

**STUDY OF SLURRY FLOW BEHAVIOUR OF MULTI-SIZED PARTICULATE ASH
SLURRY**

A

Dissertation Submitted

In partial fulfillment of the required of the degree

Of

MASTER OF ENGINEERING

IN

Thermal Engineering

By

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DECLARATION

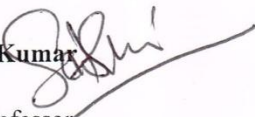
I hereby declare that the work being presented in the thesis entitled "**STUDY ON FLOW BEHAVIOUR OF MULTI-SIZED PARTICULATE ASH SLURRY**" in partial fulfillment of the requirements for the award of degree of Masters in Thermal Engineering is my own laboratory work during the period of January 2013 to June 2013, under the supervision and conception of Mr. Satish Kumar, Assistant Professors, Mechanical Engineering Department, Thapar University, Patiala, refers other researchers work which are duly listed in reference section.

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

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ACKNOWLEDGEMENT

I express my sincere gratitude to **Mr. Satish Kumar, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala**, for his valuable guidance, proper advice and constant encouragement of my work in this seminar.

I do not find enough words with which I can express my feeling of thanks to the entire faculty and staff of **Mechanical Engineering Department, Thapar University, Patiala**, for their help, inspiration and moral support.

I would also like to thank my family for their constant encouragement and moral support to pursue higher studies in the field of Thermal engineering and last but not the least; I thank numerous researchers who have published some path breaking results in the field of coal ash-water slurry technology.

Date: 15 July 2013

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Place: Patiala

ABSTRACT

Transportation of fly ash to the ash ponds from thermal power stations was disposed by slurry pipeline. Both the power plant i.e. Guru Nanak Dev Thermal power Plant, Bathinda and Rajiv Gandhi Thermal Power Plant, Hissar are transporting fly ash at low concentration which leads to more power requirement and water supply. Also reduce the life of pipeline due to excessive pipeline erosion wear.

Present work is aim to investigate the various physical as well as chemical properties such as Particle Size distribution, pH, Settling, Zeta Potential, SEM, EDX, Specific Gravity of two fly ash sample collected from Guru Nanak Dev Thermal Power Plant, Bathinda and Rajiv Gandhi Thermal Power Plant, Hissar. Rheology of both sieved as well as unsieved sample is studied at concentration varying from 30%-60% and particle size from 53-106 microns with and without additive (Sodium Lauryl Ether Sulphate). The slurry exhibit Newtonian behaviour till 40% for particle size below 53 and 53-75 microns and Non – Newtonian behaviour at 50% concentration. Addition of surfactant reduces the viscosity and makes the fly ash particle water borne at pH 6. Using rheological data, pressure drop has been calculated with the help of computer program on various efflux concentrations (40%, 50%, 60%) and flow velocity (1, 1.5, 2, 2.5, 3) m/s. The pressure drop in pipeline increases with increase in velocity. For the calculation of pressure drop in the slurry pipeline a computer program using C has been generated.

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NOMENCLATURE

Symbols	Meaning
τ	Shear Stress
γ	Shear Rate
η	Apparent Viscosity
K	Consistency Index
n	Flow Behaviour Index
τ_o	Yield Stress
μ_p	plastic viscosity
λ	Time Constant
m	Dimensionless Exponent.
V_1	Velocity of bigger pipe
V_2	Velocity of smaller pipe
H_e	Minor Head Loss due to expansion
H_c	Minor Head Loss due to contraction
h_b	Minor Head Loss due to bends
h_v	Minor Head Loss due to valve fittings
R	Radius of Curvature of the Bend
D	Diameter of the pipe
K_e	Coefficient of Expansion
K_c	Coefficient of Contraction

K_b	Coefficient of Bend
K_v	Coefficient of Valve
v	Velocity
h	Head loss
g	Gravity constant
C	Hazen-Williams Coefficient
D	Inside diameter
R	Hydraulic mean radius
f	Friction Factor
J	Hydraulic gradient
L	Length of the pipe
n	Manning's Coefficient
ESP	Electrostatic Precipitator
PSD	Particle Size Distribution
SEM	Scanning Electron Microscopy
EDX	Energy Dispersion X-Ray Spectroscopy

INTRODUCTION

A thermal power plant is an energy centre which converts heat energy into electrical energy. In this power plant, the prime mover is steam driven. Firstly Water was heated and converts into steam which spins a steam turbine and drives an electrical generator. After that exhaust steam was passed through condenser which condenses the steam and recycled to where it was heated. The difference in the design of thermal power stations was due to the use of different fossil fuel resources to heat the water. Some power plant use coal to heat water and produce electric power.

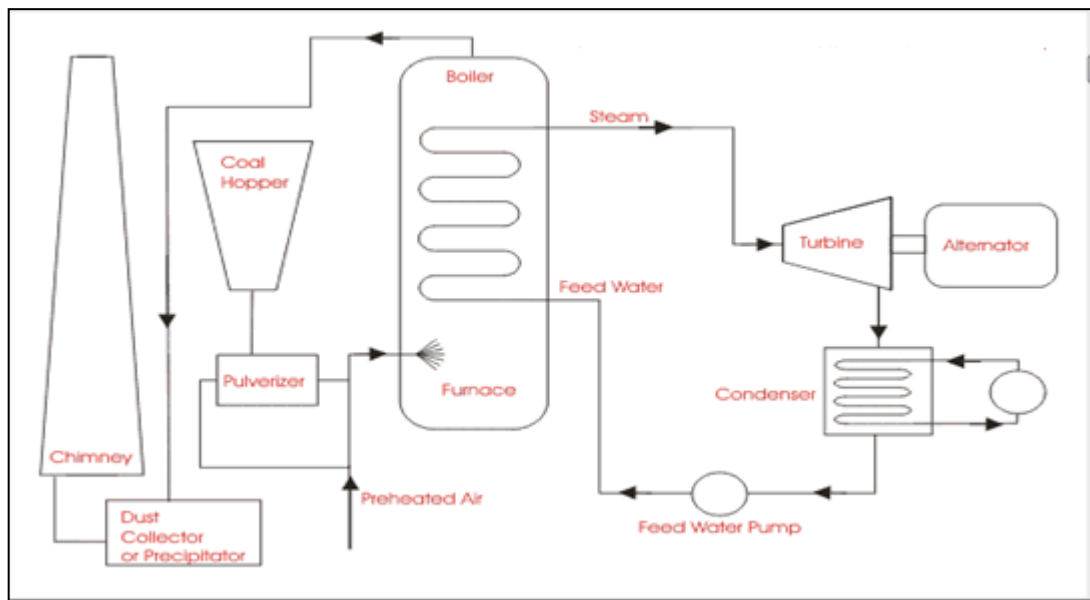


Figure 1.1: Schematic diagram of Thermal Power Plant [33]

1.1 COAL

It is one of the primary as well as largest resources of various power plants for generation of electricity. It is primarily composed of carbon along with variable quantities of other element such as hydrogen, sulfur, nitrogen, oxygen. Burning of coal causes global warming, acid rain and water pollution.



Figure 1.2: Anthracite Coal

When coal was burned in thermal power plant, it produces carbon dioxide and other emission in flue gas. About 75-80% of flue gas consists of fly ash which was collected with the help of electrostatic precipitator.



Figure 1.3: Coal Fired Thermal Power Plant [33]

In coal thermal power plant, steam was produced in boiler. This steam was passed through super heater which increases the pressure of steam. This high pressure steam enters into the turbine which rotates the turbine blades which was mechanically coupled with alternator that rotate the rotor of turbine blades. In turbine the steam pressure suddenly falls and corresponding volume of the steam increases. After imparting energy to the turbine rotator the steam passes into the condenser which condenses the low pressure wet steam with the help of cold water circulating

into it. This condensed water was further supplied to low pressure water heater and process was continued again.

1.2 COAL ASH

It is the by-product left behind when the coal is burned in the thermal power plant to generate electricity. It consists of arsenic, mercury, selenium, chromium and cadmium. It is of two types:

- 1 Fly ash
2. Bottom ash

1.2.1 Fly ash

One of the residues generated during combustion of coal which comprises of the fine particles and captured by electrostatic precipitators is named as Fly Ash. It is also known as flue ash since it rises with the flue gases. Since fly ash contain more contaminants than the bottom ash, so it was mixed with bottom ash to proportionate the level of contaminants within the range to qualify as non-hazardous waste in a given state.

1.2.2 Fly Ash Utilization in India

The fly ash generated from various volcanic activities and thermal power plants were utilized in number of areas as an alternative. Some of the areas where fly ash was utilized are shown through pie diagram given below:

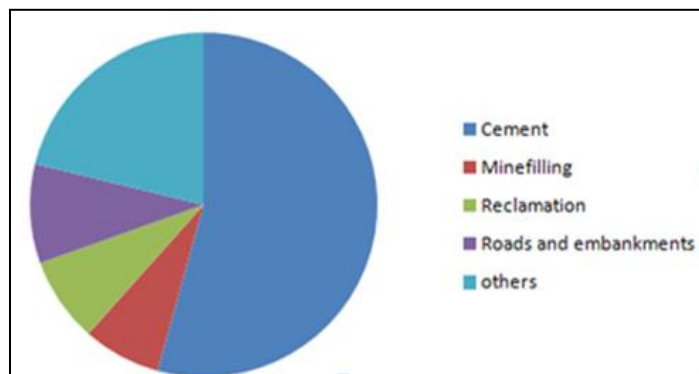


Figure 1.4: Utilization of Fly Ash in Various Areas

Others includes Distemper which replaces white cement, ceramics, and fertilizers. For fertilizer, fly ash provides vital minerals such as Ca, Mg, Fe, Zn, Mo, S and Se and can be considered as a potential growth improver.

1.2.3 Transportation of Fly Ash

Fly ash can be transported both dry and wet form:

1. Land transportation: In this fly ash was transported through trucks from thermal power plant to the source. This type of transportation was done when distance was small with 15 to 30 tons capacity. These trucks are diesel powered with back or bottom dump and most versatile of all transportation modes. However trucks suffer from many disadvantages relative to other transportation methods:
 - Highest unit energy consumption requirements
 - Highest net operating costs
 - Greatest external damage to highways



Figure 1.5: Land Transportation of Fly Ash

2. **Hydraulic Transportation:** In this type of transportation fly ash was pumped through pipeline or a network of pipelines in the form of slurry to the dam where it is disposed of. The water was somewhat recovered from the dam while some was lost to evaporation. The lower the solids concentration, the more quantity of water was transported and lost. The main advantages of slurry pipelines are:
- Large amounts of fly ash over long distances.
 - Cost-effective with a minimum potential for en-route environmental disruption.

The two major disadvantages are:

- Greater upstream water requirement.
- Lower degree of operational flexibility.



Figure 1.6: Hydraulic transportation of Fly Ash [21]

3. **Pneumatic Transportation:** In this system, air was used as medium to transport fly ash. The ratio of material to air should be high in order to transport material over long distance with less air. This system has more advantages compared to other transportation system:
- Long distance material transport in one stage.

- Lower power consumption.
- No storage in ESP hopper



Figure 1.7: Pneumatic Transportation of Fly Ash

1.3 SLURRY

Slurry is any fluid mixture made up of solid and liquid. Generally slurry was made in order to handle solid in bulk. Slurry can be classified according to the concentration.

1. High concentration slurry
2. Low concentration slurry

High concentration slurry are defined as a viscous fluid which consist of high solids content and low water content whereas low concentration slurry are made of high water content and low solid content. Slurry can cement water slurry, coal water slurry or coal ash slurry.

1.4 RHEOLOGY

Rheology is defined as study of flow of materials that exhibits a combination of elastic, viscous and plastic behaviour. Rheology has application in material science, chemistry, nano- particles, environmental studies, physiology, pharmaceuticals etc.

1.4.1 Rheological Parameters

1. Shear Stress: - The term F/A is referred to as shear stress. In fluid, amount of force applied on moving fluid area. Its units are N/m^2 which is referred as Pascal. It is expressed as τ .
2. Shear Rate: - It is defined as a ratio of velocity of a moving plate to the distance between two parallel plates. It is expressed as $\dot{\gamma}$. Its units are s^{-1} .
3. Viscosity: - It is defined as resistance to flow of fluid due to gradual deformation by shear stress. A fluid with zero viscosity is termed as Ideal fluid. It is expressed as η . Its units are Pa-s. It can be measured using two instrument:
 - a) Viscometer: - It is defined as an instrument which measure viscosity of fluid in one flow condition.
 - b) Rheometer: - It is defined as an instrument which measure viscosity of fluid in varying flow condition.
4. Fluid: - Fluid refers to both liquid and gases. It is defined as substance which deforms continuously under the applied shear stress. Fluid can be classified as:

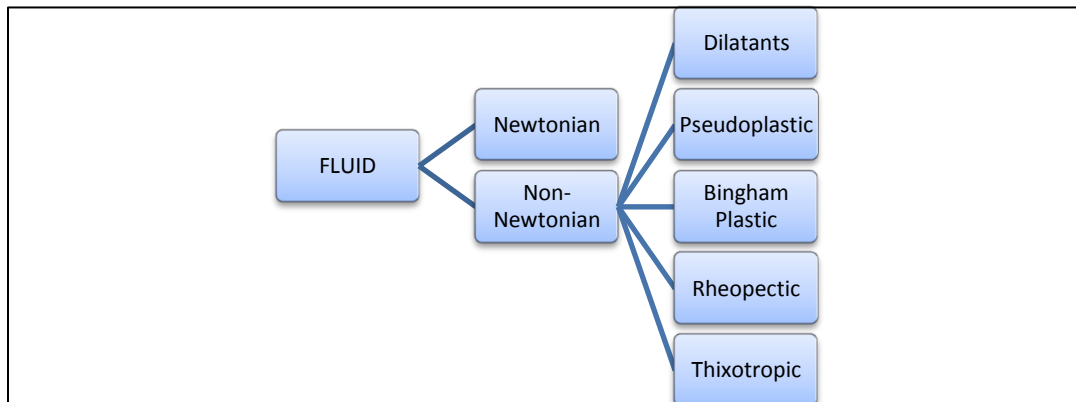


Figure 1.8: Classification of Fluids

- a) Newtonian Fluid: - Those fluids which obey Newton's law of viscosity are termed as Newtonian Fluid. In continuum mechanics, a fluid is said to be Newtonian if shear stress is directly proportional to the rate of change of shear rate.

$$\tau = \eta \cdot \dot{\gamma} \quad \text{Eq. (1.1)}$$

τ = shear stress (Pa)

$\dot{\gamma}$ = shear rate (s^{-1})

η = Apparent Viscosity (Pa-s)

- b) Non-Newtonian Fluid:-Those fluids which do not obey Newton's law of viscosity. These are further classified as:
- Pseudoplastic Fluid: These fluids are also known as shear thinning fluid. In these fluids, apparent viscosity decreases with increase in shear stress. Example: nail polish, ketchup etc.
 - Dilatants Fluid: These fluids are also known as shear thickening fluid. In these fluids, apparent viscosity increases with increase in shear stress. Example: suspension of corn starch in water, sand in water etc.
 - Bingham Plastic Fluid: These are those fluids which require some yield stress to flow. Example: Toothpaste, chocolate etc.
 - Rheopectic Fluids: - These are those fluids which require increase in shear stress to maintain constant shear rate are referred as Rheopectic fluids
 - Thixotropic Fluids: - These are those fluids which require decrease in shear stress to maintain constant shear rate are referred as Thixotropic fluids.

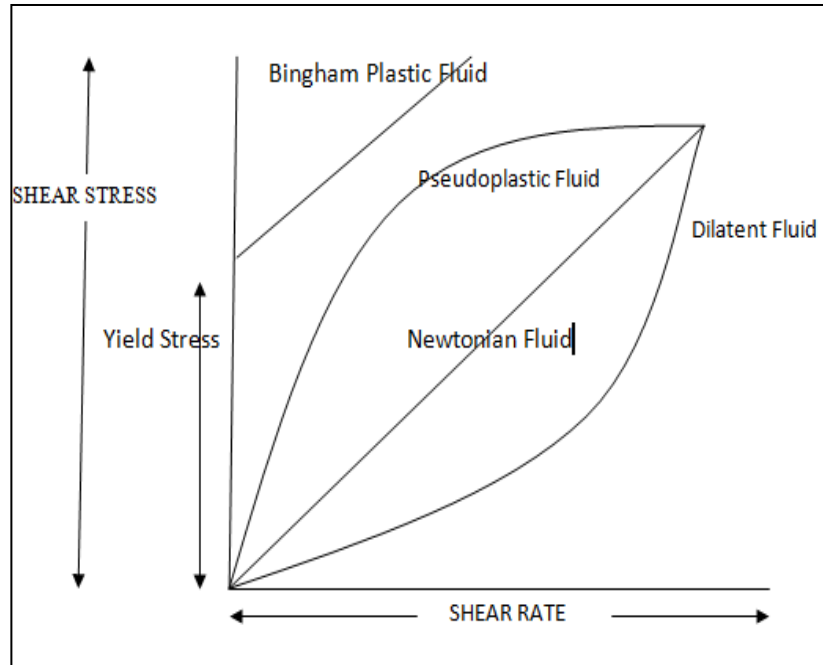


Figure 1.9: Relationship between shear stress and shear rate for different types of fluids

1.4.2 Rheological Model For Solid- Liquid Flow

In order to define the relationship between shear rate and shear stress, several models have been developed. These are classified as follow:

1. Newtonian Model: This model obeys newtons law of viscosity which states as shear stress is directly proportional to rate of change of shear rate. Hence value of flow behaviour index i.e. $n=1$ for Newtonian fluids.

$$\tau = \eta^* \frac{du}{dy} \quad \text{Eq. (1.2)}$$

τ = shear stress (Pa)

du/dy = shear rate (s^{-1})

η = Apparent Viscosity (Pa-s)

2. Non-Newtonian Model: Those models which do not obey Newtons Law of viscosity are termed as non- Newtonian model. These are further classified as:

- a) Power Law Model: This model was developed by Ostwald Reiner in 1926. It is expressed as:

$$\tau = K \gamma^n \quad \text{Eq. (1.3)}$$

The apparent viscosity is estimated as:

$$\eta = \tau/\gamma = K\gamma^{n-1} \quad \text{Eq. (1.4)}$$

Where η is the apparent viscosity (poise), τ is shear stress (dyne/cm²), γ is shear rate (s⁻¹), K is consistency index (Pa/s) which defines viscous behaviour of fluid, n is flow behaviour index which characterize the fluid as Newtonian or non- Newtonian.

$n < 1$, pseudoplastic - viscosity decreases with shear rate.

$n = 1$, Newtonian – viscosity does not change with shear rate.

$n > 1$, Dilatants – viscosity increases with shear rate.

- b) Bingham model: This model was developed by Bingham in 1922. It is expressed as

$$\tau = \tau_o + \mu_p \gamma^n \quad \text{Eq. (1.5)}$$

Where τ_o is yield stress (Pa) and μ_p is plastic viscosity. Both the parameters are independent of shear rate.

- c) Herschel-Bulkley model: This model was developed by Herschel and Bulkley in 1926. It is a three parameter model in which third parameter describe the flow behaviour in lower and upper Newtonian region as well as in power law region [20]. It is expressed as

$$\tau = \tau_o + K\gamma^n \quad \text{Eq (1.6)}$$

Where plastic viscosity in Bingham law model is replaced by consistency coefficient in power law model.

- d) Sisko model: This model was developed by Sisko in 1958. It is a three parameter model which defines flow in power law region and upper Newtonian region [20]. It is expressed as:

$$\eta = \eta_{\infty} + K\dot{\gamma}^n \quad \text{Eq. (1.7)}$$

- e) Carreau model: This model was developed by Carreau in 1968. It is four parameter models and can be used for entire shear rate range. In this model flow changes from the lower Newtonian region to the Power law region [20]. These models were mostly used for food and beverages [2] and blood flow [8]. It is expressed as

$$\frac{\eta - \eta_{\infty}}{\eta_0 - \eta_{\infty}} = (1 + (\lambda\dot{\gamma})^2)^{(n-1)/2} \quad \text{Eq.(1.8)}$$

Where λ is a time constant which is calculated from the point on the viscosity vs. shear rate curve [20].

- f) Cross Model: This model was developed by Cross in 1965. It is also four parameter model which gives best results for Non – Newtonian fluids like activated sludge. It is expressed as

$$\frac{\eta - \eta_{\infty}}{\eta_0 - \eta_{\infty}} = \frac{1}{(1 + (\lambda\dot{\gamma})^m)} \quad \text{Eq. (1.9)}$$

Where λ is the time constant and m is a dimensionless exponent.

1.5 PRESSURE DROP (ΔP) IN PIPELINE

Pipeline is defined as a long, closed conduit with a circular cross-section to transport liquids and gases inside it. There were pneumatic pipelines which transport solid capsules using compressed air. Examples include sewage, coal-slurry, water, or even beer pipelines exist.

Pressure drop in pipe is defined as the difference in pressure between two points of a fluid carrying network [32]. It is caused due to elevation changes, turbulence due to changes in direction, surface roughness and friction or resistance to flow within the pipe and fittings. It is mostly affected by viscosity and velocity of fluid within the pipe. Higher the flow velocity or fluid

viscosity, larger the pressure drop across the pipe section. The drop in pressure is proportional to the frictional shear stress within a pipe network.

1.5.1 Losses in Simple Pipe

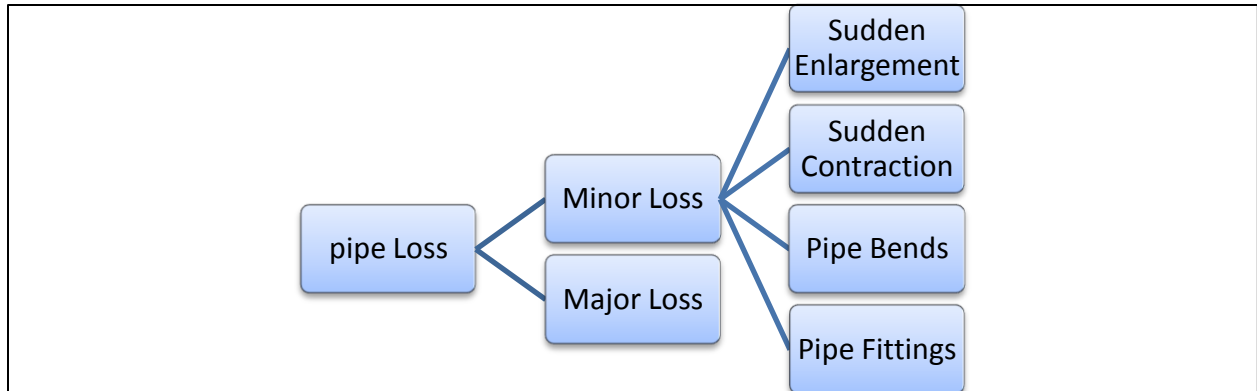


Figure 1.11: Types of Losses in Pipe

1. Due to Sudden Enlargement: This loss was caused due sudden expansion and can be reduced by introducing a gradual pipe transition known as a diffuser.

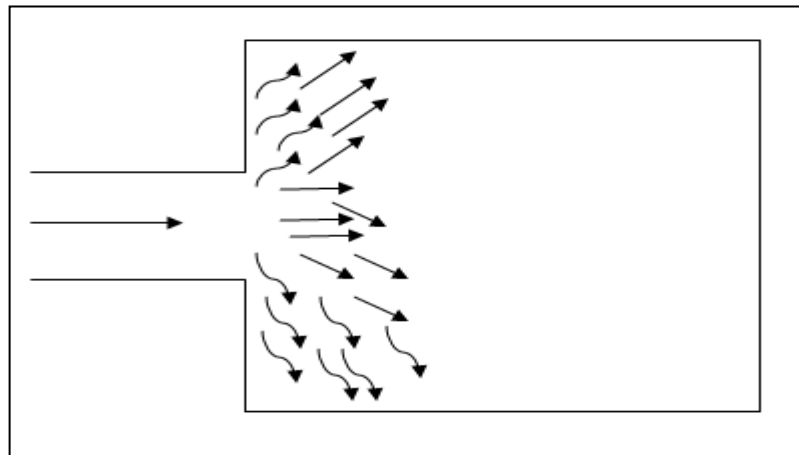


Figure 1.12: Losses due to Sudden Expansion

$$H_e = K_e \cdot \frac{(V_1^2 - V_2^2)^2}{2g} \quad \text{Eq. (1.10)}$$

2. Due to Sudden Contraction: This loss in pipe usually causes a marked drop in pressure because of both the increase in velocity and the loss of energy of turbulence.

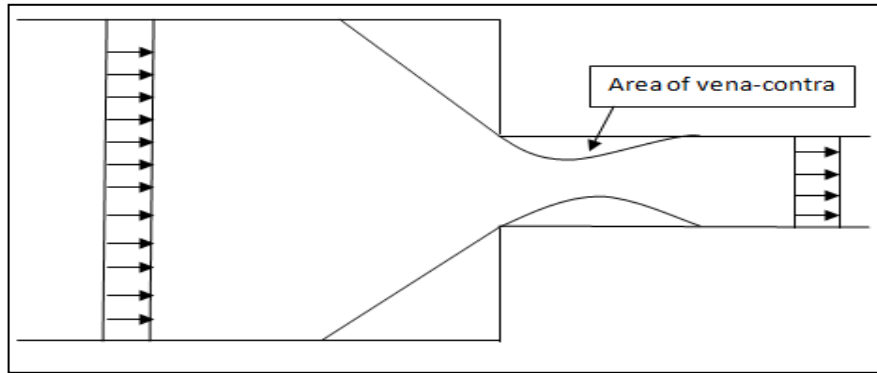


Figure 1.13: Losses due to Sudden Contraction

$$H_c = K_c \frac{V_2^2}{2g} \quad \text{Eq. (1.11)}$$

Where V_2 : velocity of smaller pipe

3. Loss due to Pipe Bends: This loss produced at a bend was depends on ratio of radius of curvature of the bend (R) to the diameter of the pipe (D). It is expressed in terms of velocity.

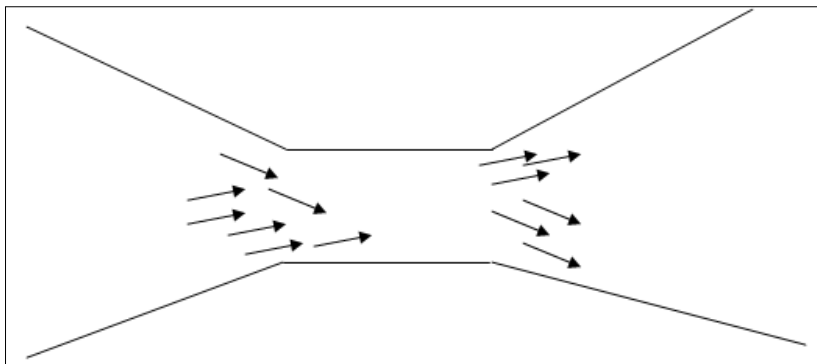


Figure 1.14: Loss due to Bends

$$h_b = K_v \frac{V^2}{2g} \quad \text{Eq. (1.12)}$$

4. Loss in Pipe Valves: Valves were installed in pipelines to control flow and hence causing high head losses. These losses were expressed in terms of velocity head in the pipe as:

$$h_v = K_v \frac{v^2}{2g} \quad \text{Eq. (1.13)}$$

1.5.2 Losses in Solid-Liquid Flow

Following are the methods used to determine the head loss / pressure drop in a pipe are:

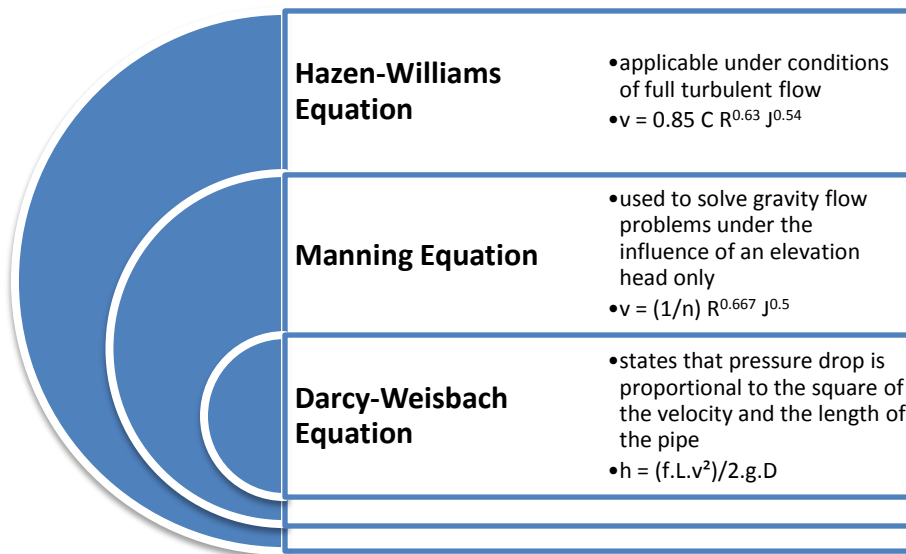


Figure 1.15: Pressure Drop Calculation Methods

Where,

v = velocity, m/s

h = Head loss, m

g = Gravity constant, 9.81 m/s²

C = Hazen-Williams Coefficient

D = Inside diameter, m

R = Hydraulic mean radius, m

f = Friction factor

J = Hydraulic gradient, m/m

L = Length of the pipe, m

n = Manning's Coefficient

1.6 SURFACTANT

Surfactants are substances which reduce surface tension of a liquid or that between a liquid and a solid. These may act as dispersant, stabilizer, additive, detergent, wetting agent and emulsifier.

1.6.1 Classification of Surfactant

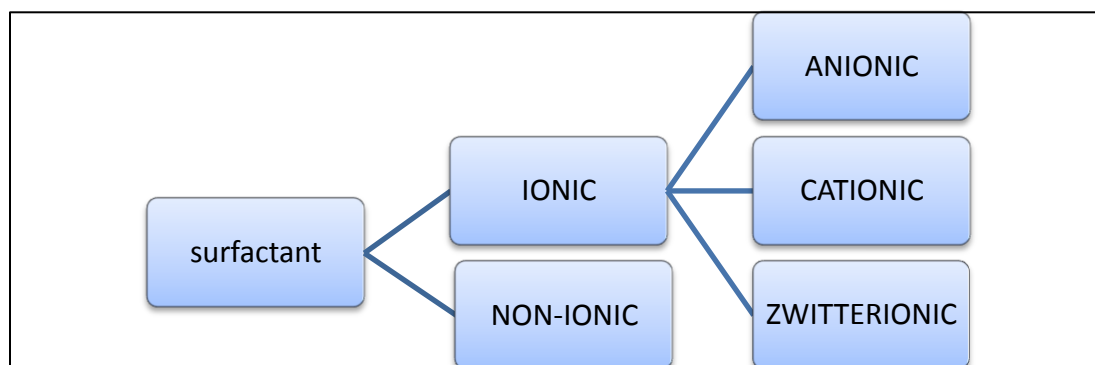


Figure 1.16: Classification of Surfactant

1. Non- Ionic surfactant: These are that surfactant which does not contain any charge group on its head. These include alcohols such as fatty alcohols, cetyl alcohol, stearyl alcohol, cetostearyl alcohol and oleyl alcohol. Examples: Glucoside alkyl ether, Gyceryl Laurate etc.
2. Ionic Surfactant: These are that surfactant which includes net charge on its head group. These are classified as:

Anionic Surfactant	The charge on head group is negative. Eg. SDS , SLES
Cationic Surfactant	The charge on head group is positive. Eg. CTAB, CTAC
Zwitterionic Surfactant	The charge on head group of is both positive and negative. Eg. CHAPS, lecithin.

MOTIVATION OF WORK

Transportation and disposal of coal ash was the major problem in thermal power plant. Several studies had been done to study the effect of concentration, particle size and range of their distribution in pipeline flow. The variation of properties of ash in thermal power plant motivated to study the various aspects of the rheological behaviour of the different samples of fly ash with and without additive.

LITERATURE REVIEW

Previously a lot of studies had been done on slurry rheology. This chapter reviews the literature of different papers which was already published and helps us in further research. The focus of my research is on transportation of fly ash slurry through pipeline at higher concentration and measure the pressure drop. This section deals with measurement of rheological properties and pressure drop of fly ash slurry.

2.1 RHEOLOGICAL PROPERTIES MEASUREMENT

Kumar et al. [2000] studied the Deposition velocity and pressure drop characteristics for transporting three slurries namely Fly ash slurry, Bottom ash slurry and Mixture slurry of Fly ash and Bottom (80:20, by wt) at high concentration. Experiments were conducted on a pilot plant test loop with 160 m long pipe and 155 mm diameter. Rheological behaviour was measured through Weissenberg Rheogoniometer. The deposition velocities of fly ash slurry varied between 1.22 to 1.05 m/s and for Bottom ash it varied in the range of 1.59 to 1.74 m/s and for the mixture varies in the range of 0.98 to 1.23 m/s which were close to those as observed for Fly ash slurries. Hence it was observed that mixing coarse particles in fine slurry reduces the transportation velocity of coarser particles. The relative pressure drop for the slurry of the mixture depicted similar behaviour to that of the bottom ash slurries. The flow characteristics in Bottom ash slurries can be improved by mixing it with Fly ash.

Usui et al. [2001] studied the rheological properties and pressure drop of dense fly ash water slurry with and without additive. He also proposed an algorithm to predict the maximum packing volume fraction to find the slurry viscosity under dispersed condition. For this, simha's cell model for concentrated slurry and Usui's model for aggregative slurry was applied to predict non Newtonian viscosity. The slurry concentration was 70% and Polystyrene sulphuric acid (PSS) of 0.3% of slurry was used as a dispersing additive. The solid volume fraction corresponding to this

concentration was 0.51. The apparent viscosity of fly ash-water slurries was measured by a remoter with coaxial rotating cylinders. It was certified that the maximum packing volume fraction for non-spherical suspension was successfully used to predict the slurry viscosity under completely dispersed conditions. It was observed that thixotropy model proposed for dense slurries by Usui was combined with the maximum packing volume fraction for non-spherical particle system to give more accurate prediction of non-Newtonian rheological characteristics of slurries

Bournonville and Nzihou [2003] studied the rheological behaviour of two municipal solid waste incinerator fly ash sample namely fly ash O and fly ash S at concentration varied from 30% to 55%. Rheological measurements were calculated with a RS150 rheostress rheometer. Model has been proposed and show good agreement with experimental data. Results reveal that fly ash O was more viscous than fly ash S and compared with Cross Model that predicts the shape of general flow curve. Both fly ash shows shear thinning behaviour under low shear rate and hence gelification was observed under these conditions. Fly ash S shows thixotropic behaviour under high shear rate. Experimental results were compared with two model based on high concentration suspension and flow regime was laminar.

Sarkar et al. [2005] studied the particle size distribution, the size fractionated ones and magnetic and non magnetic components three fly ash sample collected from different thermal power plants to point out the possible areas of application/utilization. Particle size analysis of the ash samples were carried out with LASER based Fritsch Particle Sizer Analysette 22. Each ash sample was sieved for 30 min in a sieve shaker using sieves no. 150, 250, 300 and 350. Morphological investigations were also carried out using scanning electron microscopy and Energy Dispersive X-ray analyzer. Distribution profiles revealed that fly ash obtained from Super Thermal Power Plants had better profiles than the fly ash obtained from captive power plants while those collected from Stoker-fired thermal power plants possess very poor distribution profile. It was observed that finer fractions have a better profile and maximum amount of the particles fall below 45 microns range which was important for construction industry. The magnetic particles were larger and rounder than the non-magnetic ones and can be used for coal flotation.

Seshadri et al. [2008] studied rheological characteristic of five ash sample with different particle size distribution and solid concentrations as 60%, 65% and 68% with and without additive. Sodium hexametaphosphate was used as a dispersing agent with a concentration of 0.1% by weight of the total slurry. Shear rate varied from 20-120s⁻¹ and the lower shear rate range of 2-20s⁻¹ was used for highly concentrated slurries of 68% (by weight) only. A Weissenberg Rheogoniometer was used for obtaining the relation between the rate of shear and the shear stress of the fly ash slurry samples at various concentrations. Using the rheological data, pressure drop had been predicted in a straight pipe line of 75 mm diameter with varying velocity from .5m/s-2.5m/s using mathematical calculations. It was seen that fly ash slurry shows Non-Newtonian behaviour for all concentration and can be represented by Bingham plastic model. Both yield shear stress and the relative Bingham plastic viscosity increased exponentially with increase in solid concentration and reduce with increase in particle size and similar trend was seen for viscosity. It was observed that additive sodium hexametaphosphate reduced both viscosity and yield stress of fly ash slurries significantly. It was seen that additive reduces the pressure drop at any selected velocity and at a given particle size and concentration.

Chandel et al. [2009] studied the effect of additive on pressure drop and rheological characteristics of fly ash slurry at 50%, 60%, 65%, 68% and 70% concentration. Mixture of sodium carbonate and Henko detergent had been used as additive in the ratio of 5:1. The additive concentration used is 0.2% by weight of the total slurry. The shear rate varied in the range from 20s⁻¹ to 120s⁻¹. A Weissenberg Rheogoniometer had been used for obtaining the rheological characteristics of the fly ash slurry. By using the rheological data, pressure drop had been predicted in a straight pipeline of 40mm diameter at higher concentrations. Experimental results obtained from a pilot plant test loop were compared to the analytical results based on the Darby and Melson algorithm. It was observed that fly ash slurry at these concentrations show a Bingham fluid behaviour. The Bingham viscosity and yield shear stress values increase with increase in concentration. Pressure drop increases with increase in concentration, the increase being much higher at higher concentrations. The addition of soap solution as additive to the fly ash slurries reduces the rheological parameters and can result in substantial saving in energy consumption.

Naik et al. [2009] studied the effect of additive on surface tension, zeta potential and rheology of six fly ash sample at a varying temperature. The additive used cationic surfactant i.e. cetyl trimethyl ammonium bromide (CTAB) and a counter-ion i.e. sodium salicylate. Slurry was made at a constant concentration of 30% whereas additive concentration varied from 0.1% -0.5%. Temperature was varied from 20°C-40°C at an interval of 5°C by temperature control circulator bath. Rheological data was obtained with Anton Paar Rheometer with a shear rate ranging from 25-500 s⁻¹. It was observed that surfactant improves the rheological properties and modified the surface properties. By addition of surfactant, surface tension was reduced from 43% to 46% as compared to untreated slurry of 51% to 54%. Surfactant changes the zeta potential of slurry from -25mV to +31mV at a pH of 7.30. It was also seen that at low temperature slurry exhibit shear thinning behaviour.

Senapati et al. [2010] investigated the effect of volumetric solid concentration, particle size and hydrodynamic interactions on rheological characteristics of five fly ash sample at a shear range of 10 -200s⁻¹. A model had been developed to predict the viscosity at higher solids volume fractions in the range 0.32–0.49. The rheological properties were measured at mean particle size (d_{50}) of 9.4, 18.5, 26.0, 39.3, and 51.7 μm and at concentrations of 32.02, 36.54, 39.0, 41.4, 44, 46.66 and 49.45 vol.% using HAAKE rotational viscometer (Model RV 30). All the samples of fly ash slurry exhibits shear thinning behaviour. The proposed model helped to access the motion of solid particles in a non-Newtonian flow regime. The exponential form of inverse of relative viscosity had been observed for sample 1 which appears to decrease exponentially as ϕ . It also shows that when ϕ_m reaches a value close to 0.62, relative viscosity approaches a value as low as 0.0003. They also observed the hydrodynamic effect in determining the maximum packing under shear and at high concentration, mean separation distance decreases and hence an increase in hydrodynamic interaction and viscosity.

Naik et al. [2011] studied the rheological properties of six fly ash water slurry sample at high concentration of 40% with and without surfactant at varying temperature. The cationic surfactant and counter-ion used in the study were cetyl trimethyl ammonium bromide (CTAB) and sodium salicylate respectively at five concentration of .1%,.2%, .3%,.4%, .5%. Temperature was varied from 20°C-40°C at an interval of 5°C by temperature control circulator bath. Rheological data was

obtained with Anton Paar Rheometer with a shear rate ranging from $25\text{-}1000\text{s}^{-1}$. It was observed that slurries exhibited shear thinning and Newtonian properties in the presence of surfactant. The surfactant modified the surface properties of fly ash and reduces its surface tension which implies that fly ash can be transported in pipeline with addition of surfactant.

Sharma et al. [2012] studied the efficient utilization of waste fly ash as drilling fluid and estimate its rheological properties with varying particle size, particle size distribution and percent solid loading. Aqueous zinc chloride solution was used as a floating medium. Rheological studies were done using Fann rotational viscometer. Herschel-Bulkley model were used to find the shear rate dependent viscosities. Rheological results were compared with aqueous bentonite suspensions. It was observed that the dial reading at a given rotational speed gradually increases with the specific gravity of the float medium. Flow behaviour index increases with the increase in rotational speed.

Singh and Lal [2012] studied the rheological behaviour of fly ash slurry with and without additive. The additives used in this study were cationic, anionic and non-ionic (Triton X 100) polymer and compared them on the basis of drag properties of slurry and effect on pH. The slurry concentration was taken as 40% and additives concentration as 0.5%, 1% and 1.5% of the total solution. Rheological properties were calculated on Anton Paar Rheolab QC rheometer with a shear rates varied from $0\text{-}500\text{s}^{-1}$. The model was applicable even after addition of additives and gives approximately the values of apparent viscosity at any shear rate. 0.5% of CPC was the optimal concentration both at low and high shear rates.

Singh [2012] studied the flow behaviour and drag properties at different particle size with and without additive experimentally. The slurry was made of 50% concentration with .5% of Cetylpyridinium chloride of the total solution as cationic surfactant. Rheological properties were studied on Anton Paar rheometer with shear rates varied from $0\text{-}500\text{s}^{-1}$. It was observed that slurry with small particle size bear less viscosity and result in low yield stress. The slurry behaves dilatant in nature and obeys power law model. The additive with 0.5% of concentration greatly reduced the apparent viscosity and results in establishing stability in the solution even at 50% concentration of fly ash.

Naik et al. [2013] studied the physical and chemical properties of seven fly ash samples and compare them to investigate the rheological properties of fly ash slurry with a view to transport long distance through pipeline in mine filling applications. It had seen that F₁ fly ash got better particle morphology, low specific gravity, higher surface area, abundance of CaO and silica and good particle size distribution as compared to other class F fly ash sample. Hence further study was done on this sample for flow and strength characteristic.

Kumar et al. [2013] studied the rheological behaviour of the bottom ash in the concentration range of 10-50% with and without the addition of fly ash and an additive. The mixtures of bottom and fly ash were in the ratios of 9:1, 8:2, 7:3 and 6:4 respectively whereas sodium bi-carbonate was added in a concentration range of 2%, 4%, 6% and 8% (by weight) for each concentration of bottom ash slurry. The standard Rheometer i.e. Rheolab Q-C was used to determine relationship between shear rate and shear stress. Shear rate varied from 50 to 300 s⁻¹ at constant temperature of 26° C. It was observed that slurries show the Newtonian fluid behaviour up to 50% concentration. The effect of addition of fly ash to the bottom ash slurry increases the relative viscosity whereas addition of sodium bi-carbonate decreases the relative viscosity. The accuracy of correlation developed was within +/-10% for the present range of the data.

Blissett and Rowson [2013] studied flow curves of two types of coal fly ash i.e. CFA and IFA and proposed a model to define viscosity change with shear rate and concentration. The concentration and shear rate varied from 10-70% and 2–200s⁻¹ respectively. The temperature was controlled to 20 C with a circulating chiller /heater. The rheology was studied using a TA Instruments AR-G2 controlled stress/strain/rate Rheometer. For concentrations of 30, 40 and 50 wt% shear rates varied from 2–40 s⁻¹. The proposed modelling performed satisfactorily for both fly ash types over a studied concentrations and shear rate.

Xie and Zhang [2013] studied the resistance loss in ash transportation system with a view to analyze power selection and energy consumption. The factors such as flux, flow velocity, diameter, slurry concentration and slurry specific gravity had major effects on pipeline resistance loss. The multi-factor analysis was employed to find the degree of impact factor on resistance

loss. It was obtained from mathematical model the order of influence of these factors on the resistance loss as following: $V > Q > D > C_v > R$.

2.2 PRESSURE DROP MEASUREMENT

Kaushal and Tomita [2002] studied the concentration profile and pressure drop for six particle size ranging from 38 to 739 microns for multi-sized particulate zinc tailings slurry. The pipeline was fabricated from mild steel with internal diameter 105 mm horizontal pipe. Experiments data for concentration profile were collected at three flow velocities of 2, 2.75 and 3.5 m/s using five efflux concentrations ranging from 4% to 26% by volume for each velocity whereas for pressure drop data were collected at five efflux concentrations ranging from 4% to 26% at flow velocities ranging from 1.2-4.0 m/s for each efflux concentration. Pressure drop is measured by pressure taps along with separation chambers which are provided at distance of 19.4 m in the pipeline and concentration profiles using a sampling tube having a $4 \times 6 \text{ mm}^2$ rectangular slot, 3 mm above the end to collect representative samples at nine levels in the pipe line. The Karabelas model and wasp model used were modified by modifying the assumption of the model and compared with the experimental data which shows good agreement.

Kaushal et al. [2005] studied the effect of particle size on pressure drop and concentration profile in horizontal pipe of 54.9mm diameter. The slurry was made for 50% concentration and the flow velocity was upto 5m/s. The concentration profile was measured through isokinetic sampling probe in horizontal, 45° inclined and vertical directions. The mixture was prepared by adding 125 and 400microns size particles in proportion of 50/50 by mass to the pipe loop. Experimental studies for pressure drop were compared with moody's chart. It was observed that pressure drop for a mixture decreases with at high concentration except for 5m/s.

Marn and Ternik [2006] studied the flow rate of non-Newtonian fluid in a sharp 90° curved pipe numerically and obtained the pressure loss coefficient. The Quadratic model was employed to accommodate the shear-thickening behaviour of an electrostatic ash and water mixture obtained from experimental data. The governing equations were solved using CFX-4.4 computer code which employs the standard finite volume method and Hybrid scheme of Spalding for a spatial

discretization. SIMPLEC algorithm was used to obtain such an equation for the pressure. Richardson extrapolation technique was used to quantify the numerical results for the total pressure drop and the pressure drop between the entrance and exit of a bend. Numerical results for local pressure loss coefficient were compared with values obtained for the Power law rheological model. It was observed that for Reynolds number ranges from $Re=500-1500$ it was shown that the fluid flow was not developed for a curvature $R_c = D$ and had a significant influence on very poor correlation of the ratio f_c/f_p with empirical equation of White and Mishra-Gupta.

Fester et al. [2008] studied the flow of both Newtonian and non-Newtonian fluids through sudden contractions of diameter ratios ranging from 0.66 to 0.85. The test fluids were water, glycerol solutions, lubrication oil, carboxymethyl cellulose (CMC) solutions (3% and 5% by mass) and kaolin (5%, 8%, 10% and 13% by volume) were tested experimentally. The Reynolds numbers ranged in the order of 0.01 to 100 000. The experimental setup consisted of a 42.26 mm internal diameter upstream straight pipe section and a specially machined contraction union allowing for the fitting of straight pipe sections of various diameters downstream and 5m long upstream and downstream. Rheological parameters were obtained from both the straight pipe tests and a rotational rheometer for comparison. It was observed that experimental results shows good agreement with a mechanistic analytical model. Agreement was obtained with the McNeil and Morris model indicating the validity of the results and also predicts an earlier transition from the viscous to inertia driven range with decreasing contraction ratio and a very abrupt transition to turbulent flow for larger contraction ratios.

Kaushal et al. [2012] studied the pressure drop and concentration profile for fine particles at high concentration numerically using the software Fluent and compared the results with the experimental data. The software uses mixture and Eulerian two phase model, hexagonal shape and cooper type non-uniform three-dimensional grid was chosen to discretize the entire computational domain and control volume finite difference method to solve the governing equations. Experiments were performed with 22 m long, 54.9 mm diameter recirculating pipe loop for flow velocity up to 5 m/s and four overall concentrations namely 0%, 30%, 40% and 50% by volume for each velocity. A high performance digital c-ray densitometer (AM870) mounted on traversing mechanism was used for measurement of concentration profile with an accuracy of 0.01%.

Pressure drop for flow of water, both the models found to be in good agreement with experimental data. For flow of slurry, Mixture model fails to predict pressure drops correctly as the error increases concentration whereas Eulerian model gives accurate results for both the pressure drop and concentration profiles at all efflux concentrations and flow velocities. Eulerian model also predicts Velocity and slip-velocity distributions at high concentration that have never been measured experimentally.

Capecelatro and Desjardins [2013] studied the complex multi-flow dynamics of liquid-solid slurries in horizontal pipe. A high-fidelity large eddy simulation framework is combined with a Lagrangian particle tracking solver to account for polydispersed settling particles in a fully developed turbulent flow. The two cases were coupled through volume fraction and momentum exchange terms and a two-step filtering process is employed to capture a wide range of spatial turbulent scales. The two phases were simulated matching an experimental study from Roco & Balakrishnam (1985) which considers 5.15 cm diameter pipe and mean volumetric solid concentration of 8.4% corresponding to an aspect ratio of 5 over 16 million particles and 18.7 million grid cells. The first case considers a Reynolds number of 85,000 and velocity of 1.6 m/s resulting in a heterogeneous suspension of particles throughout the pipe cross-section. The second case considers a lower Reynolds number of 42,660 and velocity of 0.83 m/s below the critical deposition velocity of 1.2 m/s leading to the formation of a stationary bed of particles. It was observed that Statistics on the concentration and velocity of the particle phase for first case show excellent agreement with experimental results and covariance of concentration and velocity of each phase was presented giving detail information on the multiphase dynamics. Computational results show segregation in particle size along the vertical direction with the smallest particles located at the top and observed that drag force dominates majority of the pipe cross-section which was balanced by inter-particle collisions in the stream wise direction and by gravity in the vertical direction.

Kaushal et al. [2013] studied flow of mono-dispersed sand particles slurry through horizontal bend experimentally and numerically. The numerical simulation was done by Eulerian two-phase model in FLUENT software with hexagonal shape and Cooper type 3D grid to discretize the entire computational domain and a control volume finite difference method to solve the governing

equations. The modeling results were compared with the experimental data collected in pilot plant test loop of length 30 m and diameter 53.0 mm and horizontal bend with radius of 148.4 mm for concentration profiles and pressure drops. The experiments was performed for three flow velocity as 1.78, 2.67 and 3.56 m/s and four efflux concentrations namely 0%, 3.94%, 8.82% and 16.28% by volume for each velocity with rough bends having seven different radius ratios around 5 for flow of water. Pressure drops were measured in the pipeline at 0, D, 2D, 4D, 8D, 16D, 32D, 64D, and 90D in the downstream of the bend exit and 0, D, 2D, 4D, 8D, 16D and 32D in the upstream of the bend inlet. It was seen that Eulerian model gives fairly accurate predictions for both the pressure drop and concentration profiles at all efflux concentrations and flow velocities. Experimental and CFD modeling results obtained for bend radius ratio indicate that $R/r = 5.60$ gives the minimum pressure drop for flow of water in rough pipe bend and hence bend geometry having a radius ratio R/r of 5.60 was chosen for flow of silica sand particles.

Ting et al. [2013] studied the characteristics and defects in the test apparatus of slurry pipeline transportation and aims to new design new test apparatus for slurry pipeline transportation in dredging projects. Hence the study designed a new air-injected pipeline system. The key parameters have been monitored include the inner pressure, quantity of flow and flow state. The test consist of three test pipes of 50, 100 and 200 mm in diameter, 20 – 60 % slurry concentration and screw pump for high-concentrated slurry and frequency cabinet to vary motor velocity to keep the flow rate in control . The optimization and design results reveal that the designed air-injected pipeline system are reasonable, inclusive in functions and reliable in accuracy and can be applied to simulation of real conditions in slurry translation in dredging projects.

CHEMICAL AND PHYSICAL PROPERTIES OF FLY ASH

In this, we studied various chemical as well as physical properties of fly ash such as energy dispersion spectroscopy (EDX), Scanning Electron Microscopy (SEM), particle size distribution, static settling, zeta potential, pH and rheology.

3.1 CHEMICAL PROPERTIES

The chemical properties of fly ash depend on the type coal being burned and the techniques used for handling and storage. It influences the environmental impacts that may rise out due to their use or disposal as well as engineering properties.

3.1.1 Energy Dispersion X-Ray Spectroscopy

It is an analytical technique used for element analysis of sample and also an important indicator of suitability of material for geotechnical application. The major constituents of fly ash are oxide of silica, alumina, iron and calcium with varying amounts of carbon. Magnesium, potassium, sodium, titanium, and sulphur are also present in smaller amount. Hence it is a heterogeneous material.

The chemical composition of two fly ash samples had been obtained with the help of EDX-720/800HS Energy Dispersive X-ray Fluorescence Spectrometers

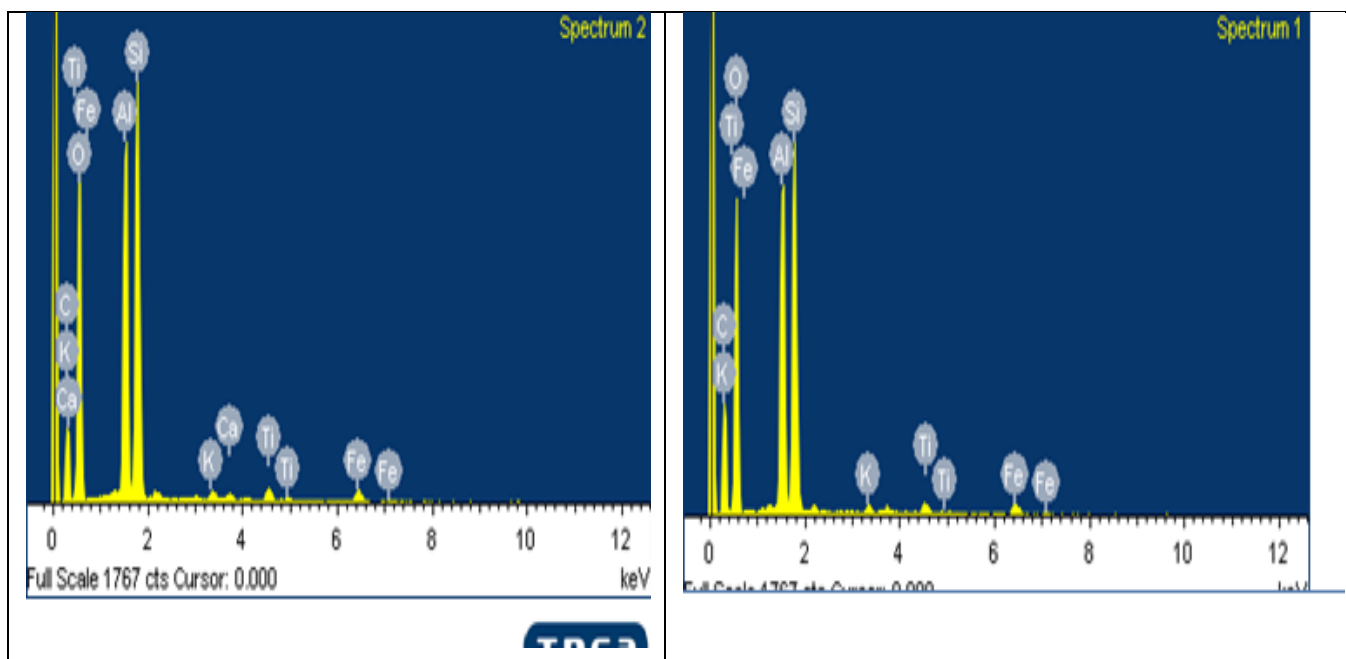


Figure 3.1: EDX of sample 1 and sample 2 respectively

Sample No.	Element weight (%)						
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaCO ₃	MAD-10 Feldspar	Wollastonite	Ti
Sample 1	62.63	10.1	1.77	23.88	0.34	0.28	0.99
Sample 2	57.81	8.98	1.30	30.86	0.44	0.38	0.6

Table 3.2: Chemical Composition of Sample 1 and Sample 2

Silicon oxide (SiO₂) helps in increasing the strength of material and offer better bearing capacity. Large amount of calcium oxide present in fly ash results in pozzolanic or cementing properties. Sample 1 contain little higher CaO which would help in strength gain. Since sum of the oxides of Si, Al and Fe were more than 70% in sample 1, it was considered as Class F fly ash whereas for sample 2, it was more than 50%. Hence sample 2 was considered as Class C Fly ash.

3.1.2 pH Value

The pH measurement tells the concentration of hydrogen atom in solution. The pH depends on temperature, time and concentration of slurry. It was measured through ORION 5 STAR (pH ISE Cond DO Benchtop). The electrode of pH meter was first calibrated with buffer solution of pH 4 or pH 7. Then it was dipped in distilled water and then into a slurry whose pH had to be known. The pH of the slurry would be displayed on the pH meter. The pH of various fly ash samples were given below.

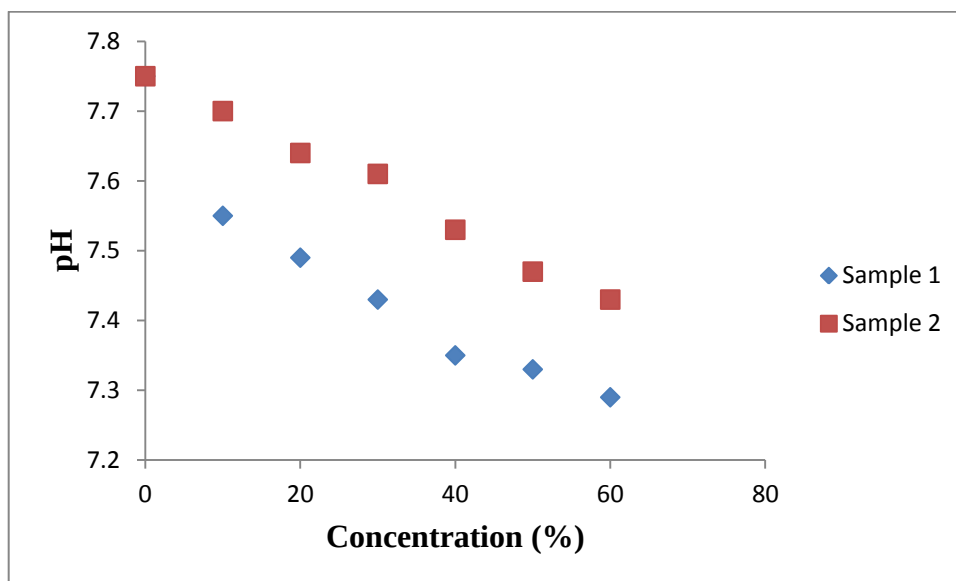


Figure 3.3: Experimental results of pH measurement for different concentration

The pH of the sample decreases with increase in concentration. The slurry will be least viscous at pH distant from its particle point of zero charge. Therefore slurry with concentration 10% was less viscous than 60%. Hence sample 2 was less viscous than sample 1.

3.2 PHYSICAL PROPERTIES

Fly ash is a fine, powdery particles mostly spherical in shape and glassy (amorphous) in nature. The carbonaceous material in the fly ash consists of angular particles. The particle distribution of most of fly ash is less than 75 μm or No. 200 sieve and range in size from 2 μm to 10 μm . specific

gravity of fly ash generally ranges from 2.1 to 3.0 while its specific surface area may vary 170 to 1000 m²/kg. The colour varies from light gray to black depending on the amount of unburned carbon in the ash.

2.1 Particle Size Distribution

The particle-size distribution (PSD) of a powder is defined as amount of particles present by mass according to size. It is also known as grain size distribution. It also helps in understanding physical and chemical properties of a material and important property for their use as pozzolanic. The most commonly used method for PSD is sieve analysis where sample is separated on sieves of different sizes. Because of its simplicity, cheapness and ease of interpretation, PSD is used for many measurements and for bulk materials. PSD may be expressed as a "range" analysis or "cumulative" form. In range analysis, amount in each size range is listed in order and suitable when a mid-range of particle size is being analysed whereas in cumulative form in which amount retained by a single sieve is given for a range of sizes.

The sample of some amount was weighted on weighing machine. Then the sample was kept in oven for 2 hours or unless temperature of oven becomes above 150⁰ C. The sample was kept in oven in order to remove moisture from the sample. The sample was again weight to measure the loss. Then sieves were arranged in increasing order according to the mesh size and sample was poured on the topmost sieve and switch on the shaker. After 15 – 20 min, sample of some amount was retained in each sieve. The mass of retained sample was measured

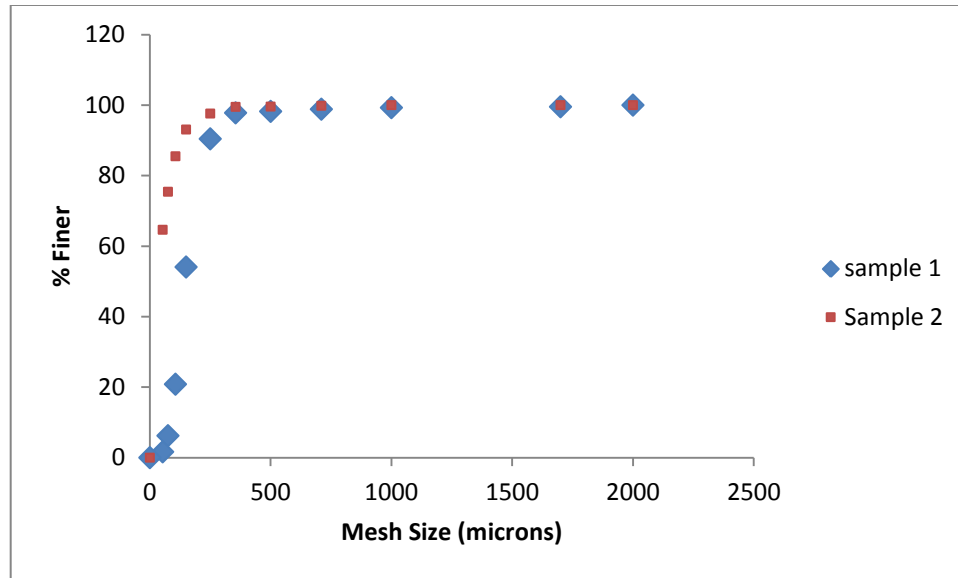


Figure 3.4: Experimental results of Particle Size Distribution of two Fly Ash sample

The particle size distribution gives information related to particle size whether coarser grain or finer grain. Sample1 contain maximum particles in a range above 500 microns whereas sample 2 having maximum particles below 500 microns. Hence sample 2 was finer than sample 1.

3.2.2 Scanning Electron Microscopy (SEM)

It is an instrument that produces images of sample scanning it with a focused beam of electrons. The electrons interact with atoms and produce various signals that can be detected which contain information about the sample's surface topography and composition. It can produce high-resolution images of a sample surface even less than 1 nm in size. The gold plating is done on the sample in order to get clear image of sample.

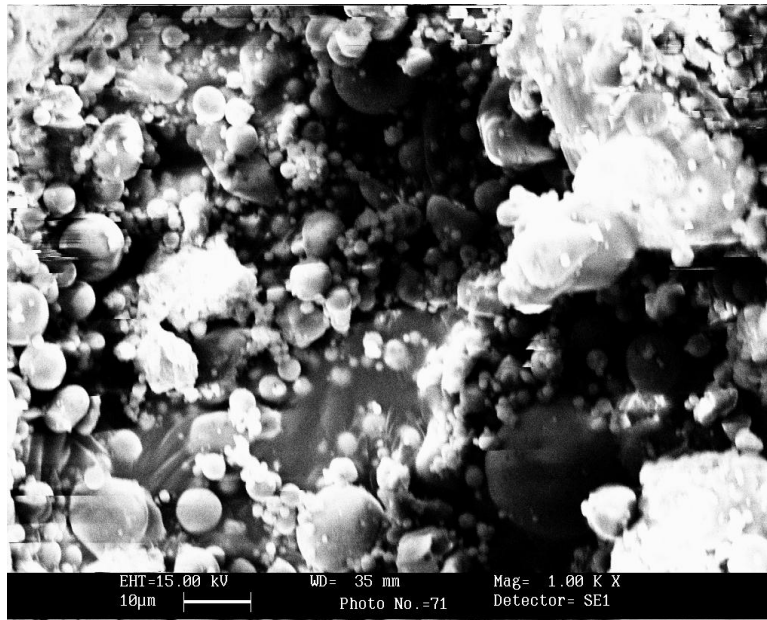


Figure 3.5: SEM Analysis of Sample 1 (1000*1000)

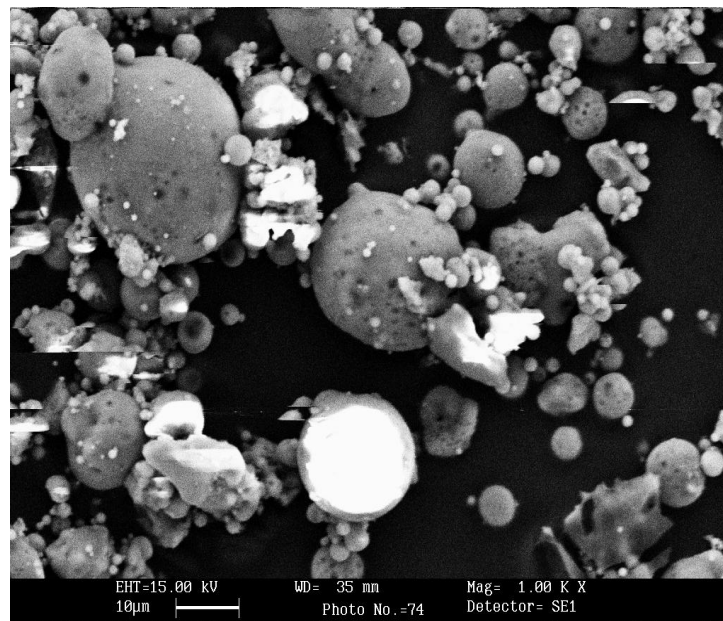


Figure 3.6: SEM Analysis of Sample 2 at 1000*1000

The SEM images were shown at a magnification of 1000*1000. Sample 1 particles were more closely packed than sample 2 which results in lower surface area. It was fine and translucent which indicate complete melting of silicate material whereas Sample 2 particles were solid and dense which indicate the presence of magnetite or iron oxide particles in it. Both the contain

similar spherical shape particles. Hence it was considered as material for transportation in pipelines.

3.2.3 Specific Gravity

It is defined as ratio of density of substance to density of reference substance. This reference substance is taken as water for liquids and air for gases. It is a dimensionless quantity and used for determination of the concentrations of substances in aqueous solutions. Since density varies with temperature and pressure so it is necessary to specify the temperatures and pressures at which the densities or weights were determined. Presence of trapped air bubble, chemical composition and hollow fly ash particles results in variation of specific gravity of fly ash particles.

The present study makes use of standard pyknometer method to find the specific gravity of fly ash sample. In this method, a 50ml pyknometer was first cleaned thoroughly and place it in oven for some time at low temperature in order to remove moisture. After that pyknometer was allowed to cooled down and then weight it (W_p). Then pour dry fly ash of about 30g in it and weight again (W_{ps}). Then pour $3/4^{\text{th}}$ water (distilled) in it slowly so that no air trap in it and shake it well so that all the fly ash get wet. Then leave the bottle for 2 hours so that all the trap air bubbles were move out of bottle. Then fill the bottle with water and weight the bottle (W_{psw}). Now clean the bottle and dry it. Now fill the bottle with distilled water and weight it (W_{pw}). Calculate the specific gravity of fly ash as given below.

$$\text{Specific Gravity} = (W_{ps} - W_p) / (W_{pw} - W_{psw} + (W_{ps} - W_p))$$

Sample No	Weight of Beaker (W_p)	Weight of Beaker+solid (W_{ps})	Weight of beaker+solid+water (W_{psw})	Weight of beaker+Water (W_{pw})	Specific gravity
Sample 1	11.0754	41.8602	88.7778	72.4729	2.120
Sample 2	11.1850	41.602	88.505	72.4366	2.1280

Table 3.7: Measurement of specific gravity of two fly Ash sample

The specific gravity of Sample 1 was lower than Sample 2 due to the presence of high percentage of fine particles.

3.3.4 Static Settled Concentration

Settling is a process in which particles settle down at bottom of liquid and form sediment. It is an important parameter to study the rheology at different concentration. The reason behind sedimentation or gravitational settling to occur is the difference in density of solids and liquids. The time required to perform settling is known as the residence time of settling.

The method used to calculate the settling rate of fly ash was gravitational settling. In this method, a graduated vertical glass cylinder (1000 ml) was taken and was cleaned thoroughly with distilled water. Water and fly ash were taken in the cylinder in such a way that the ratio remains 7:3 by weight or at 30% concentration (i.e., 700 gm water and 300 gm fly ash). The fly ash water slurry was stirred continuously with the help of a stirrer for some time. The volume of the settled fly ash was noted down.

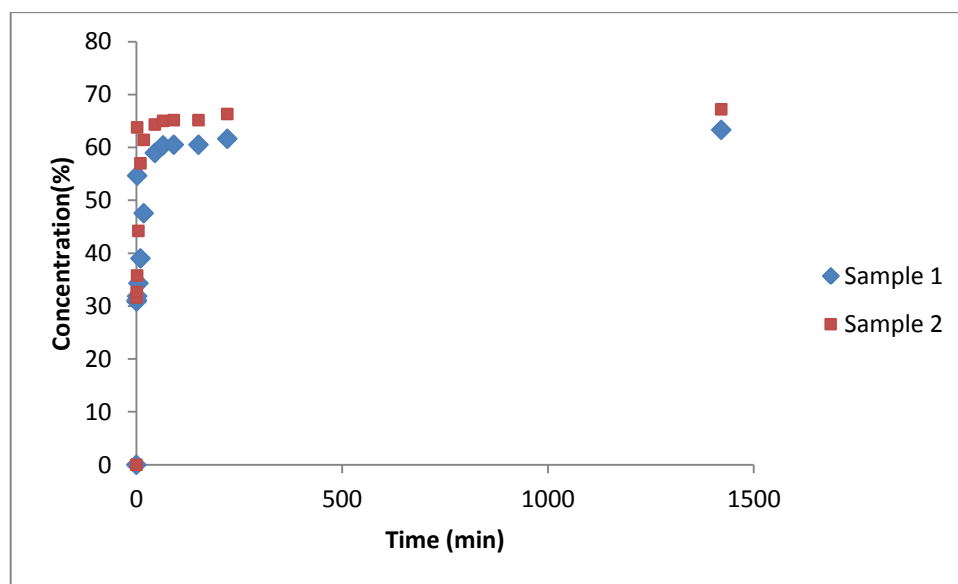


Figure 3.8: Experimental results of Static Settling at 30% Concentration in 1000 ml Graduated Cylinder

From the graph, it can be concluded that rheological properties can be best studied for concentration of 50% as settling for the samples are around 65-67%. Results revealed that settling characteristic of sample 1 was less as compared to sample 2

3.3.5 Zeta Potential

Due to the development of a net charge at the particle surface, the concentration of counter ions (ions of opposite charge to that of the particle) increased to close to the surface. Hence an electrical double layer exists around each particle. The potential that exists at this boundary is known as the Zeta potential. The electro-kinetic or zeta-potential is an important property of the electrical double layer and represents a characteristic of electrical properties of solid/liquid and liquid/gaseous interfaces [1]. Its magnitude gives the indication of potential stability and used to observe the behaviour of dispersed system in colloidal liquid. It is basically used to observe flotation and flocculation processes. The factor that affects zeta potential is pH. The point at which zeta potential is zero is known as isoelectric point. It is the point where solution is least stable.

In the present study, Zeta Potential was measured through 90 PLUS Particle Size Analyzer made by Brookhaven. The sample was prepared by adding required amount of surfactant in distilled water and mixing thoroughly with the help of magnetic stirrer. After 30-35 minutes, add required amount of fly ash of particular size in solution and stir with the help of glass rod. Then container was covered with aluminum foil to avoid evaporation of water for 1 hr. After 1 hr, the solution was filtered with the help of filter paper and the colloidal form of solution is taken for measurement at varying pH. The pH was varied with the help of pH meter.

pH	SAMPLE 1
3	-12.88
4	-23.32
5	-29.16
6	-31.35
7	-42.21
8	-42.21
9	-45.53
10	-42.24

Figure 3.9: Experimental result of Zeta Potential of sample 1

From the experiment, it concludes that with addition of additive zeta potential was negative at low pH and positive at high pH i.e at pH 7, the zeta potential of untreated fly ash -42.21 and treated fly ash was 49.5. This shows additive keeps the fly ash in colloidal form for longer period of time at pH 7.

3.3.6 Rheological Behaviour of Fly Ash Slurry

This property was measured to observe the flow behaviour of slurry at varying shear rate. It was measured by ANTAN PAAR Rheolab Q-C Rheometer. The measuring system **DG42-SN22909** was used for all concentrations. It consists of fixed cylinder (bob) and cylinder (cup). The bob was fixed with the spindle and rotated when the spindle rotate. The slurry was poured in cylinder to measure the viscosity of slurry. The graph was plotted between shear rate and shear stress.

In the present study, rheological properties were measured at a shear rate of $0-500\text{ s}^{-1}$ and for concentration varying from 30%-60% with and without additive. The measurements were taken for three particle size i.e. below 53 microns, 53-75 microns, 75-106 microns.

3.3.6.1 Sample Preparation

The sample of 100ml fly ash slurry was made at a given concentration with ordinary tap water. A required amount of fly ash was added in tap water and mixed thoroughly with glass rod. The container was then covered with aluminum foil to avoid evaporation of water and measure the pH of slurry. Experiments were carried out after 1hour of sample preparation.

3.3.6.2 Particle Size below 53 microns

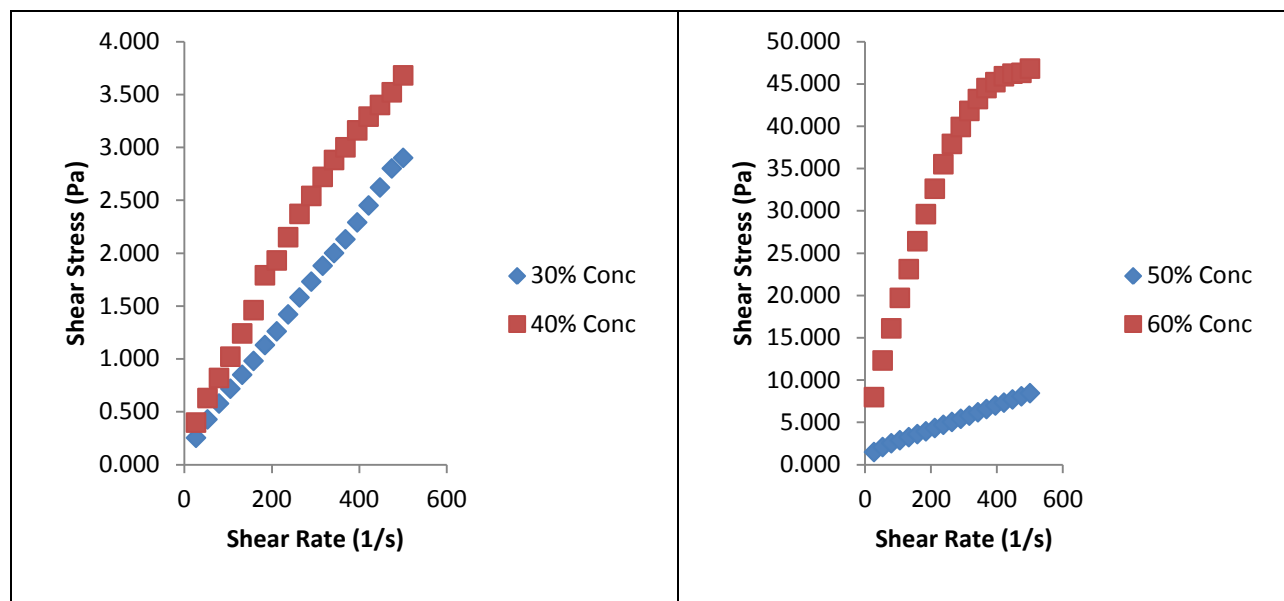


Figure 3.10: Variation of shear stress vs. shear rate for different concentration by weight for Sample1 (below 53)

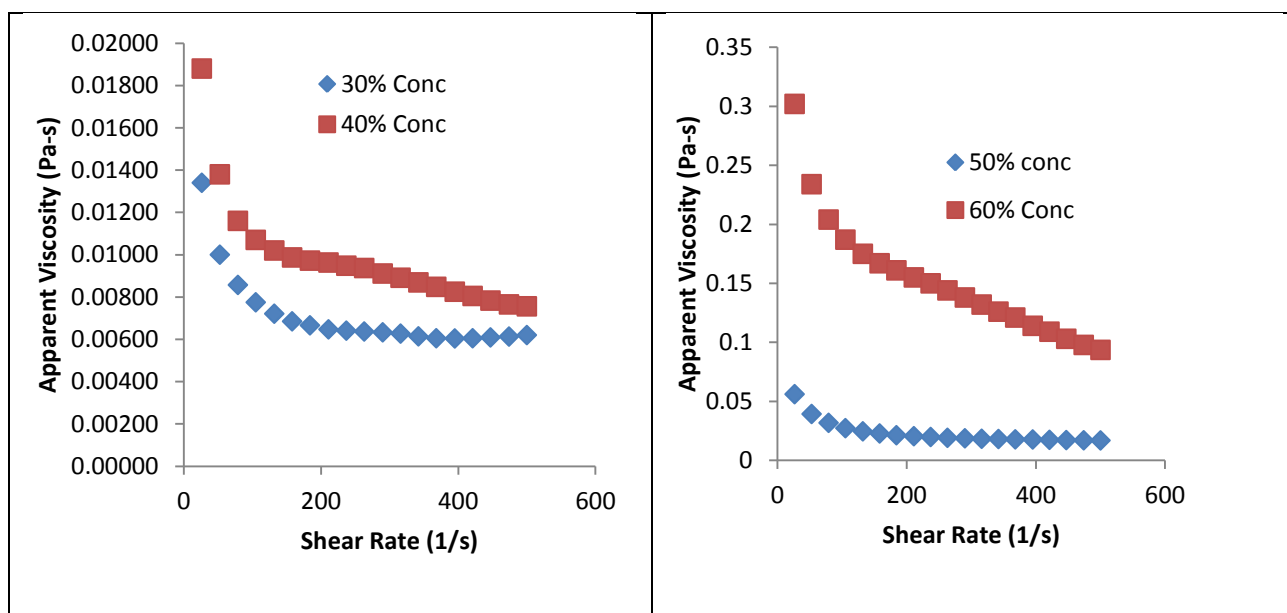


Figure 3.11: Variation of Apparent viscosity vs. shear rate for different concentration by weight for Sample 1(below 53)

From Figure 3.10-3.11, results revealed that particles size below 53 microns show Newtonian behaviour till 40% concentration and Non –Newtonian above 50% concentration and slurry was less viscous for 40% concentration as compared to 60% concentration.

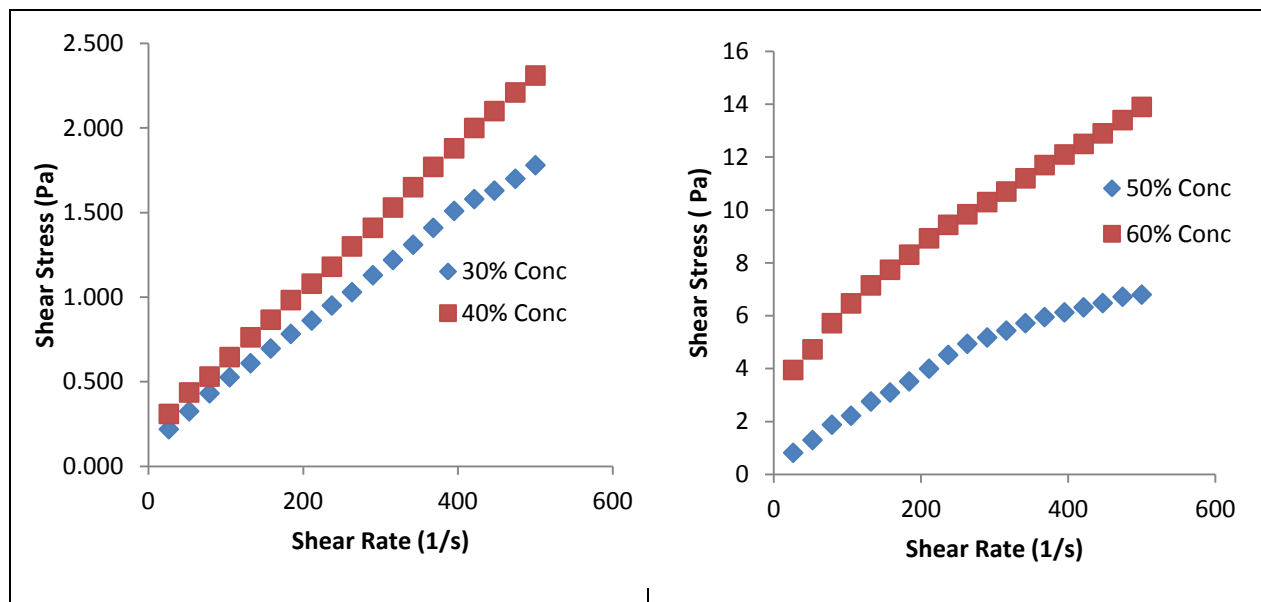


Figure 3.12: Variation of shear stress vs. shear rate for different concentration by weight for Sample 2 (below 53)

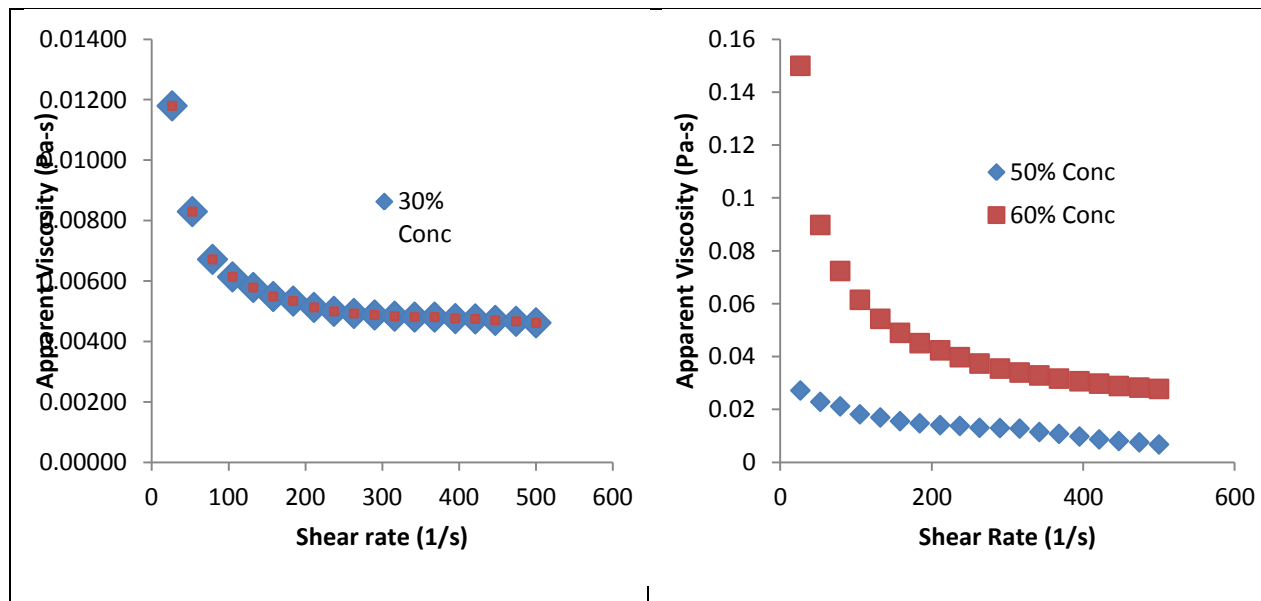


Figure 3.13: Variation of Apparent viscosity vs. shear rate for different concentration by weight for Sample 2 (below 53)

From Figure 3.12-3.13, results revealed that flow behaviour was Newtonian at a concentration of 40% and becomes Non- Newtonian at 50% concentration. Slurry becomes viscous above concentration 50% and exhibit shear thinning behaviour.

3.3.6.3 Particle Size between 53-75 microns

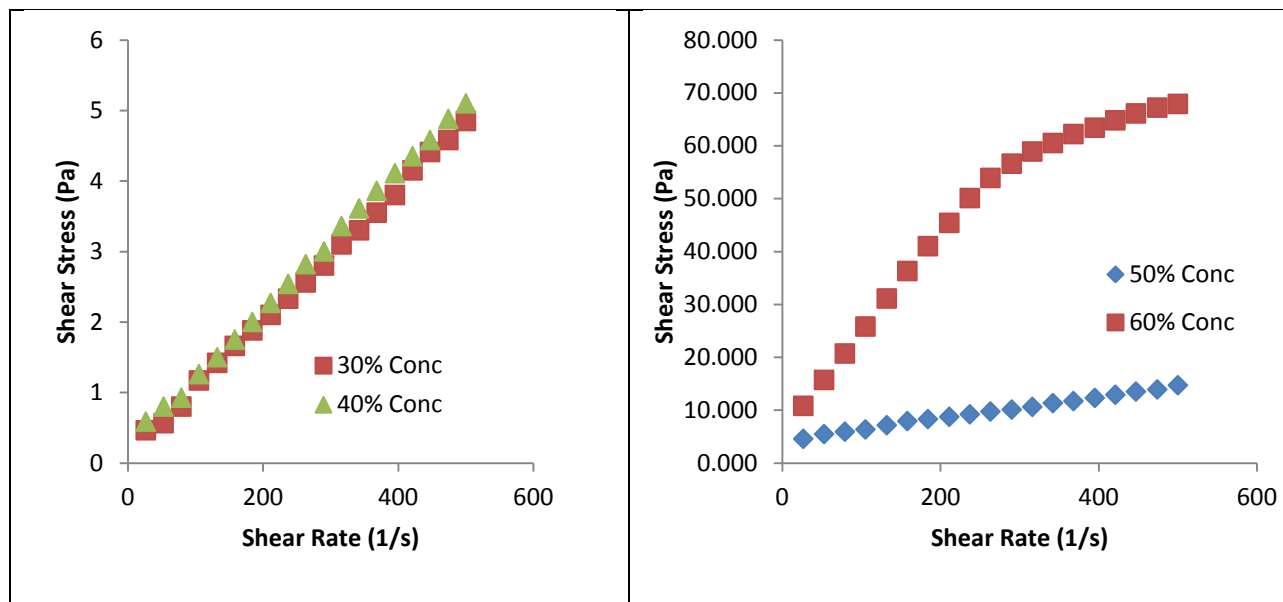


Figure 3.14: Variation of shear stress vs. shear rate for different concentration by weight for Sample1 (53-75)

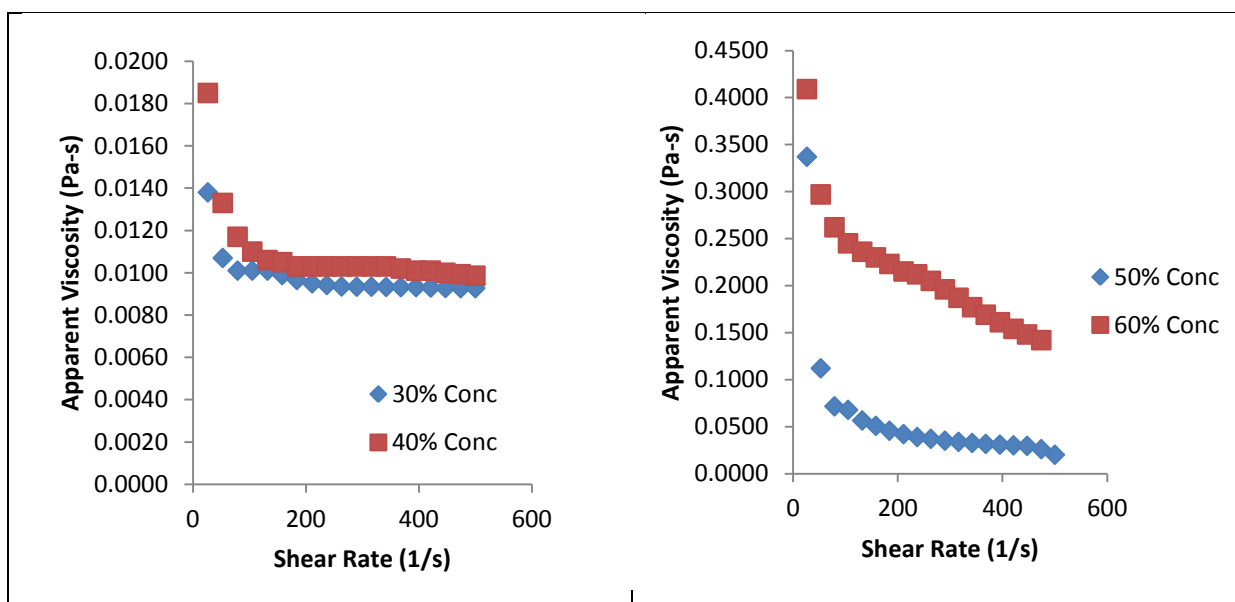


Figure 3.15: Variation of Apparent viscosity vs. shear rate for different concentration by weight for Sample 1(53-75)

From Figure 3.14-3.15, slurry exhibit Newtonian behaviour till concentration 40% and show Non-Newtonian at concentration of 50%. Apparent viscosity decreases with increase in concentration. Hence it was a pseudoplastic or shear thinning fluid.

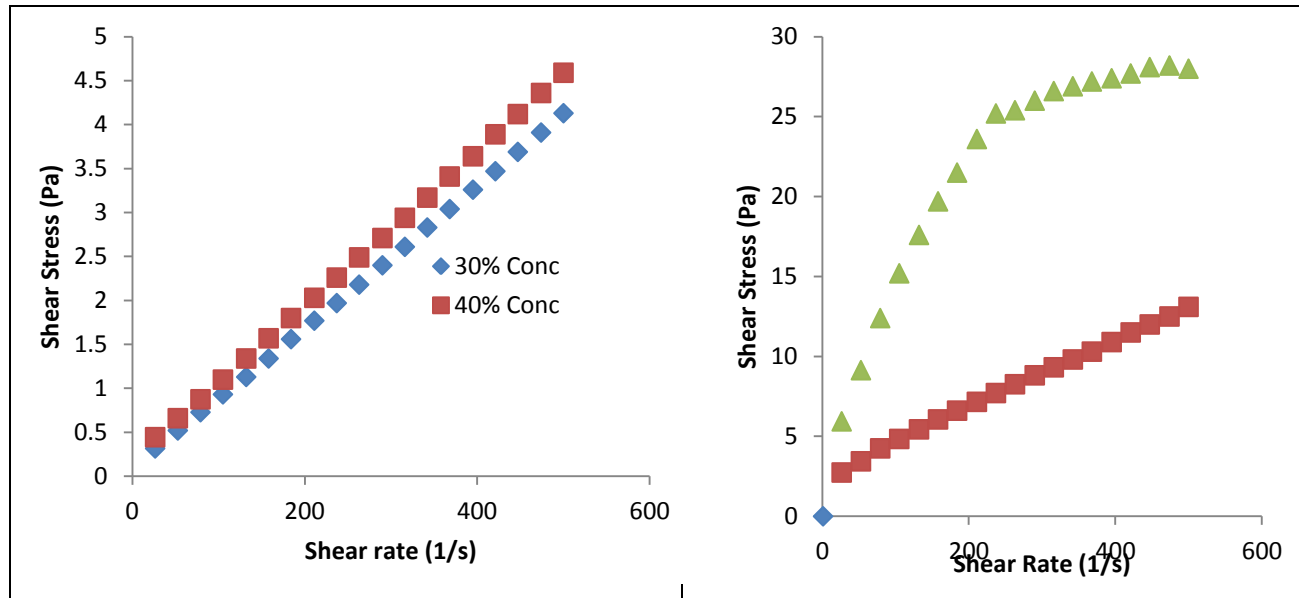


Figure 3.16: Variation of shear stress vs. shear rate for different concentration by weight for Sample 2

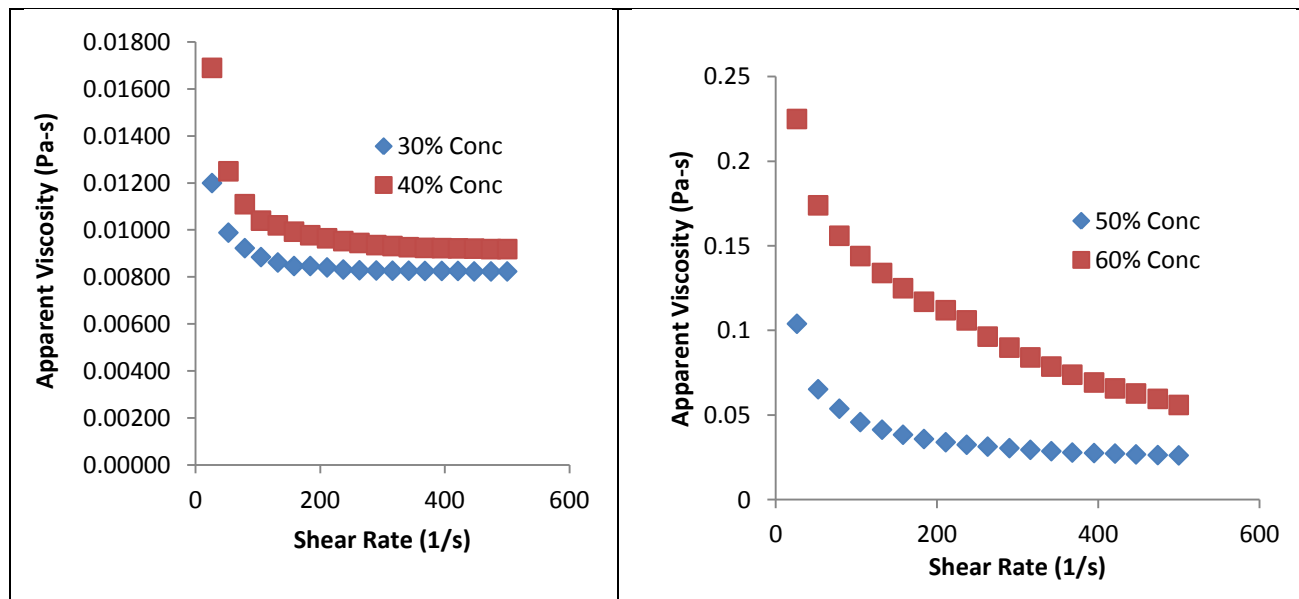


Figure 3.17: Variation of Apparent viscosity vs. shear rate for different concentration by weight for Sample 2

Figure 3.16-3.17, revealed that slurry was Newtonian at concentration of 30% and Non-Newtonian at a concentration of 50% and at 60% slurry becomes more viscous and flow becomes difficult.

3.3.6.4 Particle Size between 75-106 microns

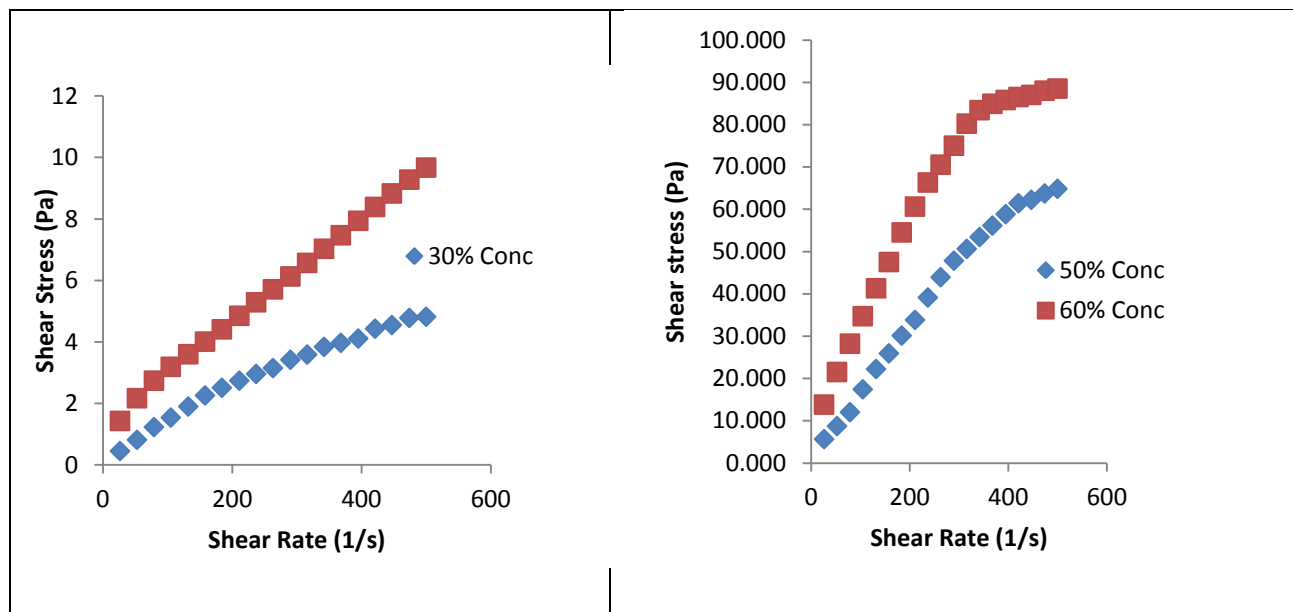


Figure 3.18: Variation of shear stress vs. shear rate for different concentration by weight for Sample1 (75-106)

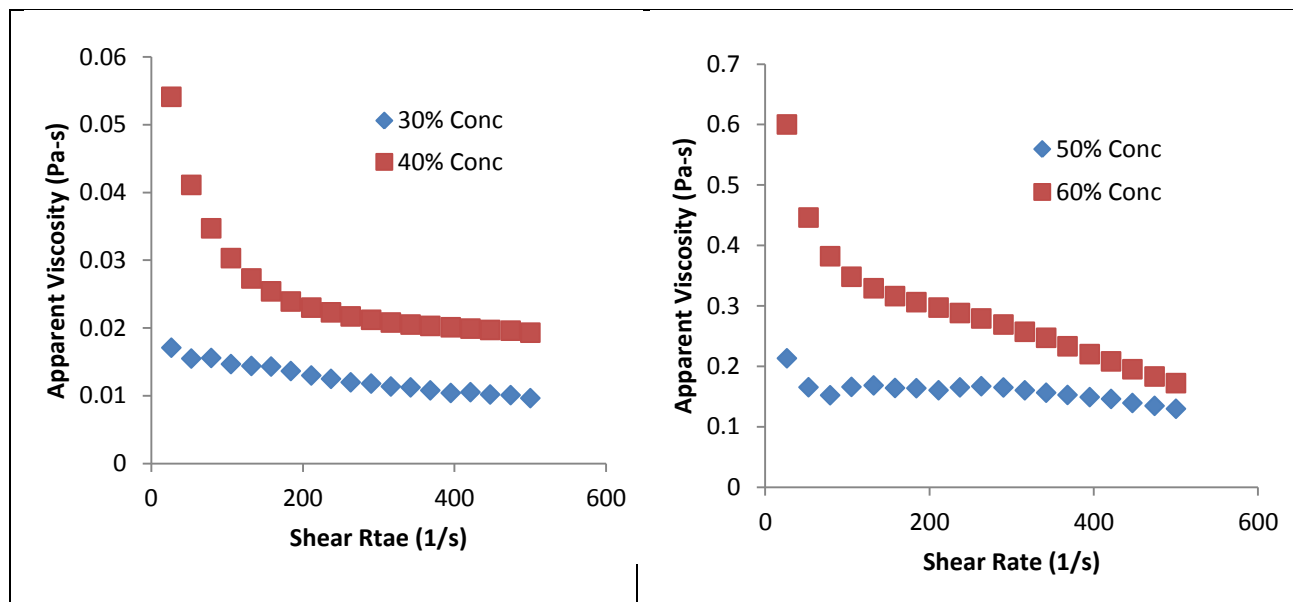


Figure 3.19: Variation of Apparent viscosity vs. shear rate for different concentration by weight for Sample 1

From Figure 3.18-3.19 slurry was Newtonian at concentration of 30% and becomes Non-Newtonian at a concentration of 40%. Slurry was most viscous at concentration of 60%.

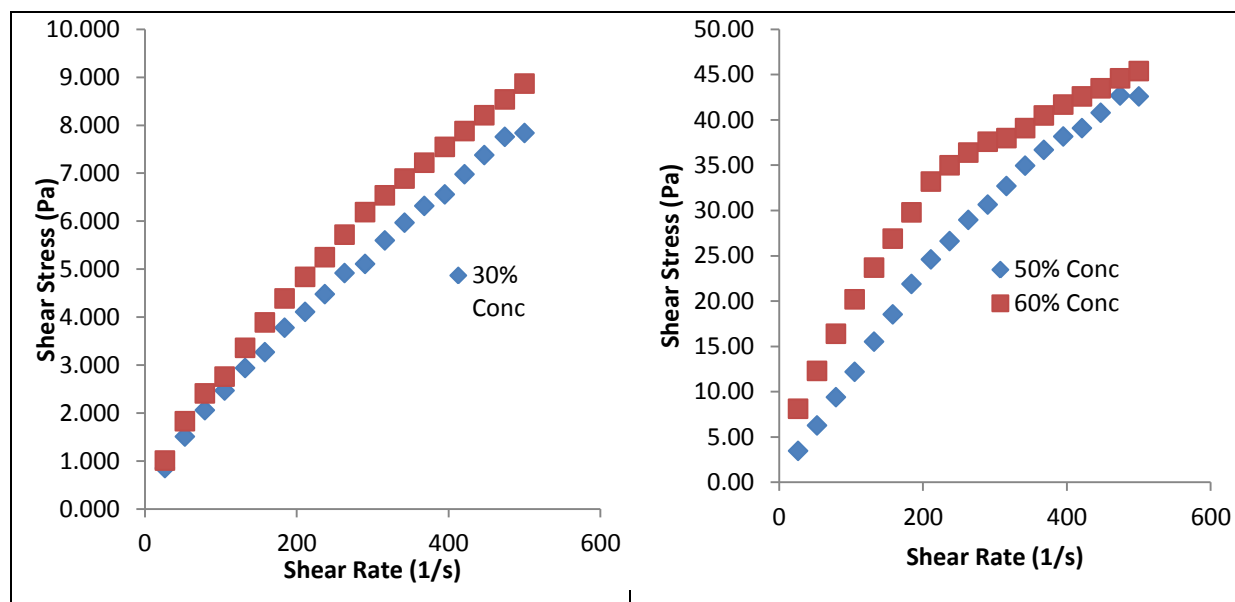


Figure 3.20: Variation of shear stress vs. shear rate for different concentration by weight for Sample2

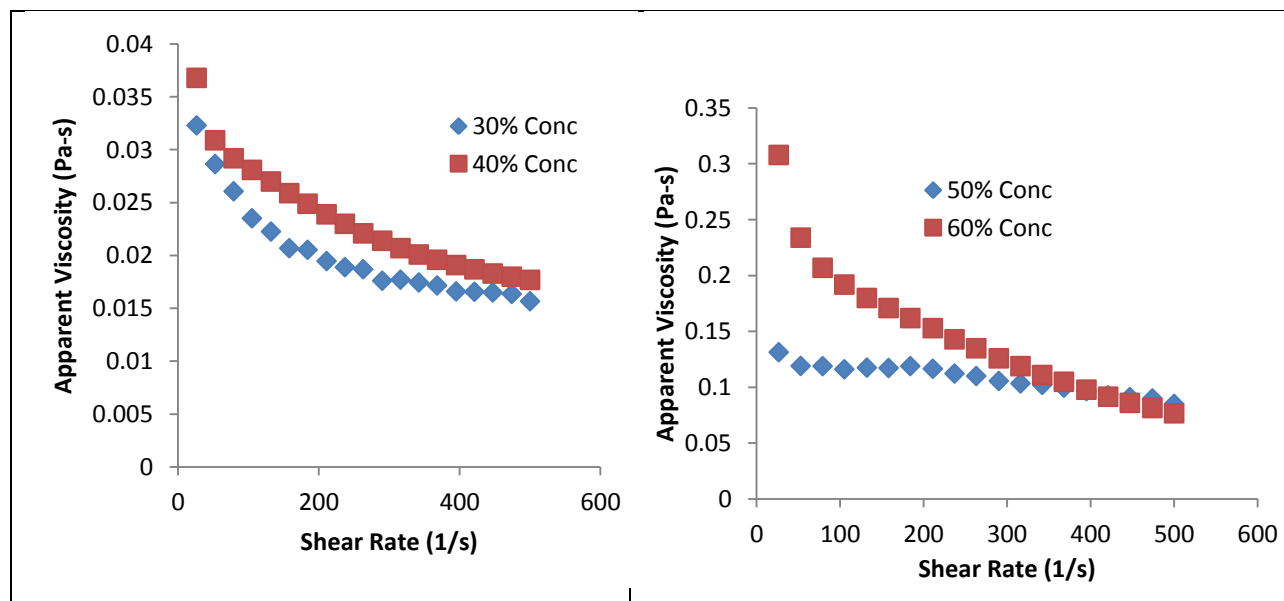


Figure 3.21: Variation of Apparent viscosity vs. shear rate for different concentration by weight for Sample 2

From Figure 3.20-3.21, results revealed that slurry exhibit Non-Newtonian behaviour at concentration of 40% and become highly viscous at concentration of 60% and exhibit shear thinning behaviour. Apparent Viscosity decreases with increase in shear rate.

RHEOLOGICAL BEHAVIOUR OF FLY ASH SLURRY WITH ADDITIVE

The problem associated with fly ash was quick settling due to high specific gravity. This problem results in pumping of fly ash as lean slurry through pipeline to ash pond area. Certain additives enable the slurries to be pumped at higher concentration of solids thus reducing the water requirements which was important consideration in power plant to minimize the size of ash pond (Seshadri et al. 2005, Verma et al. 2008, Biswas et al. 2000, Matras et al. 2007).

The present study makes use of anionic surfactant for different concentration to study the rheological behaviour of fly ash slurry. The anionic surfactant used was Sodium Lauryl Ether Sulfate (SLES).

4.1 SODIUM LAURYL ETHER SULFATE (SLES)

SLES is an anionic surfactant and found in many personal care products for their cleansing and emulsifying properties. It is an inexpensive foaming agent and behave similarly to soap.

4.1.1 Chemical Structure

SLES was prepared by ethoxylation of dodecyl alcohol. The resulting ethoxylate was converted to a half ester of sulfuric acid, which was neutralized by conversion to the sodium salt. Its chemical formula is $\text{CH}_3(\text{CH}_2)_{10}\text{CH}_2(\text{OCH}_2\text{CH}_2)_n\text{OSO}_3\text{Na}$.

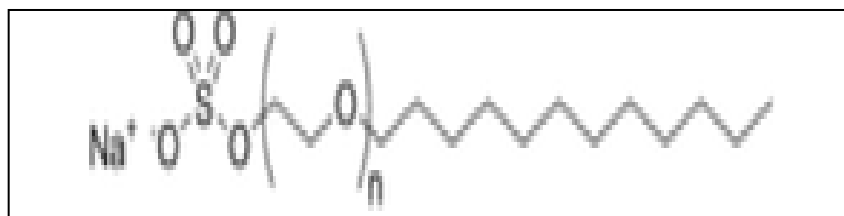


Figure 4.1: Chemical Structure of SLES

4.1.2 Toxicology

SLES is irritant like other detergents with irritation increasing with concentration of dosage of SLES. This had been shown that this surfactant causes eye or skin irritation in experiments done on animals and humans.

4.2 RHEOLOGICAL BEHAVIOUR OF COARSER TO FINER ASH PARTICLE

In this we study the effect of mixing of finer particle with coarser particle on rheology of fly ash slurry. The two fly ash samples were collected from Guru Nanak Dev Thermal Power Plant, Bathinda and Rajiv Gandhi Thermal Power Plant, Hissar. The rheological behaviour was studied for concentration ranged from 40% to 60% at a shear rate varying from 0-500 s^{-1} .

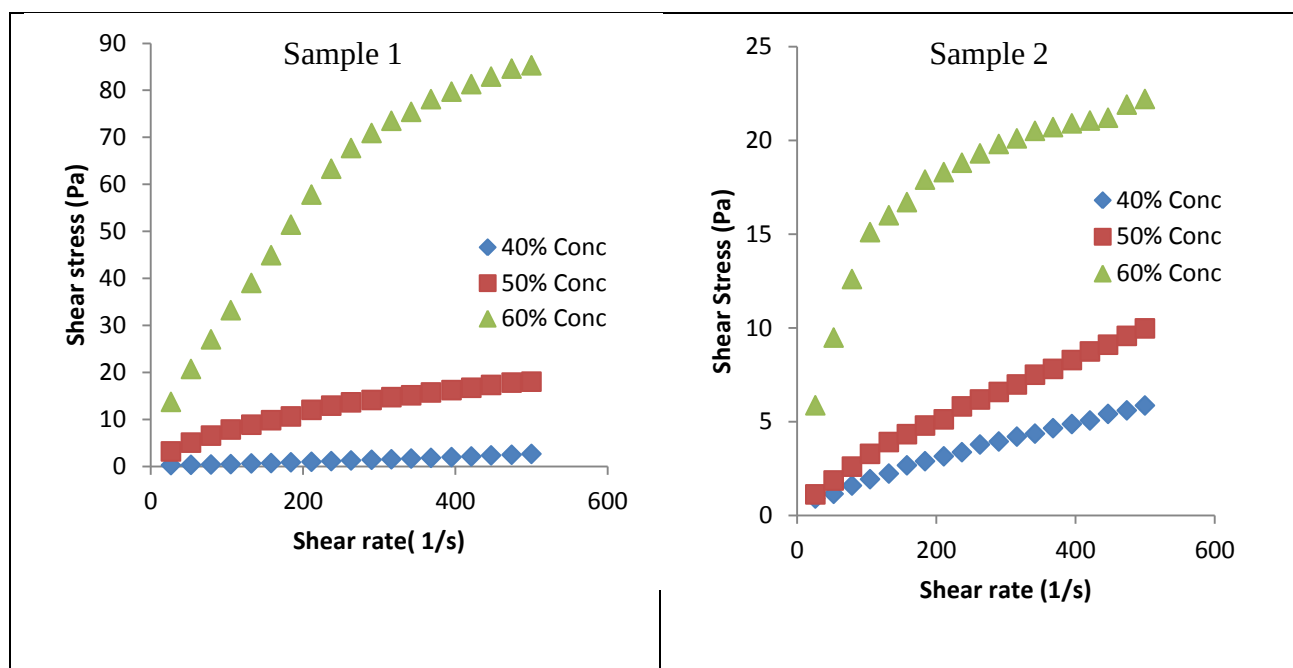


Figure 4.2: Variation of shear stress vs. shear rate for different concentration by weight for Sample1 and sample 2

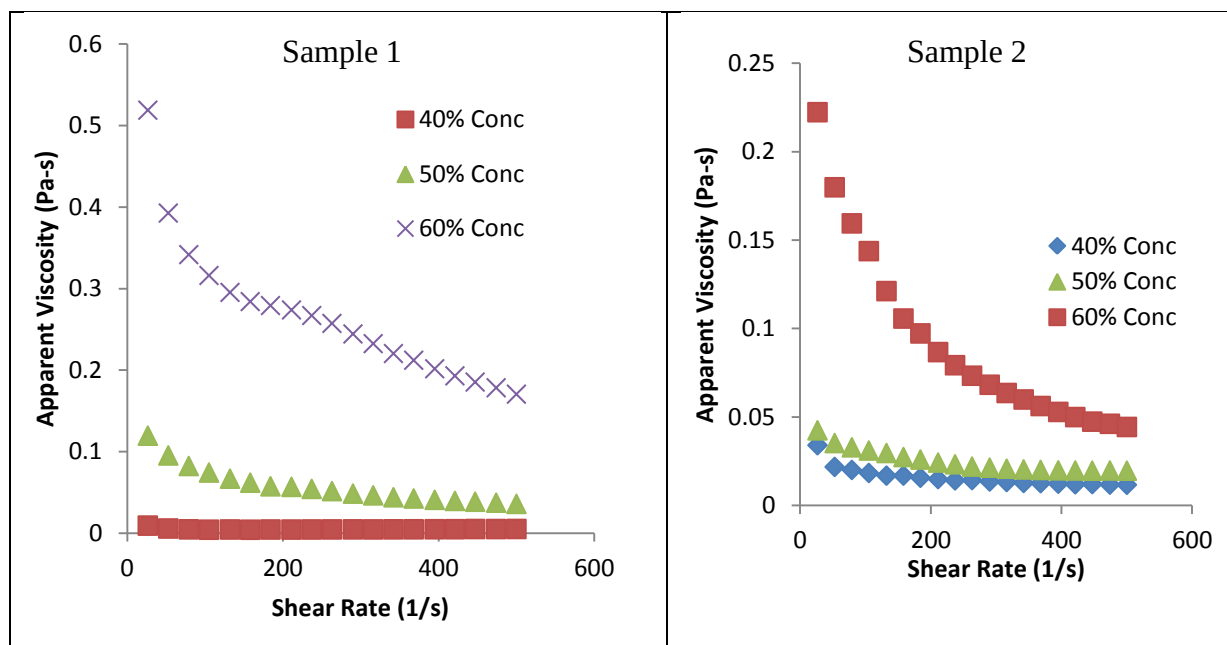


Figure 4.3: Variation of Apparent viscosity vs. shear rate for different concentration by weight for Sample 1 and Sample 2

From Figure 4.1-4.4, results revealed that sample 1 was Newtonian till 50% concentration and becomes non Newtonian at 60% whereas for sample 2, it is Newtonian at 40% and Non-Newtonian at 50%. Sample 1 slurry was more viscous at concentration of 60 % as compared to sample 2.

4.3 EFFECT OF ADDITIVE ON FLY ASH SLURRY

The anionic surfactant Sodium Lauryl Ether Sulfate purchased from Sardana Gums and Chemicals Inds, DELHI, was used to study the effect of surfactant on rheology of unsieved/coarser to finer slurry. The surfactant was taken to be .50ml, .75ml, 1ml, 1.25ml of slurry for concentration 50% and 60%.

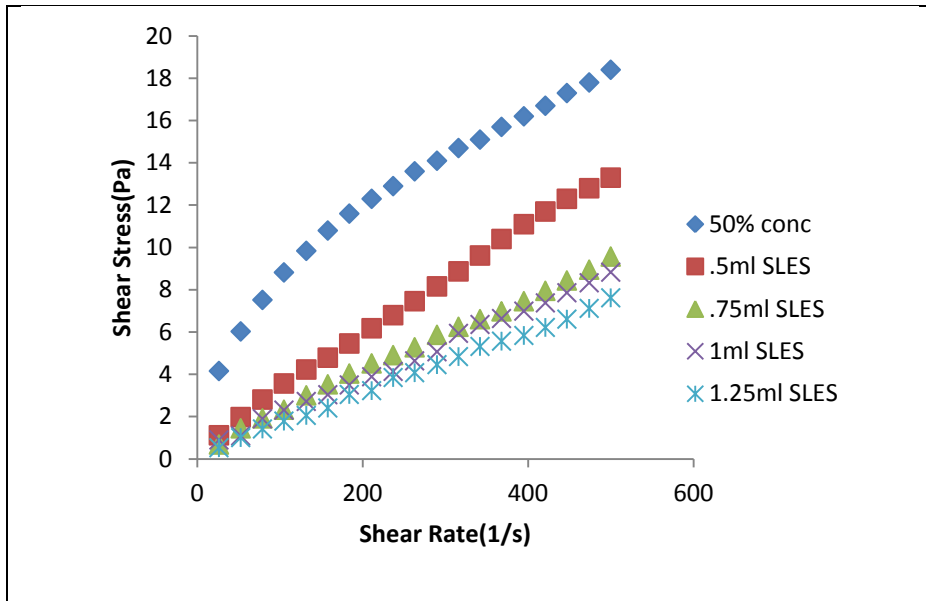


Figure 4.6: Variation of shear stress vs. shear rate for different volume of additive at concentration of 50%

From Figure 4.6, results revealed that with addition of additive slurry becomes less viscous and yield stress decreases.

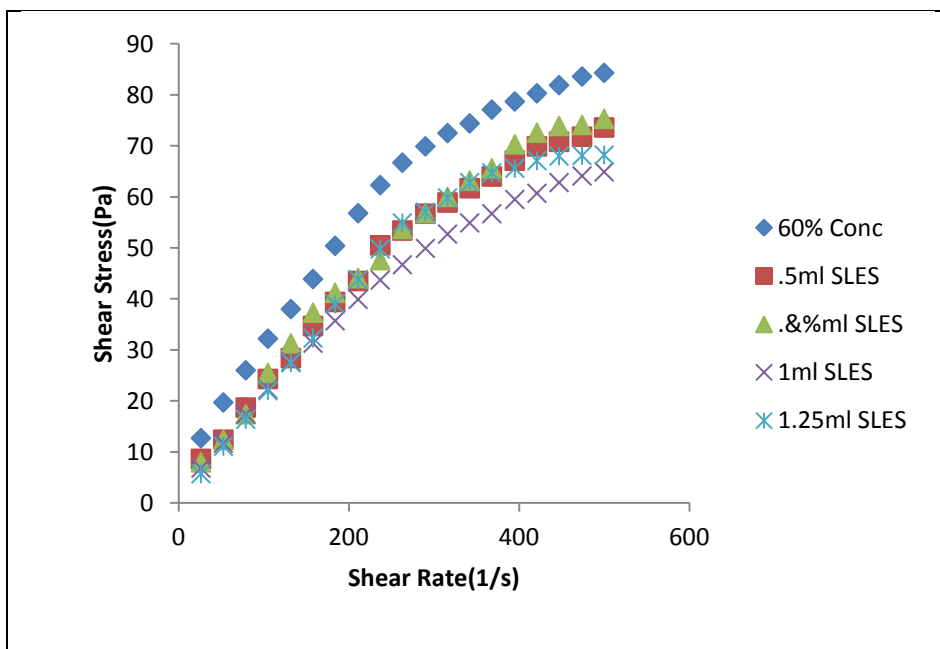


Figure 4.7: Variation of shear stress vs. shear rate for different volume of additive at concentration of 60%

From Figure 4.7, results revealed that increase in volume of additive, reduces the viscous behaviour of slurry and hence yield stress decreases for slurry from 18.425 Pa to 9.9939 Pa.

PRESSURE DROP CALCULATION

Lots of research had been done to reduce head loss and save energy consumption through slurry pipelines in the past 50 years. A number of techniques for reducing head loss in slurry transportation such as pilot plant and prototype levels. These techniques were capable of reducing the frictional pressure drop either by changing slurry rheological properties or by reducing the impact of adverse flow properties. Heywood (1986), Verma (2004), Horsely (1982) and Kolar (1970) described technically proven techniques on the laboratory scale for reducing the head loss for slurry flow in horizontal pipes [13].

Using the rheological data calculated with the help of rheometer, pressure drop had been predicted in a straight, smooth pipeline of 50mm diameter with velocities varying from 1m/s to 3m/s at higher concentrations using analytical calculation based on the Darby and Melson (1981) algorithm.

5.1 MATHEMATICAL CALCULATION TO CALCULATE PRESSURE DROP

The most important parameter to calculate pressure drop was friction factor which was dependent on Reynolds number. For laminar flow, the Fanning friction factor expression was obtained by theoretical analysis. But for transition as well as for turbulent flow regimes, the evaluation of friction factor was based on some empirical correlations [13].

In order to calculate pressure drop, some steps have to be followed to reach the desired result which are given below:

Step 1: Calculate the roughness coefficient of water which is given by Standard Colebrook Formula.

$$\frac{1}{f_T^{0.5}} = -2 \log \left[\left(\frac{(K/D)}{3.7} \right) + \frac{2.51}{Re f_T^{0.5}} \right] \quad \text{Eq. (4.1)}$$

Step 2: Calculate the density of Slurry

$$\rho_w = 100 / \left(\frac{C_w}{\rho_s} \right) + ((100 - C_w) / \rho_w) \quad \text{Eq. (4.2)}$$

Step 3: From mean velocity, diameter of pipe, density of slurry, calculate Hedstorm Number and Reynolds Number which is given as:

$$Re_b = D V \frac{\rho_m}{\mu_p} \quad \text{Eq. (4.3)}$$

$$He = D^2 \tau_{yB} \rho_m / \mu_p^2 \quad \text{Eq. (4.4)}$$

Step 4: From Hedstorm Number, Calculate critical factor

$$\frac{X_c}{(1-X_c)^3} = \frac{He}{16800} \quad \text{Eq. (4.5)}$$

Step 5: From critical factor, Calculate Critical Reynolds Number

$$Reb_c = \frac{He}{8X_c} \left(1 - \frac{4}{3} X_c + \frac{1}{3} X_c^4 \right) \quad \text{Eq. (4.6)}$$

Step 6: Calculate the Fanning friction factor equation for Bingham plastic model for laminar flow regime is related with the Hedstorm number (He), Bingham Reynolds number (Reb) and friction factor is given as:

$$\frac{1}{Reb} = \frac{f}{16} - \frac{He}{6(Reb)^2} + \frac{He^4}{3f^3Reb^8} \quad \text{Eq. (4.7)}$$

Or

$$f = \frac{16}{Re_{mod}} \quad \text{Eq. (4.8)}$$

$$Re_{mod} = \frac{6Reb^2}{6Reb + He} \quad \text{Eq. (4.9)}$$

Step 7: Calculate the Fanning friction factor equation for Bingham plastic model for turbulent flow regime

$$f_t = 10^c (Reb)^{-0.193} \quad \text{Eq. (4.10)}$$

$$c = -1.378(1 + 0.146 \exp(-2.9 * 10^{-5} Reb)) \quad \text{Eq. (4.11)}$$

Step 8: Calculate the modified friction factor valid for all regimes

$$m = 1.7 + 40000/Reb \quad \text{Eq. (4.12)}$$

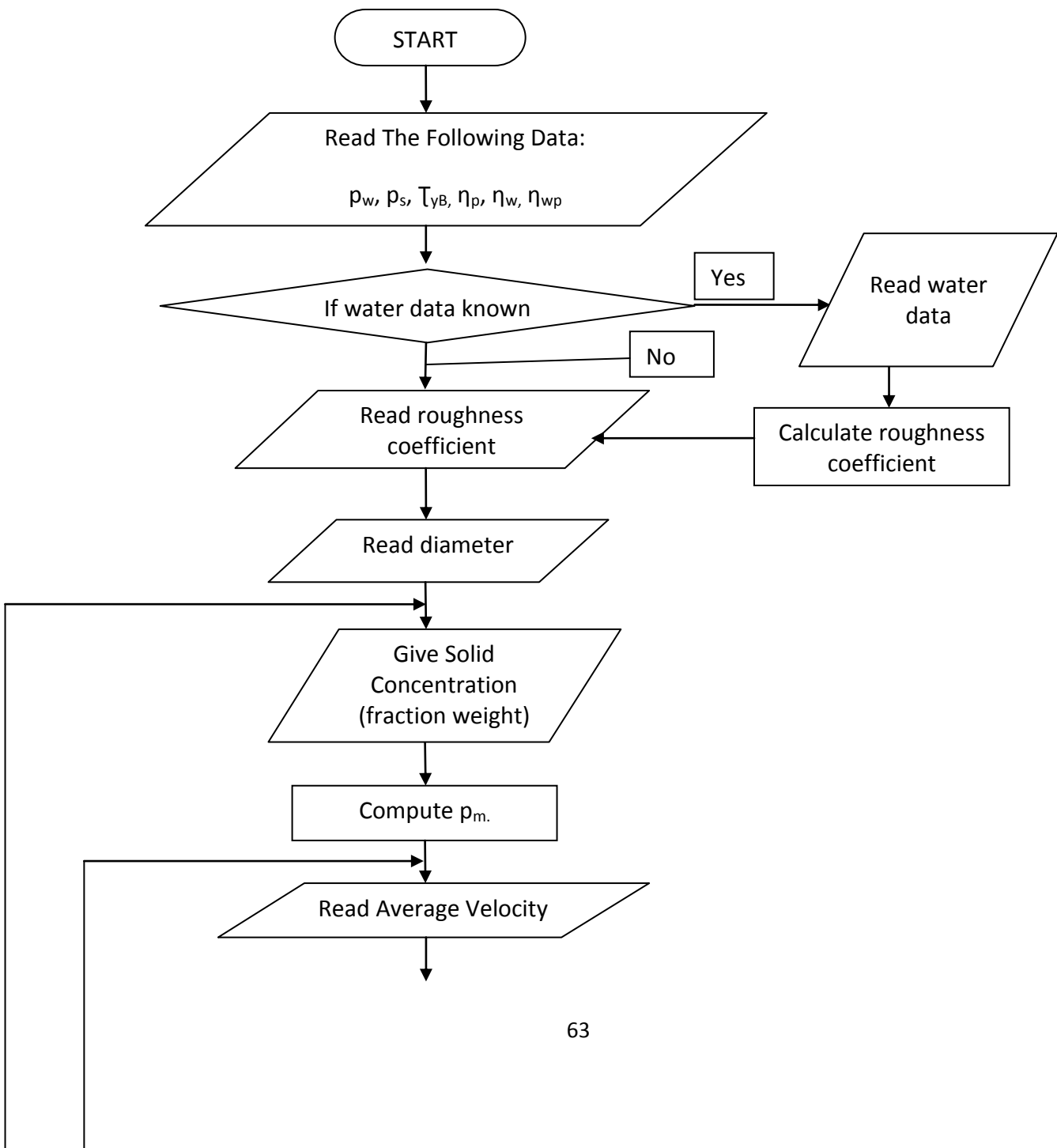
$$f = (f_L^m + f_t^m)^{1/m} \quad \text{Eq. (4.13)}$$

Step 9: Calculate the pressure Drop using Darcy -Weisbach Equation using the value of Fanning Friction Factor obtained in step 8

$$\Delta p = f (l/d) (\rho V^2)/2 \quad \text{Eq. (4.14)}$$

5.2 FLOW CHART

The methodology for reducing pressure drop is explained using analytical or mathematical calculations in the form of flowchart.



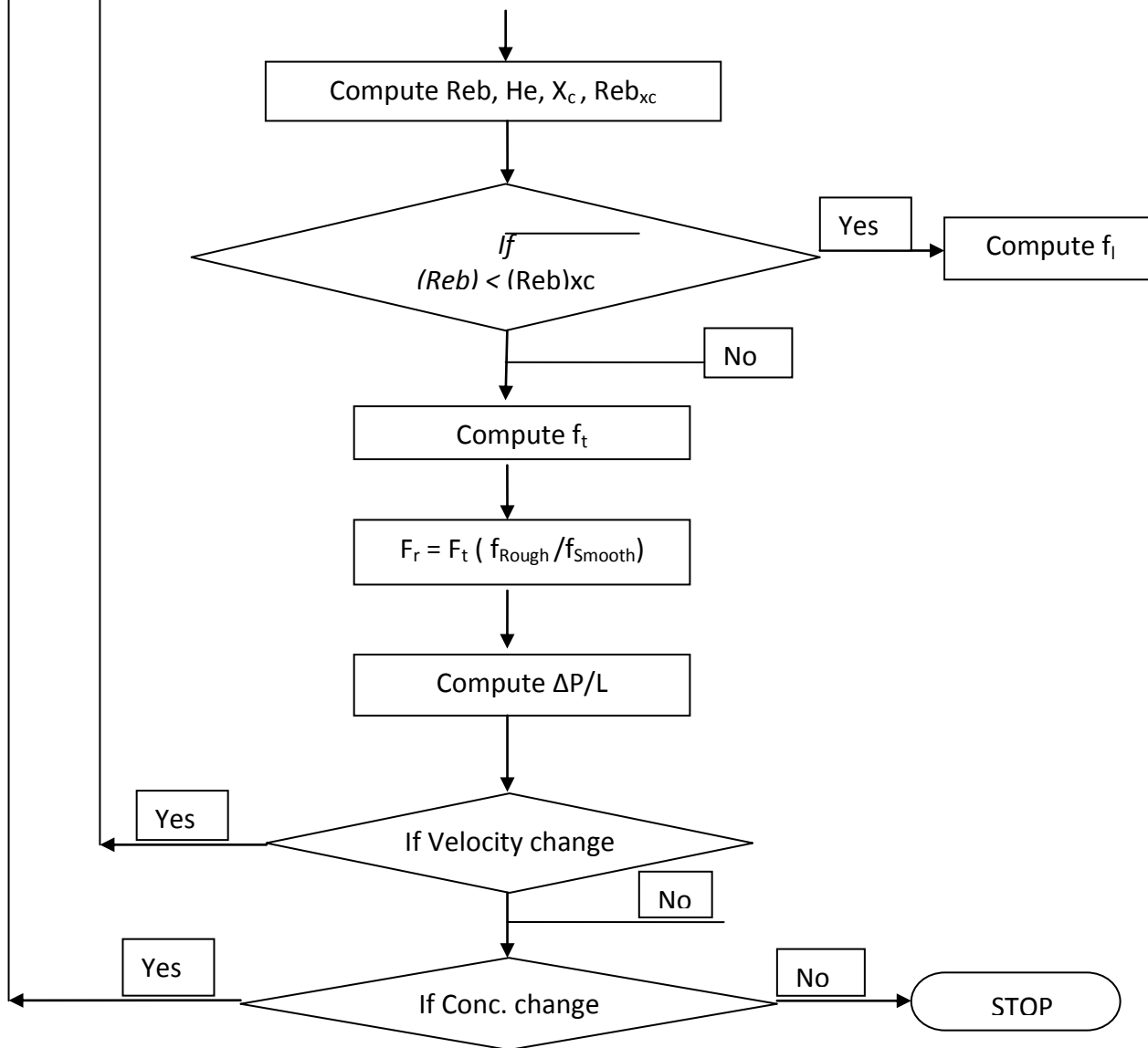


Figure 5.1: Flowchart to calculate Pressure Drop

5.3 VARIATION OF PRESSURE DROP WITH VELOCITY

The variation of pressure drop per unit length with velocity had been done with sample 1 with and without additive at higher concentration of 50% and 60%. The additive volume was varied from 0.5ml to 1.25ml. The velocity was varied from 1 m/s to 3 m/s.

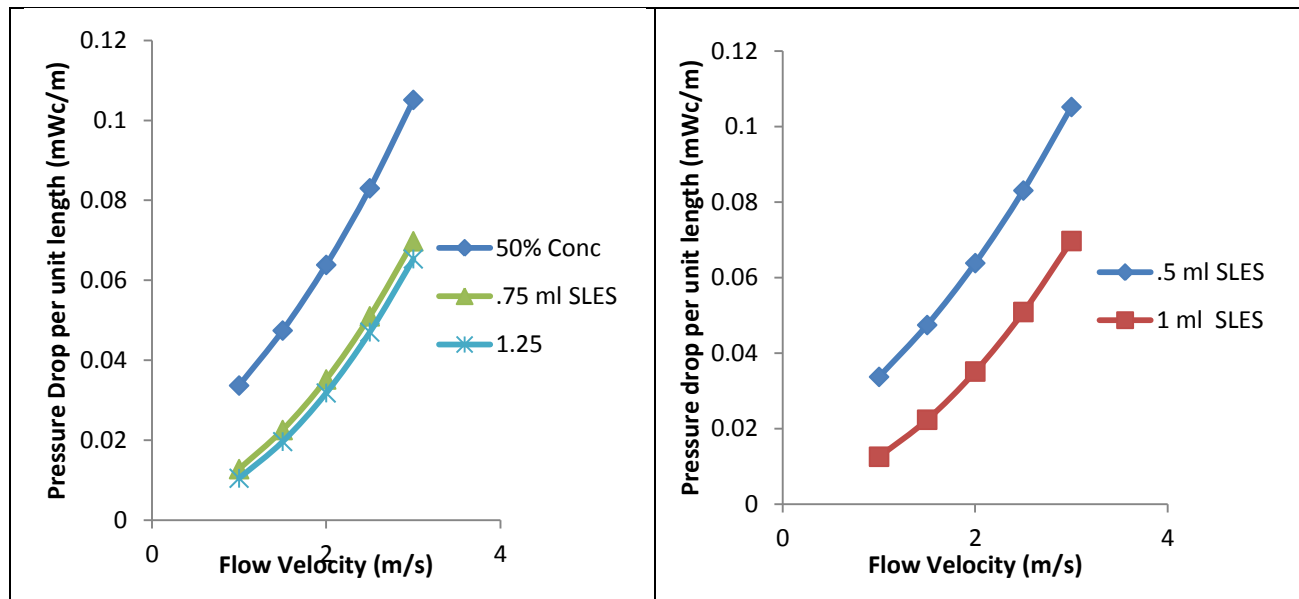


Figure 5.2: Pressure Drop variation for 50% fly ash sample with additive

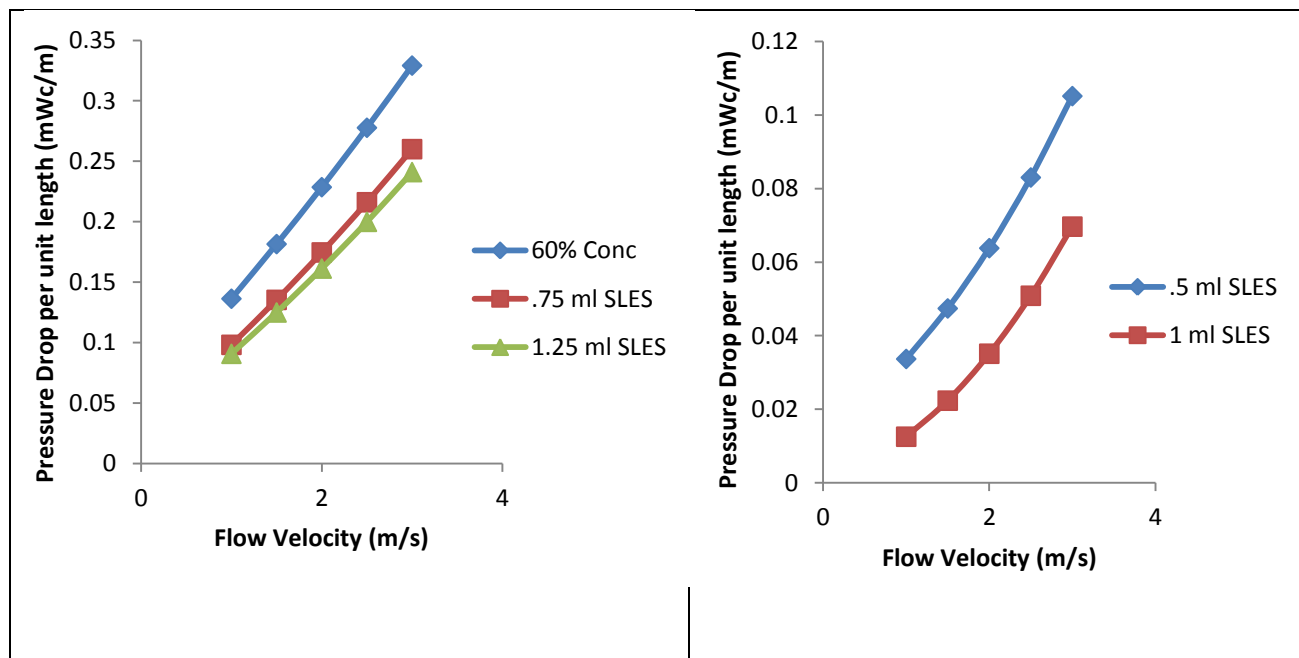


Figure 5.3: Pressure Drop variation for 60% fly ash sample with additive

From Figure 5.2-5.3, results revealed that pressure drop per unit length decreases with increase in a volume of additive used and increases with increase in velocity for both the concentration of 50% and 60%.

5.4 VARIATION OF PRESSURE DROP WITH CONCENTRATION

The variation of pressure drop per unit length with concentration had been done with sample 1 and sample 2 at varying velocity from 1 m/s to 3 m/s.

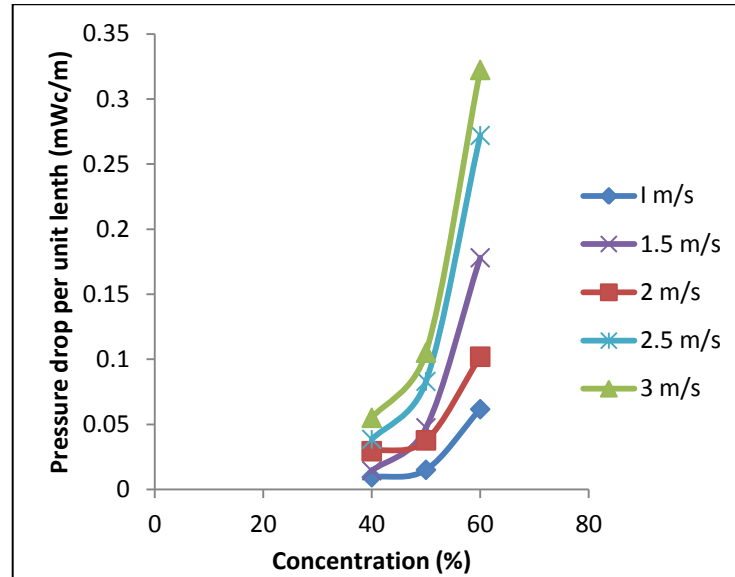


Figure 5.4: Pressure Drop variation for different concentration at varying velocity of Sample 1

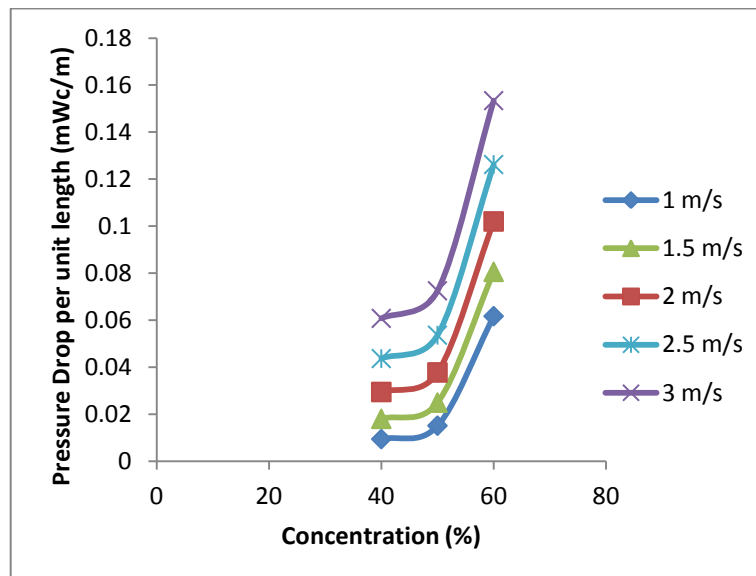


Figure 5.5: Pressure Drop variation for different concentration at varying velocity of Sample 2

From Figure 5.4-5.5, results revealed that for a given velocity pressure drop per unit length increases with increase in concentration. The drop in pressure was maximum for sample 1 at a velocity of 3m/s at a concentration of 60%.

5.5 PERCENTAGE REDUCTION IN PRESSURE DROP

The percentage reduction in pressure drop was calculated for sample 1 with additive for a concentration of 50% and 60% at varying velocity of (1, 1.5, 2, 2.5, 3) m/s.

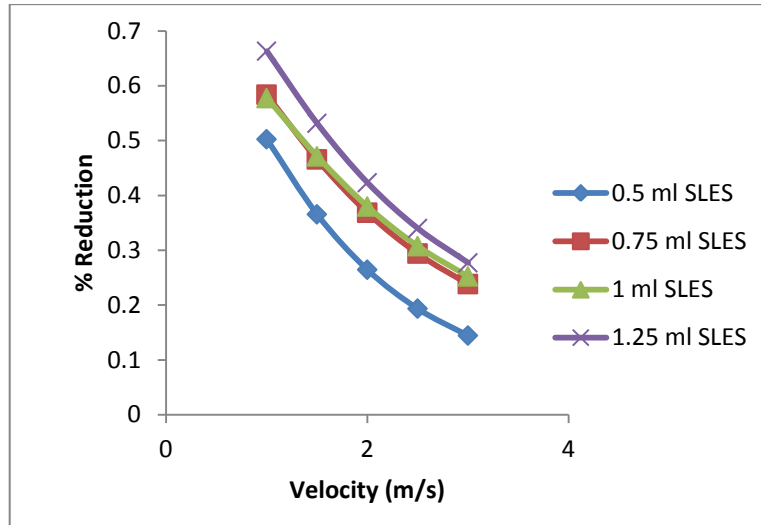


Figure 5.6: Reduction in Pressure at varying velocity for 50% with additive

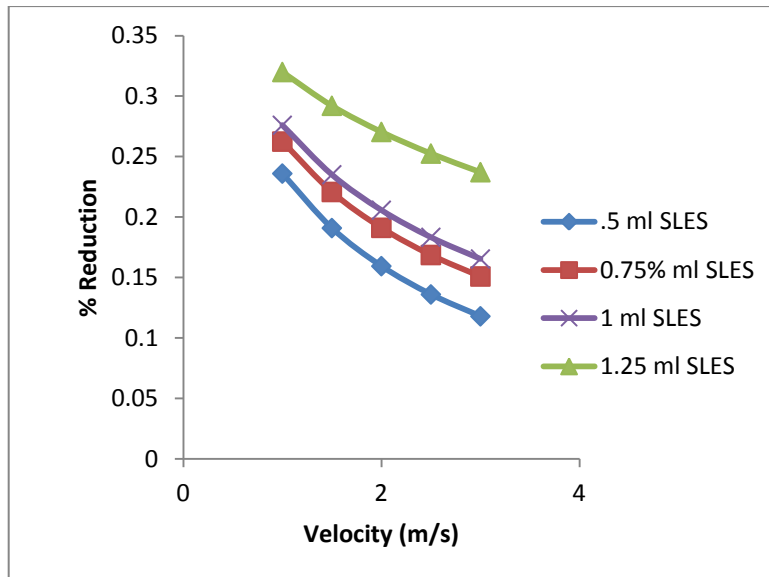


Figure 5.7: Reduction in Pressure at varying velocity for 60% with additive

From Figure 5.6-5.7, result revealed that drop in pressure was maximum for dosage of 1.25 ml of surfactant and minimum for .5 ml of surfactant. Hence surfactant reduces the pressure drop in pipeline.

CONCLUSION AND FUTURE SCOPE

In the present work various properties such as Particle Size distribution, pH, Settling, Zeta Potential, SEM, EDX, Specific Gravity had been studied of collected ash sample from Guru Nanak Dev Thermal Power Plant, Bathinda and Rajiv Gandhi Thermal Power Plant, Hissar. Rheology of both sieved as well as unsieved sample had been studied at concentration from 30%-60% and particle size from 53-106 microns with and without additive (Sodium Lauryl ether sulphate). The ash slurry shows the Newtonian behaviour up to 40% for particle size below 53 and 53-75 microns and Non – Newtonian behaviour at 50% concentration. Addition of surfactant reduces the viscosity and makes the fly ash particle water borne at pH 6. Using rheological data, pressure drop had been calculated on various efflux concentrations (40%, 50%, 60%) and flow velocity (1, 1.5, 2, 2.5, 3) m/s with the help of program generated in C language. The pressure drop in pipeline increases with increase in velocity and surfactant reduces the pressure drop. It was also observed that consistency coefficient (K) increases with increase in concentration for a given particle size exponentially.

FUTURE SCOPE

- The Computational Fluid Dynamics approach can be used to simulate the pressure drop.
- Rheological properties can be measured for higher concentration with and without additive with varying temperature.
- The pressure drop can be evaluated and validated with pilot plant test loop.

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APPENDIX

Annexure 1

Table: Experimental results of Particle Size Distribution of three Fly Ash samples

S.No.	Mesh Size (microns)	% finer (sample 1)	% finer (sample 2)
1	Below 2000	100	100
2	2000-1700	99.53469135	100
3	1700-1000	99.28652673	100
4	1000-710	98.84189846	99.81777978
5	710-500	98.22148692	99.586477
6	500-355	97.80787923	99.51229886
7	355-250	90.4353221	97.61380197
8	250-150	54.07920587	93.07774797
9	150-106	20.83548754	85.49555234
10	106-75	6.224795981	75.43514149
11	75-53	1.654430772	64.64574897
12	Below 53	0	0

Annexure 2

Table: Measurement of static settling at 30% conc of Sample 1

S.No	Time (min)	Concentration (%)	
		Sample 1	Sample 2
0	0	0	0
1	0.5	30.9	31.63
2	1	31.13	32.67
3	2	31.89	35.79
4	5	34.33	44.234
5	10	39.03	57.012
6	18	47.57	61.45
7	2	54.68	63.8
8	45	58.98	64.35
9	65	60.41	65.04
10	91	60.53	65.18
11	151	60.532	65.18
12	221	61.652	66.34
13	1421	63.34	67.23

Annexure 3

Figure: Experimental results of pH Measurement of three Fly Ash samples

S.No.	Concentration (%)	sample 2	sample 3
1	0	7.75	7.75
2	10	7.55	7.7
3	20	7.49	7.64
4	30	7.43	7.61
5	40	7.35	7.53
6	50	7.33	7.47
7	60	7.29	7.43

Annexure 4

Figure: Experimental results of Flow Behaviour Index (n) and Consistency Parameter (K) of sample 1 and sample 2 of below 53 microns

Conc(%)	Sample 1				Sample 2			
	Viscosity (Pa-s)	Yield Stress (Pa)	N	K	Viscosity (Pa-s)	Yield Stress (Pa)	n	K
30%	0.0071	0.1135	0.8423	0.0147	0.0044	0.1673	0.7365	0.017626
40%	0.0098	0.361	0.7929	0.0274	0.0056	0.1969	0.7185	0.024627
50%	0.023247	1.3001	0.6052	0.1806	0.014053	1.0336	0.7466	0.0713
60%	0.153337	12.043	0.6283	1.065666	0.0485	4.277	0.4447	0.837864

Annexure 5

Table: Experimental results of rheological behaviour at 30% concentration below 53 microns of Sample 1 and Sample 2

S.No.	Sample 1			Sample 2		
	Viscosity (Pa-s)	Shear Rate (s ⁻¹)	Shear Stress (Pa)	Viscosity (Pa-s)	Shear Rate (s ⁻¹)	Shear Stress (Pa)
1	0.01340	26.4	0.253	0.00834	26.4	0.220
2	0.01000	52.7	0.427	0.00619	52.7	0.326
3	0.00857	79	0.577	0.00547	79	0.432
4	0.00775	105	0.717	0.00501	105	0.527
5	0.00721	132	0.849	0.00464	132	0.610
6	0.00685	158	0.980	0.00442	158	0.697
7	0.00666	184	1.130	0.00425	184	0.783
8	0.00647	211	1.260	0.00409	211	0.862
9	0.00641	237	1.420	0.00401	237	0.951
10	0.00637	263	1.580	0.00392	263	1.030
11	0.00633	290	1.730	0.00390	290	1.130
12	0.00627	316	1.880	0.00388	316	1.220
13	0.00614	342	2.000	0.00384	342	1.310
14	0.00605	368	2.130	0.00383	368	1.410
15	0.00604	395	2.290	0.00382	395	1.510
16	0.00605	421	2.450	0.00375	421	1.580
17	0.00609	447	2.620	0.00365	447	1.630
18	0.00613	474	2.800	0.00358	474	1.700
19	0.00620	500	2.900	0.00356	500	1.780

Annexure 6

Table: Experimental results of rheological behaviour at 40% concentration below 53 microns of Sample 1 and Sample 2

S.No.	Sample 1			Sample 2		
	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)
1	0.01880	26.4	0.397	0.01180	26.4	0.310
2	0.01380	52.7	0.629	0.00830	52.7	0.437
3	0.01160	79	0.819	0.00672	79	0.531
4	0.01070	105	1.020	0.00614	105	0.646
5	0.01020	132	1.240	0.00579	132	0.763
6	0.00987	158	1.460	0.00549	158	0.867
7	0.00972	184	1.790	0.00534	184	0.983
8	0.00963	211	1.930	0.00513	211	1.080
9	0.00948	237	2.150	0.00500	237	1.180
10	0.00937	263	2.370	0.00493	263	1.300
11	0.00911	290	2.540	0.00488	290	1.410
12	0.00891	316	2.720	0.00484	316	1.530
13	0.00869	342	2.880	0.00481	342	1.650
14	0.00848	368	3.000	0.00481	368	1.770
15	0.00825	395	3.160	0.00476	395	1.880
16	0.00805	421	3.290	0.00475	421	2.000
17	0.00783	447	3.400	0.00470	447	2.100
18	0.00765	474	3.520	0.00467	474	2.210
19	0.00756	500	3.680	0.00462	500	2.310

Annexure 7

Table: Experimental results of rheological behaviour at 50% concentration below 53 microns of Sample 1 and sample 2

S.No.	Sample 1			Sample 2		
	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)
1	0.0561	26.4	1.480	0.0272	26.4	0.819
2	0.0393	52.7	2.070	0.0229	52.7	1.300
3	0.0318	79.0	2.520	0.0212	79	1.880
4	0.0273	105.0	2.880	0.0182	105	2.220
5	0.0246	132.0	3.240	0.0170	132	2.759
6	0.0228	158.0	3.600	0.0156	158	3.100
7	0.0213	184.0	3.930	0.0148	184	3.520
8	0.0205	211.0	4.320	0.0141	211	4.000
9	0.0198	237.0	4.700	0.0138	237	4.520
10	0.0191	263.0	5.040	0.0131	263	4.940
11	0.0187	290.0	5.410	0.0130	290	5.180
12	0.0183	316.0	5.780	0.0128	316	5.440
13	0.0181	342.0	6.180	0.0115	342	5.720
14	0.0178	368.0	6.560	0.0108	368	5.950
15	0.0177	395.0	6.980	0.0098	395	6.130
16	0.0174	421.0	7.320	0.0087	421	6.320
17	0.0172	447.0	7.700	0.0081	447	6.480
18	0.017	474.0	8.070	0.0076	474	6.720
19	0.0169	500.0	8.440	0.0068	500	6.800

Annexure 8

Table: Experimental results of rheological behaviour at 60% concentration below 53 microns of Sample 1 and Sample 2

S.No.	Sample 1			Sample 2		
	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)
1	0.302	26.4	7.97	0.1500	26.4	3.95
2	0.234	52.7	12.3	0.0898	52.7	4.73
3	0.204	79	16.1	0.0724	79	5.72
4	0.187	105	19.7	0.0615	105	6.47
5	0.175	132	23.1	0.0543	132	7.15
6	0.167	158	26.4	0.0490	158	7.74
7	0.161	184	29.6	0.0451	184	8.31
8	0.155	211	32.6	0.0424	211	8.93
9	0.150	237	35.5	0.0398	237	9.44
10	0.144	263	37.9	0.0374	263	9.84
11	0.138	290	39.9	0.0355	290	10.30
12	0.132	316	41.8	0.0340	316	10.70
13	0.126	342	43.2	0.0329	342	11.20
14	0.121	368	44.5	0.0317	368	11.70
15	0.114	395	45.2	0.0307	395	12.10
16	0.109	421	45.9	0.0298	421	12.50
17	0.103	447	46.2	0.0289	447	12.90
18	0.0978	474	46.3	0.0283	474	13.40
19	0.0936	500	46.8	0.0278	500	13.90

Annexure 9

Figure: Experimental results of Flow Behaviour Index (n) and Consistency Parameter (K) of sample 1 at 53- 75 microns

Conc(%)	Sample 1				Sample 2			
	Viscosity (Pa-s)	Yield Stress (Pa)	n	K	Viscosity (Pa-s)	Yield Stress (Pa)	n	K
30%	0.0098	0.1309	0.8667	0.021	0.0086	0.0800	0.0971	0.015
40%	0.0109	0.2371	0.7969	0.0336	0.01014	0.1853	0.8301	0.0248
50%	0.0594	4.3309	0.4127	1.0168	0.038605	2.5424	0.5558	0.3839
60%	0.2107	15.079	0.6661	1.2063	0.1068	11.001	0.5265	1.2418

Annexure 10

Table: Experimental results of rheological behaviour at 30% concentration 53-75 microns of Sample 1

S.No.	Sample 1			Sample 2		
	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)
1	0.0138	26.40	0.4640	0.01200	26.4	0.317
2	0.0107	52.70	0.5640	0.00989	52.7	0.521
3	0.0101	79.00	0.8000	0.00923	79	0.729
4	0.0101	105.00	1.1700	0.00885	105	0.932
5	0.0101	132.00	1.4200	0.00862	132	1.13
6	0.0099	158.00	1.6600	0.00847	158	1.34
7	0.0097	184.00	1.8800	0.00847	184	1.56
8	0.0095	211.00	2.1000	0.00841	211	1.77
9	0.0094	237.00	2.3300	0.00832	237	1.97
10	0.0094	263.00	2.5600	0.00829	263	2.18
11	0.0093	290.00	2.8000	0.00828	290	2.4
12	0.0093	316.00	3.1000	0.00827	316	2.61
13	0.0093	342.00	3.3000	0.00827	342	2.83
14	0.0093	368.00	3.5500	0.00826	368	3.04
15	0.0093	395.00	3.8000	0.00826	395	3.26
16	0.0093	421.00	4.1500	0.00826	421	3.47
17	0.0093	447.00	4.4100	0.00824	447	3.69
18	0.0093	474.00	4.5800	0.00824	474	3.91
19	0.0093	500.00	4.8500	0.00824	500	4.13

Annexure 11

Table: Experimental results of rheological behaviour at 40% concentration 53-75 microns of Sample 1

S.No.	Sample 1			Sample 2		
	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)
1	0.0185	26.40	0.5870	0.01690	26.4	0.445
2	0.0133	52.70	0.8000	0.01250	52.7	0.661
3	0.0117	79.00	0.9260	0.01110	79	0.876
4	0.0110	105.00	1.2600	0.01040	105	1.100
5	0.0106	132.00	1.5000	0.01020	132	1.340
6	0.0105	158.00	1.7500	0.00993	158	1.570
7	0.0103	184.00	2.0000	0.00978	184	1.800
8	0.0103	211.00	2.2700	0.00965	211	2.030
9	0.0103	237.00	2.5400	0.00953	237	2.260
10	0.0103	263.00	2.8200	0.00945	263	2.490
11	0.0103	290.00	3.0000	0.00936	290	2.710
12	0.0103	316.00	3.3600	0.00932	316	2.940
13	0.0103	342.00	3.6100	0.00927	342	3.170
14	0.0102	368.00	3.8600	0.00924	368	3.410
15	0.0101	395.00	4.1100	0.00923	395	3.640
16	0.0101	421.00	4.3500	0.00922	421	3.890
17	0.0100	447.00	4.5800	0.00921	447	4.120
18	0.0099	474.00	4.8800	0.00919	474	4.360
19	0.0099	500.00	5.1000	0.00919	500	4.590

Annexure 12

Table: Experimental results of rheological behaviour at 50% concentration 53-75 microns of Sample 1

S.No.	Sample 1			Sample 2		
	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)
1	0.3370	26.6	4.560	0.104	26.4	2.74
2	0.1120	52.7	5.460	0.0653	52.7	3.44
3	0.0716	79	5.910	0.0538	79	4.25
4	0.0678	105	6.340	0.0459	105	4.84
5	0.0565	132	7.140	0.0414	132	5.44
6	0.0508	158	7.920	0.0384	158	6.06
7	0.0456	184	8.300	0.0359	184	6.61
8	0.0420	211	8.730	0.0340	211	7.16
9	0.0389	237	9.200	0.0325	237	7.71
10	0.0370	263	9.730	0.0314	263	8.26
11	0.0350	290	10.100	0.0305	290	8.82
12	0.0338	316	10.600	0.0295	316	9.32
13	0.0326	342	11.320	0.0287	342	9.81
14	0.0316	368	11.700	0.0279	368	10.30
15	0.0308	395	12.300	0.0276	395	10.90
16	0.0301	421	12.900	0.0273	421	11.50
17	0.0295	447	13.500	0.0268	447	12.00
18	0.0260	474	13.900	0.0264	474	12.50
19	0.0201	500	14.700	0.0262	500	13.10

Annexure 13

Table: Experimental results of rheological behaviour at 60% concentration 53-75 microns of Sample 1

S.No.	Sample 1			Sample 2		
	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)
1	0.409	26.4	10.8	0.2250	26.4	5.94
2	0.297	52.7	15.7	0.1740	52.7	9.14
3	0.262	79	20.7	0.1560	79	12.40
4	0.245	105	25.8	0.1440	105	15.20
5	0.236	132	31.1	0.1340	132	17.60
6	0.230	158	36.3	0.1250	158	19.70
7	0.223	184	41.0	0.1170	184	21.50
8	0.215	211	45.4	0.1120	211	23.60
9	0.212	237	50.1	0.1060	237	25.20
10	0.205	263	53.9	0.0964	263	25.40
11	0.196	290	56.6	0.0899	290	26.00
12	0.187	316	58.9	0.0841	316	26.60
13	0.177	342	60.5	0.0787	342	26.90
14	0.169	368	62.2	0.0739	368	27.20
15	0.161	395	63.4	0.0693	395	27.40
16	0.154	421	64.8	0.0658	421	27.70
17	0.148	447	66.1	0.0628	447	28.10
18	0.142	474	67.2	0.0596	474	28.20
19	0.136	500	67.9	0.0560	500	28.00

Annexure 14

Figure: Experimental results of Flow Behaviour Index (n) and Consistency Parameter (K) of sample 1 and sample 2 at 75-106 microns

Conc(%)	Sample 1				Sample 2			
	Viscosity (Pa-s)	Yield Stress (Pa)	n	K	Viscosity (Pa-s)	Yield Stress (Pa)	n	K
30%	0.012558	0.6225	0.797	0.0366	0.020	0.912	0.7475	0.076
40%	0.0255	1.289	0.6525	0.1565	0.0234	1.1945	0.7305	0.0963
50%	0.15872	4.7021	0.8973	0.2732	0.10769	4.3367	0.8714	0.2127
60%	0.29341	20.351	0.6685	1.5872	0.1463	13.017	0.5881	1.2827

Annexure 15

Table: Experimental results of rheological behaviour at 30% concentration 75-106 microns of Sample 1 and Sample 2

S.No.	Sample 1			Sample 2		
	Viscosity (Pa-s)	Shear Rate (s ⁻¹)	Shear Stress (Pa)	Viscosity (Pa-s)	Shear Rate (s ⁻¹)	Shear Stress (Pa)
1	0.017083	26.4	0.451	0.032311	26.4	0.853
2	0.015484	52.7	0.816	0.028653	52.7	1.510
3	0.01557	79	1.23	0.026076	79	2.060
4	0.014667	105	1.54	0.023524	105	2.470
5	0.014394	132	1.9	0.022273	132	2.940
6	0.014304	158	2.26	0.020696	158	3.270
7	0.013641	184	2.51	0.020543	184	3.780
8	0.012986	211	2.74	0.019479	211	4.110
9	0.012489	237	2.96	0.018903	237	4.480
10	0.011977	263	3.15	0.018707	263	4.920
11	0.011793	290	3.42	0.017621	290	5.110
12	0.011361	316	3.59	0.017722	316	5.600
13	0.011228	342	3.84	0.017456	342	5.970
14	0.010788	368	3.97	0.017174	368	6.320
15	0.010405	395	4.11	0.016608	395	6.560
16	0.010523	421	4.43	0.01658	421	6.980
17	0.010179	447	4.55	0.01651	447	7.380
18	0.010084	474	4.78	0.016371	474	7.760
19	0.00964	500	4.82	0.01568	500	7.840

Annexure 16

Table: Experimental results of rheological behaviour at 40% conc 75-106 microns of Sample 1 and sample 2

S.No.	Sample 1			Sample 2		
	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)
1	0.0541	26.4	1.43	0.0368	26.4	1.010
2	0.0411	52.7	2.17	0.0309	52.7	1.830
3	0.0347	79	2.74	0.0292	79	2.410
4	0.0303	105	3.19	0.0281	105	2.760
5	0.0273	132	3.6	0.0270	132	3.360
6	0.0254	158	4.01	0.0259	158	3.890
7	0.0239	184	4.41	0.0249	184	4.390
8	0.0230	211	4.85	0.0239	211	4.840
9	0.0223	237	5.29	0.0230	237	5.250
10	0.0217	263	5.71	0.0221	263	5.720
11	0.0212	290	6.13	0.0214	290	6.190
12	0.0208	316	6.57	0.0207	316	6.540
13	0.0205	342	7.03	0.0201	342	6.890
14	0.0203	368	7.47	0.0196	368	7.220
15	0.0201	395	7.94	0.0191	395	7.550
16	0.0199	421	8.39	0.0187	421	7.880
17	0.0197	447	8.83	0.0183	447	8.210
18	0.0196	474	9.28	0.0180	474	8.540
19	0.0193	500	9.67	0.0177	500	8.870

Annexure 17

Table: Experimental results of rheological behaviour at 50% concentration in a range of 75-106 microns of Sample 1 and sample 2

S.No.	Sample 1			Sample 2		
	Viscosity (Pa-s)	Shear Rate (s ⁻¹)	Shear Stress (Pa)	Viscosity (Pa-s)	Shear Rate (s ⁻¹)	Shear Stress (Pa)
1	0.213144	26.4	5.627	0.131439	26.4	3.47
2	0.165218	52.7	8.707	0.119165	52.7	6.28
3	0.151987	79	12.007	0.118987	79	9.40
4	0.165781	105	17.407	0.11619	105	12.20
5	0.168235	132	22.207	0.117652	132	15.53
6	0.163968	158	25.907	0.117342	158	18.54
7	0.163625	184	30.107	0.119022	184	21.90
8	0.160223	211	33.807	0.116635	211	24.61
9	0.165008	237	39.107	0.112363	237	26.63
10	0.166947	263	43.907	0.110152	263	28.97
11	0.164852	290	47.807	0.105724	290	30.66
12	0.160149	316	50.607	0.103513	316	32.71
13	0.156161	342	53.407	0.102222	342	34.96
14	0.152465	368	56.107	0.099728	368	36.70
15	0.148878	395	58.807	0.096658	395	38.18
16	0.14586	421	61.407	0.092874	421	39.10
17	0.139166	447	62.207	0.091275	447	40.80
18	0.134403	474	63.707	0.090084	474	42.70
19	0.129614	500	64.807	0.0852	500	42.60

Annexure 18

Table: Experimental results of rheological behaviour at 60% concentration in a range of 75-106 microns of Sample 1 and Sample 2

S.No.	Sample 1			Sample 2		
	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)	Viscosity (Pa-s)	Shear Rate (s^{-1})	Shear Stress (Pa)
1	0.6	26.40	13.800	0.3076	26.4	8.12
2	0.446	52.70	21.500	0.2334	52.7	12.3
3	0.382	79.00	28.200	0.2076	79	16.4
4	0.348	105.00	34.700	0.1924	105	20.2
5	0.329	132.00	41.300	0.1795	132	23.7
6	0.316	158.00	47.500	0.1703	158	26.9
7	0.306	184.00	54.500	0.1620	184	29.8
8	0.297	211.00	60.600	0.1573	211	33.2
9	0.288	237.00	66.300	0.1477	237	35
10	0.279	263.00	70.500	0.1384	263	36.4
11	0.269	290.00	75.000	0.1297	290	37.6
12	0.257	316.00	80.200	0.1203	316	38
13	0.247	342.00	83.400	0.1143	342	39.1
14	0.233	368.00	84.900	0.1101	368	40.5
15	0.22	395.00	85.800	0.1056	395	41.7
16	0.208	421.00	86.500	0.1012	421	42.6
17	0.195	447.00	87.000	0.0973	447	43.5
18	0.183	474.00	88.000	0.0941	474	44.6
19	0.172	500.00	88.500	0.0908	500	45.4

ANNEXURE 19

```
#include<stdio.h>
#include<math.h>
#include<conio.h>
int main()
{
    float d, cw, v, np,ps,pm1,pm2,pm,pw=998.2,l=100.0,reb,he,remode,fL,ft,c,
    t,m,k1,k2,f,pl,p;

    printf("enter diameter");
    scanf("%f",&d);
    printf("enter solid concentration");
    scanf("%f",&cw);
    printf("Enter Velocity" );
    scanf("%f",&v);
    printf("Enter Viscosity" );
    scanf("%f",&np);
    printf("Enter density of flyash" );
    scanf("%f",&ps);
    printf("Enter yield stress" );
    scanf("%f",&t);

    pm1=cw/ps;
    pm2=(100-cw)/pw;
    pm=100/(pm1+pm2);
    printf("pm1 = %f",pm1);
    printf("pm2 = %f",pm2);
    printf("pm = %f",pm);

    reb=d*v*pm/np;
    printf("reb=%f\n",reb);

    he=(d*d*t*pm)/(np*np);
    printf("Value of he is %f",he);

    remode=(6*reb*reb)/((6*reb)+he);
```

```

        fL=16/remode;
        printf("friction factor= %f",fL);

c=-1.378*(1+0.146*(1/pow(reb,0.000029)));
ft=pow(10,c)*(1/pow(reb,0.193));
printf(" friction factor= %f", ft);
m =(1.7+(40000/reb));
printf(" value of m= %f", m);

k1=pow(fL,m);
k2=pow(ft,m);
f=pow((k1+k2),(1/m));
printf(" friction factor=%f", f);

pl=f*pm*v*v/(2*d);
p=pl/100;
printf("Pressure drop per unit length=%f",p);

        getch();
}

```