.9	18.6	352
18.7	19.7	368
18.7	20.7	387
18.5	21.7	403
18.5	22.8	421
18.4	23.8	437
18.3	24.8	454
18.1	25.9	469
18	26.9	486
18	27.9	502
17.8	29	516
17.8	30	533

Table B8.3: Rheology of coal-oil mixture for S-III

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	3.42
16.7	1.04	17.3
15.9	2.07	33
15.6	3.11	48.4
15.5	4.14	64
15.3	5.18	79.1
15.2	6.21	94.1
15	7.24	109
15	8.28	124
14.9	9.31	139
14.9	10.3	154
14.8	11.4	169
14.8	12.4	183
14.7	13.5	198
14.7	14.5	213
14.7	15.5	228
14.6	16.6	242
14.6	17.6	257
14.6	18.6	272
14.5	19.7	286
14.5	20.7	300
14.5	21.7	315
14.4	22.8	329
14.4	23.8	343
14.4	24.8	357
14.4	25.9	371
14.3	26.9	385
14.3	27.9	399
14.2	29	412
14.2	30	425

B9: Rheology of coal-oil mixtures at C_w = 50 % and temperature 40^o C

Table B9.1: Rheology of coal-oil mixture for S-I

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	1.07
10.9	1.04	11.3
10.6	2.07	22
10.5	3.11	32.5
10.2	4.14	42.4
10.2	5.18	52.7
10	6.21	62.4
9.95	7.24	72
9.88	8.28	81.8
9.8	9.31	91.3
9.74	10.3	101
9.69	11.4	110
9.63	12.4	120
9.59	13.5	129
9.53	14.5	138
9.47	15.5	147
9.43	16.6	156
9.38	17.6	165
9.34	18.6	174
9.29	19.7	183
9.24	20.7	191
9.21	21.7	200
9.15	22.8	208
9.11	23.8	217
9.07	24.8	225
9.02	25.9	233
8.99	26.9	242
8.94	27.9	250
8.91	29	258
8.86	30	266

Table B9.2: Rheology of coal-oil mixture for S-II

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	1.94
13.8	1.04	14.3
13.4	2.07	27.9
13.1	3.11	40.7
12.8	4.14	53
12.5	5.17	64.9
12.4	6.21	77
12.3	7.24	89
12.2	8.28	101
12.2	9.31	114
12.1	10.3	126
12	11.4	137
11.9	12.4	148
11.9	13.4	160
11.9	14.5	172
11.8	15.5	183
11.7	16.6	194
11.7	17.6	206
11.6	18.6	217
11.5	19.7	227
11.5	20.7	238
11.5	21.7	249
11.4	22.8	260
11.4	23.8	271
11.3	24.8	282
11.3	25.9	292
11.3	26.9	303
11.2	27.9	312
11.2	29	323
11.1	30	333

Table B9.3: Rheology of coal-oil mixture for S-III

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	1.37
11.2	1.04	11.7
10.7	2.07	22.2
10.5	3.11	32.5
10.3	4.14	42.8
10.2	5.18	52.7
10.1	6.21	62.6
9.97	7.24	72.2
9.86	8.28	81.7
9.8	9.31	91.2
9.71	10.3	101
9.66	11.4	110
9.6	12.4	119
9.51	13.5	128
9.48	14.5	137
9.44	15.5	146
9.38	16.6	155
9.32	17.6	164
9.27	18.6	173
9.21	19.7	181
9.17	20.7	190
9.14	21.7	199
9.08	22.8	207
9.05	23.8	215
9.01	24.8	224
8.95	25.9	232
8.94	26.9	240
8.89	27.9	248
8.87	29	257
8.82	30	265

B10: Rheology of coal-oil mixtures at C_w = 50 % and temperature 45^o C

Table B10.1: Rheology of coal-oil mixture for S-I

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0.59
8.98	1.04	9.32
8.93	2.07	18.5
8.77	3.11	27.3
8.6	4.14	35.6
8.52	5.18	44.1
8.39	6.21	52.1
8.26	7.24	59.8
8.17	8.28	67.6
8.03	9.31	74.8
7.93	10.3	82.1
7.84	11.4	89.2
7.76	12.4	96.3
7.67	13.5	103
7.6	14.5	110
7.53	15.5	117
7.47	16.6	124
7.4	17.6	130
7.33	18.6	137
7.27	19.7	143
7.21	20.7	149
7.15	21.7	155
7.09	22.8	161
7.04	23.8	167
6.99	24.8	173
6.94	25.9	179
6.88	26.9	185
6.84	27.9	191
6.79	29	197
6.75	30	202

Table B10.2: Rheology of coal-oil mixture for S-II

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	1.29
10.5	1.04	10.9
10.2	2.07	21
9.92	3.11	30.8
9.69	4.14	40.1
9.52	5.17	49.3
9.36	6.21	58.1
9.21	7.24	66.7
9.05	8.28	74.9
8.9	9.31	82.9
8.78	10.3	90.8
8.67	11.4	98.7
8.54	12.4	106
8.43	13.5	113
8.36	14.5	121
8.29	15.5	129
8.21	16.6	136
8.15	17.6	143
8.08	18.6	151
8.02	19.7	158
7.97	20.7	165
7.91	21.7	172
7.85	22.8	179
7.81	23.8	186
7.74	24.8	192
7.71	25.9	199
7.62	26.9	205
7.6	27.9	212
7.53	29	218
7.54	30	226

Table B10.3: Rheology of coal-oil mixture for S-III

Apparent viscosity (Pa.s)	Shear rate (1/s)	Shear stress (Pa)
-	0	0.85
6.81	1.04	7.07
6.54	2.07	13.5
6.46	3.11	20.1
6.45	4.14	26.7
6.36	5.17	32.9
6.32	6.21	39.2
6.29	7.24	45.6
6.24	8.28	51.7
6.23	9.31	58
6.19	10.3	64.1
6.17	11.4	70.2
6.13	12.4	76.1
6.11	13.5	82.2
6.09	14.5	88.2
6.07	15.5	94.1
6.04	16.6	100
6.02	17.6	106
6	18.6	112
5.99	19.7	118
5.97	20.7	124
5.95	21.7	129
5.94	22.8	135
5.93	23.8	141
5.91	24.8	147
5.89	25.9	152
5.87	26.9	158
5.85	27.9	164
5.83	29	169
5.82	30	174