

INVESTIGATION OF RHEOLOGICAL AND LEACHING CHARACTERISTICS OF ASH AT HIGHER CONCENTRATIONS

A thesis submitted in the partial fulfilment of the requirements for the Degree of

DOCTOR OF PHILOSOPHY

BY

Gurprit Singh

Registration Number: 901408005

Under the supervision of

Dr. Satish Kumar

Associate Professor
Department of Mechanical Engineering
TIET, Patiala

Dr. S. K. Mohapatra

Senior Professor and Head
Department of Mechanical Engineering
TIET, Patiala

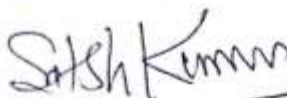


**DEPARTMENT OF MECHANICAL ENGINEERING
THAPAR INSTITUTE OF ENGINEERING & TECHNOLOGY
PATIALA- 147004**

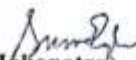
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THESIS CERTIFICATE

This is to certify that the thesis entitled "**Investigation of Rheological and Leaching Characteristics of Ash at Higher Concentrations**" submitted by **Mr. Gurprit Singh**, in the partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in the Department of Mechanical Engineering, **Thapar Institute of Engineering & Technology, Patiala (INDIA)** is a bonafide record of research work carried out by him under our supervision and guidance. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.



(**Satish Kumar**)
Associate Professor
Department of Mechanical Engineering
TIET, Patiala
(Supervisor)



(**S.K. Mohapatra**)
Senior Professor and Head
Department of Mechanical Engineering
TIET, Patiala
(Supervisor)

DECLARATION

I, **Gurprit Singh**, hereby declare that the thesis, entitled, "**Investigation of Rheological and Leaching Characteristics of Ash at Higher Concentrations**" submitted to the **Thapar Institute of Engineering & Technology, Patiala**, in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy in Mechanical Engineering is a record of original and independent research work done by me during the period January 2015- July 2017, under the supervision and guidance of **Dr. Satish Kumar**, Associate Professor, Department of Mechanical Engineering, Thapar Institute of Engineering & Technology, Patiala and **Dr. S.K. Mohapatra** Senior Professor and Head, Department of Mechanical Engineering, Thapar Institute of Engineering & Technology, Patiala. The work contained in this thesis has not been previously submitted to meet the requirements for a degree or diploma at this or any other higher education institution.



(Gurprit Singh)

Registration No: 901408005

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(Gurprit Singh)

ABSTRACT

Coal is the world's most abundant fossil fuel and its reserves are distributed in all the continents. During combustion of coal in the thermal power plants generate large amount of bottom ash and fly ash, which have low value for utilization and several environmental problems associated with their deposition. The quality of the coal ash depends on the properties of coal, combustion efficiency, pulverized coal feed and proper quality control in maintaining the particle size etc. The available Indian coal quality is very poor; generate the large quantities of ash produced as by-products of combustion. With increasing in the demand of the coal as fuel in thermal power plants combustion products, fly and bottom ash become a serious environmental problem due to their leaching characteristics. The huge amount of coal ash (fly and bottom) is generated every year worldwide whereas only a small amount of coal ash is utilized for various applications like cement, road and flyover embankments, bricks, concrete etc. Currently in India, about 60% of fly ash is used and remaining ash disposed into ash pond. The disposing of ash requires large amount of water and land. The disposal of fly ash in the thermal power plant is a challenging task. Presently coal ash with water is transported through pipeline in ash disposal system with very low solid concentration, which consumes huge amount of water and pumping energy but also causes serious environmental problems at the disposal site.

The objectives of the present study was to investigate the rheological and leaching characteristics of the fly and bottom ash at high solid concentration with an additive of sodium bicarbonate. The various physio-chemical and mineral properties were investigated to find out possibility of utilization for various applications. The fly and bottom ash samples collected from different thermal power plants namely Guru Nanak Dev thermal power plant, Bhatinda, Punjab, Guru Gobind Singh Super Thermal Power Plant, Ropar, Punjab, Guru Hargovind Singh thermal power plant, Lehra Mohabbat, Punjab and Deenbandhu Chhotu Ram thermal power plant, Yamuna nagar, Haryana. In present work, environmental risk analysis of disposal ash was carried out to predict various critical issues associated with disposal of ash. Standard leaching testing procedure like ASTM-D3987 (American Society of Testing and Materials), EP-3050B (Extraction Procedures) and TCLP-1311 (Toxicity Characteristic Leaching Procedure) were used to investigate the leaching characteristics of fly and bottom ash. The leaching characteristics of fly and bottom ash was determined at different liquid to solid ratio of 20:1 to 60:1, leaching time

duration (5-20 days) and temperature (25-40°C). The influence with addition of additives on leaching characteristics of fly and bottom ash was carried out by using sodium bicarbonate as additive. The proportion of additive was varied from 0.2-0.6% (by weight). The concentration of leachate elements like Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo increased with increase in liquid-to-solid ratio, leaching time duration and temperature for fly and bottom ash suspension. It was also observed that leachability of trace elements were affected by the pH of extraction solution. This may be attributed that metal solubility increases with decrease in pH value. Minimum leachability of the solution was observed with ASTM method, whereas maximum with TCLP method at (L/S) ratio 60:1.

It was noticed that addition of additive (NaHCO_3) in very small proportion helps to minimize the leaching potential hazards caused by trace elements present in fly and bottom ash. The pH value of slurry suspension was increased with addition of NaHCO_3 and contributed in decreasing the leaching of trace elements. The rheological characteristics of fly and bottom ash suspension was determined using standard rheometer (Anton Paar) at different solid concentration of 10-60% (by weight). Fly ash samples exhibit Newtonian behaviour up to 30% solid concentration. Beyond this it depicted non-Newtonian flow characteristics whereas bottom ash suspensions showed Newtonian behavior up to 40% solid concentration (by weight). Relative viscosity of both fly and bottom ash slurry suspensions were increased more rapidly at higher solid concentration as compared to lower solid concentration. Results indicate that addition of additive at higher solid concentration was more effective as compared to lower solid concentration of both fly and bottom ash suspension. Optimal reduction in relative viscosity was noticed with the 0.4% addition of additive. Darby and Melson (1981) empirical correlation was used to predict the head loss in slurry pipeline of 100 m length with 100 mm diameter for fly and bottom ash suspension. The head loss was predicted by taking solid concentration from 10-60% (by weight) and flow velocity 0.5 to 4.5 m/sec. It was observed that as the solid concentration and flow velocity increased head loss in slurry pipe line also increased.

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NOMENCLATURE

C_w	Concentration of solid (% by weight)
C_{wi}	Initial concentration of slurry (% by weight)
D_{wn}	Weight mean diameter (μm)
D_i	Mean diameter of two successive sized sieves
f_i	Solid fraction
N_i	Number of particle size groups
R_s	Retained sample
T_w	Total weight of wet ash (gram)
V_{mi}	Initial volume of slurry (gram)
V_w	Volume of water (ml)
W_B	Weight of beaker (gram)
W_{BS}	Weight of flask and solid (gram)
W_{BW}	Weight of flask with water (gram)
W_{BSW}	Weight of flask with solid and water (gram)
W_s	Mass of solid (gram)
W_R	Weight of solid (gram)
W_T	Total weight of dry ash (gram)
ϕ	Porosity
ρ	Specific gravity
Δ	Bulk density (gram/cm^3)
τ	Shear stress (Pa)
τ_y	Bingham yield stress (Pa)
ρ_s	Density of solid (gram/cm^3)
ρ_L	Density of liquid (gram/cm^3)

LIST OF ABBREVIATIONS

AAS	Atomic absorption spectrophotometer
ASTM	American society of testing
EDX	Energy dispersive X-ray
EP	Extraction procedure
EPA	Environment protection agency
ESP	Electrostatic Precipitator
HCSD	High concentration slurry disposal
LCSD	Low concentration slurry disposal
L/S	Liquid to solid ratio
PSD	Particle size distribution
SEM	Scanning electron microscopy
TCLP	Toxicity characteristic leaching procedure
WHC	Water holding capacity
WHO	World health organization
XRD	X-ray diffraction

Chapter 1

INTRODUCTION

Coal is used as primary energy source for generation of electricity. Coal is a combustible substance and its composition depends on earth crust. Coal from different regions shows different properties. Coal have different ranks and grades, as per its quality and carbon contents. Anthracite coal have higher carbon content followed by bituminous and lignite. Anthracite coal is hard to ignite whereas bituminous and lignite coal easily ignite. In Indian thermal power plants low rank (lignite or sub-bituminous) coal is used which has high ash content (34 to 49%) with lower calorific value.

1.1 Thermal power plants

Coal based thermal power plants are leading energy sources, which provides about 70% of electricity in India. A coal-fired thermal power plant is a complex energy generation system which deals with many sub-systems namely coal handling system, steam generator, power generation unit, condensation unit, water-cooling system and ash conveying etc. Thermal power plant works on Rankine cycle in which heat is produces from the combustion of fuel for the generation of steam. Superheated steam fed to the turbine where its heat energy is converted into mechanical energy which further makes the generator to run and produces electricity. This is forecasted that electricity generation by coal-based thermal power plants in year 2020 and 2050 to be 6.1 and 16.7MWh (billion) respectively (Amouroux et al. 2014). Ministry of power Indian government reported the current installed status of thermal power plants in India is 214654.89 MW which is 70.68% of total installed capacity as shown in Figure 1.1.

1.2 Generation of fly and bottom ash in thermal power plants

Fly and bottom ash are produced after the burning of coal. Basically, combustion of coal takes place in the boilers chamber in which hot air is blow through nozzles of combustion bed. Generation of heat after ignition produces by products i.e., ash, flue gases, coal slug etc. Heat is extracted with the help of boiler tubes, which results in lowering down the temperature of molten material and formation clinker and slag. It is non-combustible solid residual made of minerals of

coal. The large size clinker or slag are crushed in finer particles known bottom ash. Fly ash is produced after the vaporization and condensation followed by coagulation through various modes during the combustion or gasification of coal. The formation of ash is specified with a mechanism as shown in in Figure 1.2.

Bottom ash is referred as the coarser particles, irregular morphology with amorphous surfaces which can be collected under the hoppers of combustion chamber, whereas the finer ash particles called as fly ash which can be collected from electrostatic precipitator with the help of flue gases. Mainly, coal ash consists of SiO_2 , Al_2O_3 , Fe_2O_3 and CaO , that exist in form of crystalline oxides and amorphous. Coal is classified on the bases of chemical composition i.e. class C and F. Class C has high concentration of Ca content as compared to class F. class F ash is generated by combustion of harder bituminous coal. It consists of glassy silica and alumina. The total sum of SiO_2 , Fe_2O_3 and Al_2O_3 in class F is higher than 70% however in case of Class C it lies in the range of 50-70% (Antiohos and Tsimas, 2007; Ghafoori et al., 2015; Huggins et al., 2016; Xie and Kayali, 2016). The total fraction of unburnt carbon should be upto to 6% in ash samples.

1.3 Slurry pipeline transportation system

Slurry pipeline transportation system is used for various industrial applications like mineral ores of processing plants, zinc tailings, rock phosphate, coal transportation to thermal power plants, coal ash disposal etc. The slurry pipeline transportation is environment friendly which can be used to transport solid material for short and long distances.

Slurry pipeline transportation system is more safe and economical as compared to any other mode of transportation. The design of slurry pipeline required a sound knowledge about the flow behaviour of particles to be transported. Thus, it is essential to make efforts for developing an adequate data-base which will empower the designer to design the optimum procedures for solid material transportation through pipelines. Fluid flow is a very complex phenomenon with the addition of solids because the properties of solid as well as liquid affect their flow behaviour. The rheological properties are dependent on parameters like shear rate, volume fraction of solid particles and various properties of bulk solids.

Presence of solid particles in the fluid is responsible for increasing viscous resistance of the suspension. At the same time, it may also alter the behaviour of liquid from Newtonian fluid to non-Newtonian. Researchers (Kumar et al. 2014; Singh et al. 2016) reported that addition of

additive improved the rheological behaviour of coal ash slurry suspension. Additive may be a chemical compound, wetting agents like soap solution, deflocculants, fibers, long chain polymer compounds etc. These additives may influence the range of particle-particle and fluid-particle interaction without changing physical properties of the flowing slurry.

The additives mainly reduce the drag force responsible for the restriction of flow. In other term inter particle-particle friction of slurry suspension is reduction with addition of small amount of additive which further allows the head loss in the pipeline. In present bio-degradable surfactants are accessible to improve fluid flow behaviour as per requirement. However, these additive are less liable as compared to mechanical dilapidation.

1.4 Ash handling system

Coal used in our power station generate a huge amount of ash, which is around 200 million tons per year. Out of this, around 130 million tons will be fly ash and the remainder will be bottom ash (Naik et al. 2009). So, proper ash handling system is required for the disposal of coal ash which may cause various environmental issues. The coal ash handling system mainly consists of bottom and fly ash handling unit, economizer and air pre-heater unit and slurry disposal unit. The disposal system involves with preparation of slurry in tank and transports it to the ash pond. Layout of ash conveying system is shown Figure 1.3. Generation of coal ash in economizer feed out into individual hopper pipes through gravity, while ash generated in air pre-heater hopper evacuated by vacuum conveying system which is connected with ESP hopper. Currently, coal ash is transported hydraulically from production area to disposal area by pipelines with lean concentrations by using lean slurry disposal (LCSD) systems. At present, lean water ash slurry (8-20% by weight) is disposed from thermal power plant to dyke area. The operation of ash disposal pipelines is therefore extremely inefficient due to requisite of large amount of water and pumping power. This causes excessive erosion wear of the components of ash disposal system and therefore reduces their working life. Studies carried out for transportation of different solid materials at higher concentration in pipeline shows reduced skewness in concentration profile and flow velocity. These results reduce the pipeline erosion wear and hence increase the pipeline life. It is estimated that conventional ash disposal system consumes approximately 630 million m³ of water per annum and acquire more than 25,000 acre of land (Mishra 2004; Aggarwal et al. 2007).

The production of ash in the thermal power plants increases day by day and causes disposal and environmental problems. The transportation of ash by pipelines is therefore highly inefficient due to following limitations (Gahlat, 1987; Gandhi et al. 2000; Seshadri et al. 2008).

- High power consumption
- Water wastage
- Polluted ground and surface water
- Huge land requirement

Main problems associated with these systems are different losses which further affects the economy of overall system i.e., friction & head loss, with high pumping power required, settlement rate at the in ash disposal system itself etc. In order to overcome these drawbacks, the high concentration slurry disposal (HCSD) systems can be used.

The basic parameters for the design of any slurry transportation system are, hydraulic parameters, which include properties of carrier fluid, optimum particle size, optimum solid concentration in the slurry, rheology of the slurry, specific gravity of the solids and material properties (Heywood et al. 1993; Slatter, 2000; Gandhi et al. 2002; Steward and Slatter, 2009; Badoga et al. 2011; Rabinovich and Kalman, 2011). It is well known that the properties of the ash produced depend on various parameter namely as properties of coal, combustion process and its efficiency, methodology of ash collection etc.

The coal ash from different thermal power station differ greatly in their characteristics and hence the design of ash disposal system has to take in to account these variations. It is therefore essential to have information of the extent of variation in the properties of coal ash and their slurries.

1.5 Environmental impact of fly and bottom ash

In India, huge amount of fly ash and bottom ash are hydraulically disposed from thermal power plant to ash pond by slurry pipelines in coal based power plants (Kumar et al. 2016). The production of **ash** in the thermal power plants increases day by day and causes disposal and environmental problems. The huge amount of toxic elements poses negative environmental effect on environment and human health (Mishra, 2004; Ugurlu, 2004; Baba et al. 2010; Panda and Pradhan, 2014). Coal ash from different locations shows different physico-chemical properties

depending on properties of parent coal. The coal ash contains heavy trace elements like As, Pb, Hg, Cd, Cr, Al, Mo, Mg, Co, Mn, Ni, Cu, Zn etc.

Environmental Protection Agency (EPA) reported that the people have high risk near the dyke area of thermal power plant. It is also reported that unlined ash ponds are responsible for series of health hazardous by contamination of ground water i.e., cancer, lung disease, cognitive deficits, birth defects, kidney disease damage nervous system etc. Among the elements present in coal ash, arsenic is considered as most dangerous pollutant followed by cadmium, lead, and other toxic metals.

Mainly improper disposal and leaching of coal ash allows these elements to enter in the living beings through drinking, eating or inhaling. This can be minimized by the use of dry landfills and use of composite liners for prevention from leaching in ash pond. The traced elements associated with ash discharge into soil and water with span of time. These heavy toxic elements can pose destructive environmental effects as well on human health by condemnation of food chain (Senapati et al. 2012; Kumar et al. 2016; Singh et al. 2016). The improper dumping of ash polluted water sources by leaching of traced elements. The trace metal elements presence in the fly and bottom ash may cause serious health problems such as skin cancer, harm of nervous system, tumors in liver and lung etc., as shown in Figure 1.4.

1.6 Current status on utilization of fly and bottom ash in India

Indian coal due to its high ash contents generates the large amount of coal ash. Now, coal ash is utilized in various applications such as construction application, structural fill, backfilling agriculture, dam and geotechnical works (Asokana et al. 2005; Kim et al. 2005; Risto et al. 2008; Hao et al. 2015). Fly ash is used in cement industry either as a raw material or additive (Dhadse et al. 2008; Gonzalez et al. 2009; Garcia-Lodeiro et al. 2016; Noushini, et al. 2016).

According to central electricity authority (annual report 2014-15), 42.26% of fly ash was utilized by cement industry which include 13, 11.72, 10.77, 9.56, 3.32, 0.74 and 0.01 % for mine filling, bricks and tiles, reclamation, roads/highway, agriculture and concrete respectively. However, 44.31% of fly ash remains unused.

The researchers (Aggarwal et al. 2007; Loya and Rawani, 2014; Mármol et al. 2016; Yongfan and Yonghao 2016) studied the utilization of fly ash in the application of making bricks, road,

fly over, geopolymer, concrete and cement. The lower cost coal ash residuals makes it feasible for utilization in various construction applications (Quijorna et al 2010; Shafigh et al. 2016). The proper utilization and management of fly and bottom ash will be helpful to minimize direct and indirect environment problems. Many researchers (Sheoran et al 2014; Zhipeng et al. 2015; Assi, et al. 2016; Padhy et al. 2016; Pastor et al. 2016; Pavithra et al. 2016; Zheng et al. 2016) have made comprehensive efforts to enhance the utilization of ash in various applications such as soil amendment, concrete, cement, backfilling, roads, flyovers etc. Fly and bottom ash consist of various elements namely K, Mg, B, Mo, Fe, P, Ca, Mn, Zn and Fe. The elements Zn, Fe, Mn, Mo, Cu and B are micronutrients which are essential for the growth of plants and living organisms (Nayak et al. 2014).

The fly and bottom ash also consist of alkaline, refractory and spherical abrasives. Many geotechnical properties such as permeability, specific gravity, consolidation, water holding capacity, angular friction and lime-binding capability makes it feasible for construction applications. Fly and bottom ash mainly consists of silica, alumina and magnetite which make it feasible for consumption in zeolite, geopolymer and other advance application. On the basis of different properties, fly and bottom ash have various applications as shown in Figure 1.5.

1.7 Scope and motivation of the work

Combustion of coal produces in huge quantity of ash as a byproduct. Due to incomplete understanding and limited database of ash disposal through pipeline, there is a limited methods are available in literature to investigate the proper disposal of coal ash without environmental hazards. In literature most of studies were conducted on either equisized or continuous distributed ash. In present work, an effort has been made to study the influence of physical, chemical and mineralogical properties on leaching and rheological behaviour of coal ash. Leaching characteristics of traced element associated with ash particles are also investigated with additive. The rheological characteristics of each sample are obtained at various concentrations of bottom and fly ash particles by adding additives. The following experimentation was conducted for all the collected ash samples to determine various mineralogical and physico-chemical properties suitability for in different application.

Physical characterization such as:

- Particle size distribution
- Specific gravity
- Bulk density
- Porosity
- Water holding capacity
- Chemical properties such as:
- Energy-dispersive X-ray spectroscopy (EDX)
- pH
- Mineralogical characterization such as:
- Scanning electron microscopy (SEM)
- X-ray diffraction (XRD) analysis

1.8 Objectives

- To investigate the physical, chemical and mineralogical characteristics of fly and bottom ash from different thermal power plants located in the Punjab and Haryana.
- To investigate leaching characteristics of the fly and bottom ash disposed in the ash pond of different thermal power plants located in the Punjab and Haryana.
- To evaluate the rheological characteristics of fly and bottom ash slurry at higher concentration in the range of 10 to 60% (by weight) with and without addition of sodium bicarbonate as an additive.
- To investigate the effect of sodium bicarbonate as an additive on leaching characteristics of fly and bottom ash with varying range of liquid to solid ratio (L/S) of 20:1 to 60:1.
- To investigate the head loss characteristics for slurry pipeline.

1.9 Thesis outline

Chapter I: In this chapter, only the introductory part of various aspects of generation of ash, its environmental issues, current status on their utilization and rheological influence with additives has been discussed. The other chapters of this thesis are disused as follows:

Chapter II: This chapter includes extensive literature review which provides a base of knowledge already available involving the issues of interest with valuable contribution on leaching, rheology

and utilization of coal ash from thermal power plants. Objective of current study is also given at the end of the chapter.

Chapter III: This chapter presents the details of bench scale tests for fly as well as bottom ash samples collected from different locations of Punjab and Haryana. Experimental investigations have been carried out to determine the physical/chemical/mineralogical properties of fly as well as bottom ash with their potential utilizations.

Chapter IV: This chapter deals with the leaching characteristics of fly and bottom ash slurry with different leaching procedures. The influences of various parameters like time duration, liquid to solid ratio, pH and temperature on leaching characteristics of fly and bottom ash have been investigated. Effect of additive has also been examined with different liquid to solid ratio

Chapter V: This chapter presents the rheological characteristics of fly and bottom ash at different solid concentration. Effect of additives on rheological characteristics of fly and bottom ash has also been also investigated at higher solid concentration of fly and bottom ash.

Chapter VI: In this chapter, head loss in the slurry pipeline has been predicted using Darcy Melon (1981) empirical for handling fly and bottom ash slurry suspension. Experimental results of head loss was compared with predicted results at 60% solid concentration for both fly and bottom ash.

Chapter VII: It deals with summarized observations and important conclusions drawn from experimental investigations.

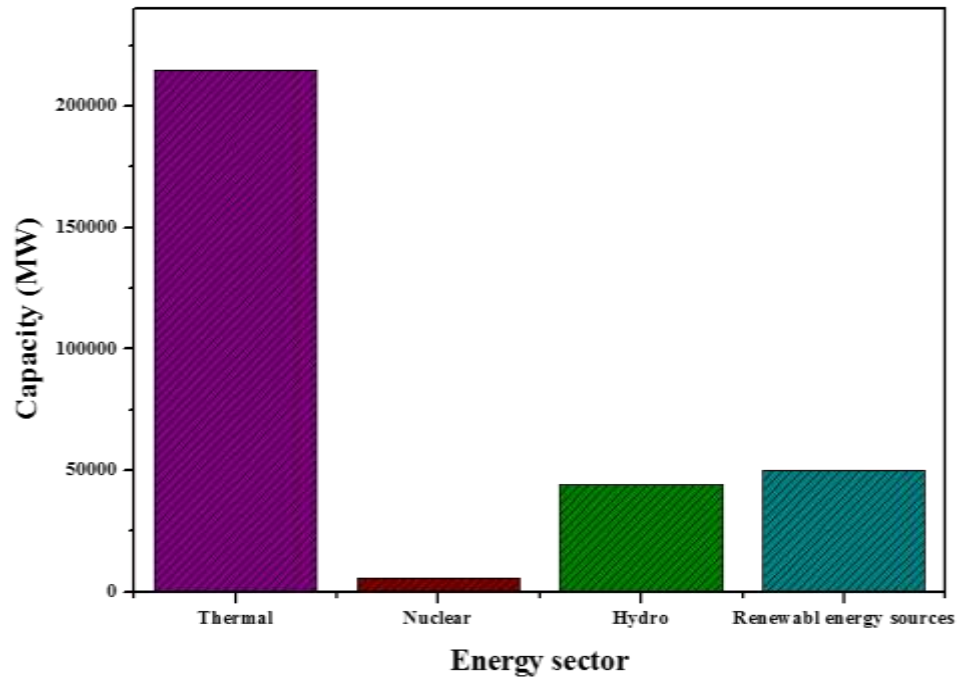


Figure 1.1: Current status of installed capacity of various energy sector (Central Electricity Authority New Delhi 2016-17)

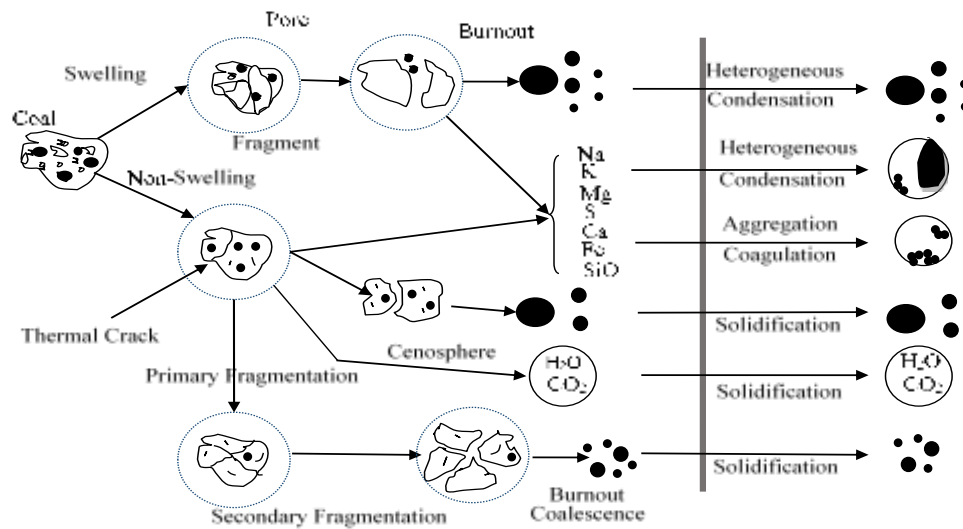


Figure 1.2: Ash formation mechanism (Conner, 1990)

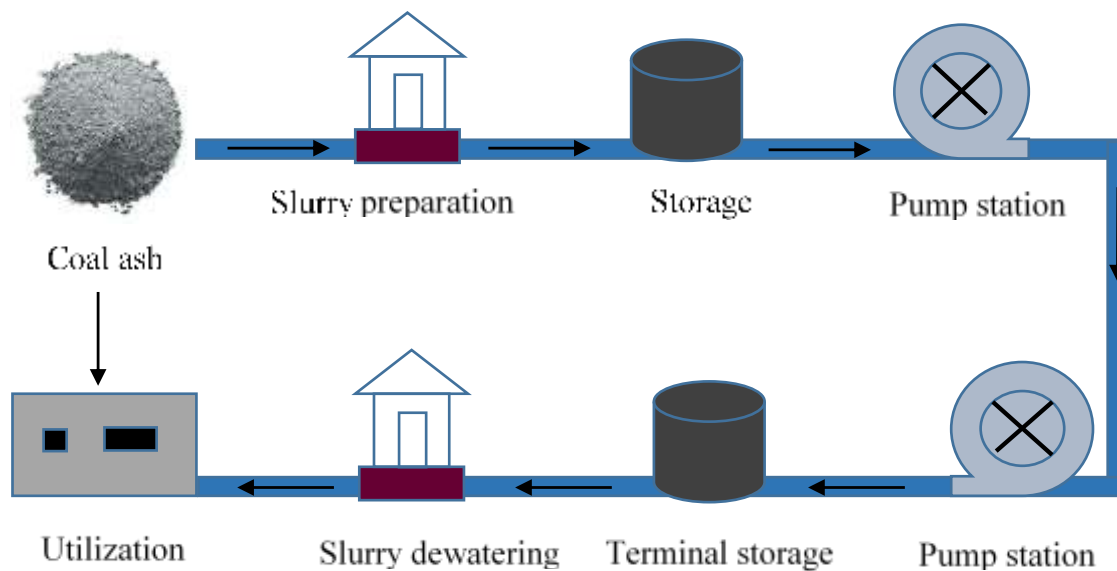


Figure 1.3: Ash handling system used of thermal power plant

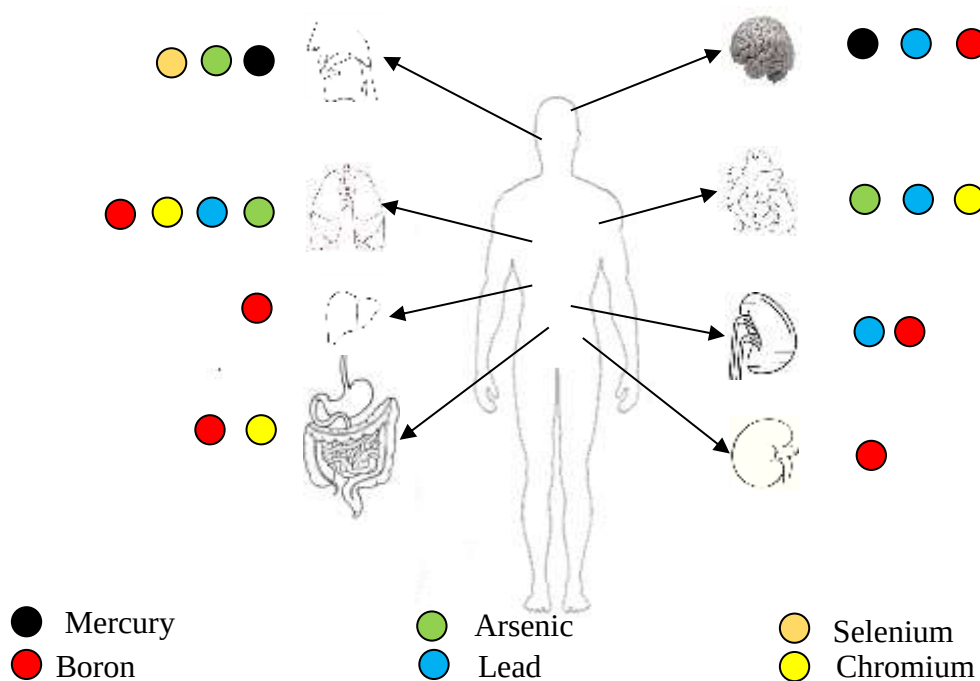


Figure 1.4: Impact of leaching of heavy toxic element on human health

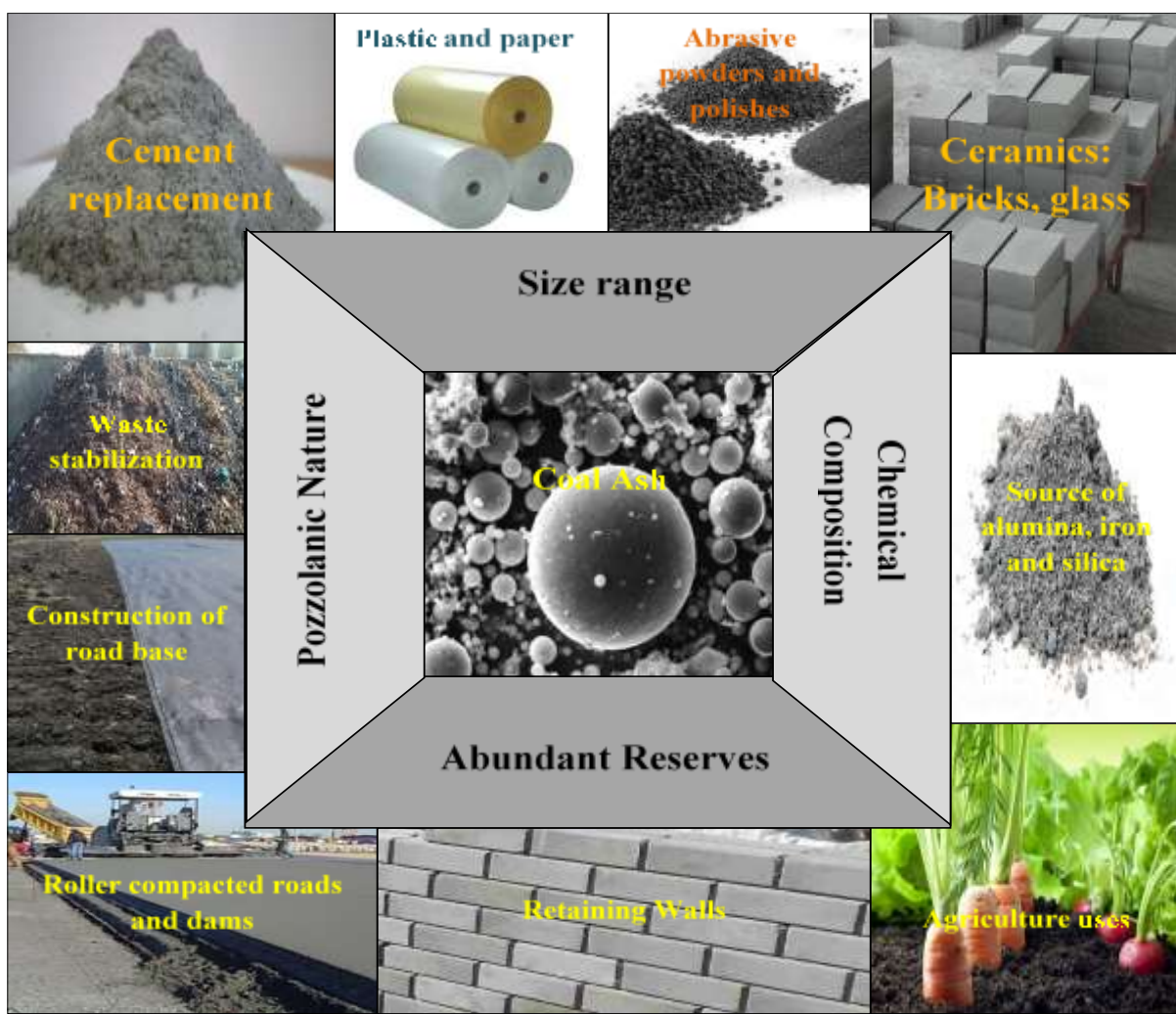


Figure 1.5: Utilization of fly and bottom ash in various applications

Chapter 2

LITERATURE REVIEW

Transportation of solids by pipelines are used for various applications such as ores processing plants, disposal of waste, material handling, ash disposal in power station etc. The primary factor for design the transportation system are; hydraulic parameters which include properties of carrier fluid, optimum particle size, optimum solid concentration of slurry, rheology of slurry, specific gravity and other material properties. It is well known that the properties of ash depends on various parameter namely as, properties of coal, combustion process and its efficiency, methodology of ash collection etc. In order to have some insight into present state of knowledge, extensive literature survey has been conducted and reported in this chapter. An attempt has also been made to highlight the gaps in the knowledge regarding the slurry pipelines which in turn has helped to decide the scope of the present study.

2.1 Characterization of fly and bottom ash

The coal ash taken from different thermal power plants differ greatly in terms of their characteristics hence, the design of ash disposal system has to consider the nominal variations. Therefore, its essential to have information of the extent of change in properties of coal ash and their slurries.

The properties ash influenced by the type of coal used in combustion, combustion conditions, coal deposition and its geological parameters etc (Ghosh et al. 2006 and Mosa et al. 2008). The coal ash is most commonly used for making bricks, concrete blocks, cement production, ceramics, agriculture, road construction, land filling and embankments (Malhotra et al. 1995; Naik et al. 1997; Asokana et al. 2005; Kim et al. 2005; Sharma et al. 2012; Nawaz, 2013). Bottom ash can be utilized in civil engineering applications like road and flyover embankment constructions, concrete, structural fill and various cement products. Bottom ash with size greater than 400 μm is used as coarser aggregate and small size is used as fine aggregate. Coal ash aggregates are feasible to be used in concrete by the fractional replacement of sand with coarser and finer aggregates. The concrete consists of coal ash as aggregates show greater compressive and tensile strength (Bakoshi et al. 1998; Naik and Kraus, 2001). Authors (Kurama and Kaya, 2008) found that fly ash residue

shows higher the porosity which may tends to increase water holding capacity. Researchers (Wei et al. 1992; Bakoshi et al. 1998; Asokana et al.2005) found that the presence of silica as a major proportion in the form of quartz improves the strength of the support materials and the presence of CaO gives cementing properties along with presence of unburned carbon leads bottom ash to be used as building materials in construction industry as a stowing application. The utilization of ash helps to reduced problem associated with disposal of ash.

Kumar et al. (2000) collected fly ash sample from three different coal based thermal power plants to study various properties. They found that fly ash consists of SiO_2 , CaO , Al_2O_3 , MgO and Fe_2O_3 oxide in major proportion (96.5-98%) with small amount of other element. They noticed that fly ash samples have significant difference in their chemical composition. They suggested that lower bulk density and water holding capacity makes it useful for used in civil construction. The fly ash can be applicable in cement, road and fly over and other construction.

Sarkar et al. (2005) studied various properties of collected fly ash sample from various location of thermal power plant situated in Eastern Indian. They study the various physical properties of collected fly ash sample for utilization in various application. They reported that wide variation in particle size distribution was found from sample to sample. They suggested that finer particle of fly ash can be used in construction works.

Stanislav et al. (2005) carried out experimental study for determine the various physico-chemical mineral properties of fly ash samples. During the experimentation various small scale labortory test was conducted to determine different properties of fly ash. X-ray diffractometry was used to find out mineral phases in solid sample. They reported that the physio-chemical properties of fly ash contributes in its utilization for various applications.

Sarkar and Rano (2007) analyzed the variation of different properties of soil by adding of fly ash. They found that fly ash increase the level of nutrient which are essential for the growth of plant. Most of Indian fly ash have alkaline nature which can be used to neutralization of acidic soil. They found that as percentage of ash was change from 10 to 30% (by weight) neutralization of soil is increase. There was a significant improvement in yield crop and change pH of soil.

Erol et al. (2008) investigate the physical and mechanical properties of ash. They noticed that fly ash consists of various oxides such as Al_2O_3 , Fe_2O_3 , SiO_2 and CaO . They reported that fly ash can be utilized for the fabrication of glass ceramics and glass products.

Chindaprasirt et al. (2008) determined variation in geopolymer properties with addition of fly ash. It was noticed that fly ash have lower reactivity with high concentration of calcium oxide. Blending of collected sample was done with active fly ash for increasing the rate of reaction used in geopolymer. The sodium silicate and sodium hydroxide was used as additive for the synthesis of polymer at relevant temperature. They suggested that fly ash geopolymer were used with PCC-fly ash to increase strength and workability of polymer.

Mahale et al. (2012) investigated the usage of fly ash in soil to increase yield of crops. Investigate the effect of addition of fly ash for agriculture production of wheat, mung bean and urad bean. They found that seed generation rate was increased with addition of fly ash. They also reported that 10-20% increase in yield production of mung and urad bean by the addition of fly ash.

Lee et al. (2014) investigated the utilization of fly ash in tailing application. They reported that ingress of water was reduced with addition of fly ash. Results show that fly ash comes in contact with water results in hydration. Electric conductivity of mine tailing with addition of fly ash was reduced and helps in minimize leaching of trace elements.

Tang et al. (2014) investigated the effect on mechanical properties of mortar with addition of bottom ash. They investigated physico-chemical properties of mortar with addition of bottom ash. They reported that with addition of finer bottom ash particles compressive strength and flexural of mortar was improved. They also found that compressive strength is function of curing time.

Latifi et al. (2015) performed experimental investigation to assess the effect of addition of bottom ash (BA) in fly ash on morphological, physic-chemical and strength of mortar. They also determined the effect of curing time on compressive strength with addition of BA. They noticed from SEM analysis the addition BA in fly ash increase the percentage of irregular particles compared to original bottom ash sample. They also reported that significant change in chemical composition was found with addition of fly ash. They concluded that with addition of bottom ash modulus of elasticity reduced from 30-70% with any significant impact of shear strength.

Baite et al. (2016) performed the experimental study to determine the effect of addition of bottom ash as coarser particle in mortar. The amount of bottom ash in sand was change from 0-100% (by volume) for manufacture of mortar. The properties namely as porosity, bulk density, thermal conductivity etc. of sand was alter with addition of bottom ash. They found that porosity of sand mixture was increased which lead to increase water holding capacity during curing of mortar.

Singh et al. (2017) studied various physic-chemical properties of bottom ash taken from four different power station situated in northern region of India. They crushed the bottom ash sample as pass through 250 μm sieve to prepare grounded bottom ash. They noticed that physical properties alter with grounding of bottom ash without major modification in chemical composition. Cementing properties of bottom ash also increased after grounding the bottom ash sample and helps in utilization for various application. They also noticed that specific gravity of grounded bottom ash was increased as compared to original samples.

Luo et al. (2017) studied the use of fly ash for replacement of quartz like material in clay and feldspar in fabrication of ceramics tile. They found that fly ash ceramics tile have good sintering properties and mechanical strength. Fly ash tiles were sintered at 1100°C showed ideal post-sintering behaviour. They found that addition of fly ash helps to achieve optimal mechanical properties of ceramic tiles and better utilization.

In India, various research institutions, Universities, Government and non-Government organizations are actively involved in depth research, experimentation and demonstration for recycle and utilization of fly and bottom ash. The Ministry of Environment and Forest (MOEF, 2003), Government of India also framed the regulatory guidelines for utilization of coal combustion residue due to various environmental concern. The details summary of benefits and limitation of utilization of fly and bottom ash is listed in Table 2.1.

2.2 Leaching characteristics of fly and bottom ash

Leaching deals with the removal of soluble components present in bulk solids. Leaching of any solids depends upon its mineralogical as well as physio-chemical properties. Physio-chemical properties includes pH value, morphology of particle, solubility of compound and initial concentration of leachant decides the leaching of any substance. Generally, coal ash considers a common solid waste and no such guideline are available for treatment before disposal. The fly and bottom ash disposes in open land or in landfilling. Fly ash consists of very fine particles which are suspended in air and causes pollution. Coal ash having 5-10 times higher trace elemental concentration as compared to parent coal. The fly and bottom ash has been considered as primary source to leach out heavy trace elements which are sensitive in environment. The trace elements leach out in water and soil which increases at various favorable conditions. The leachability of

heavy element depends on the various factors which have been discussed by different researchers as discussed below:

Georgakopoulos et al. (2002) experimental study was performed to evaluate the leachate concentration of various traced metal present in fly ash sample taken from Ptolemais coal-based power station (Northern Greece). The leaching analysis of traced elements was performed by following Column leaching testing procedure. They reported that concentration of traced elements was function of time. They also found that Sr and Mo were lost during leaching of fly ash sample.

Lin and Yang (2002) concentration of traced elements was determine by following batch experiment procedure. They prepared synthetic solution for experimentation. They noticed that bottom ash particles shows good adsorption ability from wastewater for Cu with 0.48 mg/g. Also, they suggested that bottom ash have a capacity to absorb pollutants from wastewater.

Baba and Kaya (2004) studied the leachability of traced element from coal ash collected from power plants in southwestern coast of Turkey. Three standard leaching procedure namely as EP, ASTM and toxicity characteristic leaching (TCLP) were used to investigate toxicity of fly and bottom ash. They found that leachate concentration of trace elements highly depend upon pH of extraction solution.

Ugurlu (2004) examined the leaching behaviour of traced elements during disposal of ash. The ash sample were collected from ESP (Electrostatic Precipitators) and dyke area for the experimentation. They pH of collected fly ash sample lie in range of 11.9 to 12.2 which indicated that fly ash has alkaline in nature. They observe that Cl, Na, Mg, Fe, S and Pb shows higher leaching whereas Mn, Cu, Cd, Cr and Co had lower leachability. They also observed that concentration of traced elements Ca and Mn was reduced with increase in temperature. The pH value extraction medium is most significant influence factor for leachability of trace elements.

Ahn et al. (2006) carried out their investigation on bottom ash for stabilization of Cu and Pb in municipal incineration. They noticed from experimental results that CO₂ and bottom ash, both elements were more stabilized by carbonation reaction. The pH value was quickly dropped and trace of heavy metal due to its dependency on pH value of extraction solution.

Sushil and Batra (2006) performed the leaching test for study the toxicity behaviour of traced elements from fly and bottom ash collected from thermal power stations situated in North India. They reported that elements Mn Zn,, Cr, Ni Pb, Cu, and Co show lower leachability for both fly and bottom ash whereas Zn and Cr showed higher leaching rate. They recommended that proper

unitization and management of disposal ash helps to minimize environmental impact caused by disposed ash.

Tsiridis et al. (2006) investigated the movability of traced from fly ash to predict environmental impact. The leaching analysis of traced elements Mn, Cu Ni, Cr Pb and Zn was analyzed using EN 12457-2, ASTM and TCLP procedure. The concentration of traced elements was found higher in TCLP test as compare to ASTM procedure. They concluded that pH of leaching media is most significant parameter for leachate concentration of traced elements.

Snigdha and Batra (2006) performed a study to examine the leachability of ash sample for the determination of trace elements namely Cr, Mn, Pb, Fe, Cu, Ni and Co. They noticed that element Zn and Cr showed higher leaching rate and Co showed lower leaching rate. They proposed that lining of pond ash helps to ash pond lining to control leaching of toxic elements from ash to ground water.

Zhang et al. (2008) investigate the influence of various leaching of metal from municipal-solid-waste with dogging of bottom ash. They performed leaching test to study the influence of various parameters namely as L/S ratio, leaching time, pH etc. on heavy metal extractions. They reported that extraction rate of heavy traced metal rapidly influenced with liquid to solid ratio. It was also observed that leaching concentration also partly depends upon the absorption reaction.

Prasad et al. (2008) examined the movability of heavy toxic elements in fly ash sample with the variation of pH value. The leaching test were conducted at different L/S ratio from 20:1 to 100:1. They concluded that leaching of heavy element is a resilient dependent on pH of slurry suspension.

Popovic et al. (2009) evaluated the leaching characteristics of coal ash with change in pH of extraction solution. They reported that fresh fly ash sample have higher environmental threat as compared older deposited dump coal ash because it had already lost its pollution potential. They noticed that leachability of traced elements is directly proportional to nature of extraction fluid.

Dutta et al. (2009) investigation on leaching of toxic traced elements such as Fe, K, Mn, Pb, Na, Cu, Ca, As Zn, and Cr from four different fly ash samples. A strong acidic and basic nature extraction solution was used for investigation. The concentration of traced elements was determined with pH and solid-to-liquid ratio. As the pH of extraction solution was decrease the mobility of traced elements was increase drastically. It was also observed disposal of ash in open land having high environmental risk due to leachability of toxic metal into ground and surface water.

Baba et al. (2010) examined the leaching behavior of fluidized bed fly ash by using toxicity test. They reported that pH, amount of lime in fly ash and temperature were the highly influencing parameters for the leachability. Concentration of toxic element was higher on higher temperature range and when $\text{pH} < 5$. They found that there was no detection of heavy metal in fly ash at $\text{pH} = 5$. Trace elements Sulphur and Arsenic showed higher leachate concentration as compared to other toxic metal element present in coal ash.

Sarode et al. (2010) examined the leachability of traced elements from bottom ash, pound ash, fly ash, brick and cement admixture with fly ash. Their leaching test was performed by taking ash samples from various locations of thermal power stations. The leaching standard testing procedure TCLP and batch method was used to analyze leaching characteristics of heavy elements i.e. Zn, Ni, Cu, Fe, Pb, Mn, Mg, and Cd into water. The concentration of trace elements Mn, Mg and Fe was found higher than Cu, Zn, Ni and Pb. They reported that concentration of Zn, Fe, Mn, Mg, and Cd in groundwater samples were under the permissible limits whereas Ni and Pb were found over the WHO permissible limits.

Popovic et al. (2011) studied the leachability of traced elements in six different composite samples of fly, bottom and dump coal ash taken from Obilic power plant. They have used sequential extraction procedure to study the leaching characteristics. They observed that Cd was not extracted from coal filter fly ash samples while Pb was present only in the fifth sample. Mn was not extracted from the first and second sample.

Akar et al. (2012) carried out leaching investigation for alkaline coal ash sample. They reported that particle size of ash was the most influencing leaching parameter. The metal Fe and Mn showed lower leachability as compared to Ca. The trace element Cr was found in higher concentration than the permissible limit in water as per WHO.

Cheng et al. (2012) examined the extraction of Al from coal ash by using high pressure acidic leaching procedure. They concluded that extraction efficiency of fly ash particles are highly dependent on size of ash particles. They suggested that extraction of Al is possible by using high pressure acidic leaching method from fly ash.

Singh et al. (2012) analyzed leaching behaviour of fly ash. They reported that nickel and chromium having higher leachability in extraction solution as compared to buffer and aqueous solution. In aqueous and buffer solution concentration of copper was increased as leaching time

span was increased. Similar trend was followed by Cd with change in leaching time for aqueous and buffer solution.

Senapati et al. (2012) examined the effect of addition of additive on leaching behaviour of traced elements from coal ash. Sodium silicate was used as additive for the investigation. The leachate concentration of trace elements Zn, Cd, As Fe, Ni, Co, Cu, Hg and Pb was determined by using Hansen and Fisher procedure. They found that addition of additive was significantly reduced the leaching of trace elements over a long time duration (300 days).

Jing-Yong and Shui-Yu (2012) examined the leaching behaviour of toxic trace element from fly ash and solid waste. Solid selective additives were used to control the leaching of Zn, Ni, Cd, Mn and Pb from solid waste. The leachate concentration of trace elements significantly influenced by pH of leaching media. They observed that trace elements have leaching order $Pb > Cd > Zn > Cu$ with considerable difference in concentration. The trace element Pb and Cu showed 80 and 30% volatilization respectively. They concluded that Cl present in fly ash helps to control adsorption of heavy toxic elements from solid waste.

Popovic et al. (2013) observed the leaching behaviour of trace elements associated with ash. They noticed from results that concentration of elements Si Ni, Mg Cu and Fe significantly influenced by nature of water whereas elements K, Pb, Cd, Al, Cr, Mn were not influenced.

Komonweeraket et al. (2015) performed the leaching experiments to determine influence of pH on leachate concentration. Batch water leach test procedure was used to examine leaching characteristics of Cr, Fe, Zn, Cu, Al, and Mn from soil–fly ash mixture used for construction work. Type C fly ash was used for the investigation using six different types of soils. The concentration of Mn was decreased with increase in pH whereas leachate concentration of other elements was increased. The leachate concentration of trace elements can be controlled by hydroxide and oxide.

Kumar et al. (2016) carried out experimental study to analysis the effect of liquid-to-solid ratio by following TCLP leaching testing method to determine concentration of traced elements such as Mg, Mn, Zn, Cr, Ni, Co Fe, Pb, Cu and Mo from present in fly ash sample. They concluded that concentration of traced elements was change with L/S ratio from 20:1 to 60:1. They also reported that concentration of traced elements Mg, Cu, Mn, Cr, Ni, Fe and Pb were found slightly higher than WHO permissible limit for drinking water in water sample nearby the thermal power station.

Pani et al. (2016) analyzed the leaching characteristics of fly ash samples was analyzed by following TCLP and batch methods. The leaching behaviour of traced element with addition of

natural additive i.e reetha fruit, aloe-vera juice, banana with sodium silicate and active carbon was also investigate. The reported that with dosage of sodium silicate pH of slurry was increased which helps to reduction in leachate concentration of trace elements.

Singh et al. (2016) investigated the leaching characteristics of fly ash by using ASTM leaching method. The additive NaHCO_3 dosage was range from 0.2-0.6% (by weight). The concentration of Cu, Cr, Mg, Mn and Zn was higher than other elements. The trace element Fe showed lowest leachability whereas Mn showed higher leachability from among all other traced elements. The addition of additive was effective in reduction of leachate concentration of trace elements.

Kumar et al. (2017) analyzed the leaching behaviour of bottom ash. They used TCLP method to determine the leachate concentration of trace elements for the L/S ratio range of 20:1-60:1. They found that trace elements Fe, Pb, Co and Mo showed lower leaching rate as compared to other elements present in bottom ash. They also examined that leachability of trace elements highly affected by nature of abstraction media and liquid-to-solid ratio.

Singh et al. (2017) investigate leachability of traced element in fly ash. They reported that as the solid concentration poses negative impact on pH. They also found that leaching of traced elements were highly influenced by nature of extraction solution. Traced elements namely as Mn, Ni, Cr, Pb and Fe were found across the permissible limit of drinking water that can causes series health hazards.

The detailed summary of the different leaching procedures and trace elements analyzed for fly and bottom ash is listed in Table 2.2.

2.3 Rheological characteristics of fly and bottom ash

The study of flow behavior and deformation of fluid under the effect of external force is called as rheology. The rheological behavior of slurry is complicated due to the fact that a large number of factors influence it. Historically, the rheology of suspension has been investigated mostly through experimentation on equisized particulate suspension. Correlations have been derived, on the basis of the above data, to predict the Newtonian viscosity of suspension. However, in commercial slurry, all the particles of the material will not be equisized and the ratio of the size of the largest particles to that of the smallest particles may be of the order of 1000 or even more. Further, the particles of different materials will differ in various properties like density, shape etc. The rheological behaviour of slurry plays significant role for the design of the slurry transportation

system. If the rheological data is available, it may be used to find the flow rate-head loss relationship. Rheological parameters also helps in determining the power requirement in agitating the slurry in the agitation tank. Knowledge of suspension rheology is also important to ensure a stable/energy efficient pipeline transportation system. Thus, the actual flow pattern that exists in a slurry pipeline will differ from material to material. Also the behavior of the slurries is generally non-Newtonian at the concentrations that are commercially used. Non-Newtonian slurries make the principles of fluid mechanics more complex since the resistance to flow ‘viscosity’ now must be defined through a physical model reflecting process conditions. It is essential that a good understanding of the methods of characterizing rheological properties and extrapolating these characteristics to commercial slurries be obtained.

In the absence of any suitable correlations for predicting the rheological parameters of non-Newtonian slurries contains large sized particles and wide particle size distribution, viscometric tests are unavoidable. For slurries containing large sized particles in a low viscosity carrier liquid, viscometric measurements are difficult because the large particles tend to settle down during measurements thus affecting the homogeneity of the suspension.

Several investigators (Gandhi et al. 2001; Senapati et al. 2010; Kumar et al. 2014; Kumar et al. 2016; Kumar et al. 2017) observed that fly ash slurries at higher concentration ($C_w \approx 40\%$, by weight) behave a like non-Newtonian fluid with rheological equation showing Bingham behavior. They found that the values of yield stress and Bingham plastic viscosity of slurry increases rapidly with increase in concentration. Therefore, it is essential to establish the rheological nature of fly ash slurries at high concentration.

Bournonville and Nzihou (2003) investigated the rheological characteristics of fly ash suspension with the help of parallel plate rheometer. It was found that rheological properties of slurry depends upon the physical properties of soil material used for slurry preparation. They observed that viscosity of slurry suspension is function of volume fraction of solid.

Boylu et al. (2004) carried out an experimental study to investigate the rheology of coal-water suspension influenced by volume fraction, particle size distribution and rank. It was observed that higher ranked coal has low apparent viscosity.

Mishra et al. (2004) carried out the rheological investigation to study the impact of pH, temperature and concentration on coal ash slurry using HAAKE RV-30 viscometer. They noticed that coal ash slurry suspension show pseudo-plastic nature. They also reported that viscosity of

coal ash slurry is dependent on temperature, concentration and pH. Arrhenius type of relation was used to determine influence of temperature on viscosity of coal water slurry.

Verma et al. (2006) carried out an experimental study on impact of particle size distribution on the rheological behavior of coal ash slurry suspension at higher concentrations. The experimentation was carried out by taking different samples size and each sample has different concentration. They noticed that fly ash with more than 40% solid concentration showed non-Newtonian behavior.

Chandel et al. (2009) investigated the rheological characteristics of coal ash slurry suspension at higher concentration. They found that settling of coal ash one of significant properties which effect the flow behaviour of coal ash. They found that coal slurry showed Non-Newtonian behaviour flowing Bingham plastic nature. They reported that the yield stress of suspension was function of physical properties of solid.

Senapati et al. (2009) performed rheological experimentation to investigate the flow behaviour of limestone water suspension. Experimentation was carried out at different volume fraction, particle size and temperature at shear rate varying from $1\text{--}300\text{ s}^{-1}$. It was observed that upto 37.8% Volume of suspension showed Newtonian behaviour afterward it show Non-Newtonian nature.

Sahoo et al. (2010) studied rheological behaviour of coal-water suspension by pretreatment using microwave. The sample was collected from Indian coal mine having 32-38% ash content. Bohin viscometer was used to determine the rheological characteristic of coal-water slurry. They observed that coal-water slurry exhibit pseudoplastic behaviour and microwave heating improves rheological properties of coal suspension.

Senapati et al. (2010) carried out an experimental investigation to analyze the rheology of fly ash suspension at higher concentrations. Experiments were conducted by taking five sample of fly ash with volumetric concentration 0.32 to 0.49. They found that viscosity of fly ash suspension depends upon concentration and particle size.

Assefa and Kaushal (2015) investigated the rheological characteristic of fly ash suspension with and without addition of bottom ash. They observed that fly ash suspension exhibited Bingham flow behaviour at 60-65% solid concentration. The viscosity of fly ash suspension drastically increased with increase in solid concentration. Yield stress was decreases with addition of bottom ash in fly ash suspension. They suggested that upto 30% addition of bottom ash in fly ash was

effective to improve rheological properties of suspension. They developed correction for the prediction of viscosity of bottom ash suspension using experimental data.

Rani and Jain (2017) investigated the physico-chemical and rheological behaviour of fly and fly-bottom ash mixture for use in mine filling. Bottom ash was added into fly ash by proportion 7:3, 6:4 and 5:5 at 50% solid concentration using Anton Paar rheometer. They found that addition of bottom ash helps to improve the rheological properties of fly ash at higher solid concentration.

The researchers (Usui and Suzuki 2001; Boylu et al. 2004; Verma et al. 2006; Seshadri et al. 2008, Senapati et al. 2010; Senapati et al. 2013; Kumar et al. 2014; Singh et al. 2016) concluded that behaviour of fly ash suspension depends upon concentration of fly ash. They also found that the increase in viscosity and yield stress of fly ash suspension with increase in solid concentration. The above review shows that no universal correlation has been developed to predict the rheological behavior of slurry suspension. This is due to the fact that rheology of slurry suspension is governed by large number of parameters like volume fraction, shear rate, viscosity and other properties of solid particles.

2.3.1 Effect of additives on the rheological behaviour of slurry

Presently, lean slurry transportation system is used in most of thermal power plants situated in India. The head loss in slurry pipe increases with increase in concentration of slurry. The rheological behaviour of slurry suspensions depends upon various parameters like nature of slurry suspension, flow velocity and yield stress etc. A number of techniques were employed for minimizing the pressure drop or head loss in slurry transportation system. These techniques were able to reduce the frictional losses by reducing rheological characteristics and/or impacts of adverse flow. The direct methods for reducing slurry viscosity are addition of fibers of high aspect ratio, soaps and higher molecular weight polymers. The present literature review focuses on techniques where rheological characteristics of given slurry are directly affected.

Ghanta et al. (2002) investigated impact of particle size distribution, concentration and surface properties by taking coal and copper ore slurry. They found that viscosity of coal slurry suspension is decreased with increasing particle size of coal, whereas in case of copper ore as particle size increases viscosity. They also observed that rheology of fine particulate slurry suspension improved with the addition of coarse particle of ash.

Li et al. (2002) carried out an experimental investigation to analyze the rheology and sedimentation stability of fly ash suspension by addition of different additives namely carboxym, ethyl cellulose, rhamsan and xanthan gums. The fly ash was taken from the Matsuura power Station on Kyushu Island (Japan) and slurry was prepared by mixing it with deionized water in concentration of 68% (by weight). Concentration of additives was varied up to 0.3% (by weight). They found that the additives were effective in terms of increasing stability of fly ash slurry. The optimum concentration of additive found to be 0.20 (by weight).

Senapati et al. (2005) carried out an experimental investigation to analyze the rheology of coal ashes (fly and bottom ash) suspension with/without additive by using viscometer. They reported that fly ash slurry suspension show pseudo plastic nature and bottom ash slurry suspension viscosity was determined with the help of power law model.

Senapati et al. (2008) investigated the rheology of coal-water suspension with addition of natural additive. They varied the concentration of coal-water slurry in range of 55-63.7 and additive was varied from 0.4–1.2% (by weight). They observed that coal-water slurry suspension with addition of additive showed Bingham plastic nature.

Das et al. (2008) studied the rheological properties of coal-water slurry suspension with natural additive. The experimentation was carried out to impact various factor namely as ash content, temperature, pH, and concentration of additive on rheology of coal-water slurry. They varied the concentration of coal-water slurry in range of 55-64 and additive was varied from 0.4–1.2% (by weight). They reported that 0.8% concentration of additive gave maximum improvement in rheological properties of coal slurry.

Mosa et al. (2008) carried out an experimental investigation to analyze the effect addition of additives on rheology of coal-water suspension. They used three different additives namely sodium tri-polyphosphate, sodium carbonate and sulphonic acid. The dosage of additive was ranges from 0.5-1.5% (by weight). Results showed that viscosity and flow behaviour of slurry suspension reduced with an increase in weightage of additives.

Vlasak et al. (2009) observed the effect of addition sodium hexa-meta phosphate as additive on rheology of fly ash suspension. They found that addition of sodium hexa-meta phosphate in small amount, reduced the viscosity of fly ash slurry.

Chandel et al. (2009) carried out an experimental investigation to analyze the rheology of fly ash-water slurry with addition of additive. They used two different additives namely sodium-hexa-meta phosphate and Henko detergent and their ratio was kept constant i.e. 5:1. Bingham plastic model was used to predict flow behaviour of ash slurry at higher concentration. They reported that rheological properties of ash slurry suspension was improved with addition of additive. It also helped in reducing the pressure drop.

Naik et al. (2011) investigate rheology properties of fly ash-water slurry with/without additive in the temperature range of 20-40°C at 40% solid concentration (by weight). They used Cetyltrimethyl ammonium bromide as an additive whereas NaSal was used as counter ion in fly ash slurry. The Newtonian flow behavior of slurry was observed. The viscosity of slurry was reduced with the addition of Cetyltrimethyl ammonium bromide.

Buranasrisak and Narasingha (2012) carried out experimentation to study the impact of PSD on rheology of coal-water mixture. Naphthalene sulfonate formaldehyde (NSF) and Na-CMC were used as the dispersing agent and stabilizer in coal water slurries.

Senapati et al. (2013) have studied rheological behaviour of coal ash slurry suspension by varying solid concentration in range of 62-65% (by weight). They found that dense slurry of fly ash suspension showed pseudo plastic nature.

Kumar et al. (2013) examined the influence of fly ash addition on the rheological properties of bottom ash slurry. The fly ash is added in bottom ash suspension with varying solid concentration from 10 to 30% (by weight). They noticed that rheological properties of bottom ash suspension were increased with addition of fly ash particles. Saving in power consumption was also observed.

Panda et al. (2014) inspected the rheological characteristics of fly ash samples taken from Jindal Power Limited, Raigarh. The rheological investigation was performed at solid concentrations of 50-60% (by weight). They used ghadi detergent and NaSiO₂ as additives with solid concentration of 0–0.6%. Results showed that ash slurry exhibits non- Newtonian behaviour and obtained data was fitted in Bingham plastic model. They found that sodium silicate was more effective than ghadi detergent at 0.6% concentration (by weight).

Singh et al. (2015) studied the effect of size of particles, temperature of slurry and concentration on rheological behaviour of coal-water slurry. The sample of coal was taken from the mining site

of Assam. The rheological study was carried out for both kinds of particle size distribution such as unimodal and bimodal distribution of particles. From the rheological study, it was concluded that as concentration of solid increases, the apparent viscosity also increases. The pseudoplastic behaviour of slurry was observed at high concentrations. However, in the case of bimodal slurry, the apparent viscosity of fine particles slurry suspension is decreases with addition of coarseer particals.

Kumar et al. (2017) carried out an experimental investigation to analyze the rheology of bottom ash-water slurry with/without additives. They have taken Henko detergent and sodium sulfate as an additive. The weightage of additives in bottom ash suspension was varied in range of 0.2-0.6%. They found that the reduction in apparent viscosity is highly noticeable by addition of sodium sulfate as compared to Henko detergent. The rheology of the coal ash suspension with different additive are presented in the Table 2.3.

Above studies reveal that small quantity of additives in slurry suspension is capable to improve the rheology of the slurry suspension. However, the selection of these additive agents is dependent upon the physio-chemical and mineralogical nature of slurry suspension.

2.4 Investigation of head loss characteristics of fly and bottom ash suspension

Head loss is the most important parameter to be ascertained while designing a hydraulic transportation system. In the absence of any universal correlation for head loss prediction, head loss is generally estimated by carrying out pilot plant studies and the data collected are then scaled up for prototype pipelines. These studies also lead to a better understanding of flow mechanism, which may lead to the development of an appropriate correlation. The pioneer work in this area was done by Durand and Condolios (1952) in the early fifties.

Gillies et al. (2004) studied the head loss of heterogeneous sand slurry flow at high velocities. The test loop used to conduct experiments was of 0.09 and 0.27 mm in median diameter and 0.103 m of length. They measured the head loss with the help of calibrated transducers and velocities with the help of calibrated magnetic flux flow meter. The calibration of magnetic flux flow meter was verified during experiments. Results show that friction losses were low at high velocity of slurry flow. They also developed a correlation to predict the friction generated by heterogeneous slurries at velocities.

Chandel et al. (2009) performed experimental study on the effect of additives on rheological characteristics and pressure drop of fly ash slurry by using pilot plant test loop. The pilot plant test loop consists of 40 mm diameter straight pipeline of 50 m length. The concentration of ash slurry was kept high (above 60% by weight) and mixture of Henko detergent and sodium carbonate was used as an additive. The flow rate inside pipeline was measured by calibrated electromagnetic flow meter. The results obtained from experiments showed reasonable agreement with analytical results calculated from the algorithm given by Darby and Melson (1981). They also found that the pressure drop gets reduced with the addition of soap solution in high concentrations fly ash slurry.

Chen et al. (2010) examined wall slip flow behavior of coal water slurries with the help of pilot scale slurry transportation system. The pilot plant test loop was consisting of 25, 32, 40 and 50 mm diameter straight pipeline of 2200 mm length. A screw pump was used to the flow the slurry at rate of 16 m³/h by adjusting the speed of electromagnetic motor. Results show that increase concentration, temperature and particle size tends towards the decrease in the wall slip velocity. Also, the increase in concentration and decrease in temperature/particle size resulted in increase of critical wall shear stress.

Pavel and Zdenek (2011) performed an investigation on flow behavior of high concentration slurries influenced by PSD and concentration. By the experimental investigation, flow behaviour and head loss of dense slurries which contain sand of various size, mean diameter ranging (0.20 to 1.40 mm) and inner diameter ranging (17.5 to 26.8 mm). The solid concentration of sand, sand-dust and stony dust-sand slurry lied in range 6-40%, 26-48% and 45-51% respectively. It was found that the sand slurry with coarser particles have high gradient than sand slurry with fine particles. They found that flow resistance of fine-grained stony dust slurry was reduced by adding coarse-grained material.

Mika (2012) performed an investigation on rheological behavior and pressure drop in sudden contractions and expansions of pipeline due to flow of ice slurry at low fraction. Experiments were performed at six altered pipe contractions and expansions ratios (0.813, 0.800, 0.769, 0.650, 0.615 and 0.500). They analyzed the ice slurry flow and found the minimal flow velocity ranges 0.11 to 0.32 m/s.

Kumar et al. (2017) performed an investigation on pressure drop characteristics bottom ash slurry with and without addition of additive. They have taken Henko detergent and sodium sulfate as an additive. The additive added in bottom ash suspension by weightage of 0.2, 0.4 and 0.6%. The

solid concentration of bottom ash suspension was kept in range of 10-60%. They found that the 0.4% addition of additive in slurry results in maximum pressure drop due in the pipeline.

From the available prediction tools for head loss, it is observed that none of the available methods is directly applicable to all commercial slurries operating in heterogeneous regime. Therefore, there is a need for concerted effort in this area to produce a prediction tool for head loss which will be applicable to all types of commercial slurries having wide particle distribution.

2.5 Gaps in literature

Based on literature review, following gaps in knowledge on the flow and leaching behaviour of the coal ash slurry is observed.

- Due to incomplete understanding of complex solid-liquid flow phenomena in the pipeline, and limited data base, there is limited established method available to investigate the rheology for solid-liquid mixtures.
- Empirical correlations developed experimentally for prediction of the rheology are applicable of the particular slurry and cannot predict reasonable rheology with other slurries.
- Disposal of lean solid suspension with water discharge heavy toxic metal associated with ash particle. Improper dumping of ash has high environmental risk by contaminate water source.
- Leachability of traced elements is influence by physic-chemical properties of ash
- The trace element concentrations of the metal in the bottom ash also show the variations from one plant to the other one.

Table 2.1: Environment impact of coal ash and its utilization

Application	Benefits	Limitation	Environment impact
Soil Amendment	Low cost material used for decrease the requirement of chemical fertilizer Acidic neutralizer of soil It improve physio-chemical properties.	A large amount of fly and bottom ash increases hardness, anions and cationes of soil Contaminates water soil and plants with toxic elements Huge amount of fly ash causes leaching of toxic element in soil.	Environment friendly Leaching of toxic heavy trace element into soil, plant and water causes many problem in food chain The amount of fly ash used in soil impact on soil health and texture in long term.
Adsorbent	It is used for purification of industrial waste water Low cost and required small amount of ash.	It has low absorption capacity than synthetic adsorbent	It adsorbed pollutant toxic elements from industrial waste water which environmental helps in recycling of water.
Geopolymer	Increase tensile strength, reduction of hydration, and thermal crack's formation. Denser microstructure with lower porosity and enhance workability	Low reactivity of fly and bottom ash decreases setting time, for enhance the setting time and additive like CaO and CaCl ₂ where used to increase reactivity. Mechanical properties of geopolymer is concern with Si/Al ratio, additive used and curing temperature and time. High dry shrinkage	It reduced the requirement of water. Geopolymer concrete has remains leaching of heavy element under the permissible threshold limit of ASTM standard

Table 2.2: Various method of leaching test and element investigated

Author	Location	Sample	Method	Trace Elements
Baba et al. 2004	Turkey	FA, BA, C	EP, TCLP	Ba, Cd, Cu,Cr, Co, Ni, Pb, Sb, and Zn

Aysenur et al. 2004	Turkey	FA	Batch	Ca, Mg, Na, K, SO ₄ , Mn, Pb, Cd, Cu, Co and Fe,
Moreno et al. 2004	Spain	FA	DIN 38414-S4	Pb, Zn, Sb As, Cd, Ba Sr and Ge
Claudia et al. 2006	Italy	FA	EI	As, Cd, Cr, Cu, Ni, Pb, Se and Zn
James et al. 2006	USA	FA, C	ASTM	Zn, As, Hg, Mn, Mo, Rb, Zr and Cr
Snigdha and Batra 2006	India	FA, BA	-	Cr, Mn, Pb, Zn, Cu, Ni and Co
Tsiridis et al. 2006	UK, Italy, Austria	FA	TCLP	As, Ca, Al, Cd, Cu, Fe, Cr, Mg, Mn, Na, Ni, P, Pb, Sn, Ti, and Zn
Bably et al. 2008	India	FA	CM	Pb, Cd, Cu, Zn, Cr, Fe, Mn and Ni
Popovic and Djordjevic 2009	Belgrade	CA	-	Cr, Mn, Fe, Ni Cu Zn Cd and Pb
Wilson et al. 2009	South Africa	FA	DIN-S4, ANC	Cr, Co, Ni, Cu, Zn, V, Pb, Ca, Mg, Na, K and SO ₄
Baba et al. 2010	Turkey	FA	ASTM	Zn, As, Cu, Pb, Ni, Se, Ti, Hg, Au, Bi, Mo, Cd and Ag
Dhananjay et al. 2010	India	FA, BA	TCLP, Batch	Zn, Ni, Cu, Fe, Pb, Mn, Mg, and Cd
Popovic et al. 2011	Belgrade	CA, FA	-	Al, Fe, Si, Mn, Mg, K, Cr, Ni, Cu, Pb and Cd
Senapati et al. 2012	India	FA	HF	Fe, Cd, Ni, Pb, Zn, Cu, Co, As and Hg
Singh et al. 2012	India	FA	Batch	Fe, Cr, Cu, Pb, Cd, and Ni
Singh et al. 2016	India	FA	ASTM	Mn, Mg, Cr, Cu, Ni, Pb, Fe, Zn and Co
Kumar et al. 2017	India	BA	TCLP	Mn, Mg, Cr, Cu, Ni, Pb, Fe, Zn and Co
Singh et al. 2017	India	BA	TCLP	Mn, Mg, Cr, Cu, Ni, Pb, Fe, Zn and Co

Note:- FA= Fly ash ; BA= Bottom ash; CA= Coal ash; C = Coal; EP = Extraction procedure; ASTM = American society for testing and material; TCLP = Toxicity characteristic leaching procedure; HF = Hansen and Fisher; CM = Cascade Method; DIN-S4 = De-mineralized water leaching test (German standardization organization) ; ANC = Acid neutralization capacity test

Table 2.3: Rheological properties of fly and bottom ash suspension with additive

Author	Type of slurry	Concentration (%by weight)	Shear Rate (s^{-1})	Types of Additive	Concentration of Additive (% by weight)
Kumar et. al. (2000)	FAW	0-60		Bottom ash	9:1, 8:2, 7:3*
Usui et al. (2001)	FAW	70	0.01-1000	Polystyrene sulfuric acid	0.3
Mosa et al. 2008	CW	40	0.17-1022	Sodium salt of carboxymethyl cellulose	0.05-0.25
Seshadri et al. (2008)	FAW	60-68	20 - 120	Sodium hexametaphosphate	0.1
Chandel et al. (2009)	FAW	60-70	0-120	Mixture of sodium carbonate and Henko detergent	0.2
Naik et al. (2009)	FAW	30	25-500	Cationic surfactant	0.1-0.5
Naik et al. (2011)	FAW	40	100-1000	Cetyltrimethyl ammonium bromide and sodium salicylate	0.1-0.5
Kumar et. al. (2013)	FAW	0-60	50-300	Bottom ash	9:1, 8:2, 7:3*
Singh et al. 2016	FAW	30-60	0-300	Sodium bicarbonate	0.2-0.6
Kumar et al. 2017	BAW	10-60	0-200	Henko detergent	0.2-0.6
Rani and Jain 2017	FAW	40-60	0-1000	Bottom ash	7:3, 6:4, 5:5*
Note:- FAW = Fly ash water slurry ; BAW= Bottom ash water slurry, CW= Coal water slurry Symbol * concentration in ratio					

List of Reference

- Ahn, J.W., Cho, H.C., Han, G.C., You, G.S., Um, N., Characteristic of Cu and Pb leaching behavior of municipal solid waste incineration bottom ash. *Geosystem Engineering*, 9(1), (2006) 11-14.
- Akar, G., Polat, M., Galecki, G., Ipekoglu, U., Leaching behavior of selected trace elements in coal fly ash samples from yenikoy coal-fired power plants. *Fuel Processing Technology*, 104, (2012) 50-56.
- Asokana, P., Saxena, M., Asolekar, S.R., Coal combustion residues-environmental implications and recycling potentials. *Resources, Conservation and Recycling*, 43, (2005) 239–262.
- Assefa, K.M., Kaushal, D.R., Experimental study on the rheological behaviour of coal ash slurries. *Journal of Hydrology and Hydromechanics*, 63, (2015) 303–310.
- Baba, A., Gurdal, G., Sengunalp, F. Leaching characteristics of fly ash from fluidized bed combustion thermal power plant: Case study Çan (Çanakkale-Turkey). *Fuel Processing Technology*, 91, (2010) 1073–1080.
- Baba, A., Kaya, A., Leaching characteristics of solid wastes from thermal power plants of western Turkey and comparison of toxicity methodologies. *Journal of Environmental Management*, 73, (2004) 199–207.
- Baite, E., Messan, A., Hannawi, K., Tsobnang, F., Prince, W., Physical and transfer properties of mortar containing coal bottom ash aggregates from Tefereyre (Niger). *Construction and Building Materials*, 125, (2016) 919–926.
- Bakoshi, T., Kohno, K., Kawasaki, S., Yamaji, N., Strength and durability of concrete using bottom ash as replacement for fine aggregate. *ACI Special Publication*, SP-179 (10), (1998) 159–172.
- Bournonville, B., Nzihou, A., Rheology of non-Newtonian suspensions of fly ash: effect of concentration, yield stress and hydrodynamic interactions. *Powder Technology*, 128, (2002) 148–158.
- Boylu, F., Dincer, H., Atesok, G., Effect of coal particle size distribution, volume fraction and rank on the rheology of coal–water slurries. *Fuel Processing Technology*, 85, (2004) 241– 250.

Buranasrisak, P., Narasingha, M.H., Effects of particle size distribution and packing characteristics on the preparation of highly-loaded coal-water slurry. *International Journal of Chemical Engineering and Applications*, 3, (2012) 31-35.

Chandel, S., Singh, S.N., Seshadri, V., Deposition characteristics of coal ash slurries at higher concentrations. *Advanced Powder Technology*, 20, (2009) 383–389.

Chandel, S., Seshadri, V., Singh, S.N., Effect of additive on pressure drop and rheological characteristics of fly ash slurry at high concentration. *Particulate Science and Technology*, 27, (2009) 271-284.

Chen, L., Duan, Y., Liu, M., Zhao, C., Slip flow of coal water slurries in pipelines. *Fuel*, 89, (2010) 1119-1126.

Cheng, Y.W.C., Hong, F.Y.U., Hui, F.Z. Extraction of aluminum by pressure acid-leaching method from coal fly ash. *Transactions of Nonferrous Metals Society of China*, 22, (2012) 2282-2288.

Chindaprasirt, P., Rukzon, S., Sirivivatnanon, V., Resistance of chloride penetration of blended Portland cement mortar containing palm oil fuel ash, rice husk ash and fly ash. *Construction and Building Materials*, 22(5), (2008) 932.

Das, D., Effect of organized assemblies part 4 formulation of highly concentrated coal-water slurry using a natural surfactant. *Energy & Fuels*, 22, (2008) 1865-1872.

Dutta, B.K., Khanra, S., Mallick, D., Leaching of elements from coal fly ash: assessment of its potential for use in filling abandoned coal mines. *Fuel*, (2009) doi:10.1016/j.fuel.2009.01.00.

Erol, M., Kuçukbayrak, S., Ersoy-Meriçboyu, A., Comparison of the properties of glass, glass–ceramic and ceramic materials produced from coal fly ash. *Journal of Hazardous Materials*, 153, (2008) 418-425.

Gandhi, B.K., Singh, S.N., Seshadri, V., Performance characteristics of centrifugal slurry pumps. *Transaction actions of ASME, Journal of Fluid Engineering*, 123, (2001) 271-280.

Georgakopoulos, A., Anestis, F.A., Fournaraki, A.K., Turiel, J.L.F., Liorens, J.F., Mousty, F., Leachability of major and trace elements of fly ash from Ptolemais power station, Northern Greece. *Energy Sources*, 24, (2002) 103-113.

Ghanta, K.C., Purohit, N.K., Effect of particle size distribution (psd) on the viscosity of suspension of bi-dispersed particles. *Proceedings Hydro transport 15*, (Cranfield, Bedford), England, (2002) 299-313.

Gillies, R.G., Shook, C.A., Xu, J., Modelling Heterogeneous Slurry Flows at High Velocities. *The Canadian Journal of Chemical Engineering*, 82, (2004) 1060-1065.

Ghosh, C.N., Mondal, P.K., Suitability of fly ash as a stowing material for underground coal mines - some studies. *Proceeding 1st Asian Mining Congress*. Kolkata, India, (2006) 113–123.

Hower, J.C., Sakulpitakphon, T., Trimble, A.S., Thomas, G.A., Schram, W.H., Major and Minor Element Distribution in Fly Ash from a Coal-Fired Utility Boiler in Kentucky. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 28(1), (2006) 79-95.

Jing-yong, L., Shui-yu, S., Effect of solid additive on heavy metal vaporization of fly ash from co-incineration of MSW with sludge at high temperature. *Journal of Fuel Chemistry and Technology*, 40(12), (2012) 1512-1520.

Kim, B. J., Prezzi, M., Salgado, R., Geotechnical properties of fly and bottom ash mixtures for use in highway embankments. *Journal of Geotechnical and Geoenvironmental Engineering*, 131(7), (2005) 914–924.

Kim, H. K., Lee, H. K., Use of power plant bottom ash as fine and coarse aggregates in high-strength concrete. *Construction and Building Materials*. 25(2), (2011) 1115-1122.

Komonweeraket, K., Cetin, B., Aydilek, A.H., Benson, C.H., Edil, T.B., Effects of pH on the leaching mechanisms of elements from fly ash mixed soils. *Fuel*, 140, (2015) 788–802.

Kurama, H., Kaya, M., Usage of coal combustion bottom ash in concrete mixture. *Construction and Building Materials*, 22, (2008) 1922–1928.

Kumar, K., Kumar, S., Gupta, M., Garg, H.C., Singh, G., Measurement of flow characteristics for multiparticulate bottom ash-water suspension with additives. *Journal of Residual Science and Technology*, 14(1), (2017) 11-17.

Kumar, S., Singh, G., Mohapatra, S.K. An assessment of the physical, mineral, and rheological properties of fly ash for stowing in coal mines. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 38(20), (2016) 2955-2962.

Kumar, S., Singh, G., Mohapatra, S.K., Leaching characteristics of heavy metal in bottom ash from Indian thermal power plant. *Journal of Scientific and Industrial Research*, 76, (2017) 255-258.

Kumar, S., Mohapatra, S.K., Gandhi, B.K. Performance characteristics of centrifugal slurry pump with multi-sized particulate bottom and fly ash mixtures. *Particulate Science and Technology*, 32, (2014) 466-476.

Kumar, K., Kumar, S., Gupta, M., Garg, H.C., Gurprit Singh, Measurement of flow characteristics for multiparticulate bottom ash-water suspension with additives. *Journal Residual Science and Technology*, 14 (1), (2017) 11-17.

Kumar, U., Gandhi, B.K., Singh, S.N., Seshadri, V., Gupta, V.K., Performance characteristics of demonstration unit for transportation of solid-liquid flow at high concentration setup at NCPP, Dadri, Proceedings International Seminar on Material handling Systems Indian Institute of Plant Engineers (Delhi-Haryana Chapter), November 16-18, New Delhi, 126-136 (2000).

Latifi, N., Marto, A., Safuan, A., Rashid, A., Yii, J.L.J.Y., Strength and physico-chemical characteristics of fly ash–bottom ash mixture. *Arabian Journal for Science and Engineering*, 40(9), (2015) 2447–2455.

Lee, J.K., Shang J.Q., Jeong, S., Thermo-mechanical properties and microfabric of fly ash-stabilized gold tailings. *Journal of Hazardous Materials*, 276, (2014) 323-31.

Li, L., Usui, H., Suzuki, H., Study of pipeline transportation of dense fly ash-water slurry. *Coal Preparation*, 22(2), (2002) 65-80.

Lin, C.Y., Yang, D.H., Removal of pollutants from wastewater by coal bottom ash. *Journal of Environmental Science and Health. Part A, Toxic/Hazardous Substances & Environmental Engineering*, 37, (2002) 1509–1522.

Luo, Y., Zheng, S., Ma, S., Liu, C., Wang, X., Ceramic tiles derived from coal fly ash: Preparation and mechanical characterization. *Ceramics International* Error! Hyperlink reference not valid..

Mahale, N.K., Patil, S.D., Sarode, D.B., Attrade, S.B., Effect of fly ash as an admixture in agriculture and the study of heavy metal accumulation in wheat wheat (*Triticum aestivum*), mung bean(*Vigna radiata*) and urad beans (*Vigna mungo*). *Polish Journal of Environmental Studies*, 21(6), (2012), 1713-1719.

Malhotra, V.M., Painter. K.E., Early-age strength properties, and freezing and thawing resistance of concrete were incorporating high volume of ASTM Class F Fly ash. *International Journal of Cement Composites and Lightweight Concrete* 11(1): (1995) 38–46.

Mika, L., Rheological behaviour of low fraction ice slurry in pipes and pressure loss in pipe sudden contractions and expansions. *International Journal of Refrigeration*, 35, (2012) 1697-1708.

Mishra, U.C., Environmental impact of coal industry and thermal power plants in India. *Journal of Environmental Radioactivity*, 72, (2004) 35–40.

Mosa, E.S., Saleh, A.M., Taha A. Taha, El-Molla, A.M., Effect of chemical additives on flow characteristics of coal slurries. *Physicochemical Problems of Mineral Processing*, 42, (2008), 107-118.

Naik, H.K., Mishra, M.K., Rao, K.U.M. Rheological characteristics of fly ash slurry at varying temperature environment with and without additive. *World of coal ash conference*, (2009) Lexington, KY, USA.

Naik, H.K., Mishra, M.K., Rao, K.U.M., Evaluation of flow characteristics of fly ash slurry at 40% solid concentration with and without additives. *World of Coal Ash Conference*, May 9-12, Denever, U.S.A, (2011) 1-15.

Naik, T.R., Singh, S.S., Permeability of flowable slurry materials containing foundry sand and fly ash. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, 123(5), (1997) 446–52.

Naik, T.R., Kraus, R.N. MPU Ash as a Potential Source for Construction Materials. 2001.

Panda, D., Pradhan, B., Hydraulic transport of fly ash and fly ash- bottom ash mixtures at high concentrations. *International Journal of Chemical Engineering and Applied Sciences*, 4(1), (2014) 1-4.

Pani, G.K., Rath, P., Maharana, L., Barik, R., Senapati, R.K., Assessment of heavy metals and rheological characteristics of coal ash samples in presence of some selective additives. *International Journal of Environmental Science and Technology*, 13, (2016) 725–731.

Pavel, V., Zdenek, C., Effect of particle size distribution and concentration on flow behaviour of dense slurries. *Particulate Science and Technology*, 29, (2011) 53-65.

Popovic, A., Djordjevic, D., pH-Dependent leaching of dump coal ash retrospective environmental analysis. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 31, (2009) 1553-1560.

Popovic, A., Djordjevic, D., Relic, D., Associations and pollution potential of selected trace and major elements in filter lignite ash from the “Nikola Tesla A” power plant (Obrenovac, Serbia) (I) Leaching Experiments. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 35, (2013) 529-537.

Popovic, A., Djordjevic, D., Relic D., Zelic, A.M., Speciation of trace and major elements from coal combustion products of serbian power plants (ii) Obilic power plant. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 33, (2011) 2309-2318.

Prasad, B., Mondal, A.H., Heavy metals leaching in Indian fly ash. *Journal of Environmental Science and Engineering*, 50(2), (2008) 127-132.

Rani, R., Jain, M.K., Effect of bottom ash at different ratios on hydraulic transportation of fly ash during mine fill. *Powder Technology*, 315, (2017) 309–317.

Sahoo B.K., De, S., Carsky, M., Meikap, B.C., Enhancement of rheological behavior of Indian high ash coal-water suspension by using microwave pretreatment. *Industrial and Engineering Chemistry Research*. 49, (2010) 3015–3021.

Sarkar, A., Rano, R., Water holding capacities of fly ashes: effect of size fractionation. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 29(5), (2007) 471-482.

Sarkar, A., Rano, R., Mishra, K.K., Sinha, I.N., Particle size distribution profile of some Indian fly ash a comparative study to assess their possible uses. *Fuel Processing Technology*, 86, (2005) 1221– 1238.

Sarode, D.B., Jadhav, R.N., Khatik, V.A., Ingle, S.T., Attarde, S.B., Extraction and leaching of heavy metals from thermal power plant fly ash and its admixtures. *Polish Journal of Environmental Studies*, 19(6), (2010) 1325-1330.

Senapati, P.K., Das, D., Nayak, A., Mishra, P.K., Studies on preparation of coal water slurry using a natural additive. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 30, (2008) 1788-1796.

Senapati, P.K., Mohapatra, R., Pani, G.K., Mishra, B.K. Studies on rheological and leaching characteristics of heavy metals through selective additive in high concentration ash slurry. *Journal of Hazardous Materials*, 229– 230, (2012) 390– 397.

Senapati, P.K., Mishra, B.K., Parida, A., Modeling of viscosity for power plant ash slurry at higher concentrations: Effect of solids volume fraction, particle size and hydrodynamic interactions. *Powder Technology*, 197, (2010) 1–8.

Senapati, P.K., Panda, D., Parida, A., Predicting viscosity of limestone–water slurry. *Journal of Minerals and Materials Characterization and Engineering*, 8(3), 2003, 203-221.

Senapati, P.K., Panda, D., Parida, A., Studies on high concentration fly ash -bottom mixture slurry. *Bulk Solid Handling*, 25(6), (2005) 386-290.

Senapati, P.K., Mishra, B.K., Parida, A., Analysis of friction mechanism and homogeneity of suspended load for high concentration fly ash & bottom ash mixture slurry using rheological and pipeline experimental data. *Powder Technology*, 250 (2013) 154-163.

Sharma, N.K., Mitra, S., Sehgal, V., Mishra, S., An assessment of physical properties of coal combustion residues w.r.to their utilization aspects. *International Journal of Environmental Protection*, 2, (2012) 31–38.

Singh, G., Kumar, S., Mohapatra, S.K., Kumar, K., Comprehensive characterization of grounded bottom ash from Indian thermal power plant. *Journal of Residuals Science & Technology*, 14, (2017) 1-10.

Singh, G., Kumar, S., Singh, M.K., Mohapatra, S.K. Environmental impact assessment of ash disposal system of a thermal power plant. *International Journal of Hydrogen Energy*, 41, (2016) 15887-15891.

Singh, M.K., Ratha, D., Kumar, S., Kumar, D., Influence of particle size distribution and temperature on rheological behaviour of coal slurry. *International Journal of Coal Preparation and Utilization*, 36, (2016) 44-54.

Singh, R.K., Gupta, N.C., Guha, B.K., The leaching characteristics of trace elements in coal fly ash and an ash disposal system of thermal power plants. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. 34, (2012) 602–608.

Snigdha, S., Batra, V.S., Analysis of fly ash heavy metal content and disposal in three thermal power plants in India. *Fuel*, 85, (2006) 2676–2679.

Stanislav, V., Vasilev, V., Christina, G., Vassileva methods for characterization of composition of fly ashes from coal-fired power stations: a critical overview. *Energy and Fuels*, 19, (2005) 1084-1098.

Sushil, S., Batra, V.S., Analysis of fly ash heavy metal content and disposal in three thermal power plants in India. *Fuel*, 85, (2006) 2676–2679.

Tang, S.W., Yao, Y., Andrade, C., Li, Z.J., Recent durability studies on concrete structure. *Cement and Concrete Research*, 78, (2015) 143–154.

Tsiridis, V., Samaras, P., Kungolos, A., Sakellaropoulos, G.P., Application of leaching tests for toxicity evaluation of coal fly ash. *Environmental Toxicology* (2006) DOI 10.1002/tox 409-416. 2006.

Ugurlu, A., Leaching characteristics of fly ash. *Environment Geology*, 46, (2004) 890–895.

Usui, H., Li, L., Suzuki, H., Rheology and pipeline transportation of dense fly ash-water slurry Korea-Australia. *Rheology Journal*, 13, (2001) 47-54.

Verma, A.K., Singh, S.N., Seshadri, V., Pressure drop for the flow of high concentration solid liquid mixture 90° horizontal conventional circular pipe bends. *Indian Journal of engineering and Material Science*, 13, (2006) 477-483.

Viji, R., Prasanna, P.R., Assessment of water holding capacity of major soil series of Ialagudi Trichy. *Indian Journal of Environmental Research Development*, 7(1), (2011) 393–398.

Vlasak, P., Chara, Z., Effect of particle size and concentration on flow behavior of complex slurries, In *Proceedings of the Seventh (2007) ISOPE Ocean Mining (& Gas Hydrates) Symposium*. Cupertino, California: International Society of Offshore and Polar Engineers, 188-196.

Vlasak, P., Chara, Z., Conveying of solid particles in Newtonian and non-Newtonian fluids. *Particulate Science and Technology*, 27(5), (2009) 428-443.

Wei L., Utilization of coal combustion by products for masonry production. M.S. Thesis University of Wisconsin Milwaukee, (1992).

Zhang, H., Shao, P.J., Li, M., Li, X.J., Leaching behavior of heavy metals from municipal solid waste incineration bottom ash and its geochemical modeling. *Journal of material cycles and waste management*, 101, (2008) 7–13.

Chapter 3

PHYSICO-CHEMICAL AND MINERAL PROPERTIES OF FLY AND BOTTOM ASH

In order to design the slurry transportation system in thermal power plant, it is essential to determine the physicochemical properties coal ash. Small scale laboratory tests have been conducted with high precision apparatus to determine physico-chemical and mineral properties of fly and bottom ash. In this chapter, physico-chemical properties of different fly and bottom ash samples were determined and discussed in following sections. Each experiment was done three times for coal ash to ensure the precision of measured data.

3.1 Bench scale test

The samples of fly and bottom ash were collected from different coal-based thermal power plants situated in Punjab and Haryana namely Guru Nanak Dev thermal power plant, Bhatinda, Punjab, Guru Gobind Singh Super Thermal Power Plant, Ropar, Punjab, Guru Hargovind Singh thermal power plant, Lehra Mohabbat, Punjab and Deenbandhu Chhotu Ram thermal power plant, Yamuna nagar, Haryana which were labeled as FA-I & BA-I, FA-II & BA-II, FA-III & BA-III and FA-IV & BA-IV respectively.

Various small scale experiments were carried out to calculate specific gravity, bulk density, porosity, particle size distribution (PSD), static settling concentration and pH of slurries at different concentration. Morphology of ash particles was examined by using SEM (Scanning Electron Microscopy). The elemental composition of ash samples was measured by XRD (X-ray diffraction) and EDX (Energy-dispersive X-ray spectroscopy). A brief description of bench scale tests used for investigation various properties for all fly and bottom ash samples are presented below. In the literature and also in practice in thermal power plants solid concentration is taken by weight. So in present work solid concentration was taken by weight.

3.1.1 Particle Size Distribution (PSD)

Particle size distribution (PSD) mainly used to measure the percentage of finer particles present in sample. Size of particles present in fly and bottom ash influence the different properties like specific gravity, bulk density, porosity, static settling concentration. Various methods are available to investigate PSD of solid samples i.e. hydrometer analysis and sieve analysis method. A fixed weight of fly and bottom ash sample was taken for the PSD analysis. Before determining the percentage of finer particles in each sample, initially it was dried in oven at temperature of 105°C. A well-known weight of sample poured into the top sieve which has higher mesh size. The sieve shaker was started which contains set of standard sieves for the fixed time (20 minutes). The ash retained in each sieve was weighed by using weighing machine of least count of 0.001 mg. The results of standard sieve analysis were plotted between percentage finer and particle size range. Weighted mean diameters of different samples was also calculated by using equation 3.1 whereas percentage of finer particles in any sieve was calculated by using equation 3.2.

$$D_{wm} = \sum_{i=1}^N f_i N_i \quad (3.1)$$

$$R_s = \frac{W_R}{W_T} \times 100 \quad (3.2)$$

Where R_s = Retained sample, W_R = Weight of solid particle retained (gram), W_T = Total weight of solid particles (gram), N_i = Number of particle size groups, f_i = Solid fraction and D_i = Mean diameter of two successive sized sieves (μm).

3.1.2 Static Settled Concentration

The concentration of solids in settled portion is known as static settled concentration which depends on the large number of parameters like morphology of solid particles, bulk density, volume fraction, viscosity of solid–liquid suspension etc. Static settled concentration of slurry suspension also represents the maximum value of settled concentration which was determined by gravitational settling method. It was also assumed that the optimum value of solid concentration for slurry transportation is around 5 to 10% lower than the maximum settled value.

In present work, it was measured by using fixed amount of solid concentration (30% by weight). Initially, fixed amount of ash was mixed in water then mixture was put into a glass jar. Afterwards, the initial level of mixture in jar was noted down. As the ash settled down without interruption, levels of settled slurry recorded at regular intervals of time. At beginning, the level of settled slurry was measured at small intervals while interval time was increased with slow settling rate. The static settled concentration was calculated by using equations 3.6:

$$C_{wi} = \frac{W_s}{\rho_L V_w W_s} \quad (3.3)$$

$$V_s = V_L - (V_{mi} - V_m) \quad (3.4)$$

$$(C_w)_{ss} = \frac{W_s}{\rho_L V_{LM} + W_s} \quad (3.5)$$

$$(C_v)_{ss} = \frac{(C_w)_{ss}}{\rho_L (1 - (C_w) + (C_w)_{ss})} \quad (3.6)$$

Where V_w = Volume of water (ml), ρ_s = Density of solid (gram/cm³), ρ_L = Density of liquid (gram/cm³), W_s = Mass of solid (gram), C_{wi} = Initial concentration of slurry and V_{mi} = Initial volume of slurry (ml).

3.1.3 Specific gravity

The specific gravity of solid material plays an important role in designing slurry transportation system. The ratio of density of substance to density of standard substance is called as specific gravity. Air is considered as standard substance for gases whereas water for liquids. Specific gravity of fly and bottom ash was determined by following ASTM C128 standard. The specific gravity of the slurry suspension also influences its static settled concentration. In present work, pycnometer method was used to determined specific gravity of fly and bottom ash. Initially, neat and clean glass flask (500 ml) was taken.

In order to remove the moisture, it was put in an oven for one hour and kept it for cooling before weighing. The flask was weighing again after pouring 200 gram of dried fly and bottom ash sample. Water was added into the flask up to fixed level. Afterwards, flask was closed and shaken for 15 minutes. It was kept for next one hour to make sure that there is no air bubble present in it. Then, solid was removed from the flask and flask was properly cleaned with tissue paper.

Lastly, the distilled water was poured up to same level and its weight was noted down. The specific gravity of coal ash was calculated by using following equations:

$$\text{Specific Gravity} = \frac{(W_{BS} - W_B)}{(W_{BW} - W_{BSW}) + (W_{BS} - W_B)} \quad (3.7)$$

Where W_B = Weight of beaker (gram), W_{BS} = Weight of flask and solid (gram), W_{BW} = Weight of flask with water (gram) and W_{BSW} = Weight of flask with solid and water (gram).

3.1.4 Bulk density

Bulk density of coal ash is defined as the ratio of dry oven mass of coal ash to its bulk volume. Bulk density plays a significant role for deciding the physical properties of coal ash. Generally, it is inversely proportional to pore surface of fly or bottom ash which helps to estimate the porosity of ash. ASTM C29/C29M standard procedure was followed to measure bulk density of ash sample. The mass of the fly and bottom ash sample was measured by electronic weighing machine with least count 0.001gram. The fixed amount of fly and bottom ash sample was taken and poured in a container which is tapped 50 times on a table from a fixed height (3-5 cm). This tapping procedure is considered same as packing takes place naturally in field.

The volume of the solid sample was found equal to the volume of container. Bulk density of ash samples were calculated from mass and bulk volume of ash samples. Initial weight of empty container (50 ml) was recoded and then it was filled with dry fly and bottom ash sample up to the brim by tapping and weight of container with coal ash sample was measured again. Afterwards, the container was made empty and its volume was measured with the help of burette. Equation 3.8 is used to calculate the bulk density of fly and bottom ash sample.

$$\text{Bulk Density} = \frac{M_2 - M_1}{V} \quad (3.8)$$

Where M_1 = mass of empty container (gram), M_2 = mass of sample with container (gram) and V = volume of container (cm^3).

3.1.5 Water holding capacity

Water holding capacity (WHC) is defined as the capability of solid particles to retain water. WHC of coal ash sample was determined by using standard procedure ASTM 128. Initially, the fly and bottom samples were dried in oven at 105°C. Dry coal ash sample was passed through 2000 µm sieve. The round filter paper was fixed into the plate then weighed with the help of weighing machine. The plate is then filled with fly and bottom ash sample by tapping quickly and top of coal ash sample was made plain than its weight was noted down. The perforated plate was put in enamel tray and water was poured into it till half of plate height.

The plate is kept in water for five to six hours. Afterwards, plate was removed from water and placed over the filter paper to remove the excess amount of water through filter paper for next 30 minutes then the weight of moist fly and bottom ash samples were measured. WHC of ash was measured by using equation 3.9:

$$WHC = \frac{T_w}{W_T} \times 100 \quad (3.9)$$

Where, T_w = Total weight of wet ash (gram) and W_T = Total weight of dry ash (gram)

3.1.6 Porosity

Porosity (ϕ) is defined as the ratio of the total ash volume that is taken up by the pore space. The porosity of a fly and bottom ash depends on number of factors such as density, particle size, particle size distribution etc. Porosity is divided into two categories i.e. structural and textural porosity. The textural porosity is used when fly or bottom ash particles are randomly taken and having coarser particles. On the other hand, structural porosity is defined as difference between textural porosity and net porosity of material.

Presence of moisture alters the porosity of solid sample so, a special precaution was taken to dry the sample. Porosity of fly and bottom ash sample was calculated by using equation 3.10.

$$Porosity(\phi) = \left(1 - \frac{\rho}{\delta}\right) \times 100 \quad (3.10)$$

3.1.7 Potential of hydrogen (pH)

The pH of solution is the negative log of its hydrogen ions. The determination of pH in fly and bottom ash is important as it play significant role in leaching of toxic heavy elements. The pH of ash is useful for classification of ash on the basis of alkalinity or acidity. The pH of ash was measured by using digital meter which was associated with a glass electrode. The electrometric determination of pH is based on electromotive force (e.m.f.) of buffer solution with known pH and test sample. The pH value of test sample is the measure of hydroxyl ion activity or hydrogen activity of the fly and bottom ash-water suspension. Initially, pH meter was calibrated by using aqueous solution of known pH value. The electrode was cleaned properly before engrossed it into slurry samples for measuring pH of slurry suspension. As the equilibrium value attained, pH value can be noticed for slurry suspension.

3.1.8 Scanning electron microscope (SEM)

SEM analysis was used to examine the surface morphology of fly and bottom ash particles. SEM analysis was carried out with an electron beam focused on small spot of diameter about 20-100 nm. SEM microscope works on the basis of X-rays emitted by the de-excitation of holes created by high energy beam. Energy emitted is different for element to element with small overlapping peaks. During the surface scanning or mapping operation, eight X-ray emission lines were scattered on the surface of sample. The interaction of atoms (sample) and electrons (beam) generated signals further provides the information regarding sample's surface morphology, topography, composition and other properties.

3.1.9 Chemical composition

Energy-dispersive X-ray (EDX) examination is used to determine elements present in fly and bottom ash samples. This works on the principle of spectroscopy. According its principle, every existing element have its individual unique atomic structure which permits a unique set of peaks on its electromagnetic emission spectrum (Em). This method allows the interaction between source of X-rays excitation and sample specimen. X-rays beam of high-energy strikes at the sample to stimulate the emission of X-rays from a specimen. The overlapping peaks on spectrum may decrease the accuracy of EDX spectrum and it is also affected by the nature of sample. In the

present work, EDX spectroscope was used to determine the composition of fly and bottom ash sample.

3.1.10 X-ray diffraction (XRD)

XRD is used for identification of unknown crystalline phases present in the sample. The XRD diffractometer contains of specimen holder, X-ray tube and detector. X-ray tube is used for the generation of electron beam while specimen fixed in holder rotates with angle ' θ ' which is associated with X-ray detector. Goniometer is used to adjust angle of X-ray detector and also helps to rotate around the sample. In X-ray diffraction analysis, whenever electron beam impinges on the surface of sample and fulfills the Bragg's equation, peak in intensity occurs. The locations (angles) and intensities of the diffracted X-rays are measured. A detector records X-ray signal initially change them into a count rate which is used to identify the presence of various crystalline phases. The spacing between crystals plane represents the wavelength of X-rays and used to produce the diffraction pattern (1–100 Å°).

3.2 Physical and chemical properties of fly and bottom ash

The particle size distribution of collected fly and bottom ash samples were analyzed with the help of standard sieves, as shown in Figure 3.1-3.2 and tabulated in Table 3.1-3.2. In the fly ash sample FA-I, about 38.72% particles were found below 25 μm whereas 22.81, 43.19, 24.67% particles were finer for FA-II, FA-III and FA-IV respectively. From PSD data it was also noticed that 10.75, 12.30, 7.68 and 11.92% particle were coarser than 150 μm for FA-I, FA-II, FA-III and FA-IV respectively.

D50 was calculated from the particles size distribution Figure 3.1. The weighted mean diameter (D_{wm}) of fly ash samples FA-I, FA-II, FA-III and FA-IV were determined as 64.92, 75.15, 51.87 and 74.43 μm while D50 was calculated as 39.44, 46.19, 31.26 and 44.76 μm respectively.

In the bottom ash sample BA-I, about 71.50% particles were coarser than 150 μm . Approximately 72.25, 74.52 and 71.41% particles were coarser than 150 μm in sample BA-II, BA-III and BA-IV. Only 6.13, 8.87, 5.22 and 7.4% particles were found finer than 53 μm in the bottom ash sample BA-I, BA-II, BA-III and BA-IV. It was noticed that bottom ash sample of BA-III was finer as compared to all other samples. The weighted mean diameters (D_{wm}) of bottom ash samples

BA-I, BA-II, BA-III and BA-IV were calculated as 271.56, 313.43, 269.18 and 332.15 μm whereas D_{50} were determined as 269.55, 295.23, 256.33 and 298.73 μm respectively.

The physical properties of all fly and bottom ash samples is listed in Table 3.3-3.4. The specific gravity of fly ash samples FA-I, FA-II, FA-III and FA-IV were determined as 2.29, 2.23, 2.34 and 2.26 respectively while bulk density were found as 1.41, 1.33, 1.46 and 1.37 gram/cm^3 respectively. Specific gravity of bottom ash samples BA-I, BA-II, BA-III and BA-IV were calculated as 2.19, 2.15, 2.20 and 2.16 respectively. Bulk density of bottom ash samples BA-I, BA-II, BA-III and BA-IV were measured as 1.21, 1.16, 1.27 and 1.14 gram/cm^3 respectively. The particles of bottom ash were uneven shape and coarser nature whereas fly ash are finer in nature. The higher weight per unit volume and closeness of particles is responsible for the bulk density of fly ash as compared to bottom ash (Viji and Prasanna, 2011; Zhao and Wang, 2015; Nikbin et al. 2016).

Porosity of fly ash samples FA-I, FA-II, FA-III and FA-IV were calculated as 38.42, 40.35, 37.60 and 39.38 % respectively whereas water holding capacity were determined 42.12, 40.01, 44.09 and 41.52% respectively. Porosity of bottom ash samples BA-I, BA-II, BA-III and BA-IV were determined as 44.74, 46.10, 42.28 and 47.23% whereas water holding capacity were found as 37.65, 36.14, 39.87 and 35.06% respectively. Bottom ash having higher porosity, due to irregular shape and large gap between the particles (Kim and Lee, 2011; Nikbin et al. 2016).

The static settled concentration was measured by taking $C_w=30\%$ (by weight). The final settled value of fly ash FA-I, FA-II, FA-III and FA-IV slurries were found as 62.51, 60.35, 65.05 and 61.17% (by weight) respectively, as tabulated in Table 3.5 and shown in Figure 3.3. The final settled concentration of bottom ash BA-I, BA-II, BA-III and BA-IV slurries were recorded as 55.32, 53.54, 58.10 and 52.89% (by weight) respectively, as listed in Table 3.6 and shown in Figure 3.4.

The pH values of fly and bottom ash slurry suspension have been measured at different solid concentration from 10 to 60% (by weight) as shown in Figure 3.5-3.6. The pH value of fly ash varies in the range of 6.43-5.94, 6.55-6.12, 6.31-5.81 and 6.50-6.05 for sample FA-I, FA-II, FA-III and FA-IV respectively. From the fly ash pH values data, it was observed that fly ash slurries exhibits acidic nature. The pH value of bottom ash was found in the range of 7.52-7.32, 7.54-7.34, 7.50-7.29 and 7.48-7.28 for sample BA-I, BA-II, BA-III and BA-IV respectively. The pH of slurry suspension was changed due to presence of alkaline layer and elements associated with ash

particles. As the solid concentration was increased, the outer acidic layer dissolves in water which results an increase in acidic nature of slurry suspension. So as the solid concentration was increased pH of slurry suspensions decrease (Naik et al. 2009; Chandel et al 2009). The pH of slurry is most dominating factor on leaching of traced elements (Popovic and Djordjevic, 2009 and Komonweeraket et al. 2015). Addition of additive increases the pH of slurry which reduces the leaching of traced element and helps minimized environment impact caused by leaching. The pH value of bottom ash slurries samples BA-I, BA-II, BA-III and BA-IV depicts the nonreactive nature.

3.3 Mineral properties of fly and bottom ash

The SEM and EDX spectroscopy was used to study morphology and elemental composition of ash. The scanning electron micrograph (SEM) of fly and bottom ash samples are shown in Figure 3.7-3.8. The fly ash particles were finer, smaller size, smooth surface and spherical morphology. It also seems that finer particles have cenospheres surface with adhered to coarser particles. The finer particles can be used to develop lightweight concrete with sound absorbing tendency (Bakoshi et al. 1998; Risto et al. 2008; Sultana et al. 2011). The particles of bottom ash were irregular in shape and having coarser nature.

From Figure 3.8, it was noticed that particles of bottom ash were coarser, irregular, larger size, rough surface texture and dark grey color. The chemical compositions of ash samples were measured by EDX technique. The comprehensive percentage of elemental composition present in fly ash sample FA-I, FA-II, FA-III and FA-IV is tabulated in Table 3.7. It was found that SiO_2 and Al_2O_3 present in major proportion than other elements like TiO_2 , FeO , CaO , CO_2 , MgO , etc. in all fly ash samples.

In the fly ash samples FA-I, FA-II, FA-III and FA-IV, silica oxide (SiO_2) present in the percentage of 52.78, 54.16, 51.92 and 49.92% whereas aluminum oxide (Al_2O_3) present in the percentage of 35.72, 36.57, 37.34 and 38.38% respectively. The iron oxide (FeO) was found in the percentage of 1.48, 1.06, 1.25 and 1.29% while calcium oxide (CaO) was present as 2.17, 2.36, 2.45 and 2.65% respectively. The LOI of fly ash samples FA-I, FA-II, FA-III and FA-IV were found as 1.87, 1.94, 1.97 and 1.05% respectively as shown in Figure 3.9.

In the bottom ash samples BA-I, BA-II, BA-III and BA-IV, silica oxide (SiO_2) present in the percentage of 51.21, 52.28, 48.54 and 45.26% respectively whereas aluminum oxide present in the

percentage of 37.46, 40.19, 43.67 and 41.54% respectively as listed in Table 3.8. It seems that the percentage of SiO_2 was higher in sample BA-II as compared to other bottom ash samples. The value of LOI in bottom ash samples BA-I, BA-II, BA-III and BA-IV were determined as 3.05, 3.31, 3.22 and 3.48% respectively as shown in Figure 3.10.

It was also found that all fly ash samples were categorized as type F fly ash i.e., total sum of SiO_2 , Al_2O_3 , Fe_2O_3 is higher than 70% and LOI is less than 6% (Bankowski et al., 2004; Antiohos and Tsimas, 2007; Ghafoori et al., 2015; Huggins et al., 2016; Xie and Kayali, 2016). It has good pozzolanic properties such as high compaction with low heat evolution during hydration, it is considered as low cost construction material (Kikuchi, 1999; Prabakar et al. 2004; Shafiq et al. 2007; Chaulia and Das 2008; Nochaiya et al. 2010; Plaks et al. 2010; Singh and Siddique 2013; Ukwattage, 2013; Chousidis et al. 2015; Ahn et al. 2016; Aliabdo et al. 2016; Mármol et al. 2016; Yongfan and Yonghao 2016). Fly ash has better cementing properties which makes it a valuable alternative for clinker in high strength portland cement. According to ASTM C618 standard, fly ash blending of cement. The XRD results of fly ash sample are shown in Figure 3.11. Quartz, hematite and mullite crystalline phases were appeared in XRD spectra of all fly ash. The chemical composition of quartz, hematite and mullite is SiO_2 , Fe_2O_3 and $\text{Al}_{(4+2y)}\text{Si}_{(2-2y)}\text{O}_{(10-y)}$. The value of y lies between 0.17-0.59. The phases of quartz and mullite in fly ash samples FA-I, FA-II, FA-III and FA-IV were found as 54.5 & 33%, 56.35 & 36.57%, 56 & 34.30% and 55 & 37% while hematite phase was found as 12.5, 7.08, 9.7 and 8% respectively.

The XRD results of bottom ash samples are shown in Figure 3.12. In the bottom ash samples BA-I, -BA-II, BA-III and BA-IV, quartz phase was found as 53.7, 49.0, 51.0 and 54.0% whereas mullite phase was found as 44.2, 51.0, 49.0, 46.0% respectively. Hematite phase was observed only in bottom ash sample BA-I. The strong peak due to quartz in samples BA-I, BA-II, BA-III and BA-IV were in close proximity of 26.59° , 26.55° , 26.52° and 26.57° respectively. Similarly, the peaks due to mullite were in close proximity of 26.23° , 26.23° , 26.19° and 26.20° respectively. The diffraction peaks intensities of quartz and mullite phases for fly ash were stronger as compared to bottom ash samples. The presence of silica and mullite in fly ash, make it more feasible to use as building material and for stowing purpose (Kumar et al. 2016).

3.4 Potential utilization of fly and bottom ash

The above results of physical, chemical and mineral characteristics of coal ash (fly and bottom) samples show that these can be used in different engineering applications. Utilization of fly and bottom ash in various applications is discussed in details as flowing:

3.4.1 Utilization of fly and bottom ash in construction industry

Generally, coal ash are utilized in civil and geotechnical field such as concrete, road structural fill, constructions, landfills and embankments. Coarser particles ($< 400 \mu\text{m}$) of bottom ash were used as coarser aggregate in concrete by the fractional replacement of sand (Asokana et al. 2005; Kurama et al. 2008; Kim et al. 2011; Blissett and Rowson, 2012; Nikbin et al. 2016). The fly and bottom ash are used as aggregate in concrete to increase compressive and tensile strengths. Concrete of bottom ash have higher abrasive resistance as compared to sand (Kurama et al. 2008; Kim et al. 2011).

Fly ash has been used in different stages of cement industry. Fly ash has good pozzolanic properties such as high compaction and low heat evolution during hydration, it is considered as low cost construction material (Prabakar et al. 2004; Shafiq et al. 2007; Singh and Siddique 2013; Ukwattage, 2013; Chousidis et al. 2015; Ahn et al. 2016; Aliabdo et al. 2016; Yongfan and Yonghao 2016). Fly ash has better cementing properties which makes it a valuable alternative for clinker in high strength portland cement. Fly ash has higher pozzolanic reactivity as compared to bottom ash however the pozzolanic properties of bottom ash can be enhanced by mechanical grinding (Singh et al. 2017). Coal ash are used to manufacture the blocks which have lower wet density and shrinkage (Ahmaruzzaman, 2010). In construction sector bottom ash is used as construction material for highway, flyovers and pavement. All fly ash samples have shown higher water holding capacity and lower porosity than bottom ash samples (Table 3.3-3.4). These physical properties are responsible for its better utilization in light weight concrete with dense structure (Asokana et al. 2005; Kim et al. 2005). The fly and bottom ash is also utilized for land-filling of tunnels, sewers, excavations, and other services (Jaturapitakkul et al. 2003; Datta et al. 2009).

3.4.2 Utilization of fly and bottom ash in soil amendment

Many investigators (Aggarwal et al. 2007; Patra et al. 2012; Tejasvi and Kumar 2012; Yazici and Arel 2012; Ukwattage, 2013; Lu et al. 2014; Bilir et al. 2015; Moon et al. 2016; Naganathan et al. 2016) reported that water holding capacity, pH, electric conductivity of soil increases with addition of fly ash. Physio-chemical properties of soil can be improved by using ash as additives. Addition of fly ash also alters the porosity and root penetration of soil which is responsible for improvement of crop growth rate (Khan et al. 2001; Sharma and Kalra 2006; Sheoran et al. 2014; Assi, et al. 2016). Amendment of fly and bottom ash in sandy, acidic and clay loam soil increases the crop yield by increasing nutrients. Addition of fly ash in sandy soil enhance the level of micronutrients such as K, Fe, Ca, Ni, Zn, Cu, Mn and P with toxic element Pb, Cd and Cr (Pandhy et al. 2016).

3.4.3 Utilization of fly and bottom ash as adsorbent

Fly and bottom ash were used as an adsorbent to remove metal namely as Cu, Pb, Mn, Cd, Zn, Cr and Ni from waste water (Alinnor et al. 2007; Cetin and Pehlivan 2007; Mohan and Gandhimathi 2009; Itskos et al. 2010; Hugginsa et al. 2016; Liu et al. 2016). Ahmaruzzaman et al. (2011) used fly ash for the leaching of toxic metal from industrial waste. Fly ash was used as an additive in Ca(OH)_2 for desulphurization of flue gases. This occurred due to increase in surface area and formation of calcium silicate (Cho et al. 2005; Itskos et al. 2010). Fly ash was used for replacing of activated carbon through absorption of $\text{C}_6\text{H}_6\text{O}$ (phenol). Fly ash can be used for extraction of 2,4-dichlorophenol and 2-chlorophenol (Kao et al. 2000). The fly and bottom ash has lower absorbent ability as compared to activated carbon. Its low cost and easily availability make it suitable alternative for extraction of organic compounds from waste water. Researchers (Banerjee et al. 2003; Gupta et al. 2003; Jha et al. 2008; Krishnan et al. 2011) used fly and bottom ash as adsorbent for extraction of various pollutants and trace elements from industrial waste. Fly ash can be used for extraction of heavy elements like Cu, Pb, Mg and Hg from aqueous solution (Srivastava et al. 2000; Shoumkova, 2010).

3.4.4 Utilization of fly and bottom ash as geopolymer materials

Coal ash is considered as cheapest and high potential construction materials like geopolymer concrete. Geopolymer is a material which has ring structure with long chains of silica, aluminum

and oxygen. It also consists of two main constituents namely source materials and alkaline fluids. Source material have adequate amount of Si and Al like kaolinite, clay (Pandian 2004). Coal ash geopolymer have more $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio as compared to other geopolymer. High concentration of SiO_2 and Al_2O_3 in coal ash decreases the reaction rate of geopolymer (Provis et al. 2007). Coal ash is used as an additive to modify mechanical properties of geopolymer. Porosity of geopolymer increases with addition of coarser coal ash particles whereas it decreases with addition of finer coal ash particles (Duxson and Provis, 2008; Pathak et al. 2012). Addition of additive improves the reactivity of geopolymer that helps to attain desired mechanical properties.

3.5 Reflection

Based on characterization of fly and bottom ash samples collected from different thermal power plants, following observations were made:

- The particles of bottom ash were irregular in shape and having coarser nature whereas fly ash particles were finer in nature. All fly ash samples shows higher settled concentration as compared to bottom ash sample.
- Fly and bottom ash samples contained higher proportion of Al_2O_3 and SiO_2 as compared to other elements like FeO, K_2O , CaO, CuO and MgO etc. This showed the high surface enrichment of Al/Si in both fly and bottom ash samples.
- The pH value of both fly and bottom ash samples decreases with increase in solid concentration. Fly ash shows acidic nature while bottom ash have non-reactive nature.
- The quartz and mullite were found as major crystalline phases present in all fly and bottom samples while hematite phase was observed only in bottom ash sample BA-I

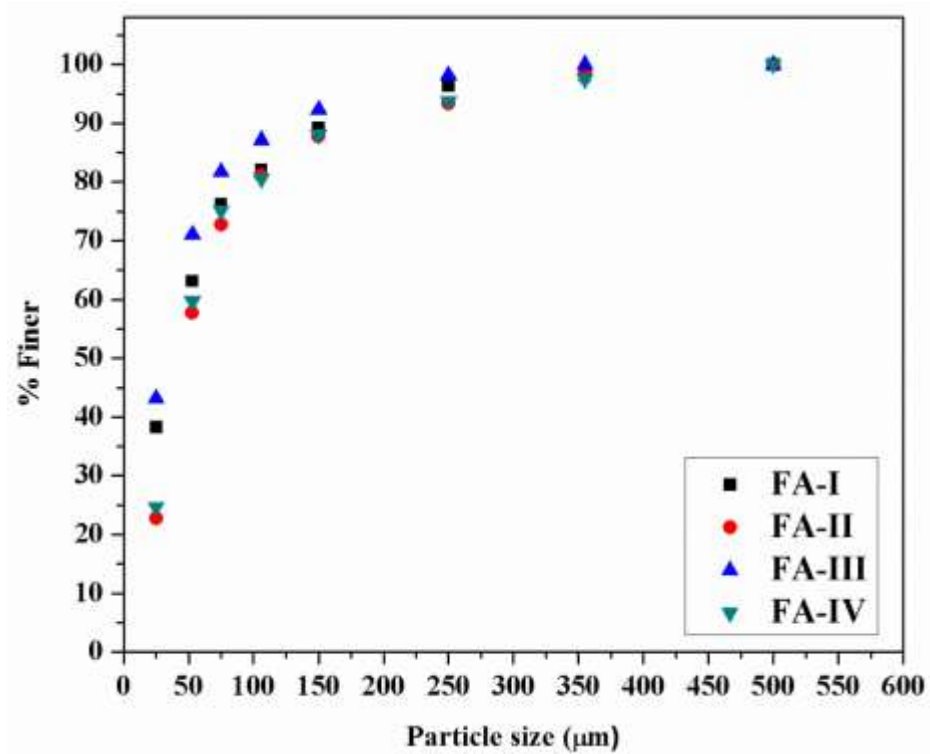


Figure 3.1: Particle size distribution of fly ash

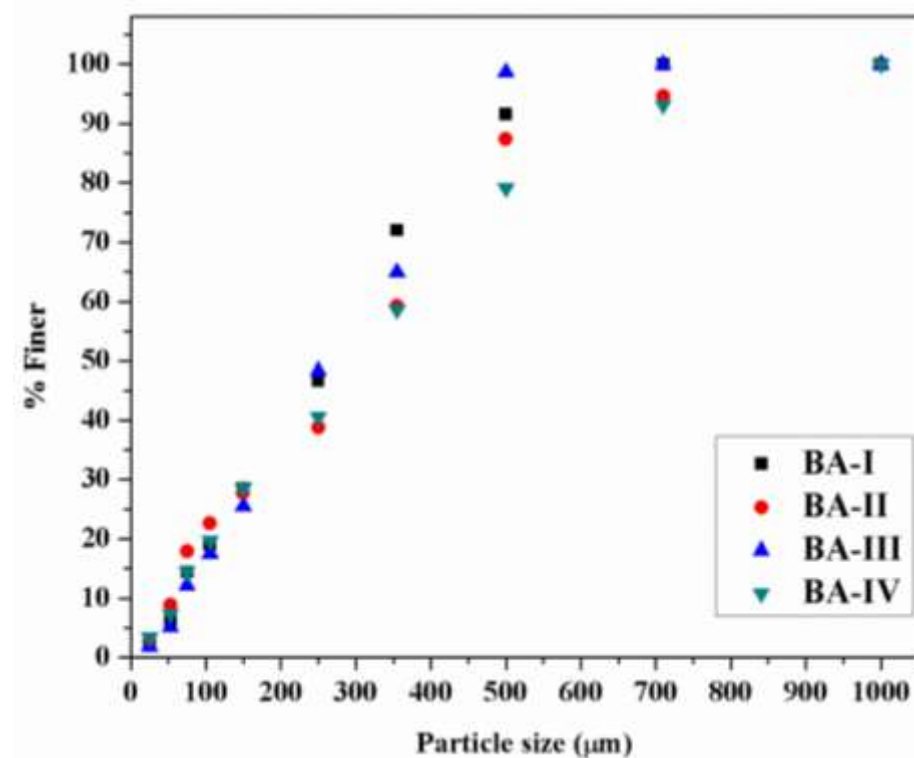


Figure 3.2: Particle size distribution of bottom ash samples

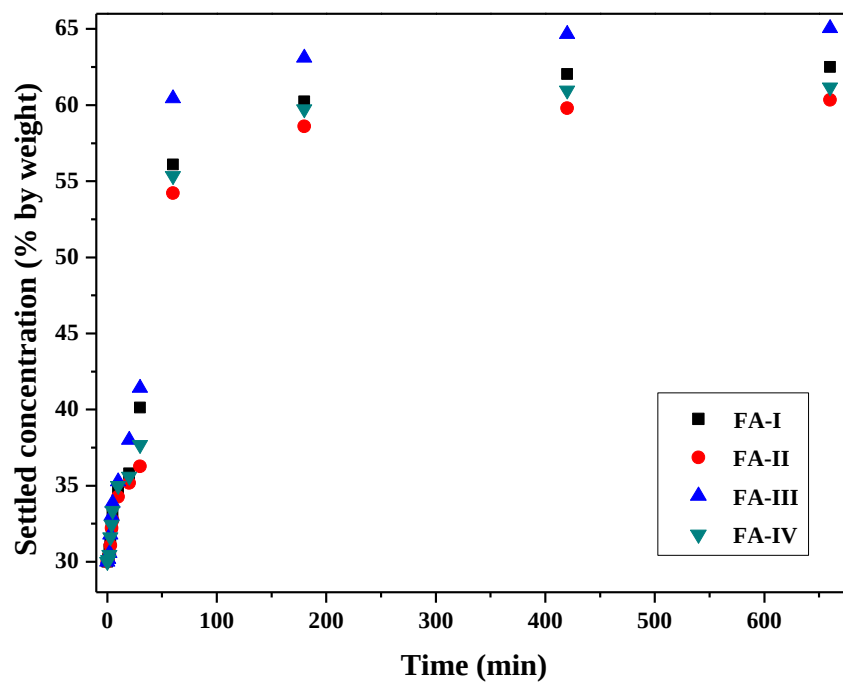


Figure 3.3: Settling concentration of fly ash

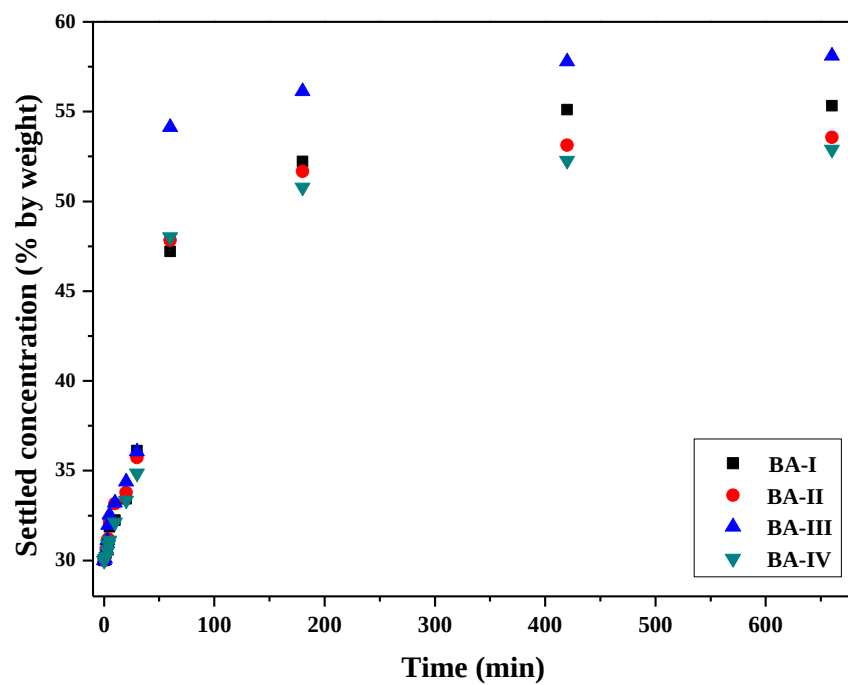


Figure 3.4: Settling concentration of bottom ash

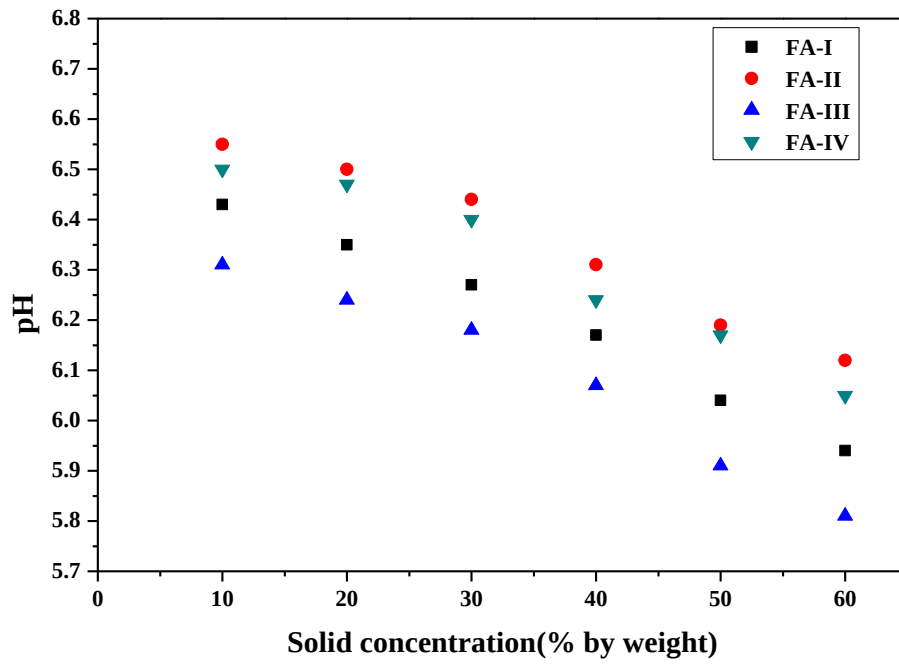


Figure 3.5: pH of fly ash

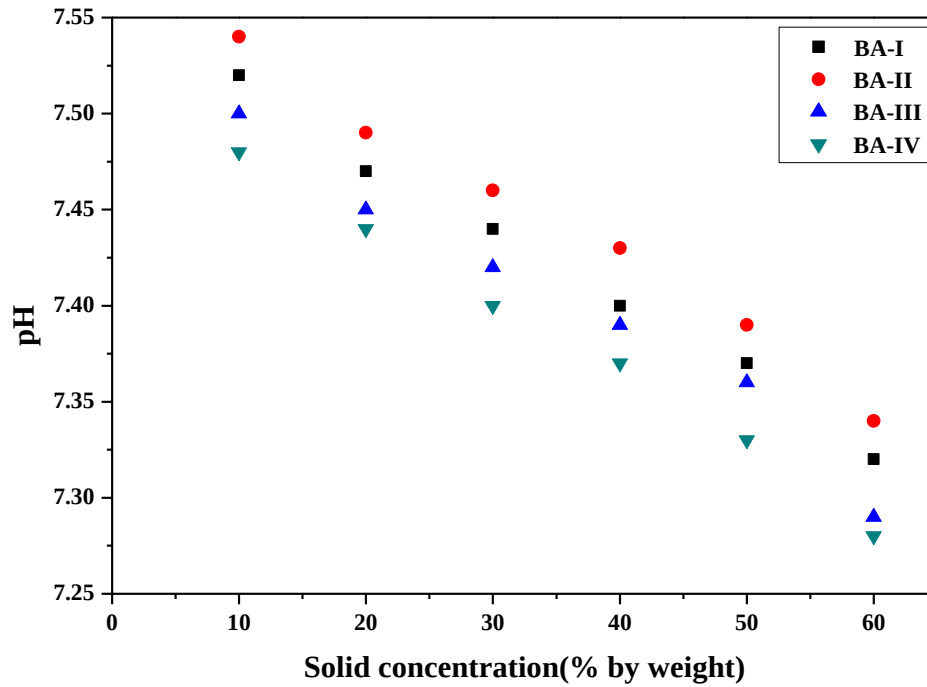


Figure 3.6: pH of bottom ash

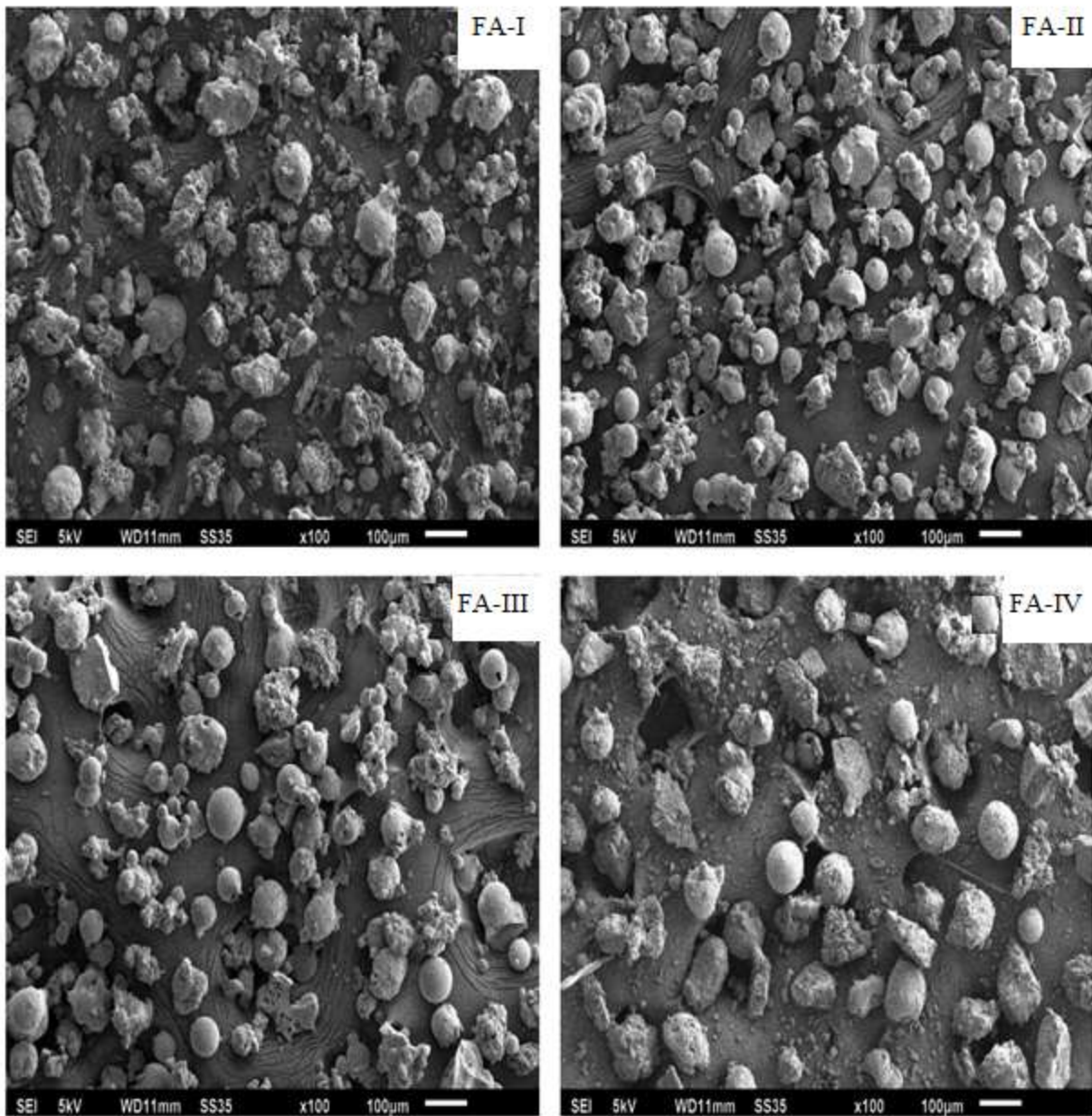


Figure 3.7: Scanning electron micrograph of fly ash

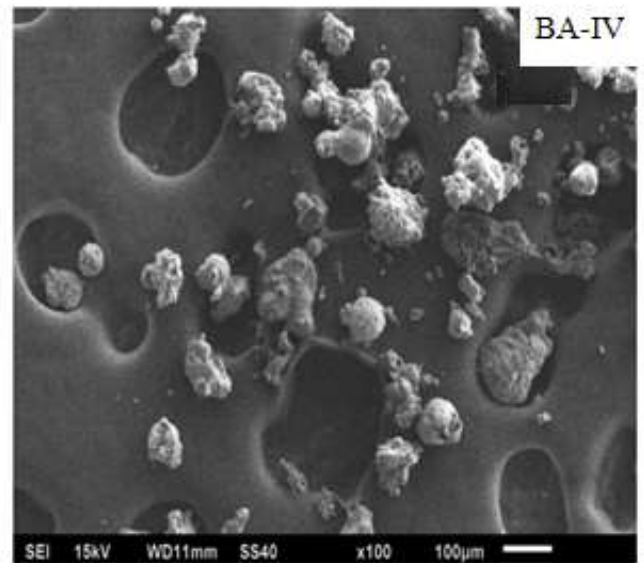
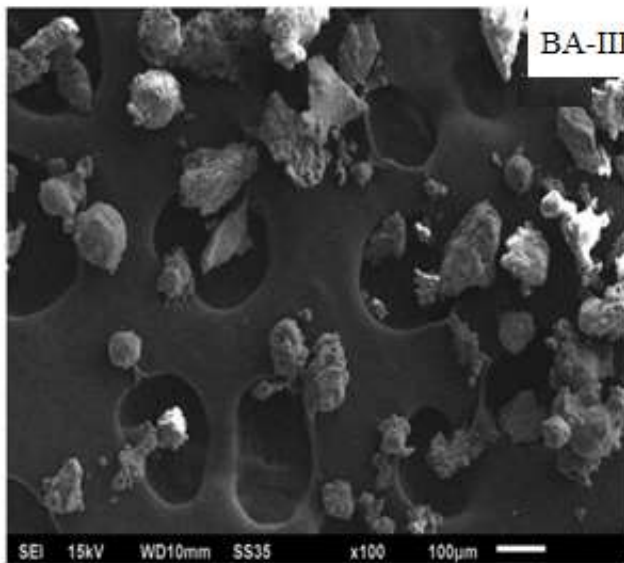
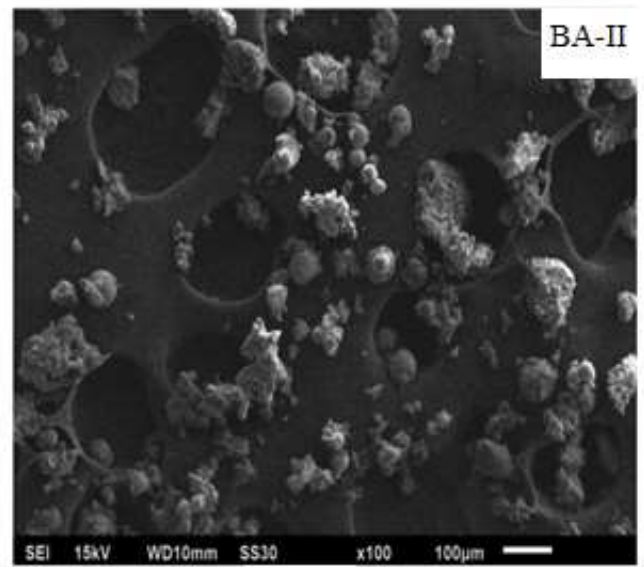
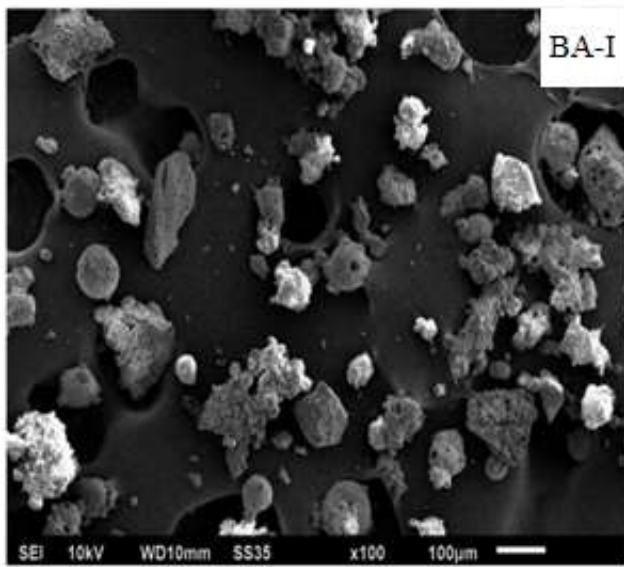


Figure 3.8: Scanning electron micrograph of bottom ash

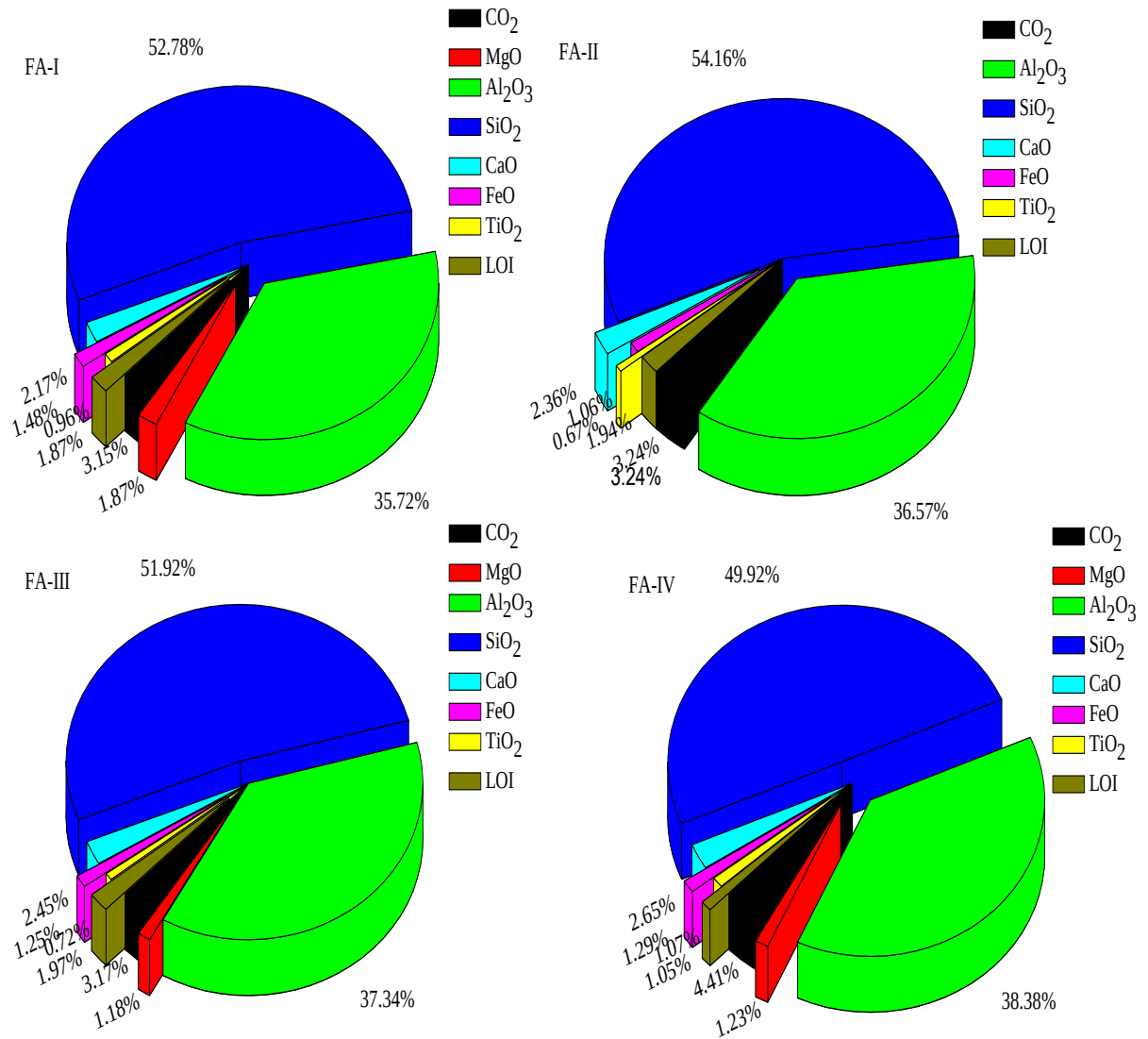


Figure 3.9: Chemical composition fly ash

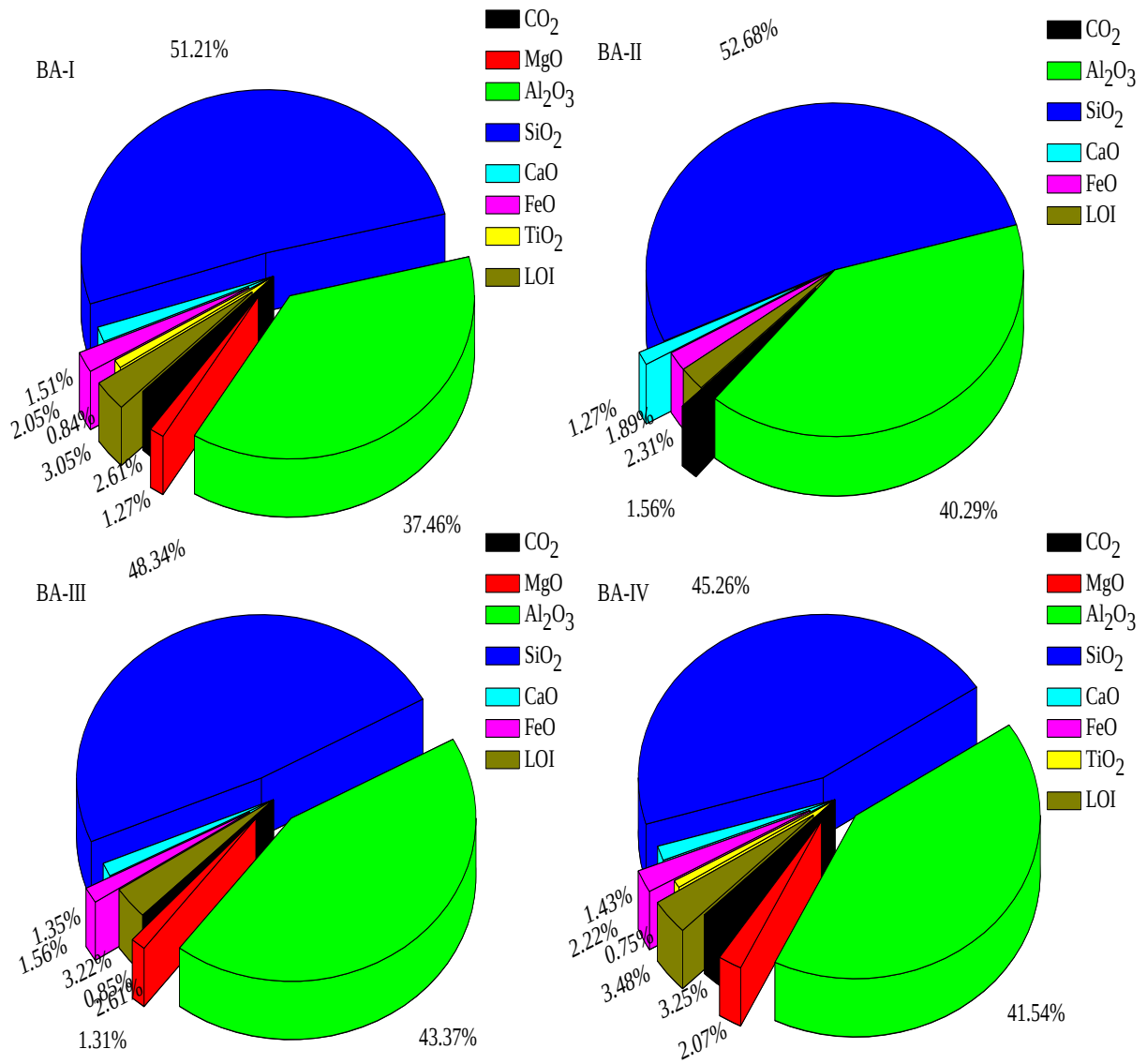


Figure 3.10: Chemical composition bottom ash

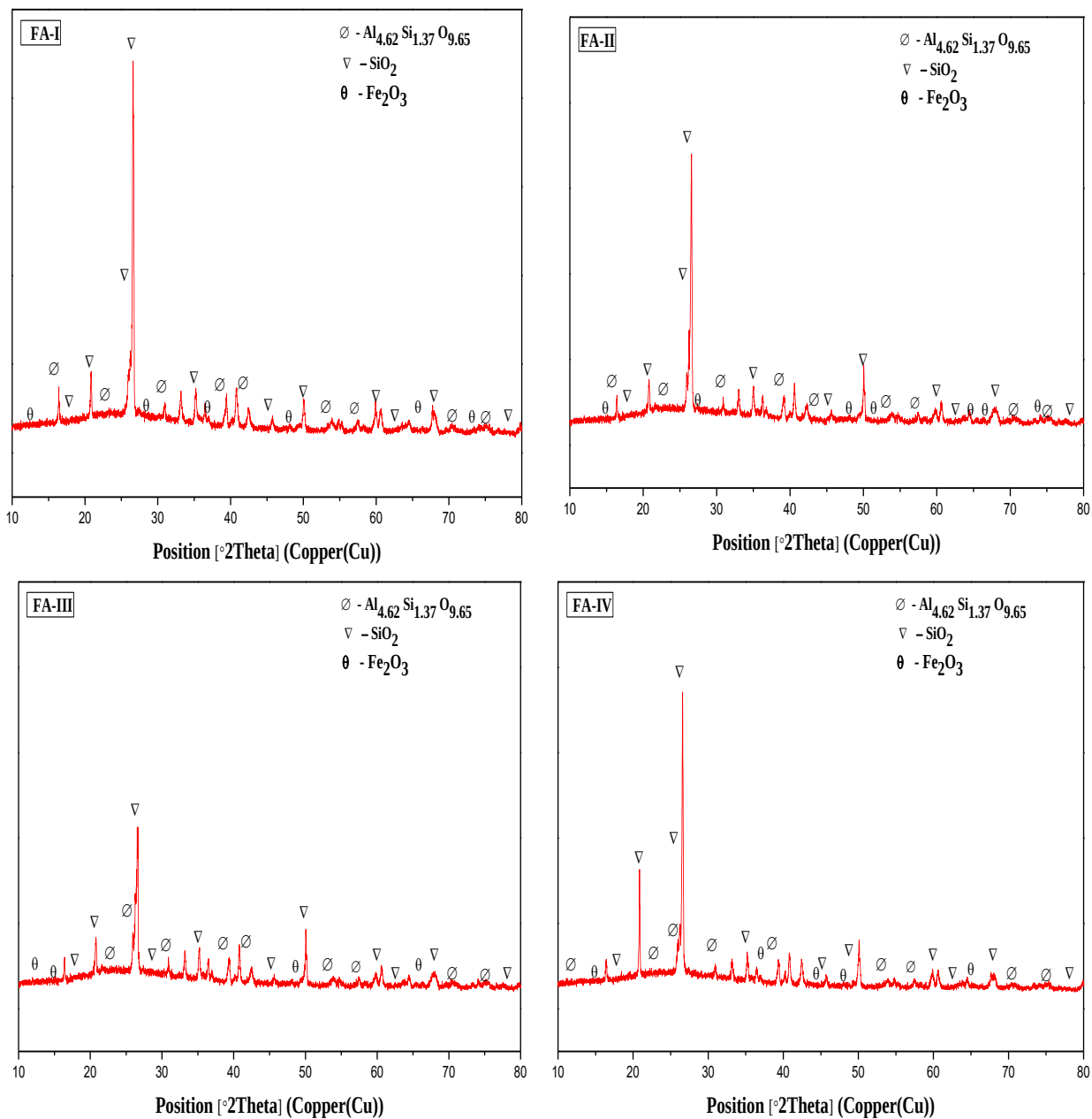


Figure 3.11: X-ray diffraction of fly ash

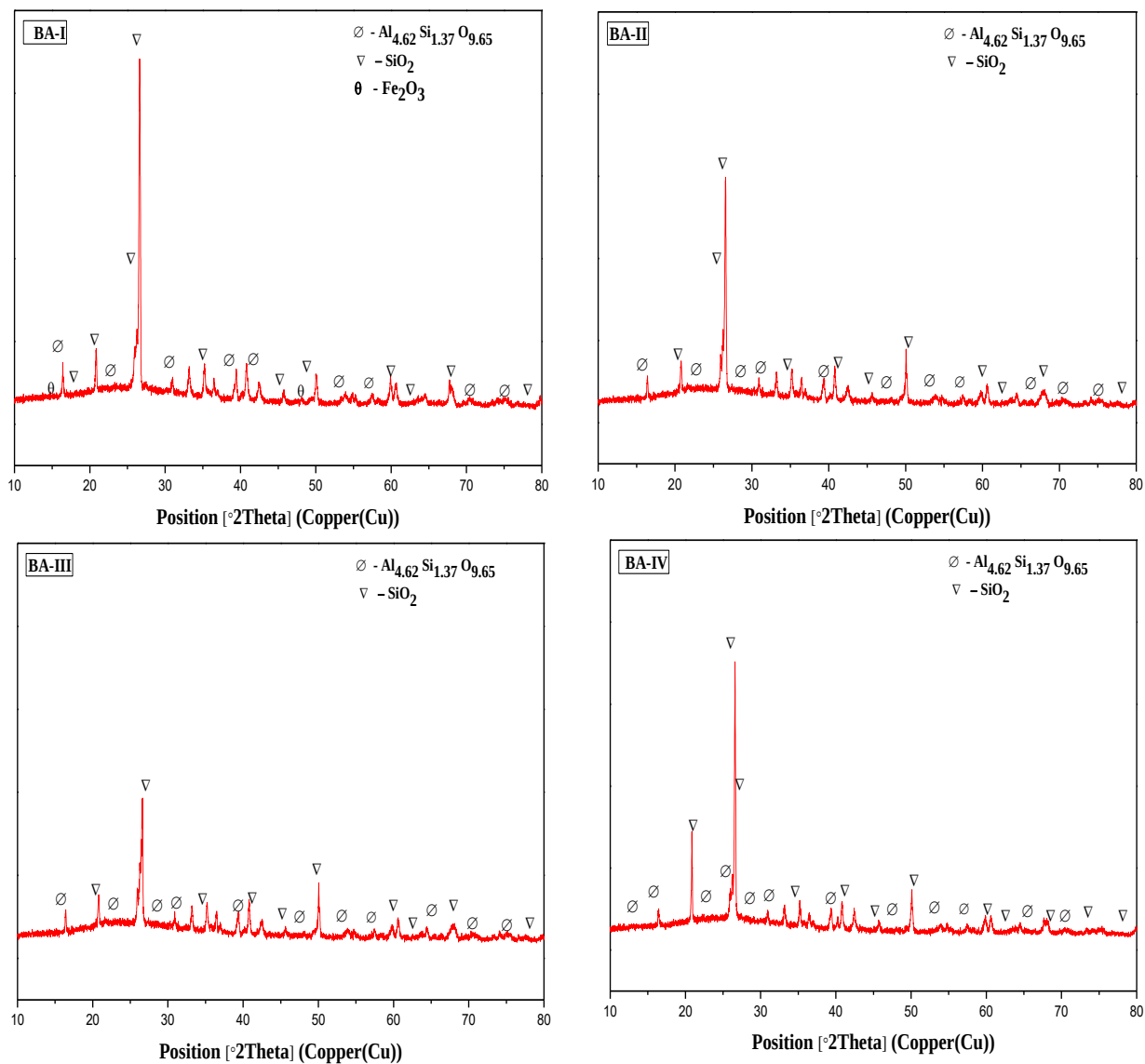


Figure 3.12: X-ray diffraction of bottom ash

Table 3.1: Particle size distribution of fly ash

Particle size (µm)	FA-I (% Finer)	FA-II (% Finer)	FA-III (% Finer)	FA-IV (% Finer)
500	100	100	100	100
355	98.07	98.6	100	97.51
250	96.42	93.4	98.14	93.79
150	89.25	87.70	92.32	88.08
106	82.03	81.20	87.18	80.63
75	76.24	72.8	81.72	75.13
53	63.15	57.7	71.06	59.76
25	38.27	22.81	43.19	24.67

Table 3.2: Particle size distribution of bottom ash

Particle size (µm)	BA-I (% Finer)	BA-II (% Finer)	BA-III (% Finer)	BA-IV (% Finer)
1000	100	100	100	100
710	100	94.65	100	93.15
500	91.54	87.32	98.65	79.15
355	72.04	59.25	64.95	58.65
250	46.64	38.75	48.35	40.6
150	28.5	27.75	25.48	28.59
106	19	22.65	17.56	19.72
75	14.4	17.95	12.2	14.45
53	6.13	8.87	5.22	7.4
25	2.14	2.69	1.87	3.36

Table 3.3: Physical properties of fly ash

Samples	Standard followed	FA-I	FA-II	FA-III	FA-IV
Specific gravity	ASTM-C128	2.29	2.23	2.34	2.26
Bulk density (gram/cm³)	ASTMC29/C20M	1.41	1.33	1.46	1.37
Porosity	-	38.42	40.35	37.6	39.38
Water holding capacity	ASTM-128	42.12	40.01	44.09	41.52

Table 3.4: Physical properties of bottom ash

Samples	Standard followed	BA-I	BA-II	BA-III	BA-IV
Specific gravity	ASTM-C128	2.19	2.15	2.20	2.16
Bulk density (gram/cm³)	ASTMC29/C20M	1.21	1.16	1.27	1.14
Porosity	-	44.74	46.10	42.28	47.23
Water holding capacity	ASTM-128	37.65	36.14	39.87	35.06

Table 3.5: Static settled concentration of fly ash

Time (min)	FA-I	FA-II	FA-III	FA-IV
0	30	30	30	30
1	30.18	30.14	30.19	30.12
2	30.81	30.49	30.56	30.47
3	31.28	31.08	31.78	31.61
4	32.34	32.20	33.02	32.45
5	33.03	32.73	33.87	33.35
10	34.79	34.27	35.28	35
20	35.81	35.17	38	35.61
30	40.12	36.26	41.43	37.68
60	56.10	54.22	60.45	55.34
180	60.23	58.60	63.10	59.73
420	62.04	59.80	64.67	60.97
660	62.51	60.35	65.05	61.17

Table 3.6: Static settled concentration of bottom ash

Time (min)	BA-I	BA-II	BA-III	BA-IV
0	30	30	30	30
1	30.11	30.18	30.10	30.09
2	30.41	30.62	30.54	30.21
3	30.76	31.10	31.11	30.53
4	31.02	31.21	31.97	30.89
5	31.87	32.14	32.55	31.12
10	32.24	33.16	33.21	32.12
20	33.43	33.79	34.39	33.34
30	36.12	35.73	36.07	34.86
60	47.21	47.83	54.14	48.02
180	52.23	51.67	56.12	50.78
420	55.10	53.12	57.78	52.27
660	55.32	53.56	58.10	52.89

Table 3.7: Chemical composition of fly ash

Element	FA-I	FA-II	FA-III	FA-IV
CO₂	3.15	3.24	3.17	4.41
MgO	1.87	-	1.18	1.23
Al₂O₃	35.72	36.57	37.34	38.38
SiO₂	52.78	54.16	51.92	49.92
CaO	2.17	2.36	2.45	2.65
FeO	1.48	1.06	1.25	1.29
TiO₂	0.96	0.67	0.72	1.07
LOI	1.87	1.94	1.97	1.05

Table 3.8: Chemical composition of bottom ash

Element	BA-I	BA-II	BA-III	BA-IV
CO₂	2.61	1.06	0.85	3.25
MgO	1.27	-	1.31	2.07
Al₂O₃	37.46	40.19	43.37	41.54
SiO₂	51.21	52.28	48.34	45.26
CaO	1.51	1.27	1.35	1.43
FeO	2.05	1.89	1.56	2.22
TiO₂	0.84	-	-	0.75
LOI	3.05	3.31	3.22	3.48

Chapter 4

LEACHING CHARACTERISTICS OF FLY AND BOTTOM ASH

Leaching is a process in which soluble solids are extracted in dissolution of suitable solvent. Solid elements which are mixed up with fluid are known as leachates whereas fluid responsible for leaching is known as leachant. Leaching process takes place due to the concentration gradient between leachant and leachate. It is a complex mechanism which combines chemical, biological and physical reactions of the soluble elements extracted or absorbed. Elemental transformation occurs from higher concentration to lower concentration until equilibrium stage is not achieved (Conner 1990; Alexander et al. 1994). The leaching of elements depend upon number of parameters such as initial concentration, chemical properties, size and shape of particles, leaching time duration and nature of extraction fluid (Fallman 1997; Bialucha 2000). Leaching process takes place in three phases namely solid to liquid, liquid to solid and within bulk solid or liquid as shown in Figure 4.1. Now-a-days, leaching of leachate from the solid waste into water or soil is most critical environmental issue. The leaching of organic and inorganic element causes water and soil pollution. It is also directly associated to ecosystem and causes various harmful potential hazards (Gitari et al. 2009; Singh et al. 2016).

In India, coal based thermal power plants are leading energy sector which contributes about 70% of total electricity generation. Fly and bottom ash are solid residual products produced after combustion of coal. The particles of coal ash have wide range of size with different shape. Fly and bottom ash consists of Al_2O_3 , SiO_2 , MgO , CaO , Fe_2O_3 , SO_3 , K_2O and Na_2O etc (Baba et al. 2010; Kumar et al. 2017). Presently, coal ash is dumped in dyke area or in landfill. Trace elements present ash have ability to leach into ground and surface water at normal environmental conditions. Fly and bottom ash particles come in contact with water and trace elements associated with ash particles are migrated into water (Popovic et al. 2013; Sharma et al. 2015).

The leaching cycle of coal ash from thermal power plants to food chain is as shown in Figure 4.2. The contamination of water caused by disposed fly and bottom ash is major problem faced all over the world. The discharge of trace elements from coal ash may cause several environmental and health hazards (Mishra, 2004; Hower et al. 2006; Singh et al. 2012). The leaching of element

Cr contaminated in water can cause cancer in stomach and anemia. Hemochromatosis may be caused by consumption of Fe in large amount (Indian Minerals Yearbook, 2012). Though, fly and bottom ash has toxic elements which has ability to leach out while coming in contact with water. So, it is essential to examine the leaching characteristic of traced elements present in ash. In current study, an effort has been made to examine the leachability of traced elements in order to predict the environmental risk caused by dumped ash.

4.1 LEACHING TESTING

Leaching tests were conducted to determine concentration of various elements in aqueous phase from solid particles while come in direct contact with each other. Standard leaching testing procedure like ASTM-D3987 (American Society of Testing and Materials), EP-3050B (Extraction Procedures) and TCLP-1311 (Toxicity Characteristic Leaching Procedure) were used to evaluate leaching characteristics of solid waste. The procedure of ASTM-D3987, EP-3050B and TCLP-1311 are discussed in details as below:

4.1.1 American society for testing and material (ASTM D-3987)

ASTM D-3987 testing procedure is widely used to analyze the leaching of toxic trace elements from waste. The extract can be used to predict the leachability of trace constituents under specific laboratory test condition. In ASTM method, distilled water is used for extraction of leachate. This method is useful to determine the leaching potential of a material being exposed to normal precipitation.

The extraction procedure of ASTM method is shown in Figure 4.3. In this method, initially dry fly and bottom ash samples were taken for preparation of slurry with distilled water. Afterwards, slurry sample was agitated in lubricating type temperature controlled Remi orbital shaker for 18 hrs time duration with speed 100 rpm at temperature of 25 °C. After the shaking operation, extraction solution was extracted with the help of filter paper membrane of size 0.45 µm. Before the analysis of trace elements present in sample, the extracted solution was stored in a refrigerator. The concentration of trace elements present in sample was examined by using atomic absorption spectrophotometer. Before the analysis of trace elements, extracted solution was kept in a refrigerator. The concentration of trace elements present in ash samples were measured by using AAS (Atomic Absorption Spectrophotometer) by using APHA-1995 methods.

4.1.2 Extraction procedure (EP-3050B)

The extraction procedure (EP) is developed to discretize the potential hazards caused by solid waste residual of organic and inorganic constituents labeled in the US Federal Register (1980). The EP is the analytical technique used to measure the concentration of leachate present in solid waste residual slurry, waste water and sludge.

The concentration of trace elements higher than specific value is known as EP toxic. EP test is quite effective to investigate trace elements such as Al, Br, Cr, Cd, Ca, Cu, Mg, Mn, Co, V, Fe, Ni, K, Th, Pb, Zn and As elements. The extracted solutions from slurry are not interchangeable and used only for measuring the concentration of trace elements. In this procedure, a very strong acid extraction solution is used to absorb the wide range of trace elements which are associated with solid samples. Extraction procedure (EP) involves mixing of a fixed amount of solid into water and agitated it properly. The details of extraction procedure (EP) is shown in Figure 4.4.

Initially, the collected samples were dried in free air and then passed through standard sieve to separate the ash particles higher than 200 μm . After the separation of finer particles, ash particles were fully dried in oven at 105 $^{\circ}\text{C}$. Extraction liquid was ready by diluting 5.7ml glacial acetic acid with distilled water to a volume of 1 liter. Distilled water was taken and maintained pH of solution to 5.0 ± 0.2 with addition of acetic acid to about 1 liter in volume. Solution was properly agitated in temperature controlled water bath of Remi orbital shaking lubricator shaker. The agitation process was carried out for 24 hours by taking fixed amount of liquid-to solid (L/S) ratio of slurry suspension. After the completion of shaking process, solid-liquid mixture was kept stationary for 10 minutes and extracted fluid was passing through fine grain filter paper membrane of size 0.45 μm . The concentration of trace elements present in ash samples were measured by using AAS.

4.1.3 Toxicity characteristic leaching procedure (TCLP -1311)

Initially, TCLP procedure was used to classify the hazardous solid waste materials caused by leaching of toxic elements. TCLP leaching method is efficiently used to measure leachate concentration of trace elements form all types of organic and inorganic waste solids materials. It is assumed that solid waste is degradable and release acidic liquid when comes in contact with liquid.

This is the reason that acetic acid is used for the preparation of extraction solution for TCLP leaching method. In this method, investigation is carried out with various liquid to solid ratio (L/S). Extraction procedure of TCLP leaching test is shown in Figure 4.5. Before the leaching investigation, ash sample was crushed to pass through a 200 μm sieve. The moisture present in collected samples were removed by drying it in oven. The pH of extraction liquid was maintained as 2.88 ± 0.5 . The mixture shaking operation was carried out at constant speed for time period of 18 hours. Afterwards, solid-liquid mixture was kept stationary for 10 minutes and extraction solution was filtered by passing through fine grain filter paper membrane of size 0.45 μm . The extent of trace elements present in ash samples were AAS.

4.2 Comparison of different leaching test procedure

Samples of FA-I and BA-I were taken for present investigation. Leaching experiments were performed to compare the results obtained from different leaching test procedure of ASTM D-3987, EP and TCLP method. Leaching experiments were carried at different liquid-to-solid ratio of 20:1, 40:1 and 60:1 respectively. The trace elements like manganese (Mn), magnesium (Mg), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), iron (Fe), zinc (Zn), cobalt (Co) and molybdenum (Mo) were determined by ASTM method, extraction procedure (EP) and TCLP method. The leaching order of fly ash sample was found as $\text{Mn} > \text{Mg} > \text{Cr} > \text{Cu} > \text{Zn} > \text{Ni} > \text{Co} > \text{Pb} > \text{Fe} > \text{Mo}$ with all the leaching test method namely, ASTM D-3987, EP and TCLP method. The variation of leachate concentration of fly ash with ASTM D-3987 method for liquid-to-solid ratio of 20:1, 40:1 and 60:1 is shown in Figure 4.6. From the Figure 4.6, it is observed that leachate concentration of fly ash increased with increase in L/S (liquid-to-solid) ratio. The concentration of leachate elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo increases from 152-166, 103-116, 85-97, 48-56, 51-57, 25-30, 12-14, 14-16, 4.5-5.5 and 3-3.5 mg/kg with increase L/S ratio from 20:1 to 40:1 while leachate elements increases from 166-171, 116-122, 97-102, 56-60, 57-61, 30-33, 14-14.5, 16-16.5, 5.5-6 and 3.5-4 mg/kg respectively as L/S ratio change from 40:1 to 60:1.

The leachate concentration of fly ash with extraction procedure (EP) method for different liquid to solid ratio is represented in Figure 4.7. From the Figure 4.7, it seems that the leachate elements extracted from the fly ash was found in same order as ASTM D-3987 at all liquid to solid ratio. The variation in leachate concentration of fly ash for elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo was found as 169-174, 119-125, 99-106, 56-65, 58-67, 31-36, 14-17, 15.5-17, 6-8

and 4.5-6 mg/kg respectively as L/S ratio varied from 20:1 to 40:1 whereas 174-179, 125-128, 106-112, 65-72, 67-73, 36-39, 17-18, 17-18, 8-9 and 6-7 mg/kg respectively as solid to liquid ratio was increase from 40:1 to 60:1.

The leachate concentration of fly ash with toxicity characteristic leaching procedure (TCLP) for different liquid to solid ratio is shown in Figure 4.8. The leachate concentration of elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo was increased from 173-188, 122-138, 104-117, 60-73, 65-75, 35-39, 15-17, 17-19, 8-10 and 5-6 mg/kg respectively with increase in liquid-to-solid ratio (L/S) from 20:1 to 40:1 respectively. Similarly as the liquid to solid ratio was increased from 40:1 to 60:1, the leachate concentration of trace elements increases from 188-196, 138-146, 117-124, 73-78, 75-80, 39-44, 17-19, 19-22, 10-12 and 6-8 mg/kg respectively.

Experimental data indicate that the leachate concentration of traced elements from ash are highly influenced by nature of extraction liquid. This may be because solubility of elements increases as pH was decrease (Popovic et al. 2000; Baba et al. 2010). The leachate concentration of traced elements was found maximum by TCLP method whereas minimum for ASTM method. The experimental results found to be good aggregate with the results reported by researchers (Gentzis and Goodarzi 1999; Baba et al. 2010; Popovic et al. 2011; Kumar et al. 2017).

Leaching testing procedures ASTM, EP and TCLP were followed to analyze the leachate concentration of bottom ash sample BA-I at different solid to liquid ratio. All ten traced elements present in sample were analysis by leaching testing method i.e ASTM-3987, EP-3050B and TCLP-1311 method. The variation of leachate concentration of bottom ash with ASTM D-3987 method for L/S (liquid-to-solid ratio) of 20:1, 40:1 and 60:1 is shown in Figure 4.9. . Leaching order of trace elements was also found as $Mg > Mn > Zn > Cr > Cu > Ni > Fe > Pb > Co > Mo$ for all liquid to solid ratio. The leachate concentration of elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo was increases from 46-48, 60-62, 29-33, 31-35, 13-16, 9-12, 8-10, 2-2.5, 6-7 and 1-1.2 mg/kg with increases in liquid-to-solid (L/S) ratio 20:1 to 40:1 whereas 48-53, 62-66, 33-38, 35-38, 16-20, 12-13, 10-12, 2.5-3.5, 7-7.8 and 1.2-1.5 mg/kg respectively with increase of liquid-to-solid (L/S) ratio from 40:1 to 60:1.

The leachate concentration of bottom ash with extraction procedure (EP) for different liquid to solid ratio is plotted in Figure 4.10. From Figure 4.10, it was noticed that as the liquid to solid ratio increases from 20:1 to 40:1, the leachate concentration of trace elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo increases from 59-65, 75-80, 42-45, 43-44, 20-26, 21-26, 10-14, 2.5-3,

11-13 and 1.3-1.5 mg/kg. Similarly these trace elements were increased from 65-71, 80-86, 45-50, 44-46, 26-30, 26-31, 14-15.5, 3-5, 13-14 and 1.5-2 mg/kg respectively with increase in liquid to solid ratio from 40:1 to 60:1.

The variation in leachate concentration of trace elements with solid to liquid ratio by using TCLP method is shown in Figure 4.11. The concentration of leachate elements namely Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo was increased from 62-68, 80-85, 45-48, 46-47, 22-28, 23-29, 11-15, 3-3.5, 11-14 and 1.5-2 mg/kg with increase in liquid-to-solid (L/S) ratio 20:1 to 40:1 while increase from 68-75, 85-92, 48-54, 47-50, 28-33, 29-35, 15-17, 3.5-6, 14-15 and 2-2.5 mg/kg respectively with increases in liquid to solid ratio 40:1 to 60:1.

The leaching results reveals that concentration of trace elements was found higher for TCLP method as compared to EP and ASTM procedure. These results show that pH of extraction medium was a significant factor influencing the leachate concentration from coal samples. As the pH value of extraction solution increased the leaching rate of trace elements present in ash was decreased. This is due to reduction in strength of attack on ash particles (Baba et al. 2004; Popovic et al.2009). It was noticed that the leachate concentration of trace elements increased with increase in L/S ratio. It is also found that the leached concentration of the trace elements in the fly ash is more as compared the bottom ash at same liquid to solid ratio (Ahn et al. 2006; Baba et al. 2010; Kumar, 2010; Kumar et al. 2017; Singh et al. 2017).

4.2.1 Influence of different variables on leaching characteristics of fly and bottom ash

All fly and bottom ash sample were used for investigate effect of various leaching parameter on leachability of traced elements. The concentration of ten major elements associated with fly and bottom ash were determined by using TCLP-1311method. Leaching experiments were performed with different leaching variable parameters namely as liquid to solid ratio, time duration and temperature for all fly and bottom ash samples.

4.2.2 Effect of liquid to solid ratio

The leachate concentration of traced element was determined by L/S ratio was taken as 20:1, 40:1 and 60:1. The experimental results of trace elements existing in fly ash samples FA-I, FA-II, FA-III and FA-IV are shown in Figure 4.12 and listed in Table 4.2. The leaching order of fly ash sample FA-I was found as $Mn > Mg > Cr > Cu > Zn > Ni > Co > Pb > Fe > Mo$ at all liquid-to-

solid (L/S) ratio. In the fly ash sample FA-II, FA-III and FA-IV, the order of the leaching was found as $Mn > Mg > Cr > Cu > Zn > Ni > Pb > Co > Fe > Mo$ at all liquid to solid ratio. The leaching results of all bottom ash samples BA-I, BA-II, BA-III and B-IV at different liquid to solid ratio are presented in Figure 4.13 and listed in Table 4.3. From the Figure 4.13, it was observed that the leachate concentration of the trace element increases with increase in liquid-to-solid ratio for all samples of bottom ash.

It was observed from leaching results that the leaching order of fly ash sample FA-I was found as $Mn > Mg > Cr > Cu > Zn > Ni > Co > Pb > Fe > Mo$ whereas the leaching order of fly ash sample FA-II, FA-III and FA-IV was found as $Mn > Mg > Cr > Cu > Zn > Ni > Pb > Co > Fe > Mo$ at all liquid to solid ratios. The element Mn shows highest leachability whereas Mo shows the lowest leachability for all fly ash samples. The experimental results found to be good aggregate with the results reported by researchers (Datta et al. 2008; Baba et al. 2010; Singh et al. 2012). The leaching order bottom ash sample BA-I was found as $Mg > Mn > Cr > Zn > Ni > Cu > Pb > Fe > Co > Mo$ whereas $Mg > Mn > Cr > Zn > Cu > Ni > Pb > Fe > Co > Mo$, $Mg > Mn > Cr > Zn > Cu > Ni > Pb > Fe > Co > Mo$ and $Mn > Mg > Zn > Cu > Cr > Ni > Pb > Fe > Co > Mo$ for bottom ash sample BA-II, BA-III and BA-IV respectively for all liquid to solid ratios. Trace element Mg shows maximum leachability for samples BA-I, BA-II and BA-III whereas Mn in sample BA-IV. Element Mo show minimum leaching for all bottom ash samples. It is also found that trace elements Cr, Cu, Fe, Mg, Mn, Ni, Pb and Zn were shows higher leachability while Co and Mo are the least abundant elements. The experimental results found to be good aggregate with the results reported by researchers (Mathur et al. 2008; Singh et al. 2016; Kumar et al. 2017; Singh et al. 2017).

4.2.3 Effect of time duration

Extensive experimentation was carried out to investigate the influence of time duration on leaching behaviour of fly and bottom ash for L/S (liquid-to-solid) ratio of 20:1. During the experimentation time duration was changes from 5-20 days with set size 5 days. The variation in trace element concentration of fly ash with time duration is shown in Figure 4.14. As the time duration was increased from 5 to 20 days, the leachate concentration of trace elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo was increased with increase in leaching time duration which is tabulated in Table 4.4. The influence of time duration on leachate concentration of bottom ash samples is

represented in Figure 4.15 and listed in Table 4.5. In sample BA-I, the leachate concentration of trace elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo was increased from 48-54, 61-65, 31-32, 32-34, 14-17, 10-11, 9-10, 2-2, 6-7 and 1.2-1.6 mg/kg with increase in time duration from 5-20 days. It was noticed from experimental data that trace elements Cr, Co and Mo were leaching at higher rate as compared to other trace elements with time duration of 5-20 days. It was also noticed that fresh fly and bottom ash samples have higher potential for environmental hazards. Similar observation is also made by researchers (Lin and Yang, 2002; Sushil and Batra, 2006; Dutta et al. 2009) on coal ash collected from various locations.

4.2.4 Effect of temperature

The leaching investigation was carried out to analysis the impact of temperature on leachability of traced elements at 20:1 L/S ratio. During the investigation temperature was varied as 25, 30, 35, 40 °C for both fly and bottom ash samples. The variation in leachate concentration with temperature for fly ash sample FA-I, FA-II, FA-III and FA-IV is represented in Figure 4.16 and tabulated in Table 4.6. As temperature was increased the leachate concentration of trace elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo was increased from 173-191, 122-136, 104-118, 60-71, 65-74, 35-40, 15-19, 17-20, 8-12 and 5-8 mg/kg respectively for fly ash sample FA-I. The influence of temperature on leachate concentration of bottom ash samples is represented in Figure 4.17 and tabulated in Table 4.7. In sample BA-I, the leachate concentration of trace elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo was increased from 62-80, 80-94, 45-54, 46-58, 22-32, 23-28, 11-18, 3-6, 11.5-18 and 1.5-3.5 mg/kg with increase in temperature from 25-40 °C. It was noticed from experimental data that leachate concentration of trace elements increases with increases in temperature. It was also found that leaching concentration of trace elements in fly ash was higher than bottom ash. This is due to rate of reaction in acidic medium is more at given temperature.

4.3 Leaching characteristics of fly and bottom ash with additives

Additives are compound of chemicals or minerals which can modify the chemistry of coal ash and increases the pH of slurry suspension. Addition of small amount of additive help to achieve the desired goal of investigation. Researchers (Senapati et al. 2012; Pani et al. 2016; Singh et al. 2016) used various chemical additives with coal ash slurry suspension to investigate their effect on

leaching of trace elements from coal ash. In the present investigation, Sodium bicarbonate was used as additive. Sodium bicarbonate (NaHCO_3) having alkali in nature and have fine powered crystalline of white color. TCLP leaching method was used to investigate the effect of addition of additives on leaching characteristics of fly and bottom ash at liquid to solid ratio of 20:1.

4.3.1 Effect of addition of additive on leaching characteristics of fly ash

The experiments were carried out to analyze leaching behaviour of traced elements with addition of additive in fly ash sample FA-I, FA-II, FA-III and FA-IV with and without addition of additive. NaHCO_3 was selected as an additive. The dosage of additive was ranges from 0.2-0.6% (by weight) at L/S (liquid-to-solid) ratio of 20:1. The effect of addition of additive on leachate concentration of trace elements is represented in Figure 4.18. From the Figure 4.18, it was noticed that concentration of trace elements considerably decreases with addition of additive. The leachate concentration of elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo in fly ash sample FA-I was decreased from 173-162, 122-104, 104-84, 60-54 65-57, 35-32, 15-13, 17-14, 8-7 and 5-4 mg/kg respectively with 0.2% addition of additive while the leachate concentration of trace elements reduced as 162-138, 104-76, 84-71, 54-42, 57-45, 32-26, 13-10, 14-10, 7-5 and 4-3 mg/kg respectively with addition of 0.4% additive. Similarly, the leachate concentration of trace elements was reduced as 138-126, 76-67, 71-63, 42-37, 45-39, 26-22, 10-9, 10-8, 5-4 and 3-2.2 mg/kg with addition of 0.6% additive. Leachate concentration of trace elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo was decreases from 175-166, 103-86, 105-88, 60-55, 65-59, 36-32, 15-13, 20-18, 7-7 and 4-3 mg/kg in fly ash sample FA-II with addition of 0.2% additive while decreases from 166-143, 86-75, 88-76, 55-43, 59-44, 32-24, 13-10, 18-13, 7-5 and 3-1.5 mg/kg respectively with addition of 0.4% additive. As the 0.6% of additive was added, the leachate concentration of trace elements was decreased from 143-132, 75-67, 76-69, 43-37, 44-39, 24-20, 10-8, 13-11, 5-4 and 1.5-0.5 mg/kg respectively. In fly ash sample FA-III, the leachate concentration of trace elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo was reduced from 171-158, 98-85, 82-77, 49-44, 55-49, 26-23, 12-11, 18-16, 7.5-7 and 7-5 mg/kg with addition of 0.2% additive while reduced from 158-136, 85-69, 77-65, 44-37, 49-41, 23-19, 11-8, 16-11, 7-5 and 5-3.5 mg/kg respectively by addition of 0.4% additive. While 0.6% of additive was added, the leachate concentration of trace elements decreased from 136-128, 69-58, 65-61, 37-34, 41-37, 19-17, 8-7, 11-9.5, 5-3 and 3.5-2 mg/kg respectively. Similarly for fly ash sample FA-IV, the leachate concentration of trace

elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo was decreased from 183-169, 109-98, 92-86, 56-52, 55-52, 37-33, 14-13, 16-14, 8-7 and 6-5 mg/kg with 0.2% addition of additive while 169-143, 98-83, 86-72, 52-43, 52-44, 33-26, 13-10, 14-11, 7-5 and 5-4 mg/kg respectively with 0.4% addition of additives. The 0.6% addition of additive reduced the leachate concentration of trace elements from 143-131, 83-75, 72-64, 43-39, 44-41, 26-22, 10-9, 11.5-9, 5-4 and 4-3 mg/kg respectively.

4.3.2 Effect of addition of additive on leaching characteristics of bottom ash

The leaching characteristics of trace elements in bottom ash samples BA-I, BA-II, BA-III and BA-IV were investigated with addition of additive. The variation of leachate concentration of bottom ash with addition of additive is shown in Figure 4.19. From the Figure 4.19, it was observed that concentration of trace elements in bottom ash drastically decreases as same manner of fly ash with addition of additive. The leachate concentration of elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo in bottom ash sample BA-I was decreased from 62-57, 80-74, 45-43, 46-43, 22-19, 23-21, 11-10, 3-2 11.5-11 and 1.5-1.3 mg/kg respectively with 0.2% addition of additive while the leachate concentration of trace elements reduced as 57-46, 74-61, 43-37, 43-35, 19-14, 21-17, 10-8, 2-1.5, 11-9, 1.3-1 mg/kg respectively with 0.4% addition of additive. Similarly, the leachate concentration of trace elements reduced as 46-42, 61-57, 37-33, 35-31, 14-13, 17-13, 8.5-7.5, 1.5-1.3, 9-8 and 1-0.8 mg/kg with 0.6% addition of additive.

The leachate concentration of elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo in bottom ash sample BA-II was decreased from 55-51, 71-63, 50-44, 40-35, 20-17, 19-17, 10-9, 2.5-2, 9-8 and 1.2-1 mg/kg with 0.2% addition of additive whereas reduced from 51.43-43.14 63.33-52.09, 44-36, 35-29, 17-14, 17-15, 9-7, 2-1.8, 8-6 and 1-0.7 mg/kg respectively with 0.4% addition of additive. Similarly as the 0.6% additive was added, the leachate concentration was decreased from 43-40, 52-49, 36-32, 29-27, 14-12, 15-13, 7-6.5, 1.8-1.4, 6-5.5 and 0.7-0.6 mg/kg respectively.

In the bottom ash sample BA-III, the leachate concentration of elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo was decreased from 65-59, 73-66, 41-37, 44-37, 26-24, 17-16, 13-12, 2-1.8, 13-12 and 1.5-1.4 mg/kg respectively with 0.2% addition of additive while decreased from 59-48, 66-52, 37-31, 37-32, 24-18, 16-14, 12-9, 1.8-1.4, 12-9 and 1.4-1.2 mg/kg respectively with 0.4% addition of additive. Similarly as 0.6% additive was added, the leachate concentration was decreased from 48-44, 52-47, 31-28, 32-29, 18-16, 14-13, 9-8, 1.2-0.9, 9-8.5 and 1.2-0.6 mg/kg

respectively. Similarly in bottom ash sample BA-IV, leachate concentration of trace elements Mn, Mg, Cr, Zn, Cu, Ni, Pb, Co, Fe and Mo was reduced from 75-68, 69-62, 36-32, 48-41, 26-23, 18-17, 8-7, 4-3, 7.5-7 and 1.3-1 mg/kg with 0.2% addition of additive whereas leachate concentration was decreased from 68-55, 62-51, 32-25, 41-33, 23-18, 17-14, 7-6, 3-2.5, 7-5.5, and 1-0.7 mg/kg respectively with 0.4% addition of additive. The leachate concentration of trace elements was decreased from 55-47, 51-45, 25-21, 33-29, 18-16, 14-12, 6-5.5, 2.5-1.5, 5.5-4 and 0.7-0.4 mg/kg respectively as 0.6% additive was added.

It is found from the results that addition of NaHCO_3 in very small proportion helps to minimize the leaching potential hazards caused by trace elements present in fly and bottom ash. Addition of NaHCO_3 in water causes hydrolyse and form NaOH . The pH value of slurry suspension is increased with addition of NaHCO_3 . This happens due to formation of additive layer over the surface of solid particles which prevents the leachability of trace elements. Also, the addition of additive enhance the pH of fly and bottom ash slurry suspension which also contribute in decreasing of leaching of trace elements (Senapati et al. 2012; Pani et al. 2016; Singh et al. 2016).

From the analysis of experimental data, it was concluded that leaching concentration of all trace elements in ash samples reduces with increase in percentage of addition of additive from 0.2 to 0.6%. The maximum reduction in leaching concentration rate of all trace elements in both fly and bottom ash samples was found with 0.4% addition of additive whereas marginal reduction was observed with 0.2 and 0.6%.

4.4 Leaching characteristics of water sample nearby thermal power plants

The leaching behaviour of trace elements in ash pond water and water nearby thermal power station were collected for prediction of environment hazards caused by disposal of ash. The water sample were taken from Guru Nanak Dev thermal power plant, Bhatinda, Punjab, Guru Gobind Singh Super Thermal Power Plant, Ropar, Punjab, Guru Hargovind thermal power plant, Lehra Mohabbat, Punjab and Deenbandhu Chhotu Ram thermal power plant, Yamuna nagar, Haryana which are labeled as S-I, S-II, S-III and S-IV respectively. The leachate concentration of trace elements in pond ash water and water nearby thermal power plants is represented in Figure 4.20-4.21. From leaching results it was found that concentration of trace elements Cu, Mg, Mo, Mn and

Zn show under the prescribed limits of WHO for water while other elements were across limits. The various health problem caused by traced element is tabulated in Table 4.1.

4.5 Reflection

Leaching characteristics of fly and bottom ash collected from different thermal power plants were investigated by following ASTM-3987, EP-3050B and TCLP-1311 standard procedure. The following conclusions can be drawn on the basis of leaching experimentation.

- The leachate concentration of trace elements in both fly and bottom ash was found higher with TCLP method as compared to ASTM and EP method. So the pH of the extraction solution is most influencing factor for leaching of traced element.
- The addition of additive are most effective in control the leaching of traced element namely as Cr, Ni, Mo, Co and Fe as compared to other elements associated with ash particle. The reduction in leachate concentration of Cr, Ni, Mo, Co and Fe was found as about 39, 37, 60, 52 and 50% for fly ash.
- The maximum reduction in leaching concentration rate of all trace elements in both fly and bottom ash samples was found with 0.4% addition of additive whereas marginal reduction was observed with 0.2 and 0.6%.
- The concentration of heavy metal elements Mg, Mo, Mn, Zn and Cu is within the permissible limits of Indian standard while elements of concentrations of elements Cr, Pb, Ni, Co and Fe have crossed the standard limits. These may cause many harmful effects on the human health.

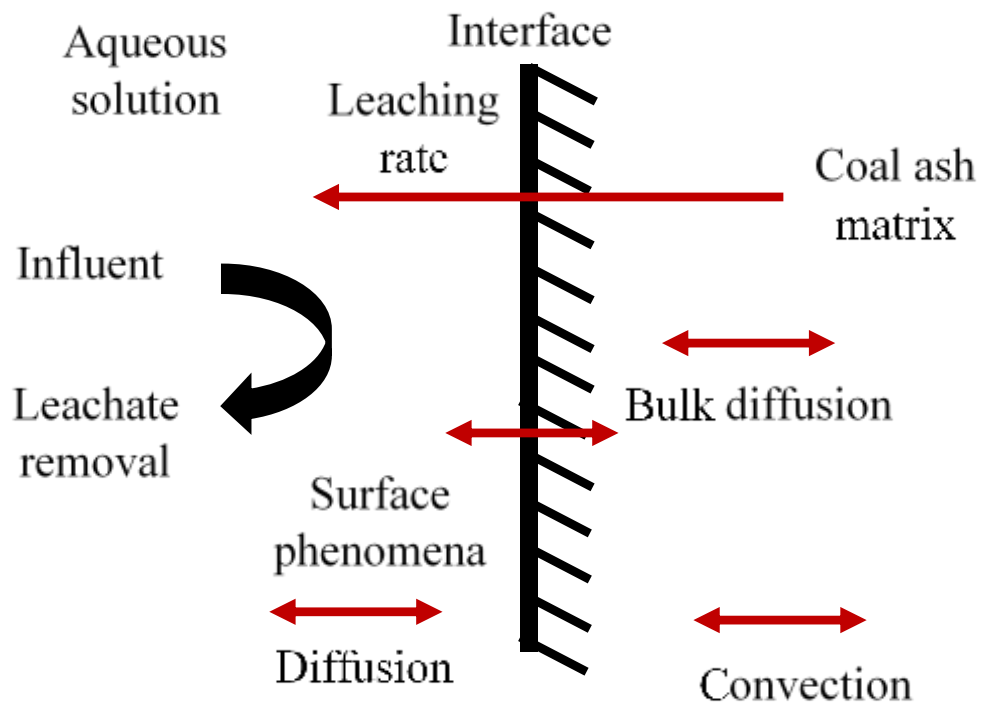


Figure 4.1: Schematic of conceptual leaching in coal ash (modified from Conner, 1990)

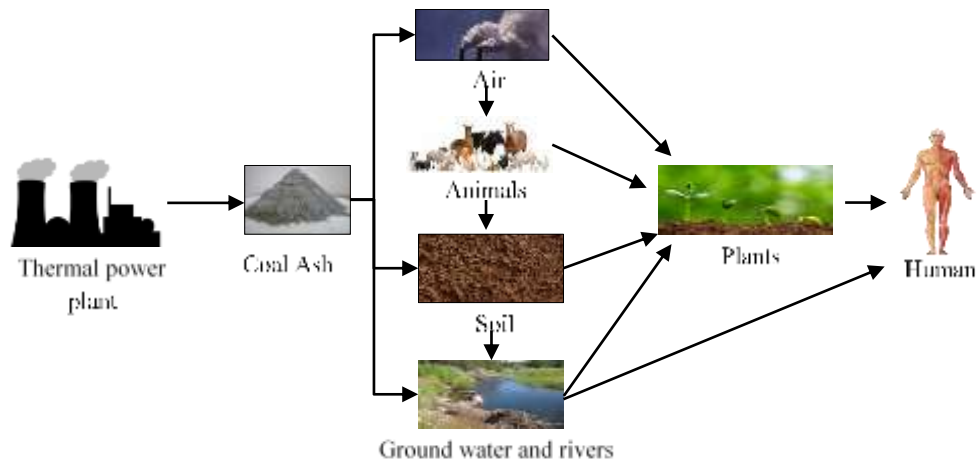


Figure 4.2: Leaching cycle of trace element from coal ash to human body

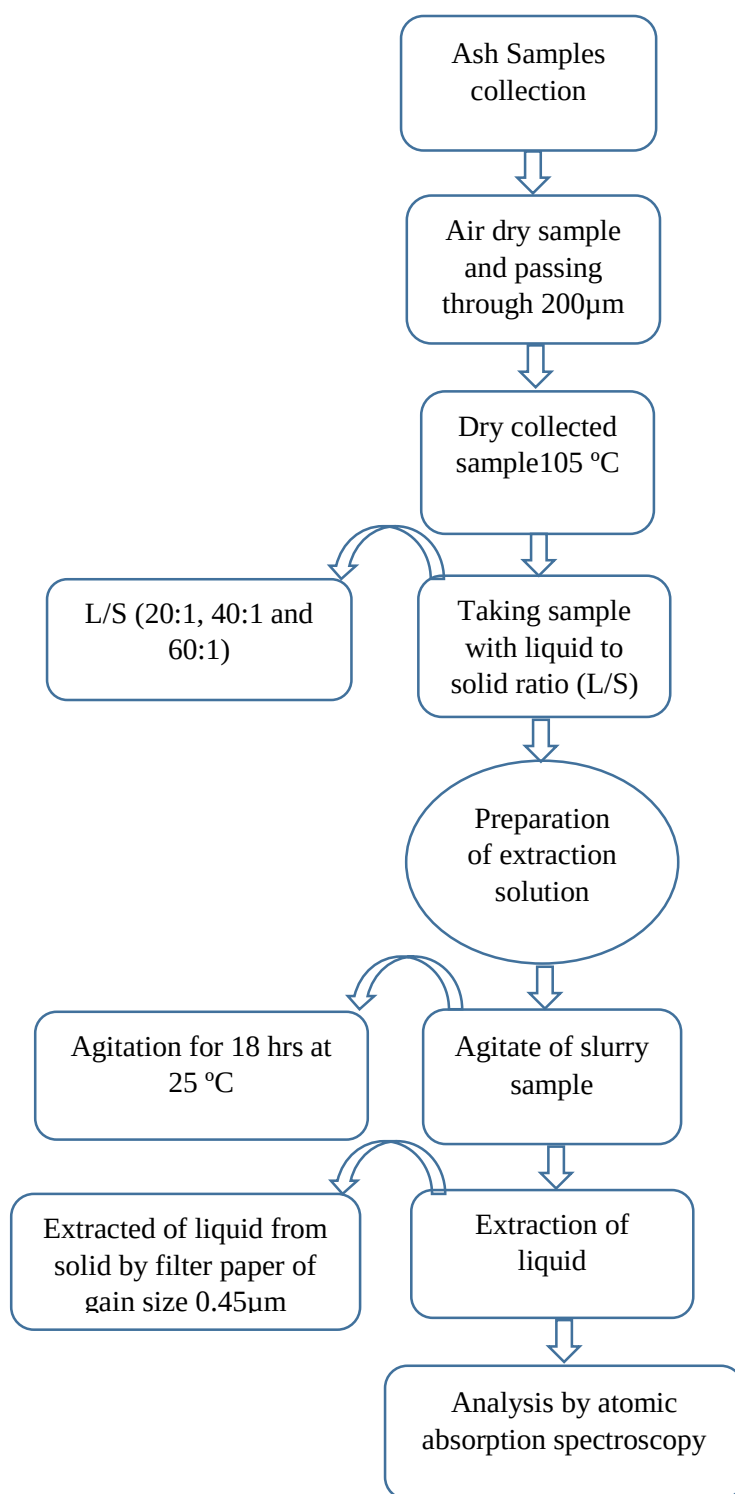


Figure 4.3 Extraction procedure of ASTM-3987 method

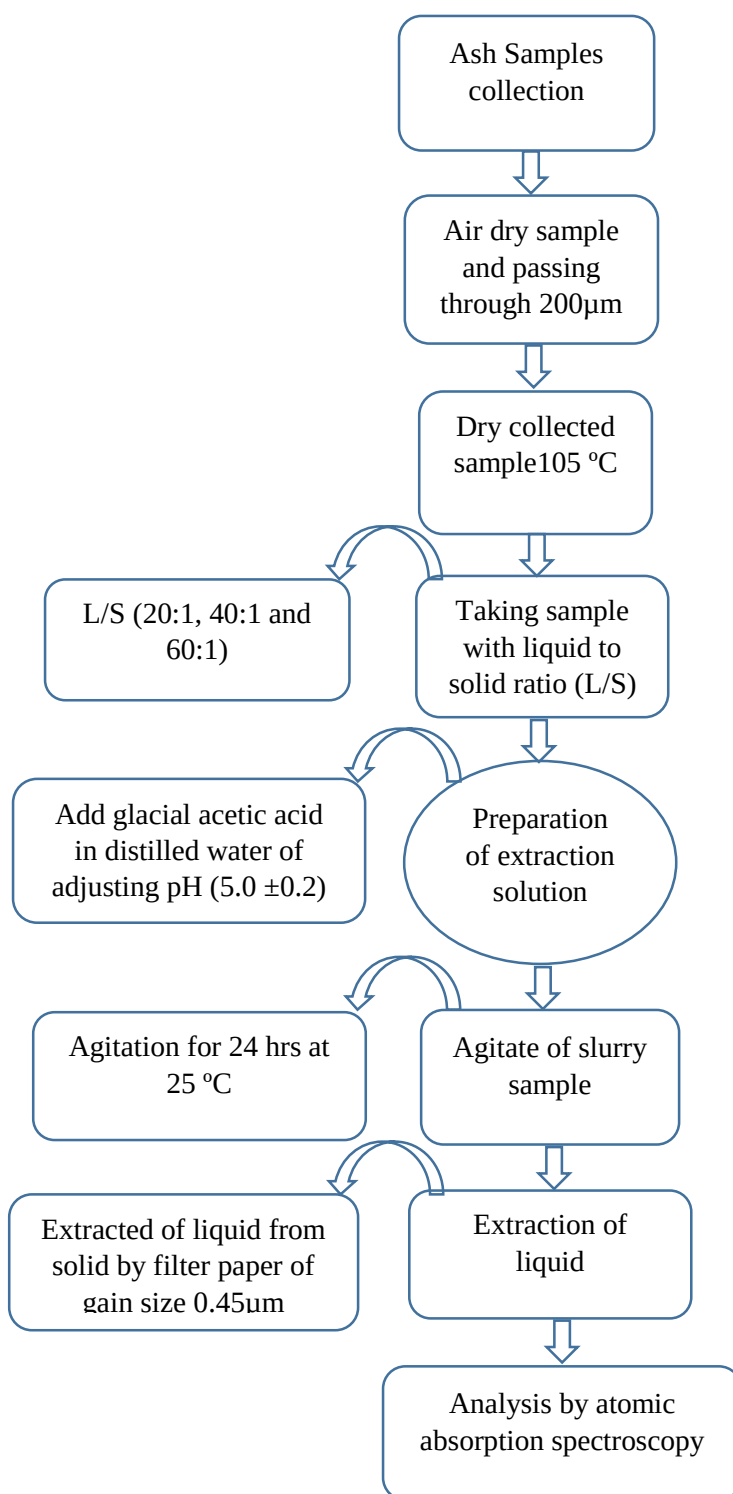


Figure 4.4: Extraction procedure of EP-3050B method

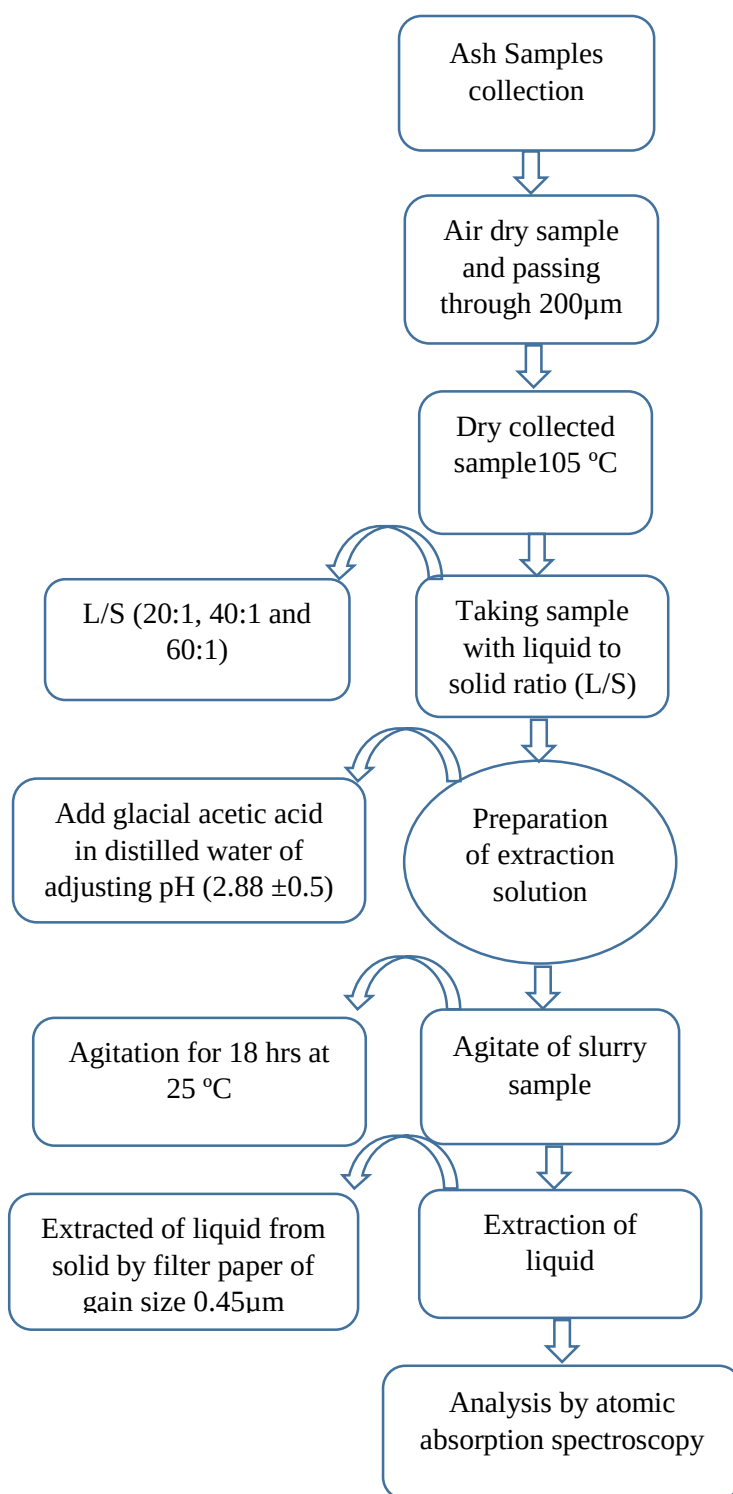


Figure 4.5: Extraction procedure of TCLP-1311 method

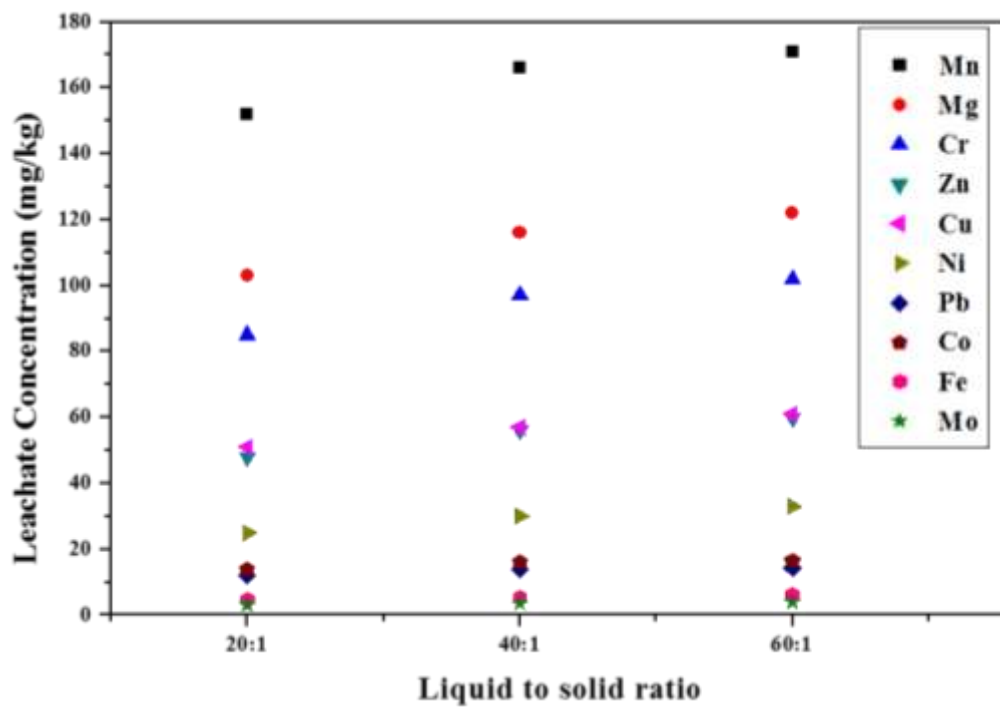


Figure 4.6: Variation in leachate concentration of trace elements with different liquid to solid ratio of fly ash using ASTM method (fly ash sample FA-I)

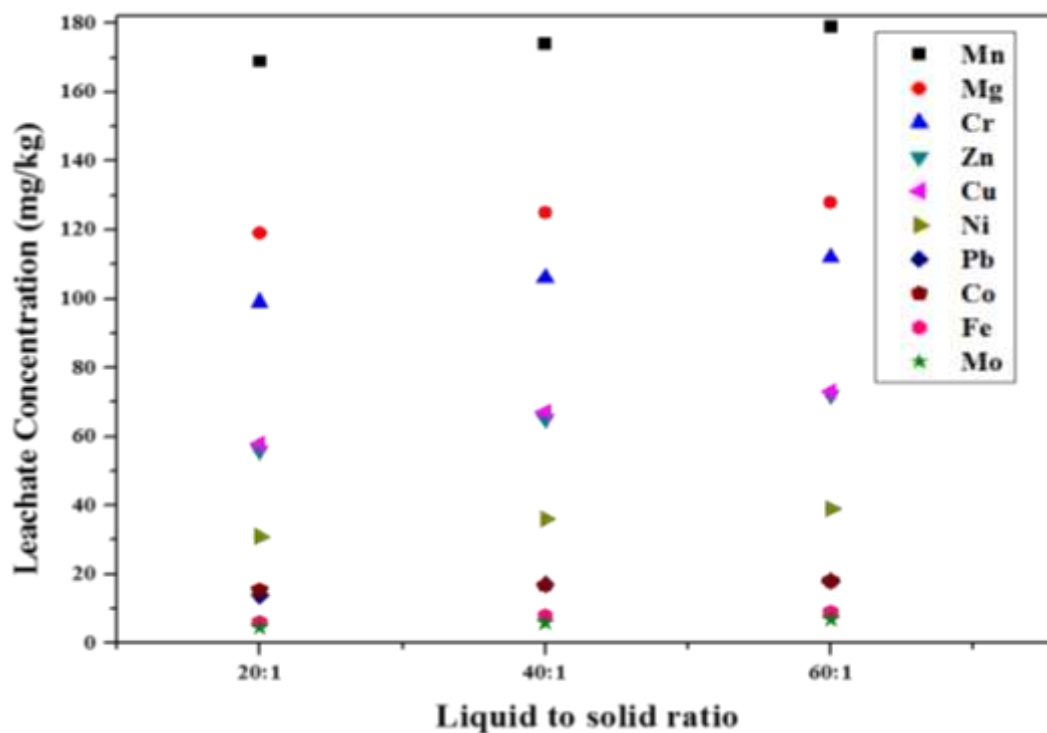


Figure 4.7: Variation in leachate concentration of trace elements with different liquid to solid ratio of fly ash using EP method (fly ash sample FA-I)

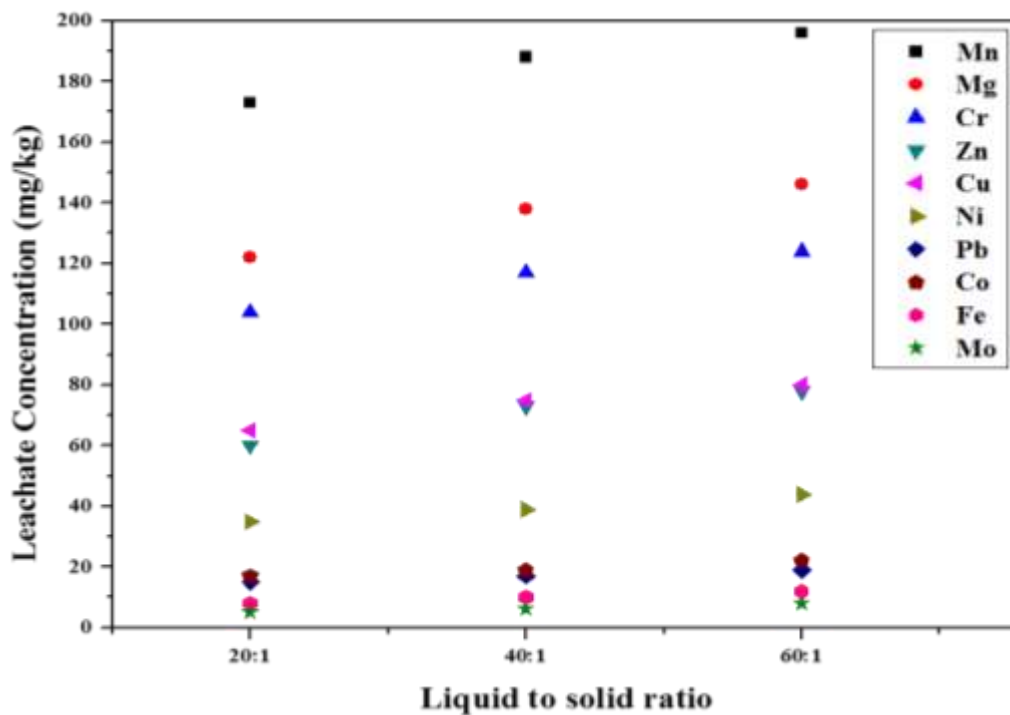


Figure 4.8: Variation in leachate concentration of trace elements with different liquid to solid ratio of fly ash using TCLP method (fly ash sample FA-I)

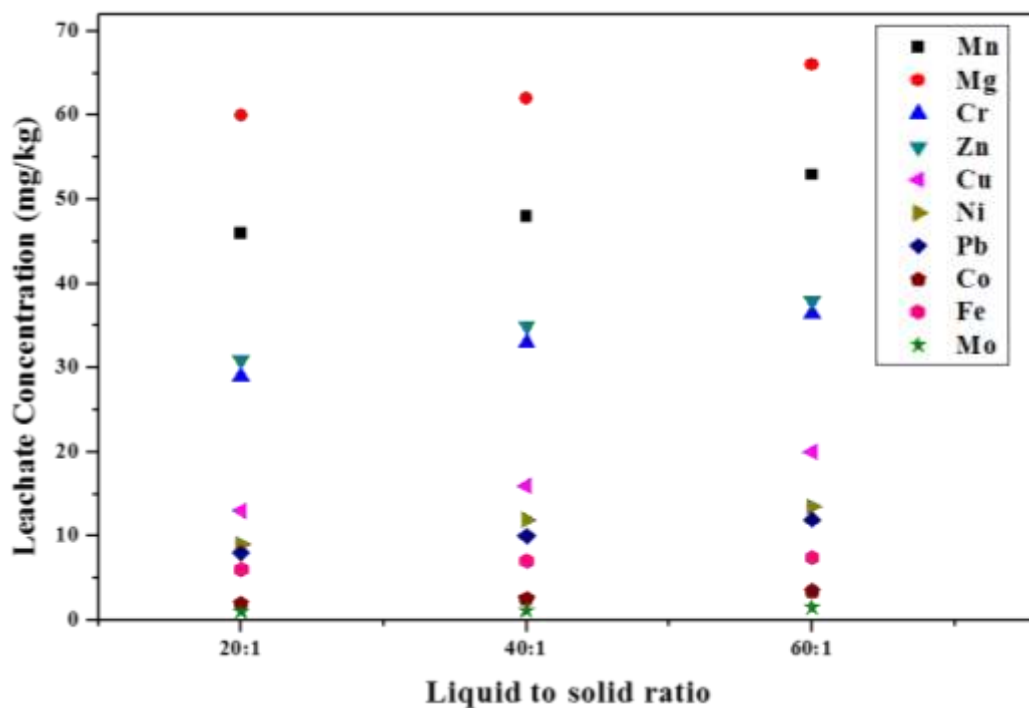


Figure 4.9: Variation in leachate concentration of trace elements with different liquid to solid ratio of bottom ash using ASTM method (bottom ash sample BA-I)

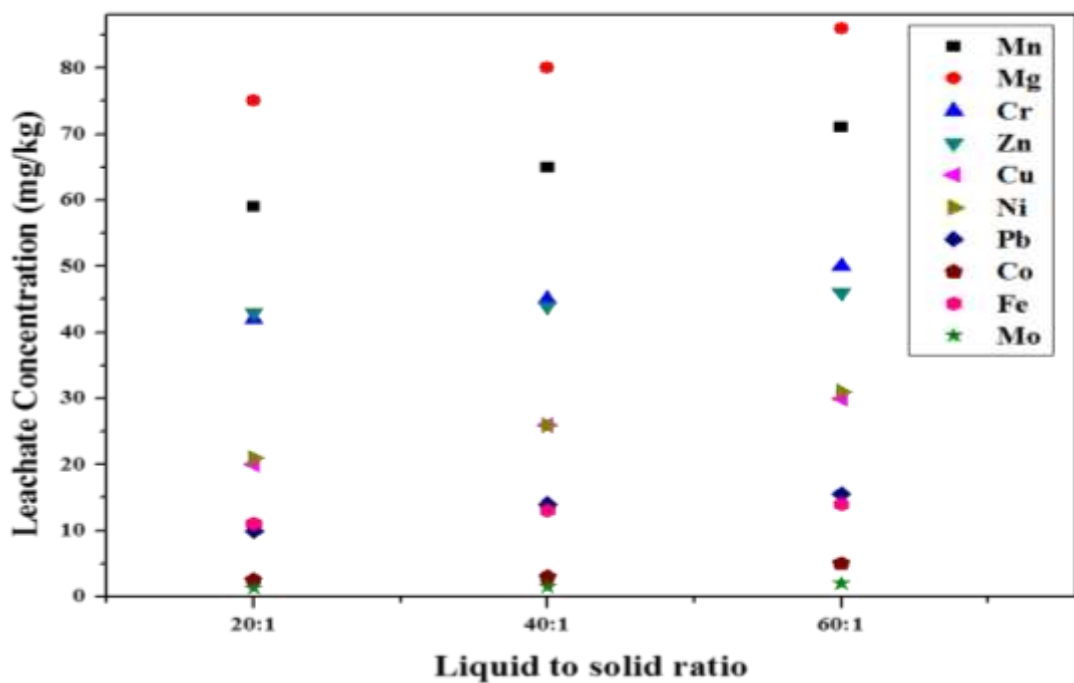


Figure 4.10: Variation in leachate concentration of trace elements with different liquid to solid ratio of bottom ash using EP method (bottom ash sample BA-I)

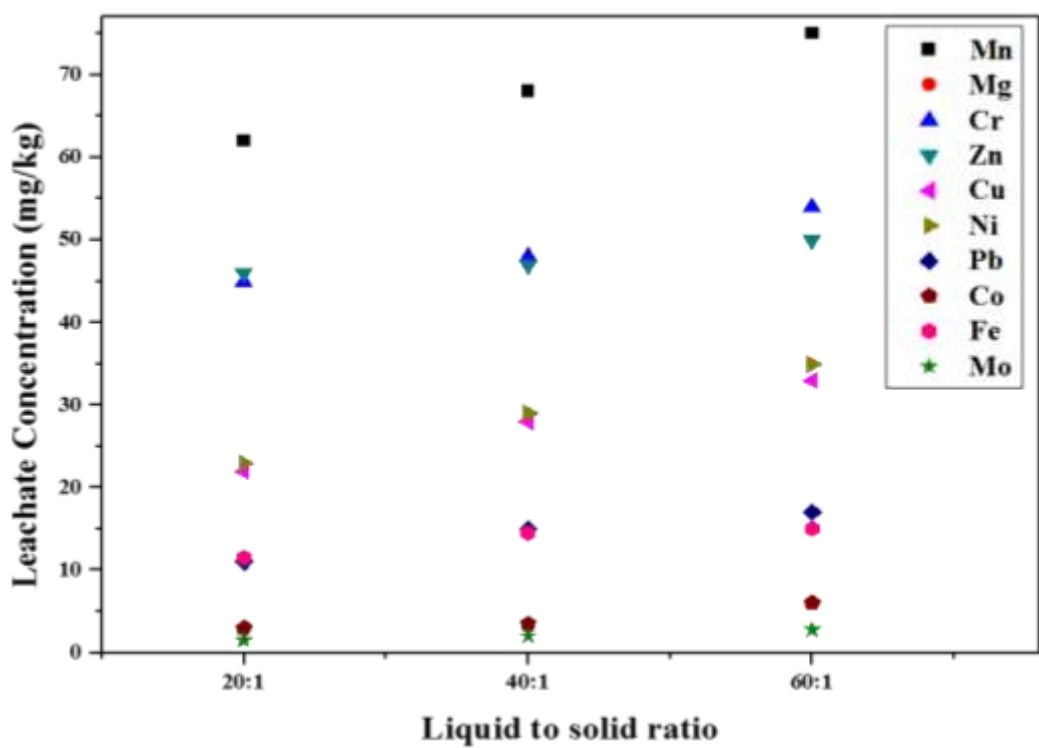


Figure 4.11: Variation in leachate concentration of trace elements with different liquid to solid ratio of bottom ash using TCLP method (bottom ash sample BA-I)

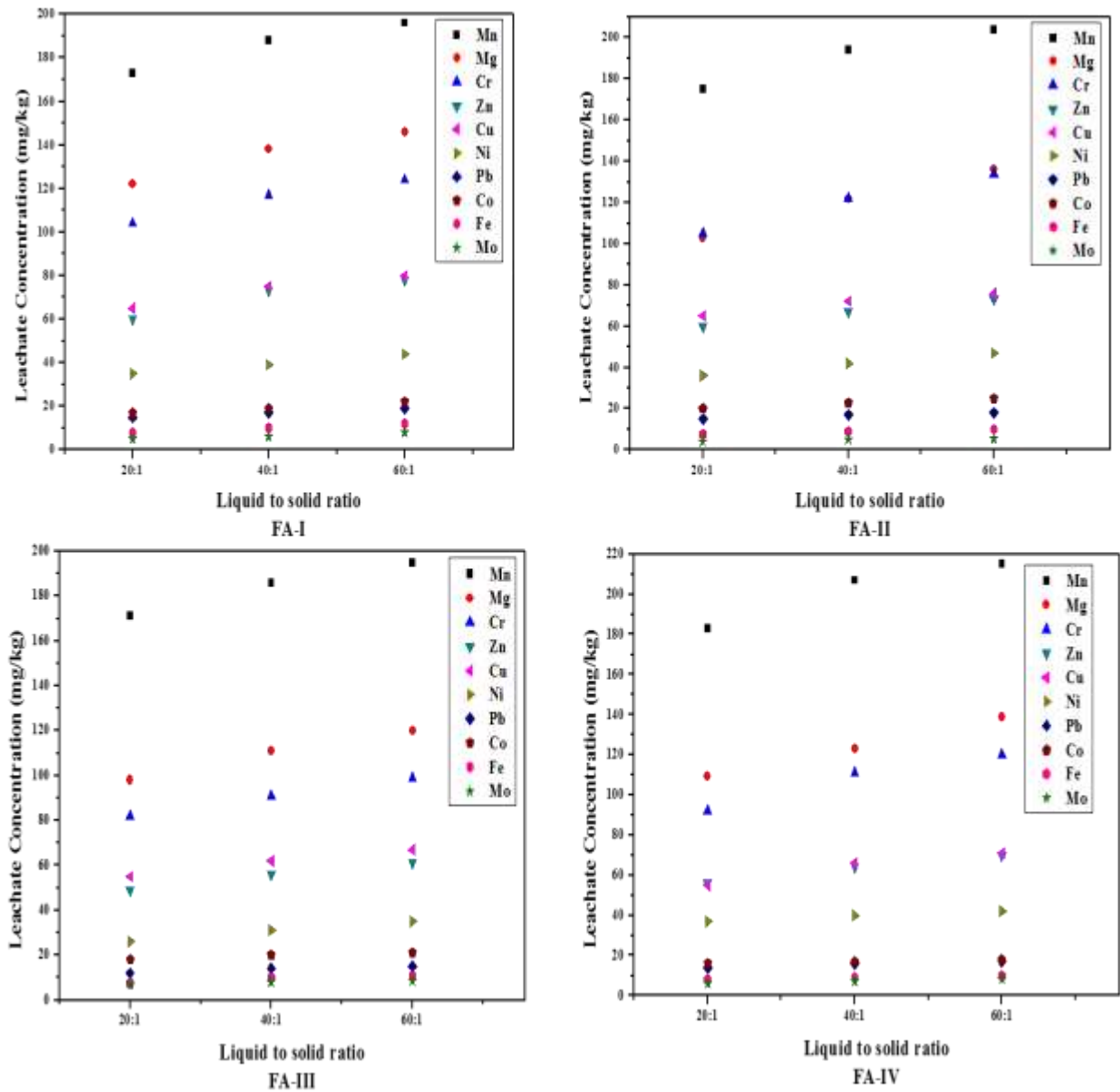


Figure 4.12: Variation of leachate concentration of trace elements with liquid to solid ratio in fly ash

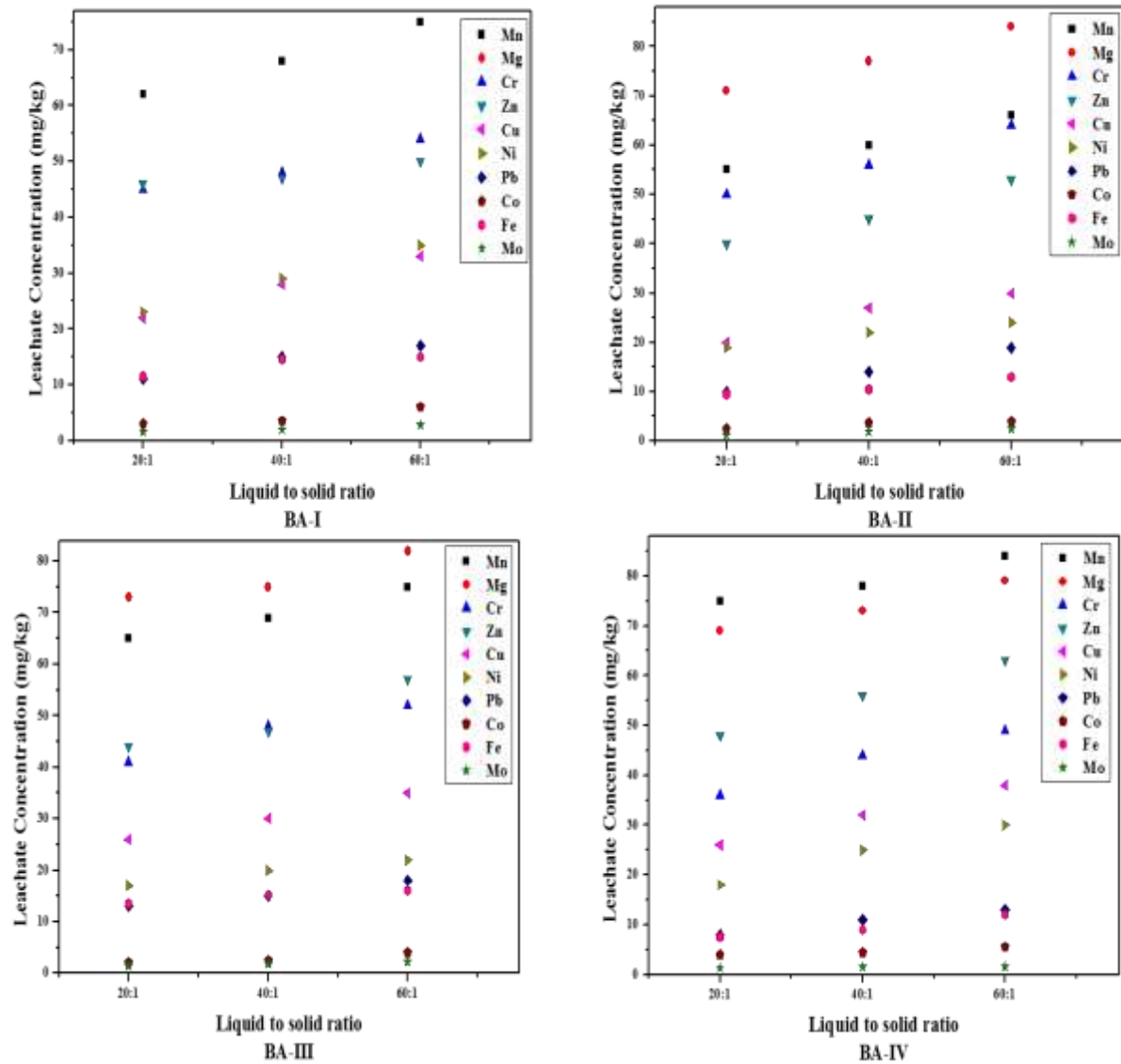


Figure 4.13: Variation of leachate concentration of trace elements with liquid to solid ratio in bottom ash

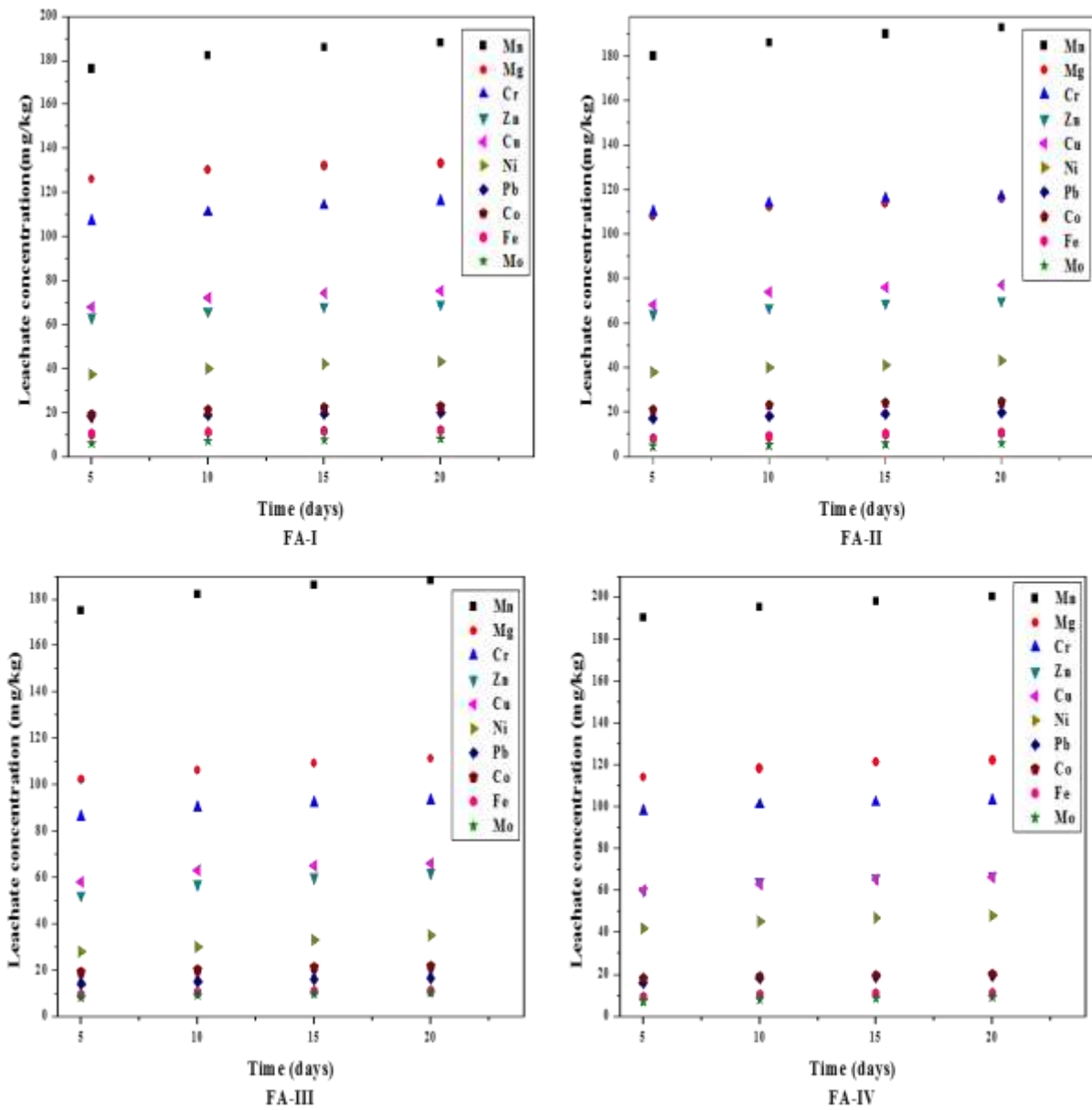


Figure 4.14: Influence of time duration on leachate concentration of trace elements present in fly ash

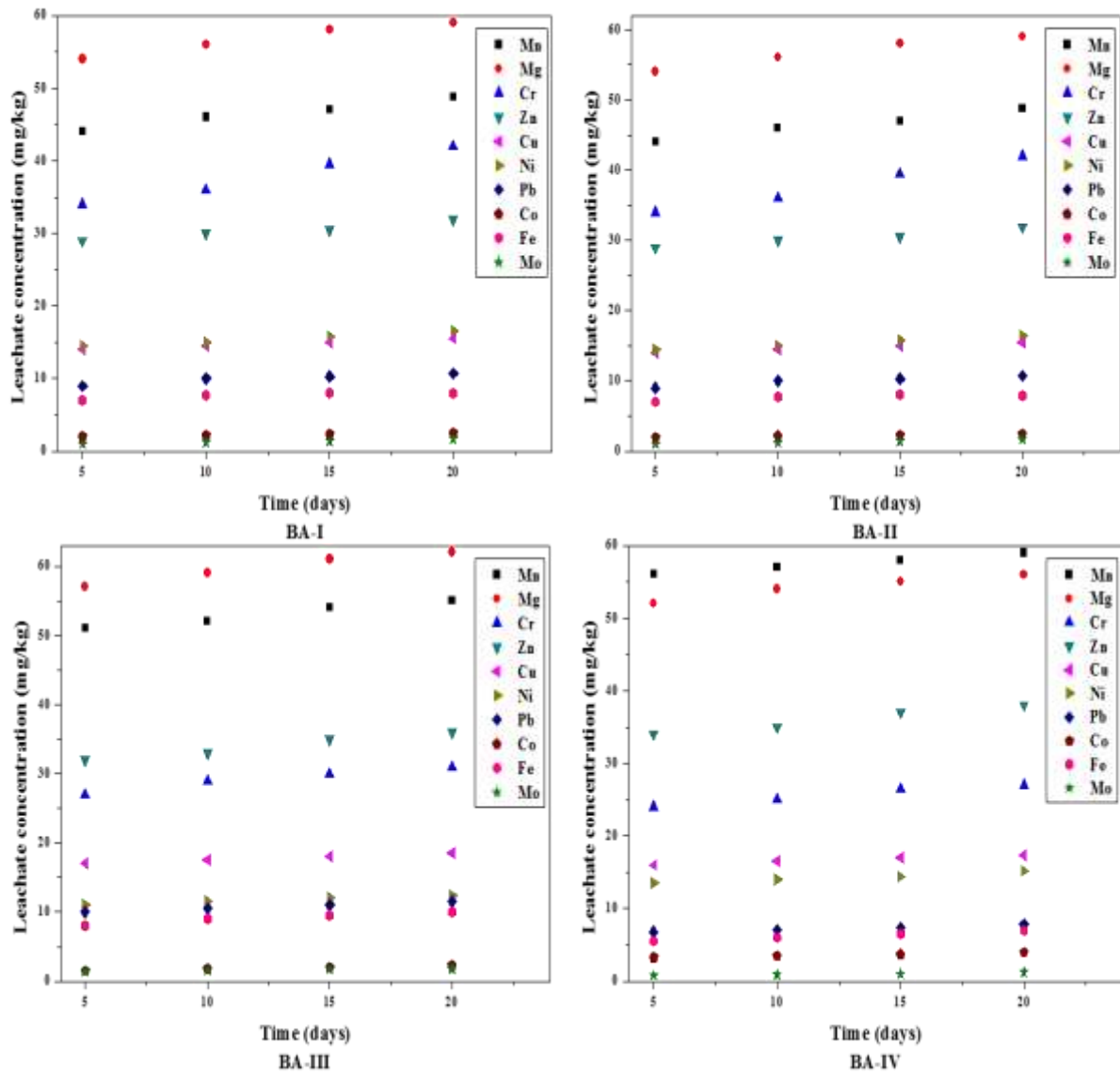


Figure 4.15: Influence of time duration on leachate concentration of trace elements present in bottom ash

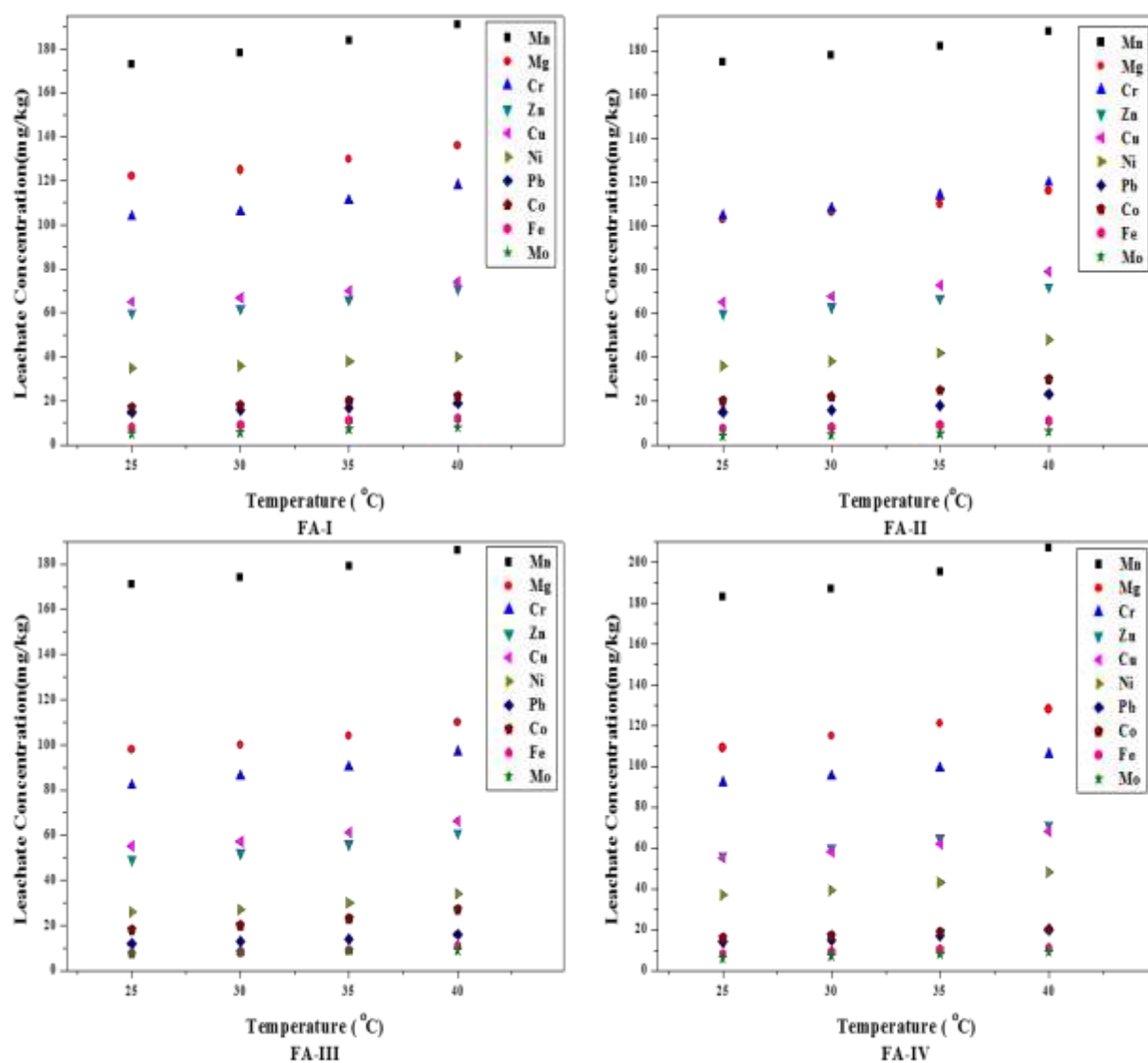


Figure 4.16: Influence of temperature on leachate concentration of trace elements in fly ash

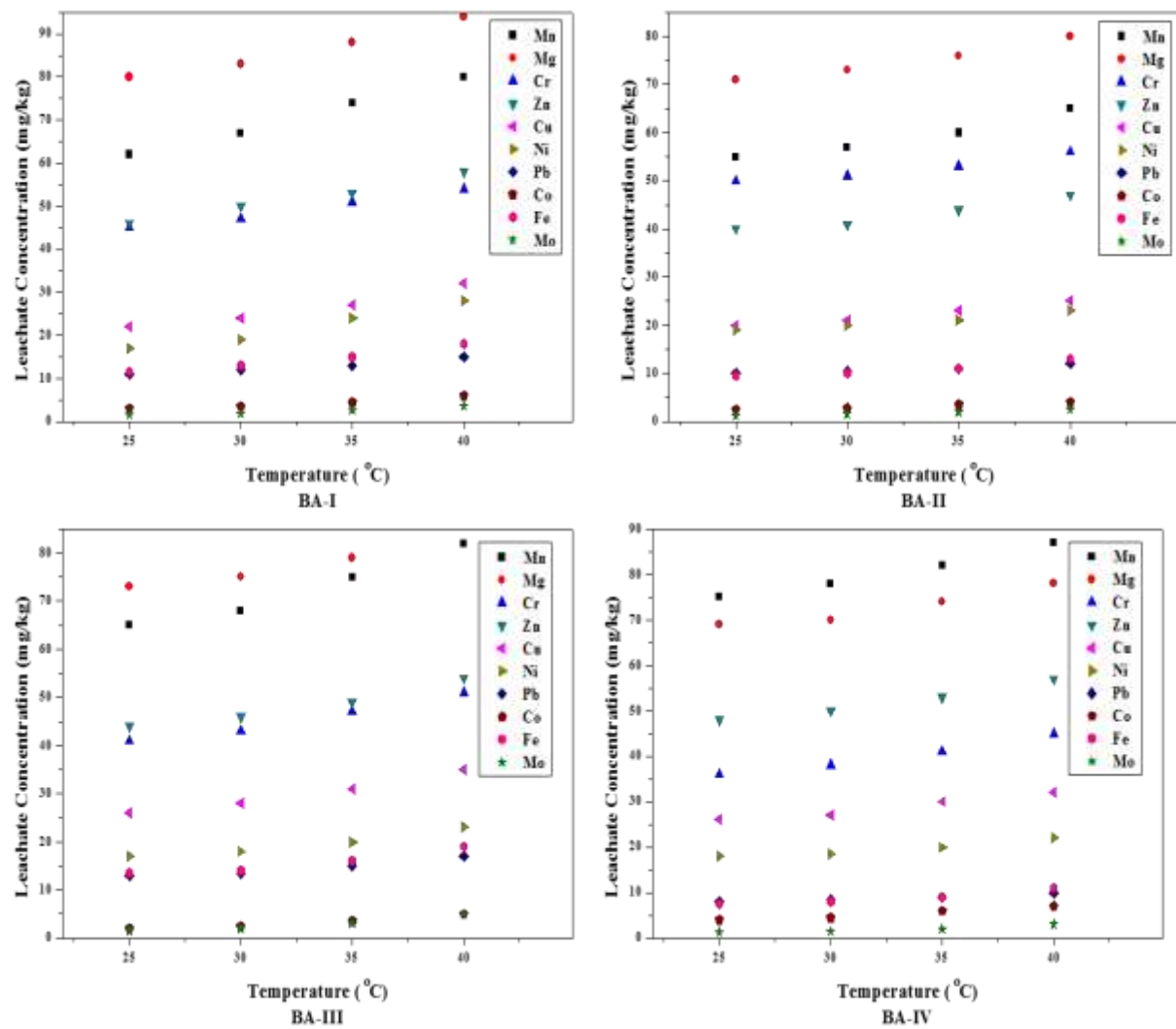


Figure 4.17: Influence of temperature on leachate concentration of trace elements present bottom ash

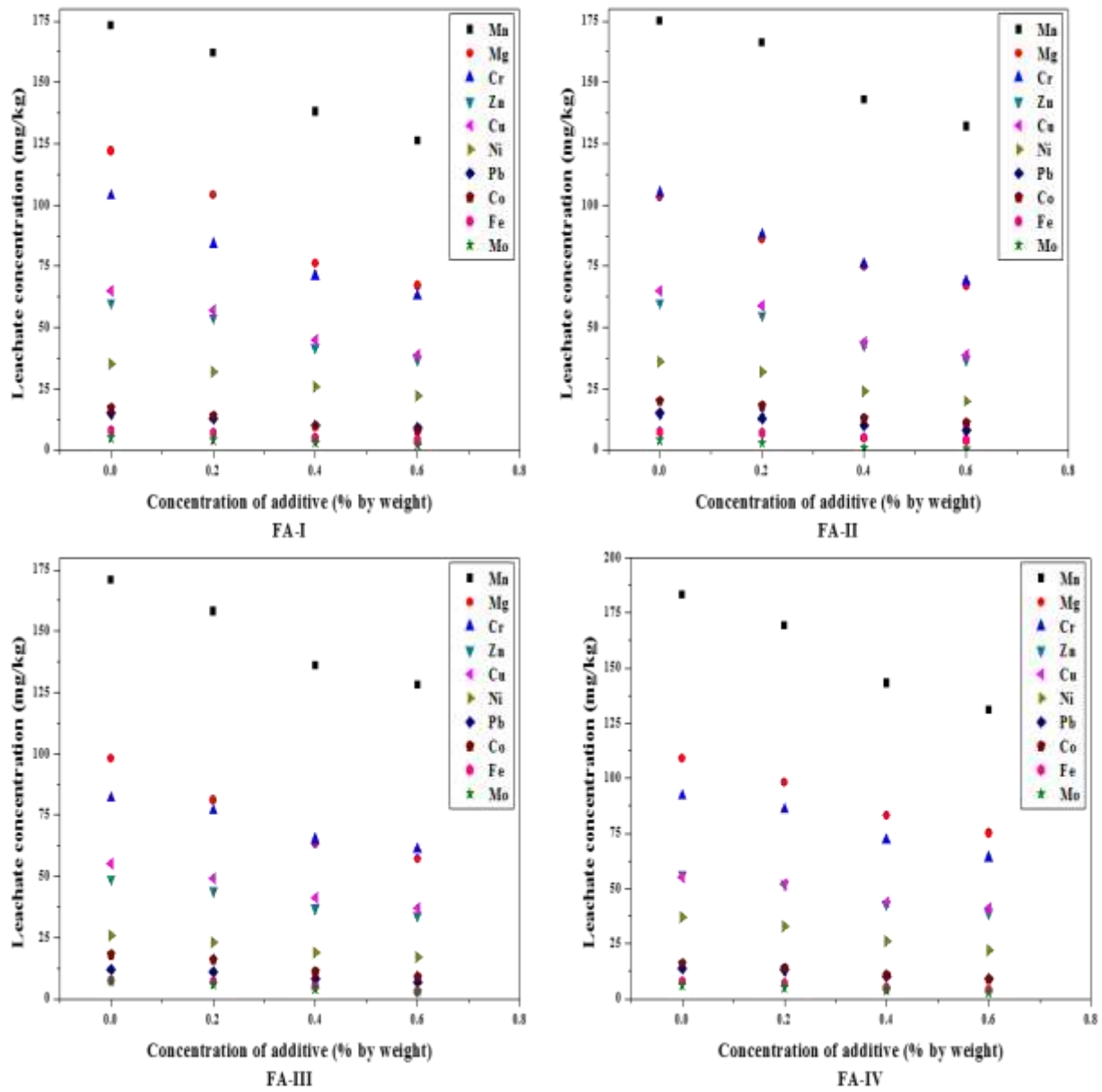


Figure 4.18: Effect of addition of additive on leachate concentration of fly ash

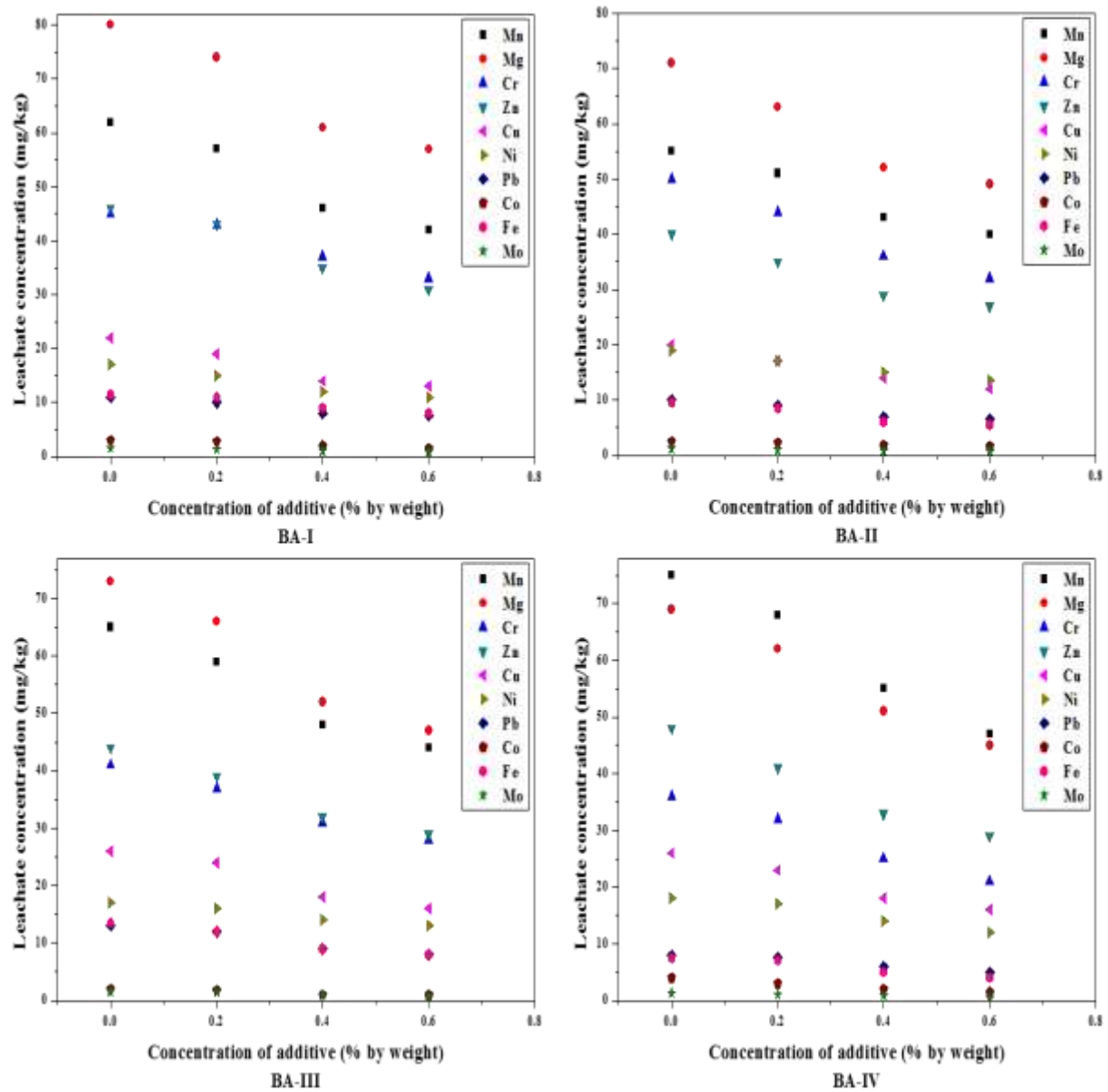


Figure 4.19: Effect of addition of additive on leachate concentration of bottom ash

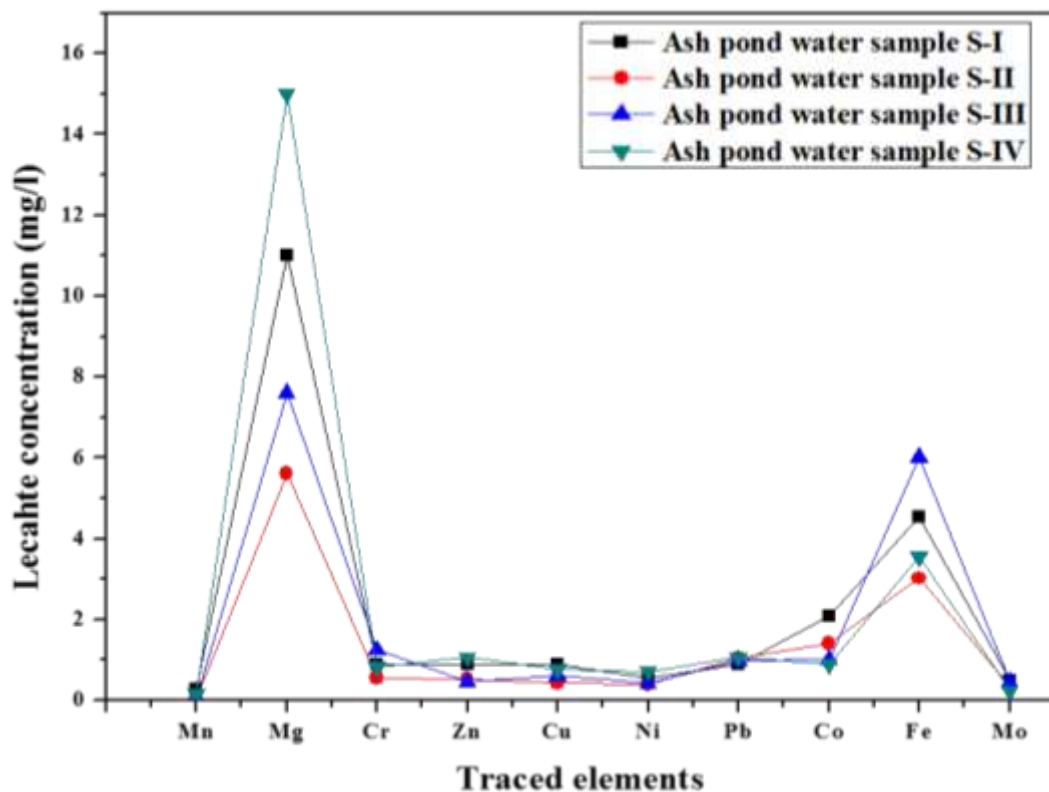


Figure 4.20: Leachate concentration of trace elements in pound ash water

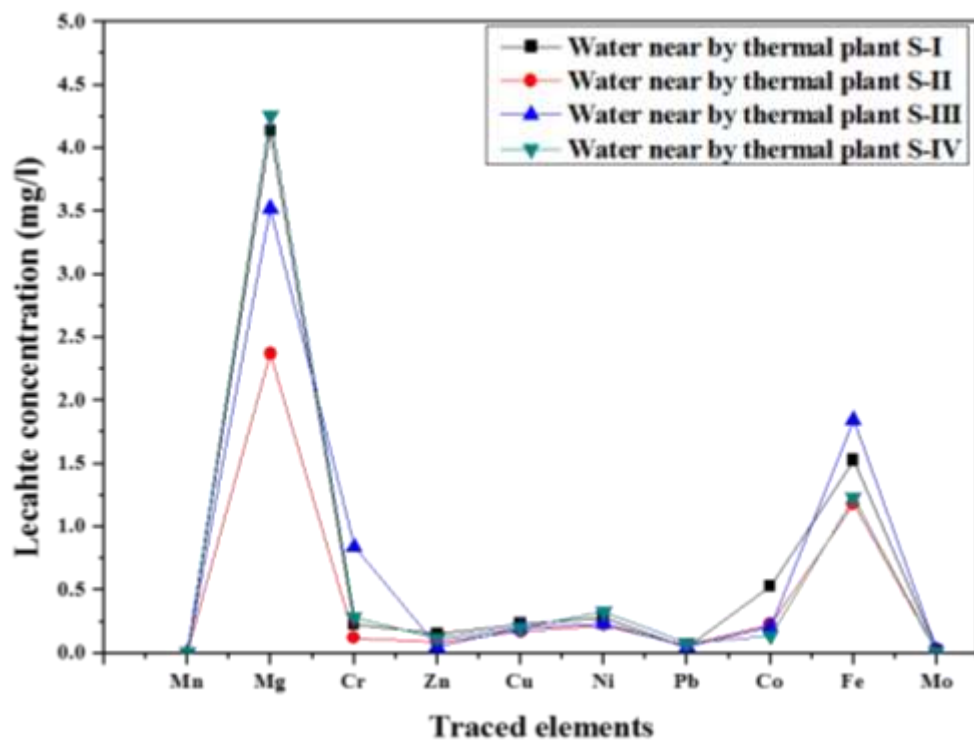


Figure 4.21: Leachate concentration of trace elements in water nearby thermal power plant

Table 4.1: Harmful effects of heavy metals on human health

Element	Effect on human health
Mn	Mental disorders
Mg	Diarrhea and abdominal cramping
Cr	Lung cancer
Zn	Gastroenteritis and stomach cramps
Cu	Liver cancer, kidney, and intestinal disorders
Ni	Heart attack and respiratory diseases
Cd	Pulmonary cancer
Pb	Cardiovascular, reproductive, gastrointestinal, and renal disorders
Fe	Nausea, vomiting, and liver failure
Mo	Liver dysfunction and Lung cancer

Table 4.2: Effect of liquid to solid ratio on leaching of fly ash

Sample	FA-I			FA-II			FA-III			FA-IV		
L/S Ratio	20	40	60	20	40	60	20	40	60	20	40	60
Mn	173	188	196	175	194	204	171	186	195	183	207	215
Mg	122	138	146	103	122	136	98	111	120	109	123	139
Cr	104	117	124	105	122	134	82	91	99	92	111	120
Zn	60	73	78	60	67	73	49	56	61	56	64	70
Cu	65	75	80	65	72	76	55	62	67	55	66	71
Ni	35	39	44	36	42	47	26	31	35	37	40	42
Cd	15	17	19	15	17	18	12	14	15	14	16	17
Pb	17	19	22	20	23	25	18	20	21	16	17	18
Fe	8	10	12	7.5	9	10	7.5	10	11	8	9	10
Mo	5	6	8	4	5	5.5	7	8	8.5	6	7	8

Table 4.3: Effect of liquid to solid ratio on leaching of bottom ash

Sample	BA-I			BA-II			BA-III			BA-IV		
L/S Ratio	20	40	60	20	40	60	20	40	60	20	40	60
Mn	62	68	75	55	60	66	65	69	75	75	78	84
Mg	80	85	92	71	77	84	73	75	82	69	73	79
Cr	45	48	54	50	56	64	41	48	52	36	44	49
Zn	46	47	50	40	45	53	44	47	57	48	56	63
Cu	22	28	33	20	27	30	26	30	35	26	32	38
Ni	23	29	35	19	22	24	17	20	22	18	25	30
Cd	11	15	17	10	14	19	13	15	18	8	11	13
Pb	3	3.5	6	2.5	3.8	4	2	2.5	4	4	4.5	5.5
Fe	11.5	14.5	15	9.5	10.5	13	13.5	15.2	16	7.5	9	12
Mo	1.5	2	2.75	1.2	1.9	2.5	1.5	1.9	2.5	1.3	1.5	1.6

Table 4.4: Effect of leaching time on leaching of fly ash

Sample	FA-I				FA-II				FA-III				FA-IV			
Time	5	10	15	20	5	10	15	20	5	10	15	20	5	10	15	20
Mn	176	182	186	188	180	186	190	193	175	182	186	188	190	195	198	200
Mg	126	130	132	133	108	112	114	116	102	106	109	111	114	118	121	122
Cr	107	111	114	116	110	114	116	117	86	90	92	93	98	101	102	103
Zn	63	66	68	69	64	67	69	70	52	57	60	62	60	64	66	67
Cu	68	72	74	75	68	74	76	77	58	63	65	66	60	63	65	66
Ni	37	40	42	43	38	40	41	43	28	30	33	35	42	45	47	48
Cd	18	19	19.5	20	17	18	19	19.5	14	15	16	16.5	16	18	19	19.5
Pb	19	21	22	22.5	21	23	24	24.5	19	20	21	21.5	18	19	19.5	20
Fe	10	11	11.5	11.8	8	9	10	10.5	9	10	10.5	10.8	9	10	10.5	11
Mo	6	7	7.5	8	4.5	5	5.5	5.8	8	9	9.5	10	7	8	8.5	9

Table 4.5: Effect of leaching time duration on leaching of bottom ash

Sample	BA-I				BA-II				BA-III				BA-IV			
Time	5	10	15	20	5	10	15	20	5	10	15	20	5	10	15	20
Mn	63	66	67	68	56	59	62	64	67	70	74	76	66	69	72	74
Mg	82	86	88	89	73	75	78	79	74	76	78	80	75	78	80	81
Cr	46	49	50	52	51	53	55	56	42	46	47	50	42	44	47	49
Zn	48	50	52	53	41	42	44	45	46	48	50	51	46	49	51	52
Cu	23	25	27	28	22	23	24	26	27	30	32	33	28	30	32	34
Ni	24	26	27	29	20	21	22	23	18	20	21	22	18	19	20	21
Cd	12	13	14	15	11	12	13	14	14	16	17	19	14	15	17	18
Pb	4	4.5	5	6	3	4	5	6	2.5	3	4	4.5	2.5	3	4	4.5
Fe	12	14	15	15.5	10	11	12	12.5	14	15	16	17	14	15	16	17
Mo	2	2.5	3	3.5	1.5	2	2.5	3	2	2.5	3	3.5	2	3	3.5	4

Table 4.6: Effect of temperature on leaching of fly ash

Sample	FA-I				FA-II				FA-III				FA-IV			
Temperature	25	30	35	40	25	30	35	40	25	30	35	40	25	30	35	40
Mn	173	178	184	191	175	178	182	189	171	174	179	186	183	187	195	207
Mg	122	125	130	136	103	106	110	116	98	100	104	110	109	115	121	128
Cr	104	106	111	118	105	108	114	120	82	86	90	97	92	95	99	106
Zn	60	62	66	71	60	63	67	72	49	52	56	61	56	60	65	71
Cu	65	67	70	74	65	68	73	79	55	57	61	66	55	58	62	68
Ni	35	36	38	40	36	38	42	48	26	27	30	34	37	39	43	48
Cd	15	16	17	19	15	16	18	23	12	13	14	16	14	15	17	20
Pb	17	18	20	22	20	22	25	30	18	20	23	27	16	17	19	20
Fe	8	9	11	12	7.5	8	9	11	7.5	8	9	11	8	9	10	11
Mo	5	5.5	7	8	4	4.5	5	6	7	8	8.5	9	6	7	8	9

Table 4.7: Effect of temperature ratio on leaching of bottom ash

Sample	BA-I				BA-II				BA-III				BA-IV			
Temperature	25	30	35	40	25	30	35	40	25	30	35	40	25	30	35	40
Mn	62	67	74	80	55	57	60	65	65	68	75	82	75	78	82	87
Mg	80	83	88	94	71	73	76	80	73	75	79	86	69	70	74	78
Cr	45	47	51	54	50	51	53	56	41	43	47	51	36	38	41	45
Zn	46	50	53	58	40	41	44	47	44	46	49	54	48	50	53	57
Cu	22	24	27	32	20	21	23	25	26	28	31	35	26	27	30	32
Ni	17	19	24	28	19	20	21	23	17	18	20	23	18	18.5	20	22
Cd	11	12	13	15	10	10.5	11	12	13	13.5	15	17	8	8.5	9	10
Pb	3	3.5	4.5	6	2.5	2.8	3.5	4	2	2.5	3.5	5	4	4.5	6	7
Fe	11.5	13	15	18	9.5	10	11	13	13.5	14	16	19	7.5	8	9	11
Mo	1.5	1.8	2.5	3.5	1.2	1.5	2	2.5	1.5	2	3	5	1.3	1.5	2	3

Chapter 5

RHEOLOGY OF FLY AND BOTTOM ASH SLURRY

Rheology is the branch of science which deals with multiphase flow as well as slurry suspension under the influence of external force. Generally, slurry suspension undergoes plastic deformation under the effect of external forces (shear stress). The rheological characteristics can be investigated for those materials which can deform under the action of external forces like coal ash slurry, mud etc. The investigation of flow properties of slurry suspension has been focal interest for many years due to wide industrial application. The role of flow characteristics in designing of slurry transportation system is already highlighted in pervious chapters. The study of flow properties of solid-liquid suspension is a complex phenomenon, due to change in flow behaviour of fluid after addition of solid particle. The physical properties of solid particles affect the flow behaviour of slurry suspension. This deviation in flow behaviour of slurry suspension mainly arise when slurry is subjected to shear forces and allows dissipation of external energy. The dissipation rate of solid depends on various factors like solid volume fraction, viscosity of slurry, physical properties of solid and shear rate. The addition of solid in liquid leads to increase in the viscosity and may alter the fluid behaviour from Newtonian fluid to non-Newtonian. Currently, in thermal power plants coal ash is transported through pipelines at very low solid concentration. This leads to consumption of large amount of water and electricity. The transportation of ash slurry at higher concentrations requires thorough knowledge of rheological behaviour of solid suspension at different solid concentrations and flow conditions. Available literature states that there are various parameters which play an important role to determine the rheological behaviour of solid suspension like viscosity, particles size, solid concentration etc. The behaviour of slurry suspension at different parameters is measured with the known as rheometer.

For the hydraulic design of the slurry system, the designers need extensive data covering all aspects of two-phase solid–liquid flow. The extensive literature shows that enough data is not available to support the design methodology for all solid materials. So it is essential to establish the flow characteristics of a particular slurry flow for making the design methodology suitable for it. For any slurry suspension, the flow properties data has been generated by conducting the experiments.

In India low concentration ash disposal system is used for disposal of ash. Currently, lean water ash slurry (8-20 % by weight) is disposed from thermal power plant to ash pound (Ministry of Power, Government of India (<http://powermin.nic.in/>)). Low concentration ash disposal system required high amount of water and pumping power. So, present study was carried out to motivate the use of high concentration ash disposal system to save water and pumping power.

Present work is focused to investigate the rheological properties of coal ash suspension at different solid concentration (10-60%). Moreover, this study is also carried out to investigate the effect of additives. The sodium bi-carbonate was used as additive and added in the range of 0.2-0.6% (by weight).

5.1 Rheological measurement

The rheological behaviour of fly and bottom ash slurry suspension were determined with the help of standard rheometer (Anton Paar, Manufactured by: Rheolab Q-C, APC Ltd. Germany). The schematic diagram of rheometer used in present work is represented in Figure 5.1. Specification of rheometer and sensor system used in present study are tabulated in Table 5.1. It consists of bob and cylindrical cup assembly both are made up from zirconia coated stainless steel. The slurry sample (50ml) of coal ash is poured into outer stationary cylinder. To control the temperature of slurry suspension, a thermal jacket is mounted over the cylinder which is used for circulation of water. Inductive position sensors are used to measure speed of inner cylinder during shearing of slurry. Rheological testing of slurries was determined by determining shear stress at shear rate ranging from 0-300 s⁻¹. The various flow properties such as shear stress, viscosity were measured at fixed shear rate for all slurry samples at each concentration.

5.1.1 Preparation of the slurry samples

The rheological experiment, 50 ml ash slurry was prepared by proper mixing of necessary amount of solid. Initial during experimentation, cup and bob assembly than fixed with the help of locking device. The ash-water suspension was poured into cylinder till the specified level. The testing was carried out by changing shear rate value (0 to 300 s⁻¹) at constant temperature with varying concentrations 10 to 60 (% by weight) for all samples. The experimental study was also performed with addition of additive. Sodium bi-carbonate (NaHCO₃) was used as additive to improve rheological properties of ash suspension. The concentration of additives was varied from 0.2 to 0.6

(% by weight). Each experiment was done three times for coal ash slurry suspension to ensure the precision of measured data.

5.1.2 Range of parameters

The rheological experiments were performed with addition of additive in coal ash slurry. The rheology of the fly and bottom ash slurry suspension was measured in the solid concentration range of 10 to 60% (by weight) all coal ash. The dosage of additive take in the range of 0.2-0.6% (by weight). The constant temperature circular bath was connected to rheometer for variation of temperature of slurry.

5.2 Rheology of fly ash slurry

The fly ash samples FA-I, FA-II, FA-III and FA-IV were used to investigate rheological behaviour with change in solid concentration from 10-60% (by weight). The change in shear stress with shear rate at different solid concentration of fly ash sample is shown in Figure 5.-5.7. Results represent non-Newtonian nature of slurry suspension and follows Bingham fluid behaviour as shown in equation 5.1:

$$\tau = \tau_y \eta \frac{du}{dy} \quad (5.1)$$

Where, τ = shear stress (Pascal), τ_y = Bingham yield stress (Pascal), η = coefficient of rigidity or Bingham viscosity.

Relative viscosity is defined as the ratio of slurry viscosity to the water (fluid) under the constant conditions. All data were plotted to find the viscosity for each slurry suspension sample. The value of τ_y was zero for suspensions of till 30% solid concentration (by weight). This implies that fly ash samples exhibit Newtonian behaviour till 30% solid concentration than it shows non-Newtonian flow behaviour.

Results indicated that as the shear stress increased as shear rate increase. The value of shear stress at shear rate of 100 s^{-1} was observed as 0.16, 0.47, 0.81, 2.87, 3.82 and 5.419 Pascal respectively for solid concentration of 10, 20, 30, 40, 50 and 60% (by weight) whereas at it was 0.51, 1.29, 2.20, 4.21, 7.77 and 11.44 Pascal at shear rate of 300 s^{-1} for sample FA-I. For fly ash sample FA-II, shear stress value was found as 0.15, 0.47, 0.75, 1.98, 3.10 and 4.91 Pascal at shear rate 100 s^{-1} whereas it was determined as 0.49, 1.30, 2.02, 3.88, 7.14, 10.17 Pascal respectively at

shear rate 300 s^{-1} . Similarly at shear rate 100 s^{-1} , the shear stress value of fly ash sample FA-III was determined as 0.23, 0.50, 0.99, 2.62, 4.37 and 6.71 Pascal while at shear rate 300 s^{-1} , it was found as 0.57, 1.33, 3.01, 5.21, 9.15 and 15.62 Pascal respectively. In fly ash sample FA-IV, the shear stress was found as 0.14, 0.45, 0.64, 1.79, 3.32 and 4.47 Pascal at 100 s^{-1} shear rate and 0.48, 1.24, 1.76, 3.52, 6.98, 9.71 Pascal respectively at shear rate of 300 s^{-1} . Rheology results indicate that the value of shear stress is function of solid concentration at any shear rate. Initial some shear force is required to deform ash slurry that may be presence of large number of ash particle at higher concentration. Similar observation is also made by researchers (Gandhi et al. 2001, Seshadri et al. 2008, Chandel et al. 2009, Naik et al. 2011, Senapati et al. 2010) with fly ash slurry suspension. The shear stress of fly ash samples FA-I, FA-II, FA-III and FA-IV was increased about 33.17, 31.25, 28.26 and 31.06 times at 100 s^{-1} shear rate with increase in solid concentration from 10 to 60% whereas it was increased as 22.27, 20.58, 27.20 and 20.24 times respectively at shear rate of 300 s^{-1} .

5.3 Rheology of bottom ash slurry

The bottom ash samples BA-I, BA-II, BA-III and BA-IV were used for investigate rheological properties at 10-60% (by weight) same as fly ash. The change in shear stress with shear rate at different solid concentrations of bottom ash sample is shown in Figure 5.138-5.13. It was observed that the shear stress-shear rate curve of bottom ash slurry showed quite similar trend as fly ash slurry. The value of τ_y was zero for suspensions of bottom ash till 40% solid concentration (by weight). This implies that bottom ash slurry suspension showed Newtonian behaviour up to 40% solid concentration (by weight) beyond this, it depicted non-Newtonian flow characteristics. The value of shear stress of sample BA-I at shear rate of 100 s^{-1} was found as 0.11, 0.19, 0.27, 0.54, 1.09, and 1.92 Pascal respectively for solid concentration 10, 20, 30, 40, 50 and 60% (by weight) whereas 0.33, 0.45, 0.84, 1.62, 2.99 and 4.78 Pascal respectively at shear rate of 300 s^{-1} . In bottom ash sample BA-II, the value of shear stress was found as 0.10, 0.16, 0.28, 0.41, 0.92 and 1.49 Pascal at shear rate of 100 s^{-1} while 0.35, 0.45, 0.76, 1.39, 2.49 and 3.95 Pascal respectively at shear rate of 300 s^{-1} . Similarly in bottom ash sample BA-III, the shear stress was found as 0.13, 0.20, 0.34, 0.65, 1.18 and 2.17 Pascal respectively at 100 s^{-1} shear rate while 0.35, 0.61, 0.92, 1.83, 3.21 and 5.36 Pascal respectively at shear rate 300 s^{-1} . However in bottom ash sample BA-IV, it

was found as 0.09, 0.16, 0.25, 0.38, 0.84 and 1.39 Pascal at 100 s^{-1} shear rate whereas 0.31, 0.42, 0.71, 1.27, 2.29 and 3.68 Pascal respectively at shear rate of 300 s^{-1} .

The wide variation was observed in value of shear stress which varies sample-to-sample at particular shear rate and given solid concentration. It was also observed that shear stress of bottom ash sample BA-IV was higher as compared to other samples. This happens due to finer nature of bottom ash sample BA-IV as compare to other samples. The shear stress of bottom ash samples BA-I, BA-II, BA-III and BA-IV was increases about 9.69, 14.61, 15.98 and 15.45 times respectively at 100 s^{-1} shear rate with increases in solid concentration from 10 to 60% whereas it was increase 8.22, 11.19, 15.10 and 11.54 times respectively at shear rate 300 s^{-1} .

5.4 Effect of solid concentration on viscosity of fly and bottom ash slurry

The relative viscosity of fly and bottom ash samples are shown in Figure 5.14-5.15. The rheological results shows that relative viscosity of fly and bottom ash highly depend upon solid concentration of their respective slurry suspensions. It was observed that fly ash samples FA-III have higher relative viscosity as compared to other samples. The relative viscosity of fly ash sample FA-I, FA-II, FA-III and FA-IV was determined as 2.10, 2.02, 2.62 and 1.97 at 10% solid concentration whereas 62.57, 56.65, 80.00 and 53.78 respectively at 60% concentration. Similarly the relative viscosity of bottom ash was observed as 1.16, 1.12, 1.28 and 1.11 at 10% solid concentration of bottom ash sample BA-I, BA-II, BA-III and BA-IV while it was observed 24.37, 19.33, 28.19 and 17.13 respectively at 60% solid concentration. It was noticed that relative viscosity increased with increase in solid concentration. Furthermore, relative viscosity of fly and bottom ash slurry suspension was increased more rapidly at higher solid concentration as compared to lower solid concentrations.

As the solid concentration was increased the number of solid particles per unit volume in slurry suspension was also increased. Thus for starting the shear process, a high shear stress was required. The experimental results indicated that fly and bottom ash slurry suspension follows time independent suspension behaviour. Similar type of phenomenon had been observed by investigators (Gandhi et al. 2000; Seshadri et al. 2008; Chandel et al. 2009; Senapati et al. 2010; Naik et al. 2011 and Kumar et al. 2014) with coal ash slurry.

The yield stress of fly and bottom ash samples are tabulated in Table 5.2-5.3. Yield stress of slurry suspension also function of solid concentration of fly and bottom ash slurry suspension. Fly ash having higher yield stress as compared to bottom ash. The yield stress of fly and bottom ash sample increases monotonically at higher concentrations. It was observed that yield stress value for fly ash sample FA-I have 0.91, 1.39 and 1.67 Pascal at solid concentration of 40, 50 and 60% while it was 0.72, 1.07 & 1.64 Pascal, 0.98, 1.57 & 1.71 Pascal and 0.64, 1.05 & 1.53 Pascal for fly ash samples FA-II, FA-III and FA-IV respectively. The bottom ash samples have lower yield stress as compared to fly ash and this was due to coarser nature of bottom ash. Yield stress was observed as 0.19, 0.14, 0.38 and 0.13 Pascal respectively for bottom ash samples BA-I, BA-II, BA-III and BA-IV at 50% solid concentration while 0.51, 0.36, 0.63 and 0.32 Pascal respectively for 60% solid concentration.

5.5 Effect of additives on the rheology of fly and bottom ash slurry

The additives are compound of chemicals or minerals which can improve the rheological behaviour of slurry suspension. The flow resistance and drag friction of fluid can be reduced by addition of additive which further leads to decrease in head loss. Researchers (Seshadri et al. 2008; Chandel et al. 2009; Naik et al. 2011; Kumar et al. 2013; Singh et al. 2016; Kumar et al. 2017) used different additives (surfactants and polymers) for improving the rheology of slurry suspension. Most common surfactants are cationic, anionic and non-ionic. Anionic surfactants are water soluble negative charged particles. On the other hand cationic surfactant particles are stable, self-reparability and positive charged. Cationic surfactants show good drag reduction characteristics at various temperature. Non-ionic surfactants are called as neutral head particles which are stable and have a tendency of self-repair after degradation. It provides significant reduction in drag at higher flow rate. Natural polymer, counter-ion and gum also effective for drag deduction of coal ash suspension.

In present investigation of sodium bicarbonate was used as an additive. It was used as an additive in the fraction of 0.2, 0.4 and 0.6% (by weight) of total solid concentration of fly and bottom ash suspensions. The solid concentration varied within the range of 10-60% (by weight). The fly and bottom ash samples (FA-III and BA-III) was taken from Guru Hargovind thermal power plant, Lehra Mohabbat, Punjab to evaluate the effect of additive on rheological characteristics of their respective suspensions.

5.5.1 Effect of additives on fly ash suspension

The value of shear stress for fly ash suspension with addition of additives at solid concentration of 10 to 60% (by weight) is shown in Figure 5.16-5.21. Results show that shear stress was increased with increase in solid concentration. The value of shear stress was decreased from 0.55 to 0.52, 0.52 to 0.45 and 0.45 to 0.42 Pascal with addition of 0.2, 0.4 and 0.6% additive at 10% solid concentration while it was reduced from 52.07 to 45.21, 45.21 to 36.57 and 36.57 to 32.48 Pascal at 60% solid concentration respectively at 300 s^{-1} shear rate. The addition of additives in fly ash slurry suspension improves molecular chain structure of fly ash suspension. This improvement is responsible for the reduction of drag force between adjacent layers of fly ash slurry suspension.

Thus viscosity of fly ash suspension was reduced with addition of additive. The addition of additive may influence the particle-particle and fluid-particle interaction in slurry suspension. The variation in relative viscosity with addition of additive in fly ash suspension is represented in Figure 5.22. The relative viscosity of fly ash suspension was reduced from 2.62 to 2.47, 2.47 to 2.17 and 2.17 to 2.11 at 10% solid concentration while it was reduced from 80.00 to 71.93, 71.93 to 59.79, and 59.79 to 54.52 at 60% solid concentration with addition of 0.2, 0.4 and 0.6% additive respectively. Results show that addition of additive at higher solid concentration was more effective as compared to lower solid concentration of fly ash suspension. Optimal reduction in relative viscosity was noticed with the addition of 0.4% additive for fly ash suspension. The reduction in relative viscosity of fly ash sample was found as 5.55, 12.37 and 2.80% for solid concentration of 10% while it was found as 10.08, 16.87 and 8.81% for solid concentration of 60% with addition of 0.2, 0.4 and 0.6% additives respectively.

5.5.2 Effect of additive on bottom ash suspension

In order to investigate the effect of additives on the rheology of bottom ash suspension, extensive experimentation has been repeated. The value of shear stress for bottom ash suspension with addition of additives at shear rate of $0\text{--}300\text{ s}^{-1}$ is shown in Figure 5.23-5.28. The addition of additive helps to decrease the viscosity of bottom ash slurry suspension due to reduction in drag forces between adjacent layers. At shear rate of 300 s^{-1} , the value of shear stress was reduced from 0.35 to 0.33, 0.33 to 0.27 and 0.27 to 0.24 Pascal respectively with 0.2, 0.4 and 0.6% addition of additive at 10% solid concentration while 5.36 to 4.65, 4.65 to 3.76 and 3.76 to 3.34 Pascal respectively at

60% solid concentration. Figure 5.29 represents the variation of relative viscosity of bottom ash suspension with addition of additives at different solid concentrations. However, the relative viscosity of bottom ash suspension was reduced from 1.26 to 1.18, 1.18 to 1.02 and 1.02 to 0.93 with 0.2, 0.4 and 0.6% addition of additive at 10% solid concentration while 28.19 to 25.42, 25.42 to 21.12 and 21.12 to 19.28 respectively at 60% solid concentration. It was noticed that addition of additives shows higher impact on viscosity of bottom ash suspension at higher concentrations. The viscosity reduction was found optimum for 0.4% addition of additive in bottom ash suspension. At 10% solid concentration, the reduction in relative viscosity of bottom ash sample was found as 6.37, 14.08 and 8.20% respectively with 0.2, 0.4 and 0.6% addition of additives while 9.84, 16.88 and 8.73% with 60% solid concentration.

5.5.3 Effect of temperature on rheology of fly and bottom ash with additive

The rheological behaviour of fly and bottom ash slurry suspension is highly dependent on temperature of slurry. The viscosity of fly and bottom ash varies with variation in temperature thus it is necessary to evaluate the effect of temperature on solid concentration of fly and bottom ash suspension with addition of additive. The rheological experimentation has been carried out for the variation of temperature ranging from 25 to 40°C at different shear rates lies in between 0-300 s⁻¹. It is observed that relative viscosity of fly and bottom ash was decreased with increase in temperature as shown in Figure 5.30-5.31. At 60% solid concentration, the relative viscosity of fly ash suspension was observed as 71.93, 59.79 and 54.52 respectively with 0.2, 0.4 and 0.6% addition of additive at 25 °C whereas 61.60, 48.80 and 45.37 respectively at 40°C. Similar trend was also observed for bottom ash sample, the relative viscosity of bottom sample was found as 25.42, 21.12 and 19.28 with addition of 0.2, 0.4 and 0.6% additive at 25 °C and 21.61, 17.86 and 16.85 respectively at 40°C. At 60% solid concentration, the relative viscosity of fly ash suspension was reduced as 4.76, 6.46 and 3.85% with increase in temperature from 25-30, 30-35 and 35-40 °C with 0.2% addition of additive while 5.47, 8.5 and 5.63% respectively with 0.4% addition of additive. Reduction in relative viscosity with 0.6% addition of additive was determined as 4.29, 8.37 and 5.02% with increase in temperature from 25-30, 30-35 and 35-40 °C respectively. The variation in relative viscosity of bottom ash suspension was decreased with increase in temperature. Also, it was decrease from 3.49, 6.38 and 3.85% as the temperature was increased from 25-30, 30-35 and 35-40 °C with 0.2% addition of additive whereas it was noticed as 4.90,

6.11 and 5.24% respectively with 0.4% addition of additive at 60% solid concentration. Similarly, it was reduced as 4.0, 5.47 and 3.68% with 0.6% addition of additive. Maximum reduction in relative viscosity was observed for temperature range of 30-35 °C. This may be attributed that increase in kinetic energy of molecules leads to deformation of intermolecular force between two adjutant layers of suspension. Moreover, it was also observed that rate of relative viscosity was decreased with increase in temperature.

5.6 Reflection

Rheological characteristics of fly and bottom ash collected from different thermal power plants were investigated with solid concentration ranging from 10-60% (by weight). Rheological experimentation was also carried out with varying temperature from 25-40 °C with addition of additive. The following conclusions can be drawn on the basis of above studies:

- Fly ash slurry suspension show Newtonian behaviour up to 30% solid concentration (by weight) beyond follows non-Newtonian flow characteristics. Whereas bottom ash slurry suspension show Newtonian behaviour up to 40% solid concentration. The addition of additive modified the flow behaviour of coal ash suspension.
- The maximum reduction in relative viscosity is observed with addition of sodium bicarbonate as additives in proportion of 0.4% (by weight). It was noticed that at 60% solid concentration 9.84, 25.07 and 31.59% reduction in relative viscosity of fly ash with addition of 0.2, 0.4 and 0.6 % additive similar trend was shown for bottom ash.

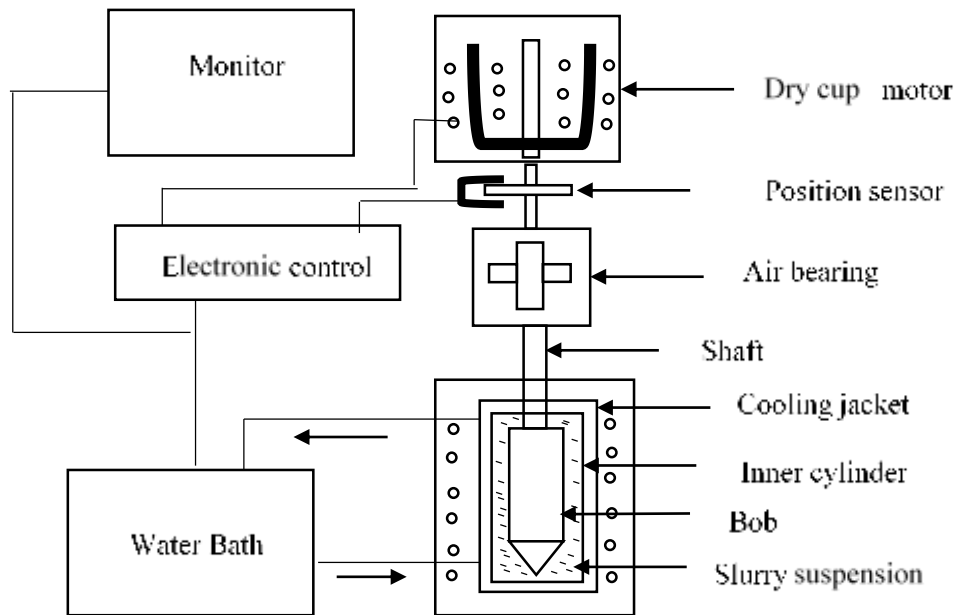


Figure 5.1: Schematic diagram of rheometer used for rheological experimentation

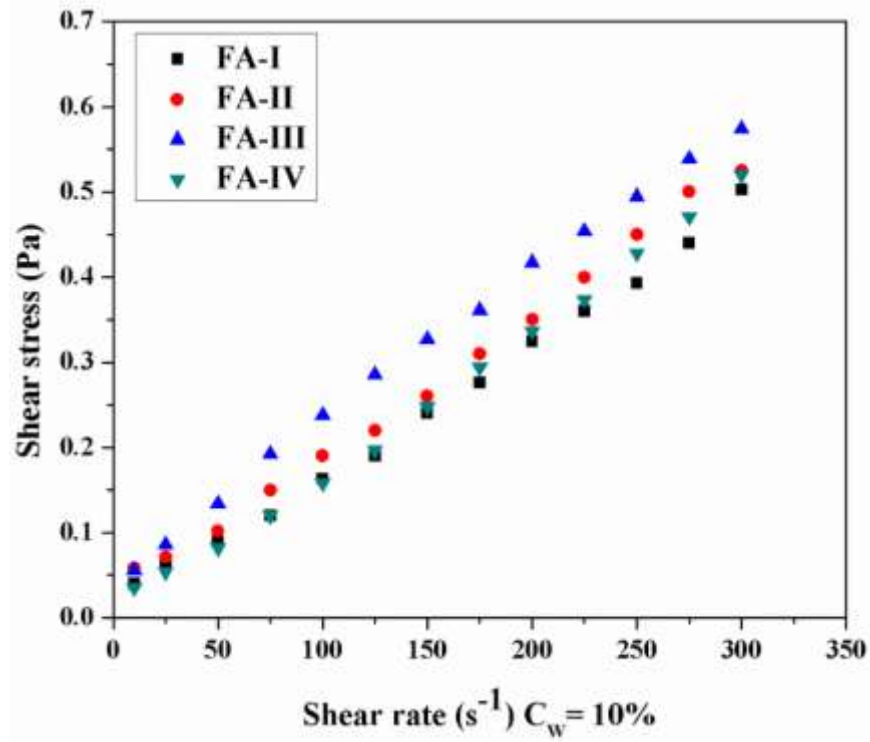


Figure 5.2: Shear stress-shear rate curves of fly ash suspensions at $C_w = 10\%$

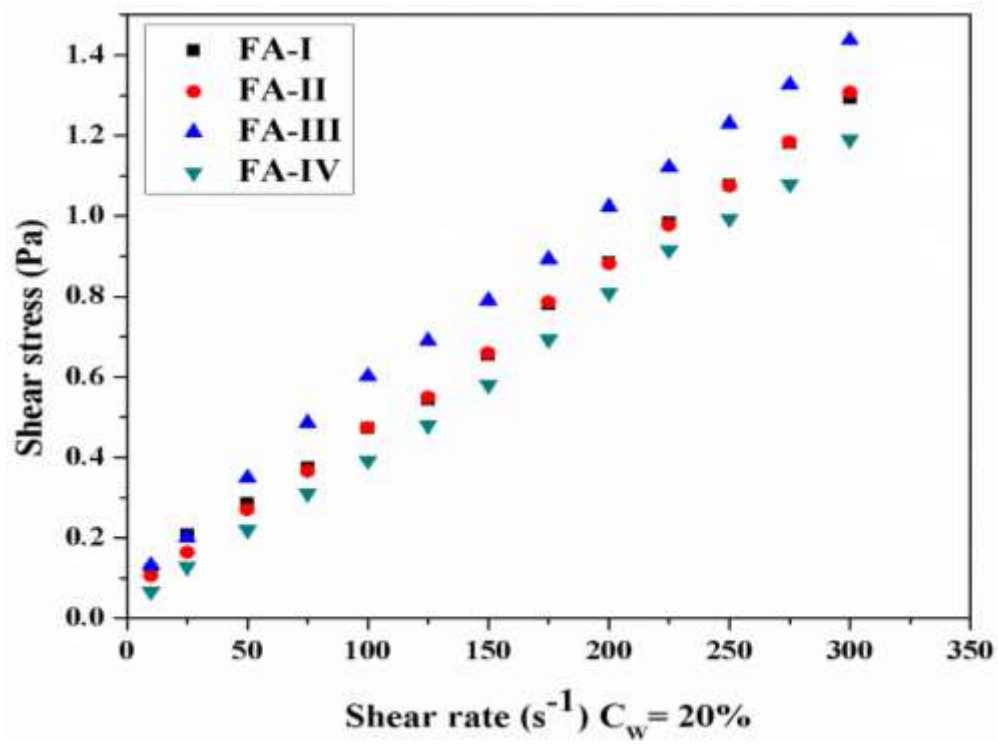


Figure 5.3: Shear stress-shear rate curves of fly ash suspensions at $C_w = 20\%$

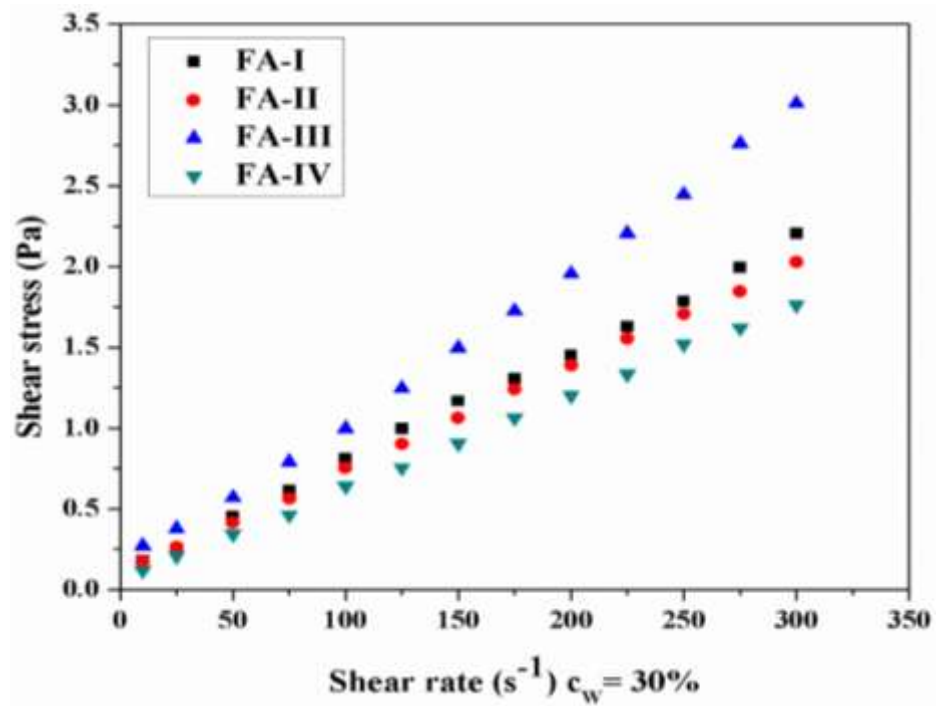


Figure 5.4: Shear stress-shear rate curves of fly ash suspensions at $C_w = 30\%$

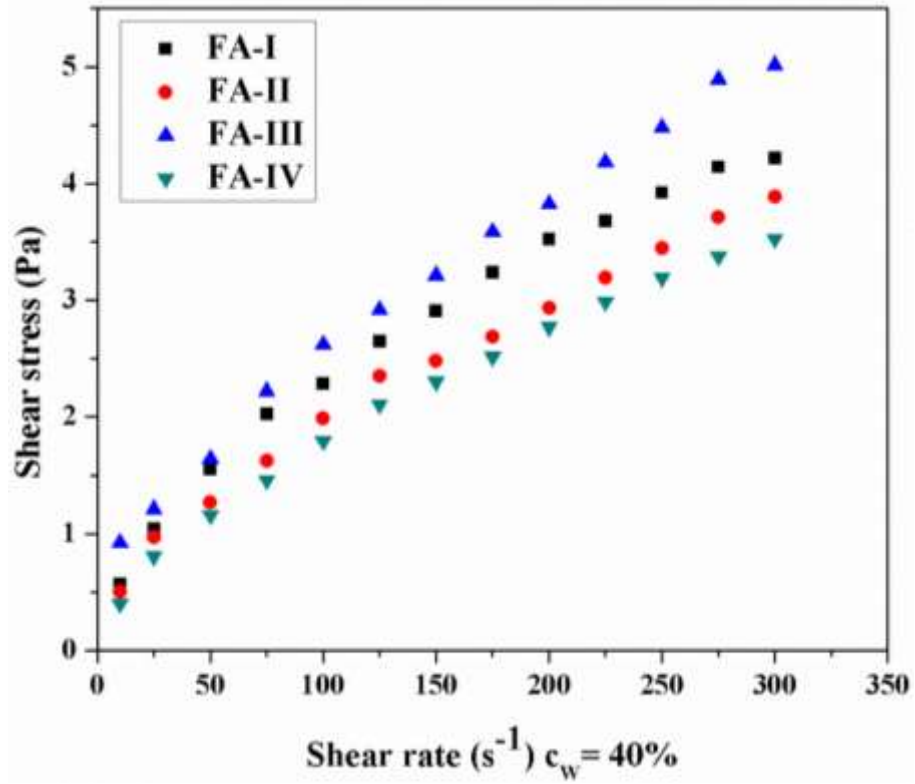


Figure 5.5: Shear stress-shear rate curves of fly ash suspensions at $C_w = 40\%$

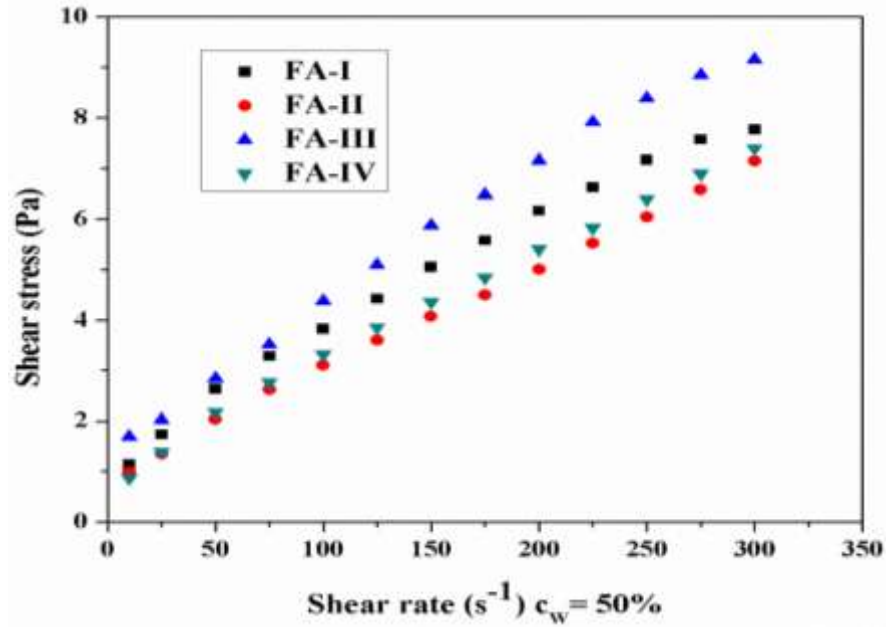


Figure 5.6: Shear stress-shear rate curves of fly ash suspensions at $C_w = 50\%$

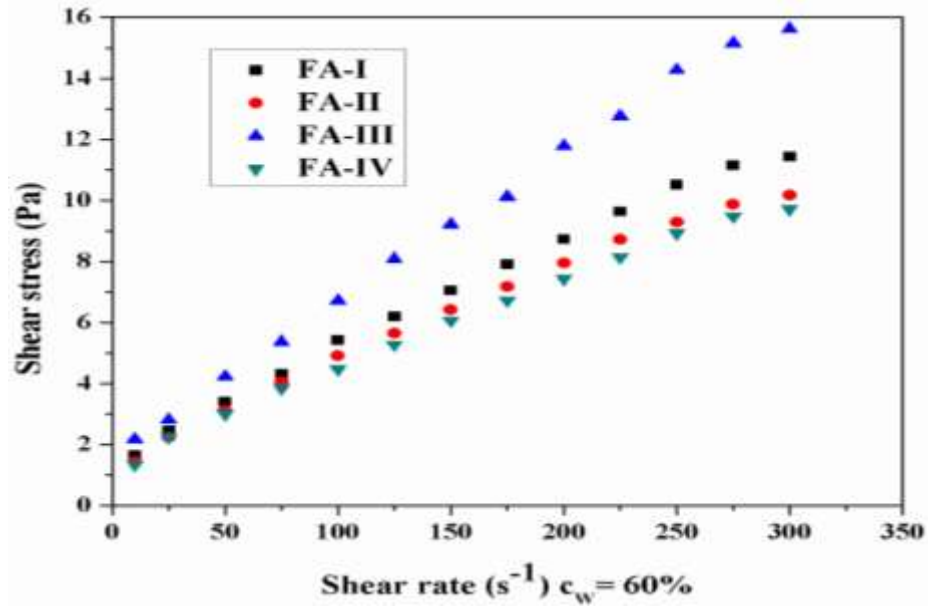


Figure 5.7: Shear stress-shear rate curves of fly ash suspensions at $C_w = 60\%$

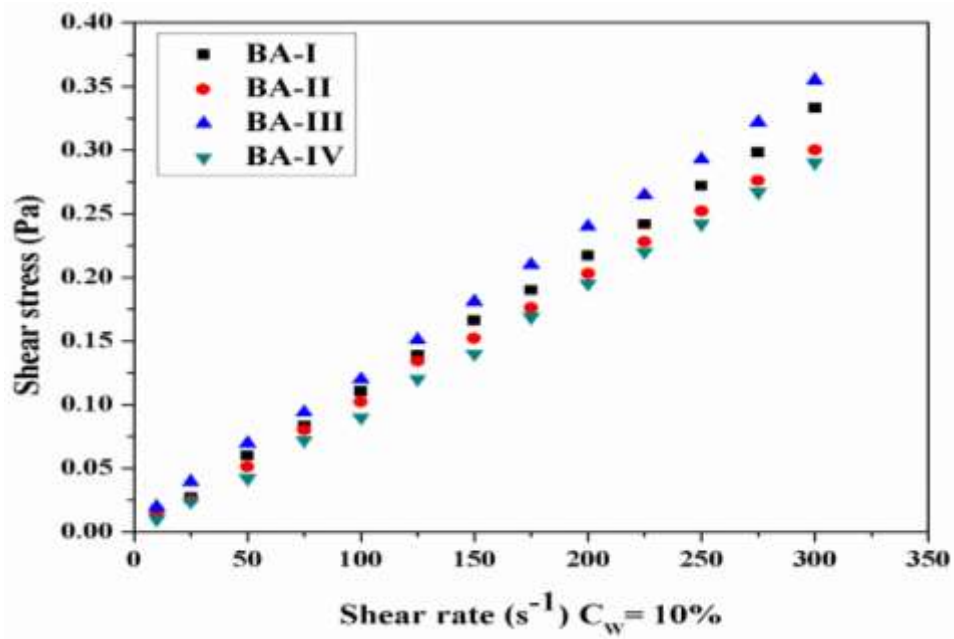


Figure 5.8: Shear stress-shear rate curves of bottom ash suspensions at $C_w = 10\%$

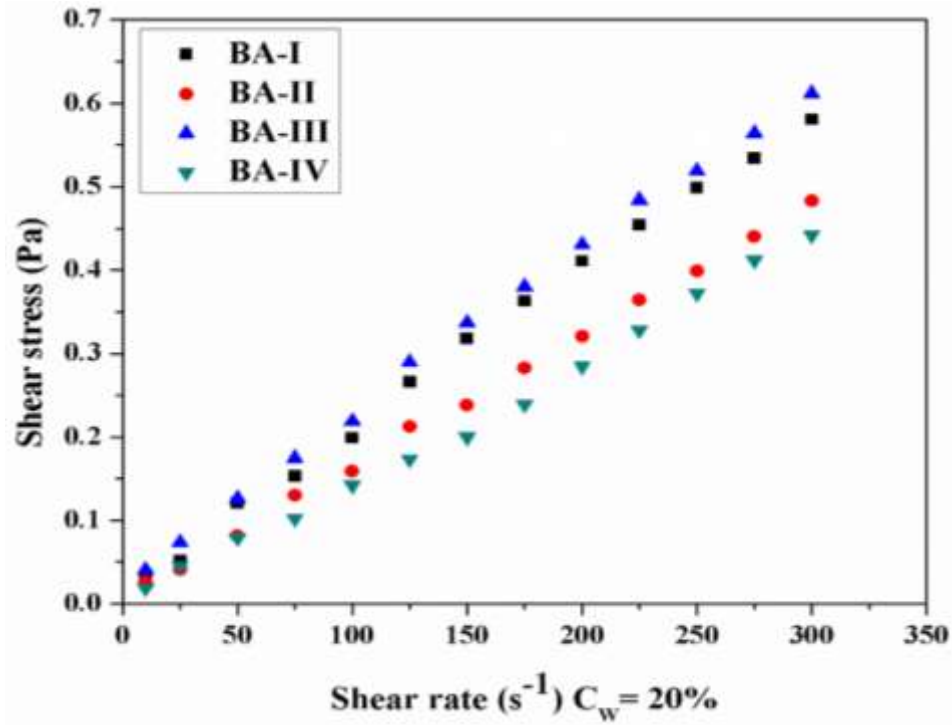


Figure 5.9: Shear stress-shear rate curves bottom ash suspensions at $C_w = 20\%$

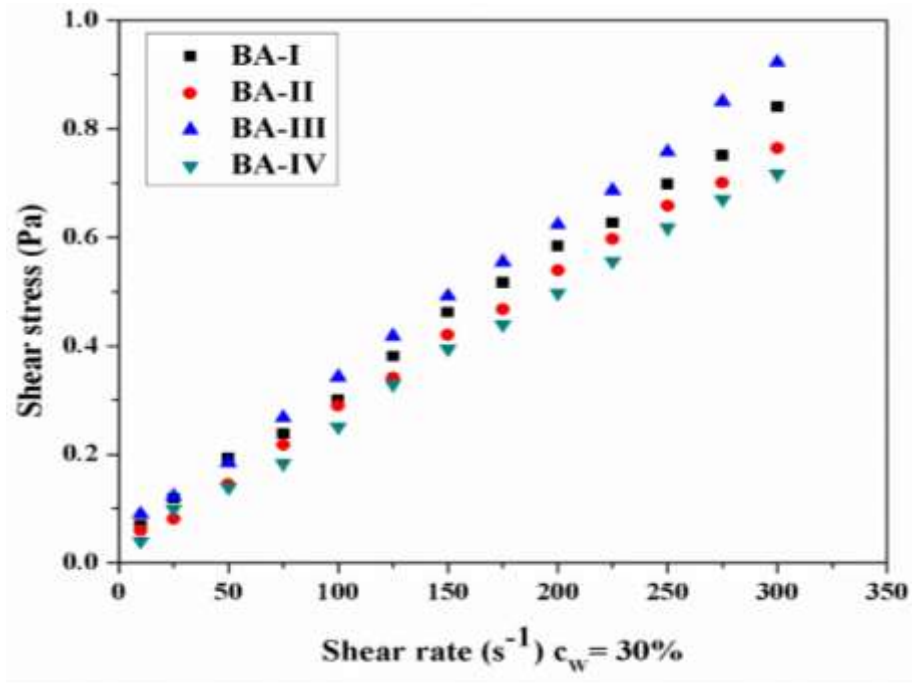


Figure 5.10: Shear stress-shear rate curves of bottom ash suspensions at $C_w = 30\%$

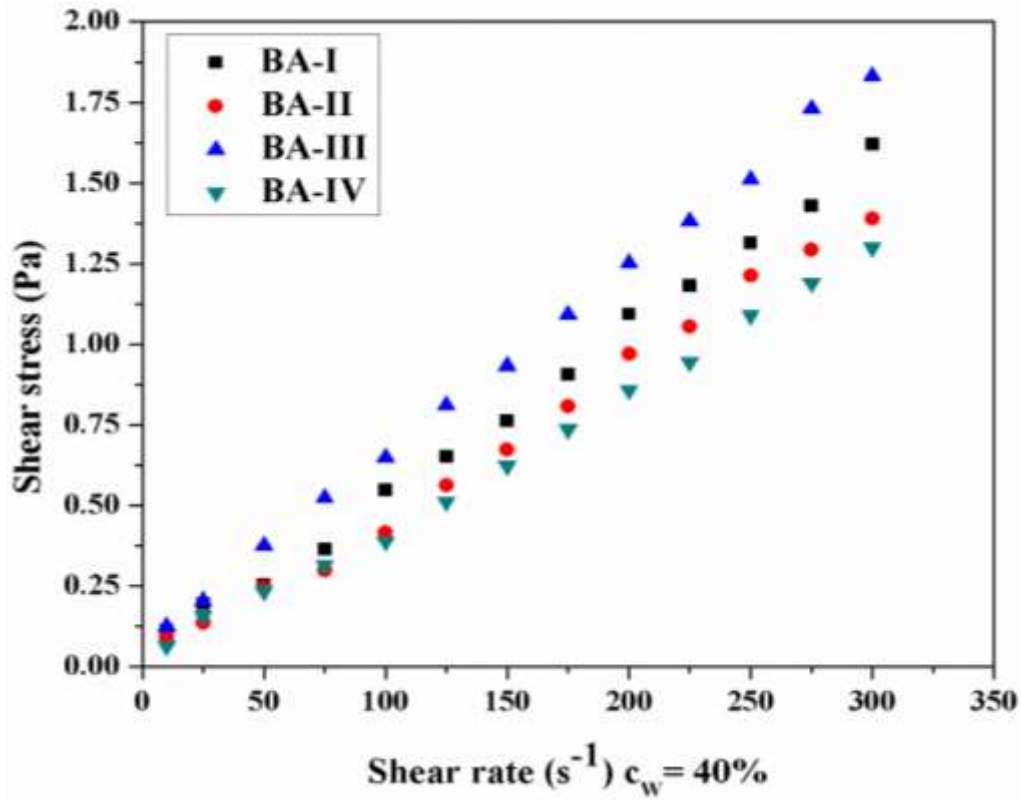


Figure 5.11: Shear stress-shear rate curves of bottom ash suspensions at $C_w = 40\%$

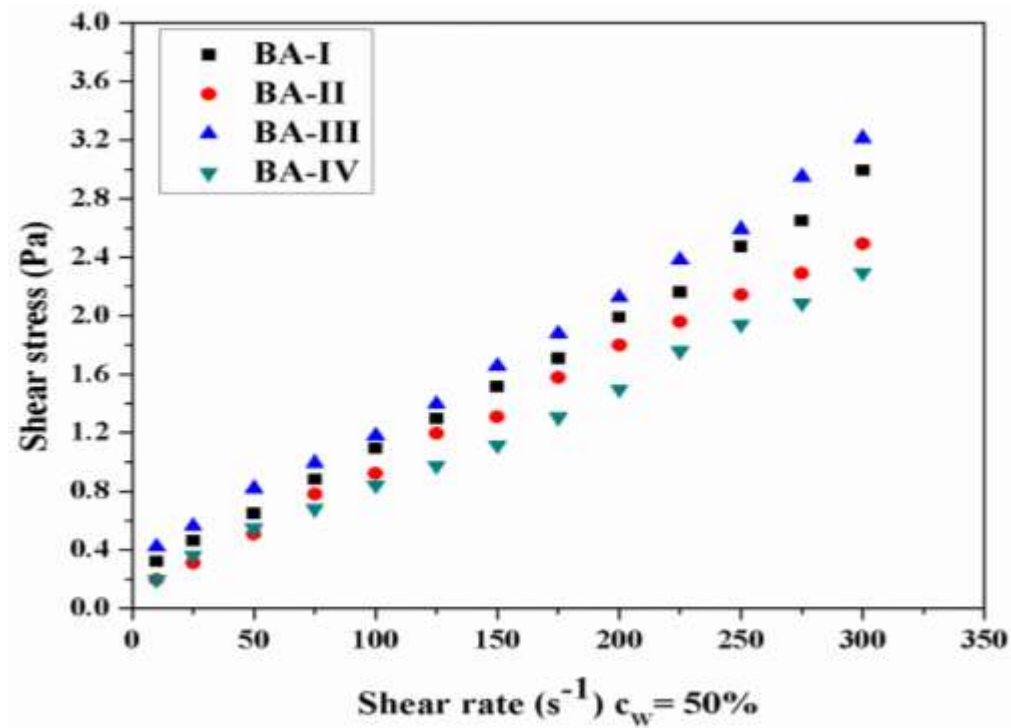


Figure 5.12: Shear stress-shear rate curves of bottom ash suspensions at $C_w = 50\%$

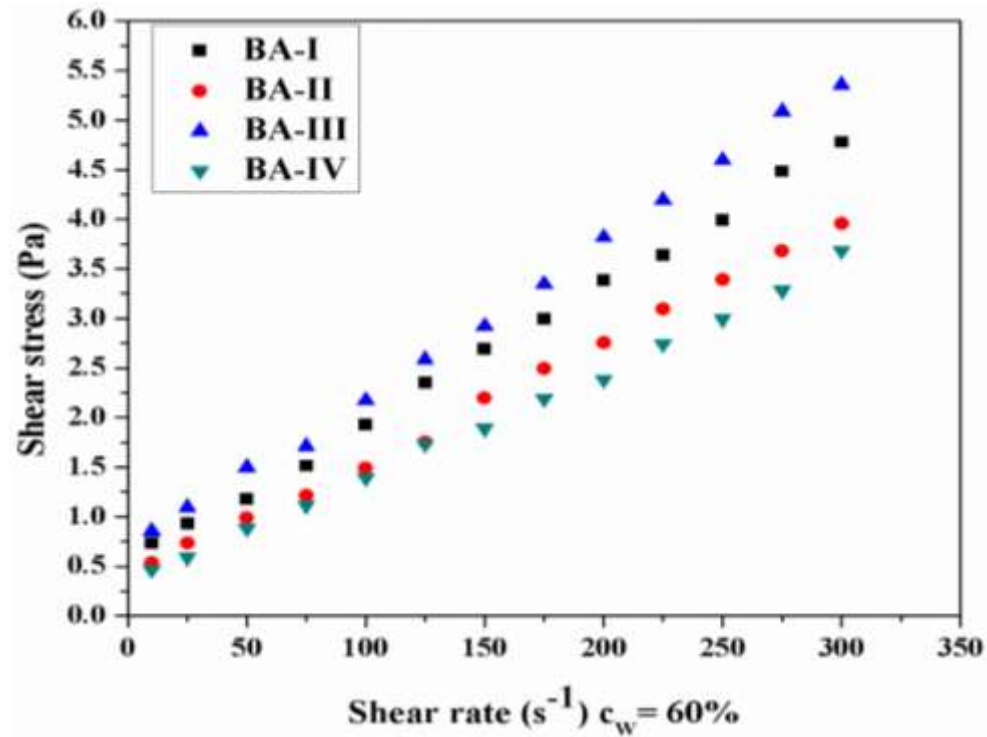


Figure 5.13: Shear stress-shear rate curves of bottom ash suspensions at $C_w = 60\%$

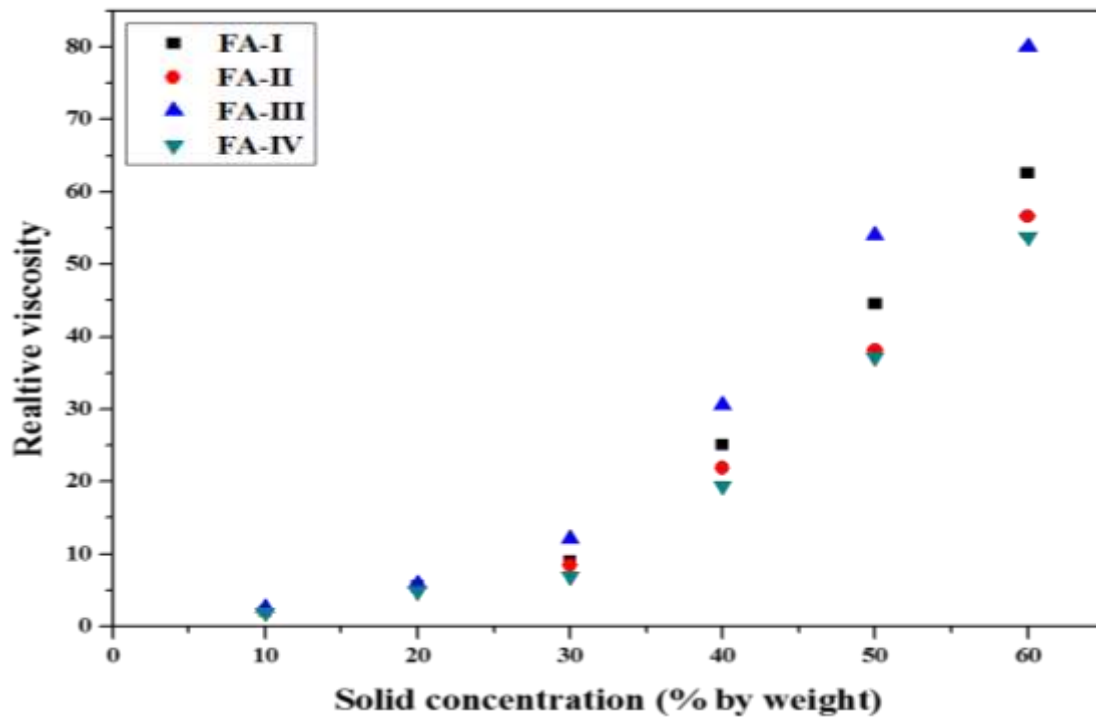


Figure 5.14: Variation in relative viscosity of fly ash suspension at different solid concentration

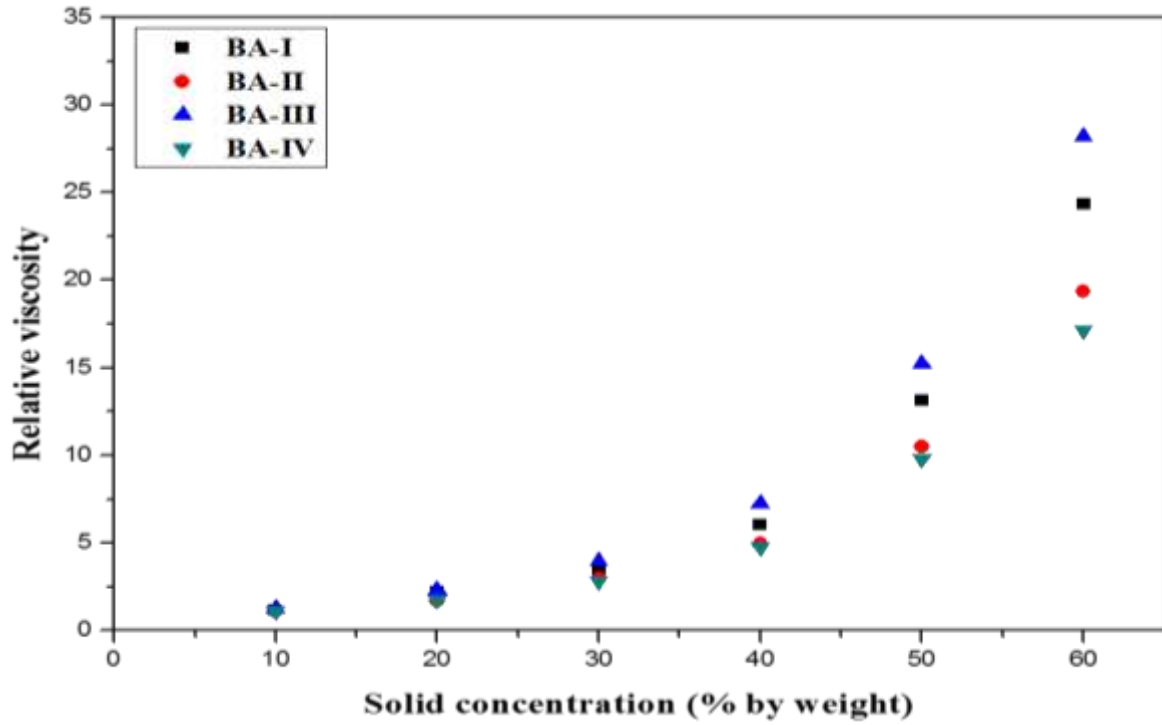


Figure 5.15: Variation in relative viscosity of bottom ash suspension at different solid concentration

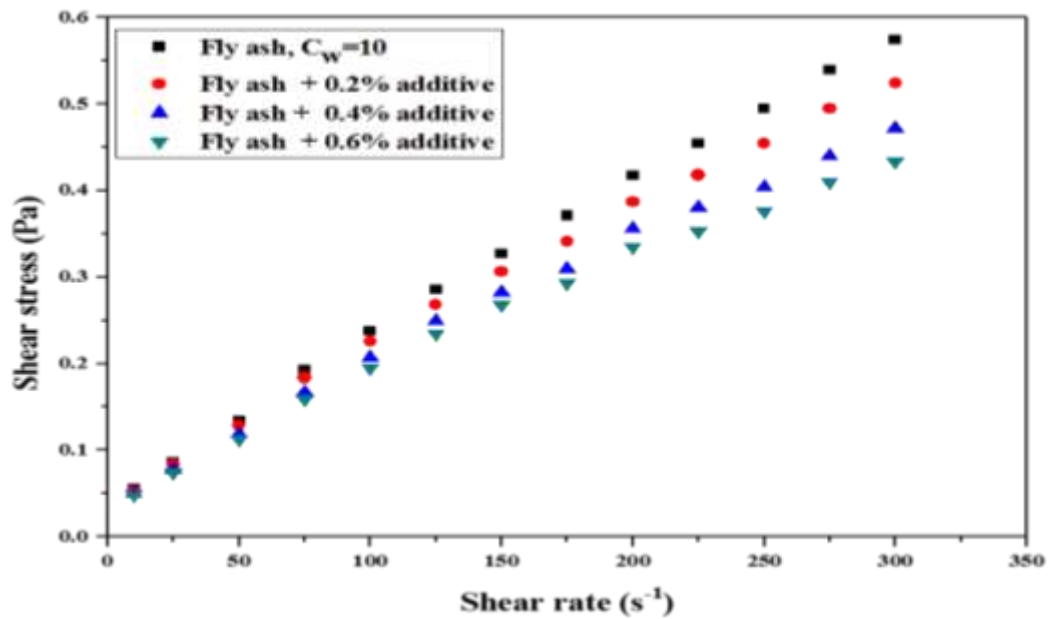


Figure 5.16: Shear stress-shear rate curves of fly ash suspensions at 10% solid concentration with and with addition of additive

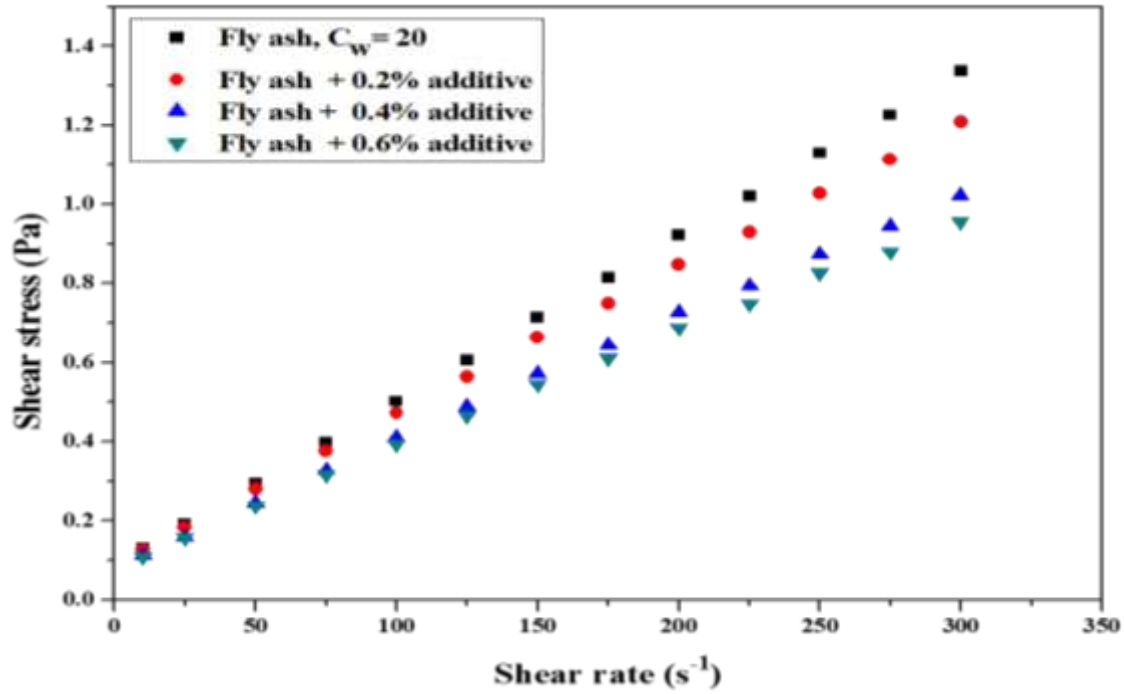


Figure 5.17: Shear stress-shear rate curves of fly ash suspensions at 20% solid concentration with and with addition of additive

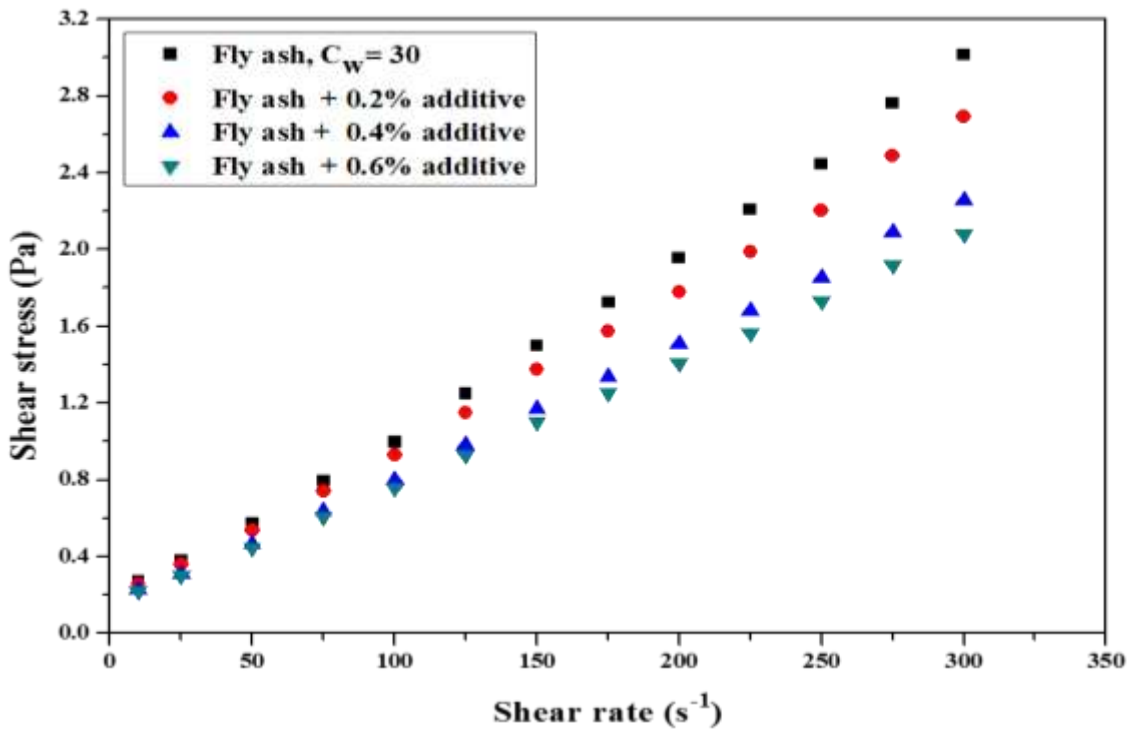


Figure 5.18: Shear stress-shear rate curves of fly ash suspensions at 30% solid concentration with and with addition of additive

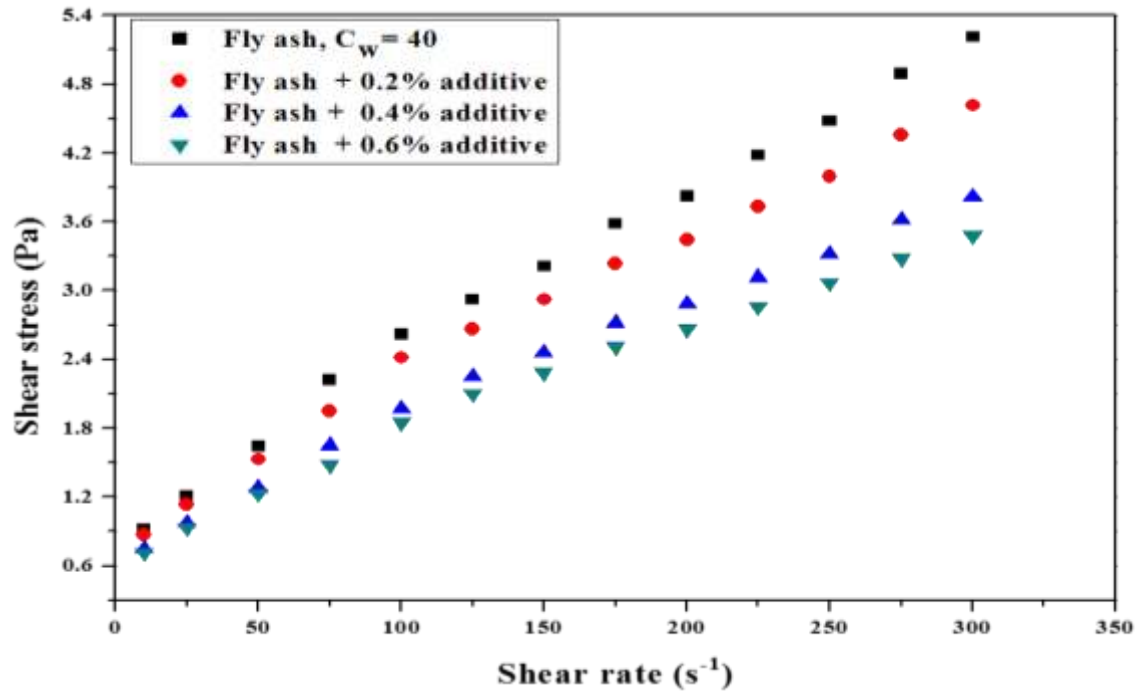


Figure 5.19: Shear stress-shear rate curves of fly ash suspensions at 40% solid concentration with and with addition of additive

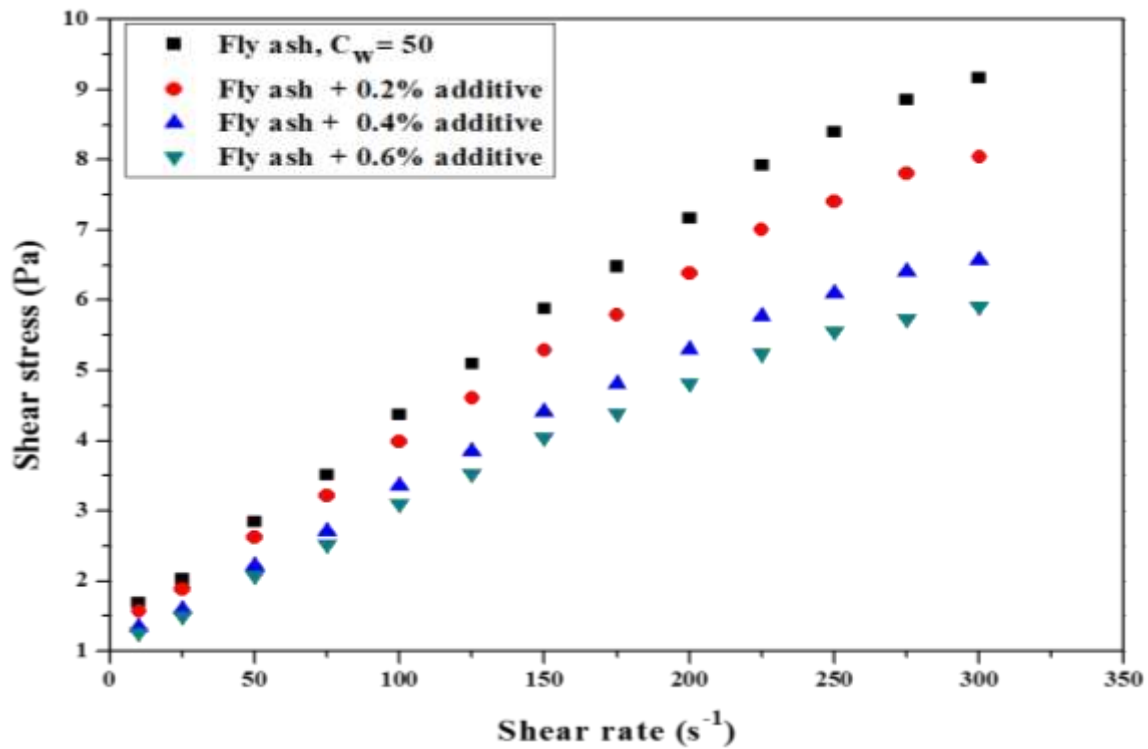


Figure 5.10: Shear stress-shear rate curves of fly ash suspensions at 50% solid concentration with and with addition of additive

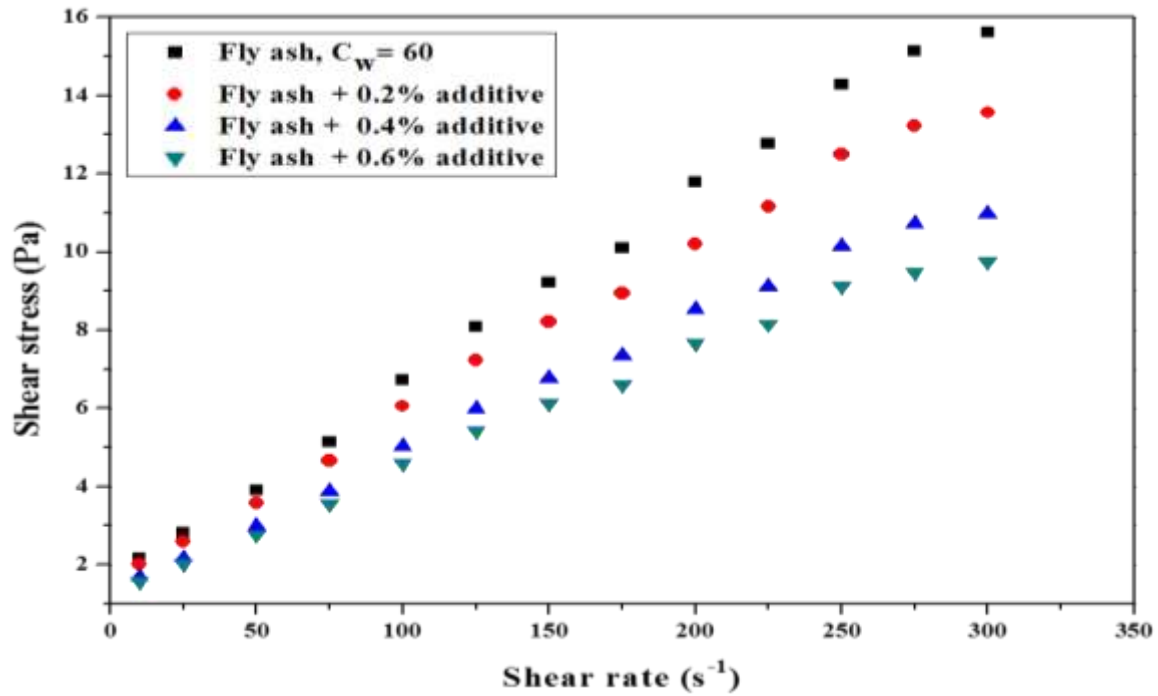


Figure 5.11: Shear stress-shear rate curves of fly ash suspensions at 60% solid concentration with and with addition of additive

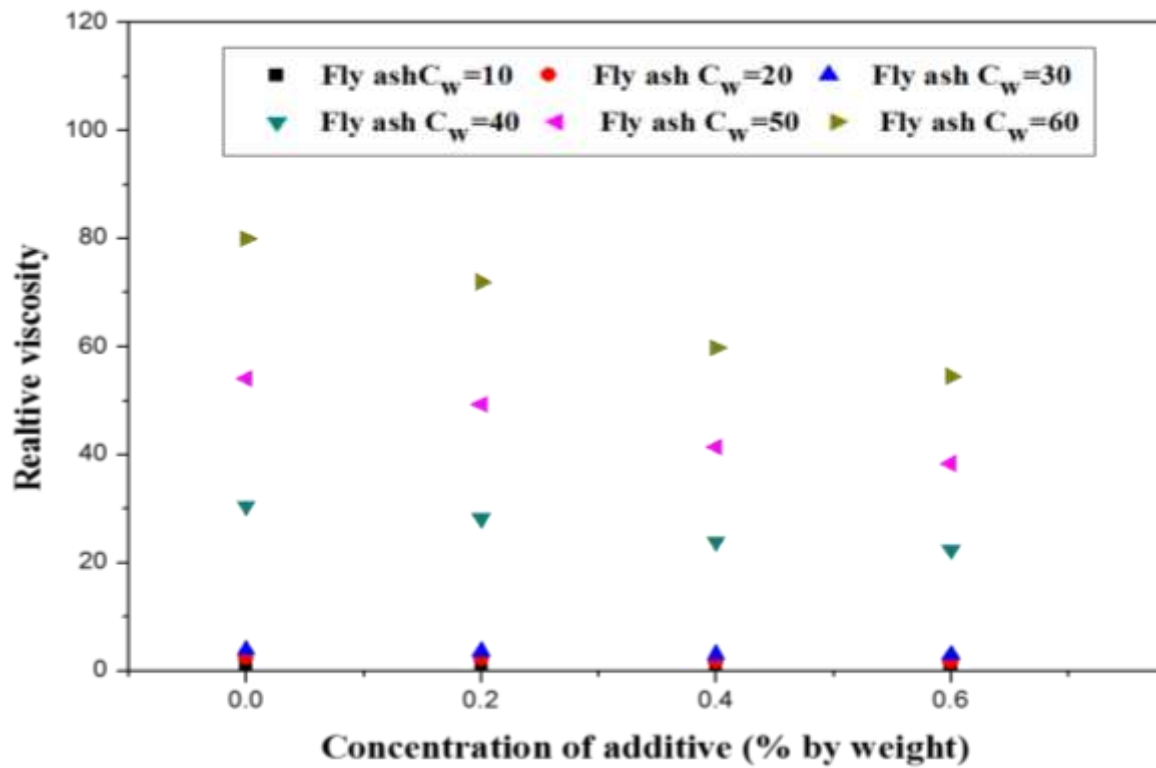


Figure 5.22: Variation of relative viscosity of fly ash suspension at different solid concentration with and with addition of additive

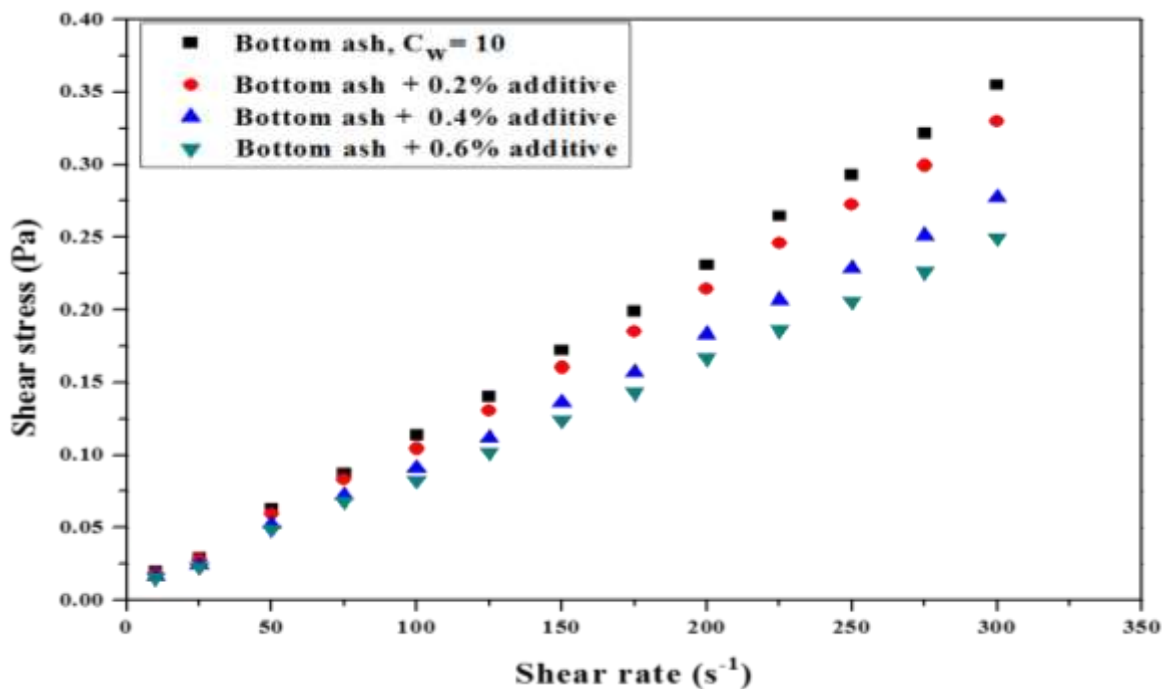


Figure 5.23: Shear stress-shear rate curves of bottom ash suspensions at 10% solid concentration with and with addition of additive

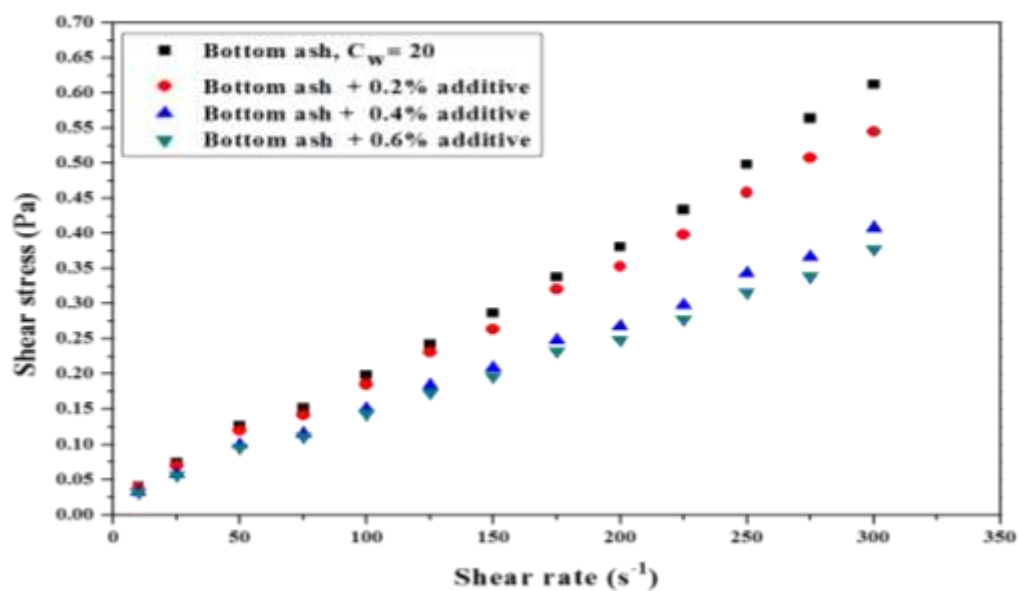


Figure 5.24: Shear stress-shear rate curves of bottom ash suspensions at 20% solid concentration with and with addition of additive

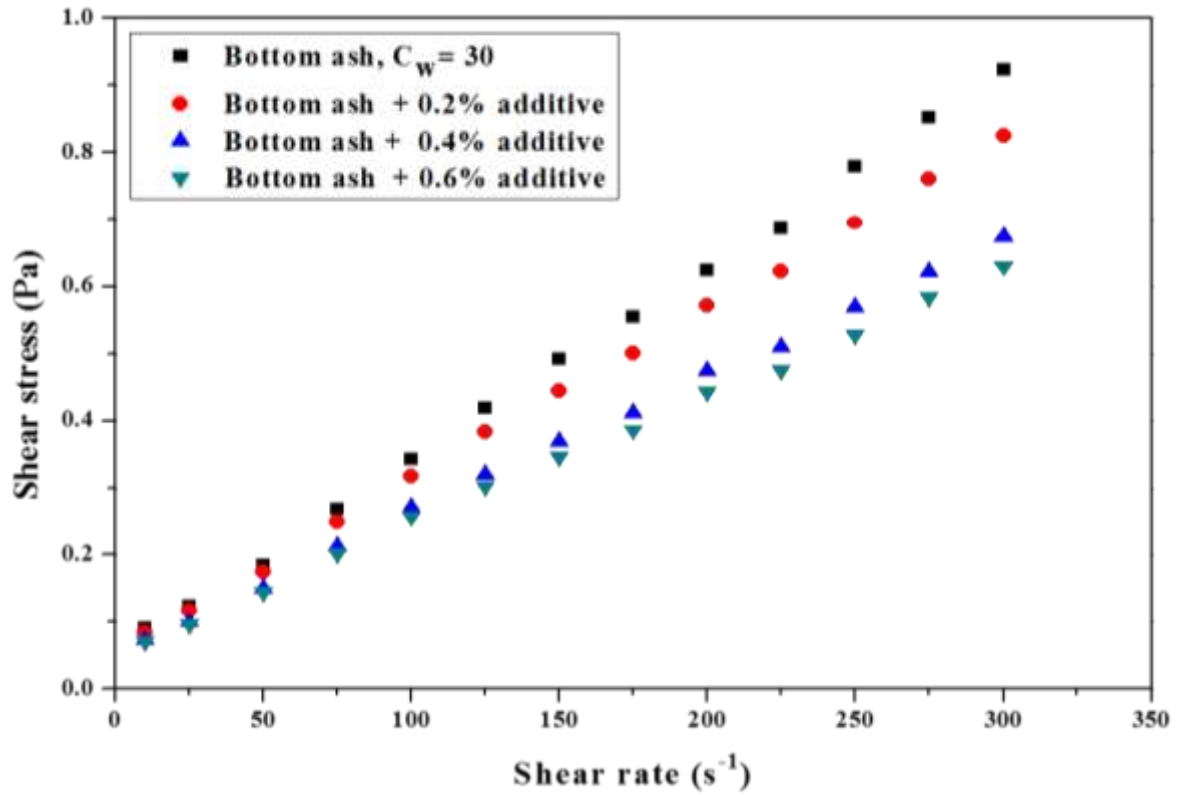


Figure 5.25: Shear stress-shear rate curves of bottom ash suspensions at 30% solid concentration with and with addition of additive

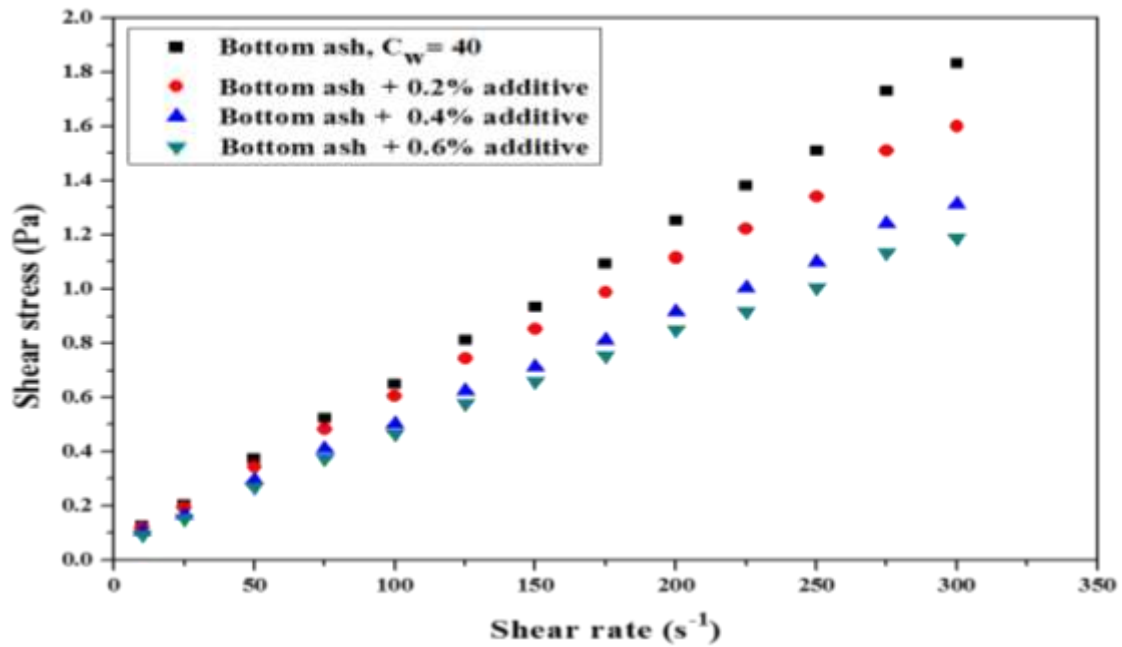


Figure 5.26: Shear stress-shear rate curves of bottom ash suspensions at 40% solid concentration with and with addition of additive

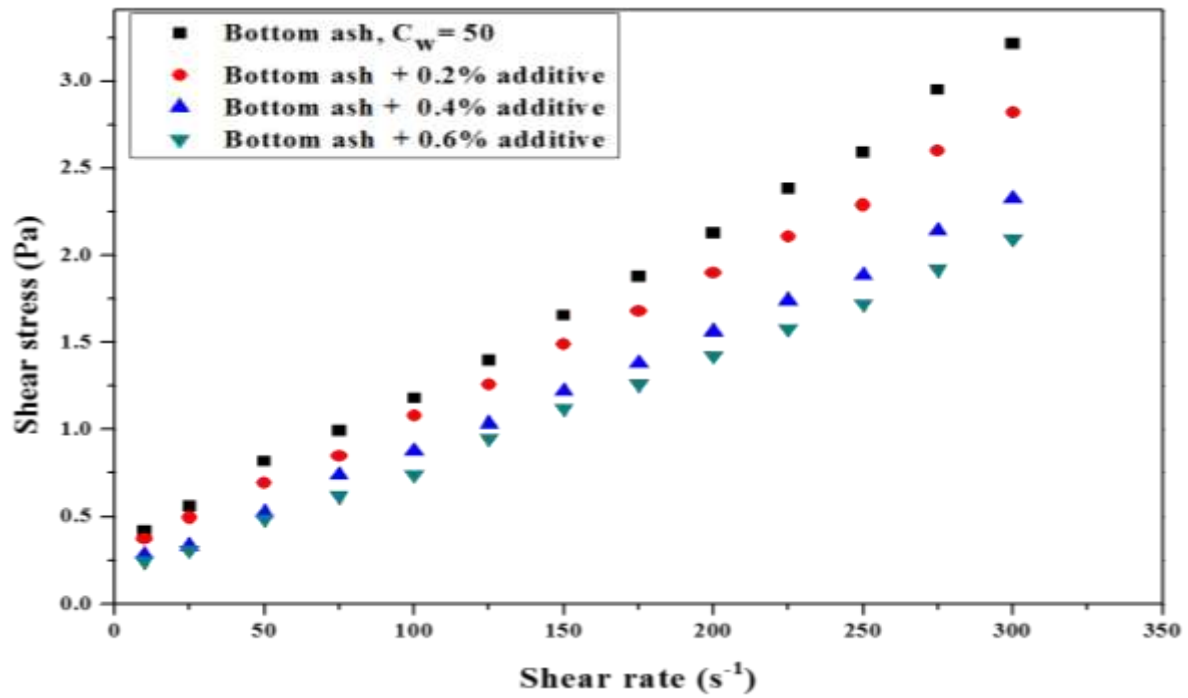


Figure 5.27: Shear stress-shear rate curves of bottom ash suspensions at 50% solid concentration with and with addition of additive

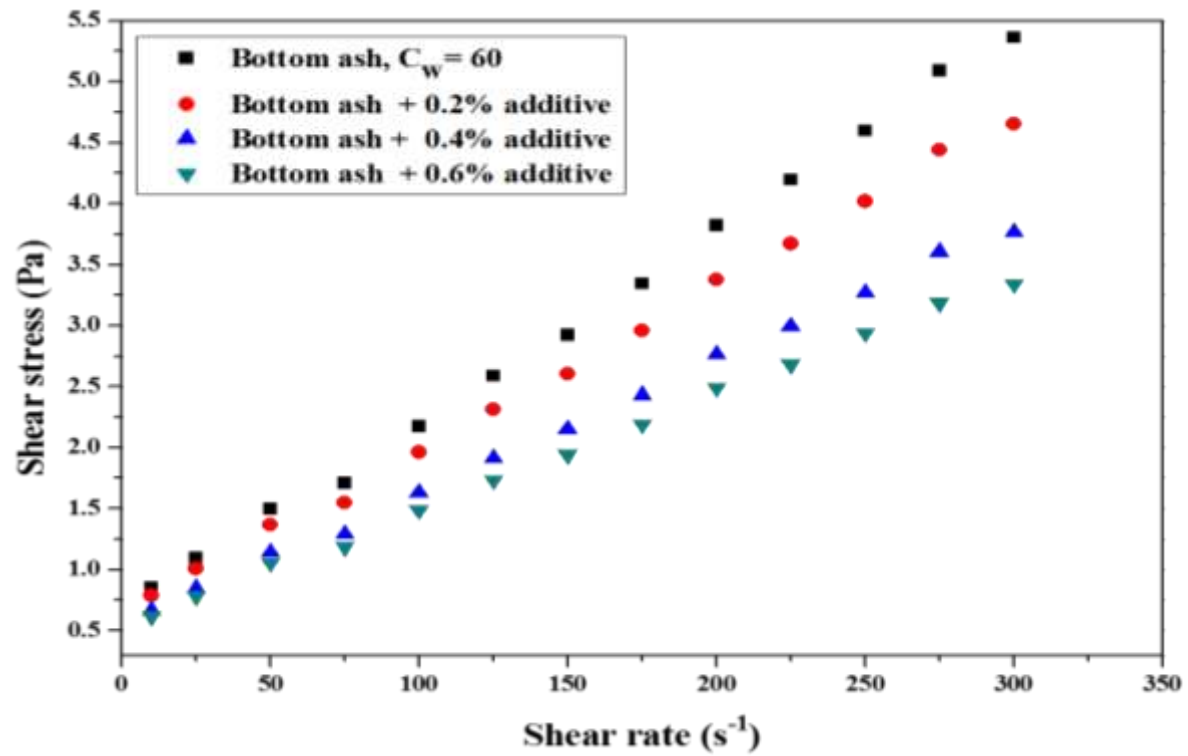


Figure 5.28: Shear stress-shear rate curves of bottom ash suspensions at 60% solid concentration with and with addition of additive

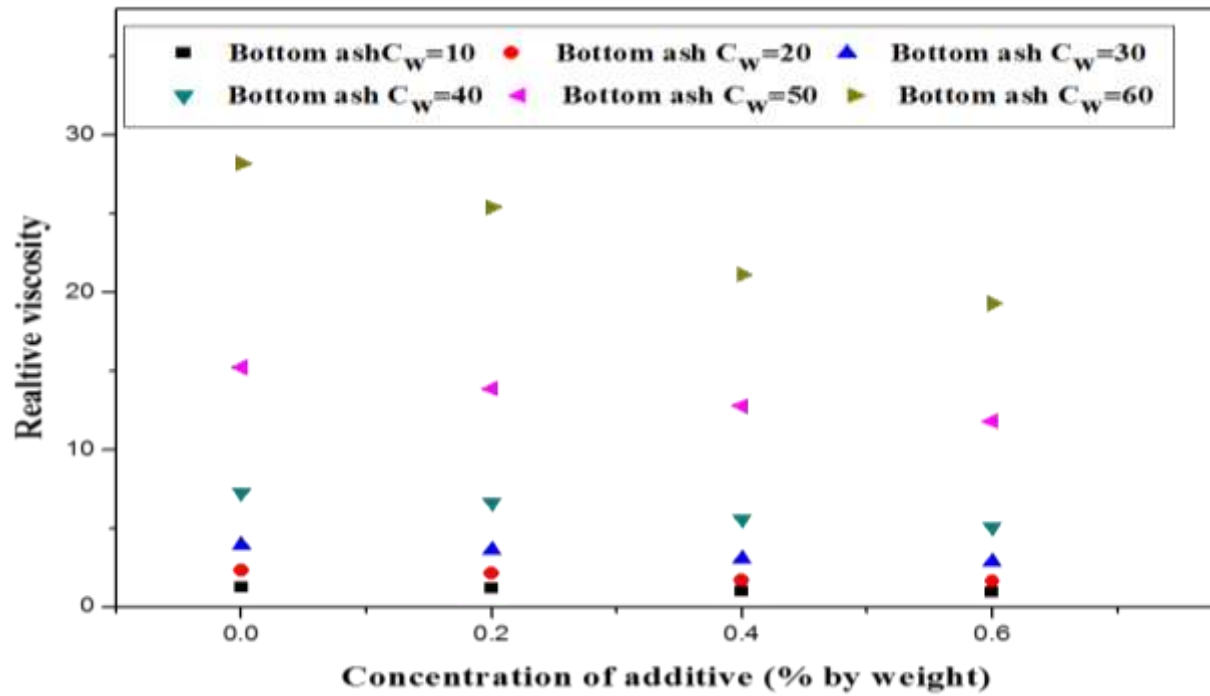


Figure 5.29: Variation of relative viscosity of bottom ash suspension at different solid concentration with and with addition of additive

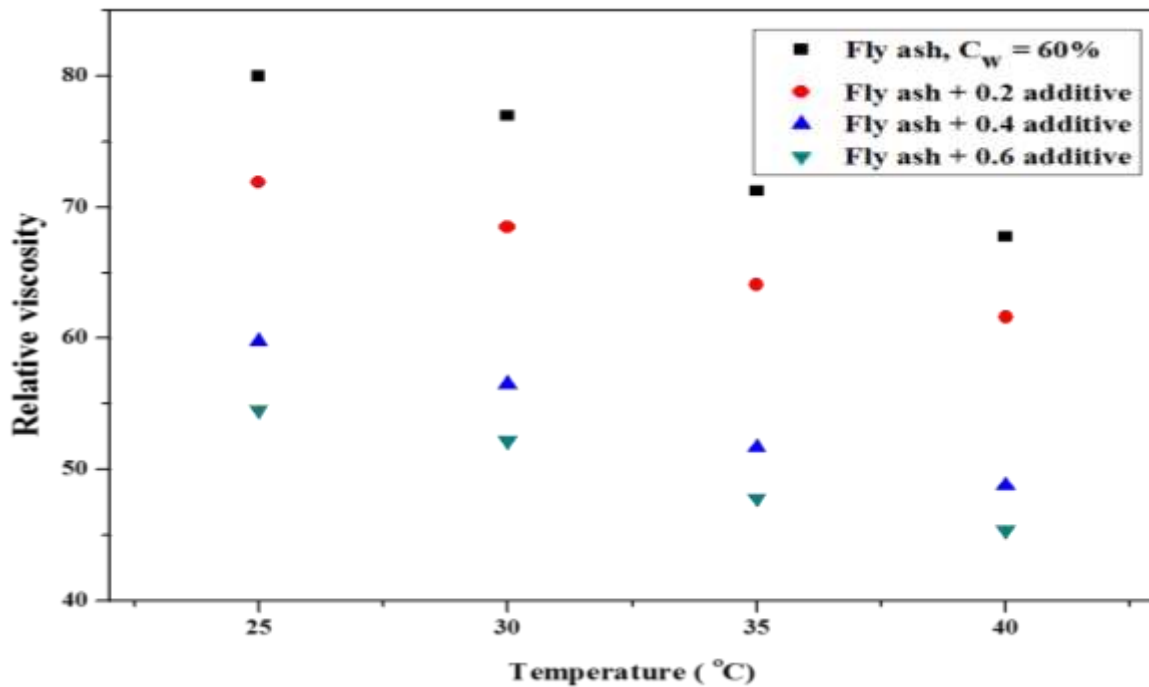


Figure 5.30: Effect of temperature on relative viscosity of fly ash suspension at C_w 60% solid concentration with and with addition of additive

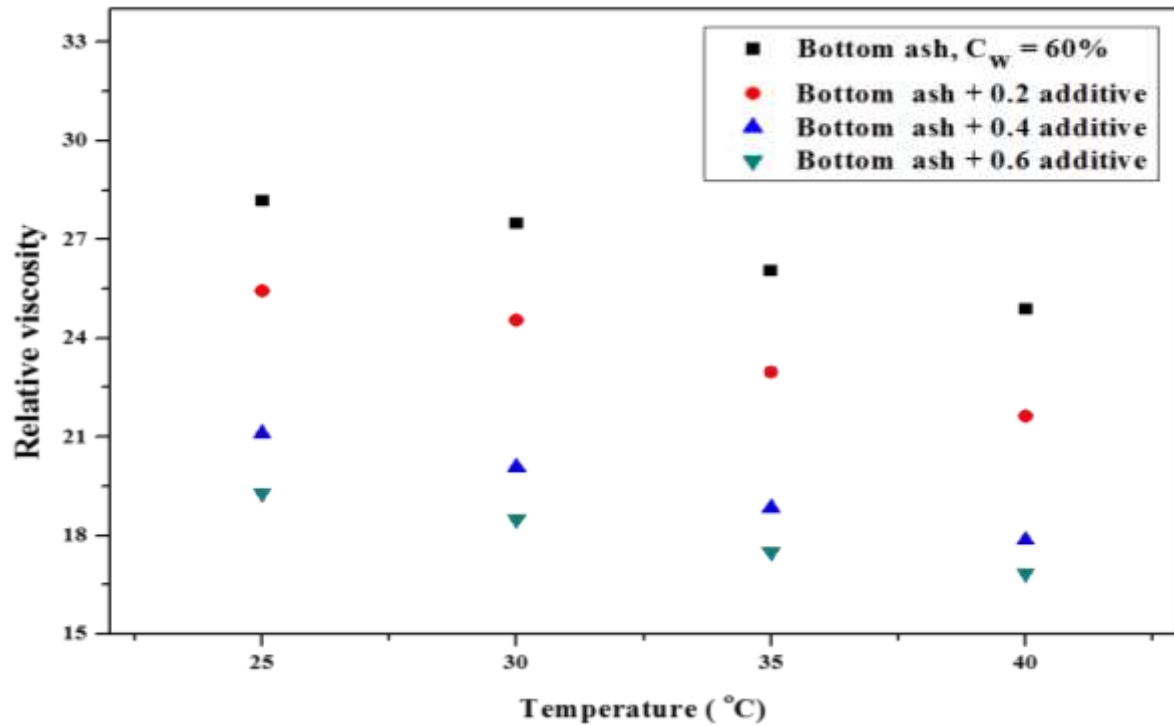


Figure 5.31: Effect of temperature on relative viscosity of bottom ash suspension at C_w 60% solid concentration with and with addition of additive

Table 5.1: Specification of rheometer (Rheolab QC)

S. No.	Component	Specification
1	Motor type	Synchronous EC motor
2	Speed range	0.01 to 1200 (min^{-1})
3	Shear stress range	0.5 to 3×10^4 (Pa)
4	Shear rate range	0.01 to 4000 sec^{-1}
5	Viscosity range	1 to 10^9 (mPa.s)
6	Temperature range	-20 to 180 ($^{\circ}\text{C}$)

Table 5.2: Flow behaviour of fly ash at different solid concentration

S. No.	Concentration (C_w)	Yield stress				Relative viscosity				Flow type
		FA-I	FA-II	FA-III	FA-IV	FA-I	FA-II	FA-III	FA-IV	
1	10	0	0	0	0	2.10	2.02	2.62	1.97	Newtonian
2	20	0	0	0	0	5.60	5.31	5.86	4.88	Newtonian
3	30	0	0	0	0	8.98	8.49	12.18	6.94	Newtonian
4	40	0.91	0.72	0.98	0.64	25.14	21.87	30.57	19.42	Non-Newtonian
5	50	1.39	1.07	1.57	1.05	44.50	38.11	54.08	37.24	Non-Newtonian
6	60	1.67	1.64	1.71	1.53	62.57	56.65	80.00	53.78	Non-Newtonian

Table 5.3: Flow behaviour of bottom ash at different solid concentration

S. No.	Concentration (C_w)	Yield stress				Relative viscosity				Flow type
		BA-I	BA-II	BA-III	BA-IV	BA-I	BA-II	BA-III	BA-IV	
1	10	0	0	0	0	1.16	1.11	1.28	1.10	Newtonian
2	20	0	0	0	0	2.22	1.71	2.33	1.72	Newtonian
3	30	0	0	0	0	3.47	2.98	3.95	2.80	Newtonian
4	40	0	0	0	0	6.06	5.00	7.25	4.73	Newtonian
5	50	0.19	0.14	0.28	0.13	13.12	10.48	15.22	9.81	Non-Newtonian
6	60	0.51	0.36	0.63	0.32	24.37	19.33	28.00	17.13	Non-Newtonian

Chapter 6

HEAD LOSS CHARACTERISTICS FOR THE FLOW OF FLY AND BOTTOM ASH SLURRIES

Combustion of coal produces large amount of fly and bottom ash as the residual products. The disposal of these residual products become a challenging task for researchers and scientists. Design of ash disposal system is one of the important aspect which depends upon number of parameters like rheology, flow rate head loss of slurry suspension etc. Researchers reported that head loss is the highly influencing parameter for designing of ash disposal system (Chandel et al., 2012; Kumar et al., 2014; Kumar et al., 2017). Extensive review of literature in Chapter 2, indicating towards the requirements of head loss data for the flow of fly and bottom ash suspensions. The problems of ash disposal and its better utilization have also been discussed in Chapter 3.

Basically, the design of slurry pipelines consists of the calculation of head loss which can be determined by performing rheological tests. However, the multisized particles present in slurry makes the rheological experiments quite insufficient and complex. The ashes produced in different locations have different physical properties like specific gravity, bulk density and particle size distributions. Therefore, in order to design the slurry pipeline, it is essential to identify the optimal parameters with the help of correlation. The present investigation pilot plant loop has been used for experimental investigation of head loss while Darby and Melson (1981) model is used to calculate predicted head loss in slurry pipeline. Results obtained from the study are beneficial for the design of ash disposal pipeline with high precisions.

6.1 Characterization of fly and bottom ash

The samples of fly and bottom ash are collected from Guru Hargovind Singh thermal power plant, Lahra Mohbat (Punjab), India. Different small scale tests were conducted for the measurement of physico-chemical, mineralogical and rheological characteristics of fly and bottom ash samples that are already discussed in Chapter 3 and 5.

6.2 EXPERIMENTAL PROCEDURE

The head loss in horizontal slurry pipelines of pilot-plant testing loop (100 mm NB) is calculated with the help of the pressure transducer. A pilot test loop used measured head loss is shown in Figure 6.1. The major component of test loop are slurry pump, flow meter, pressure transducer, flow control valves, measuring tank, stirrer, motor, observation chamber, preparation tank and pipeline etc. Electromagnetic type flow meter and pressure transducer is used to measured flow, inlet head and delivery head. The total length of loop is about 60 meters. Coal ash slurry was prepared in slurry preparation tanks of conical shape. To avoid settling of coal ash slurry in tank a stirrer is provided. A screw type cavity slurry pump is used to transfer coal ash slurry from slurry tank to pipelines to measure head loss in pipeline. The actual concentration of coal ash slurry was determined by taking sample from sampler. The collected sample was dry and then calculated the weight of ash to determine actual concentration of solid pass through the pipeline. Before start the experiment with coal ash slurry, initial loop was run with water and its head loss was measured. Afterwards, the coal ash slurry was prepared by addition of fly and bottom ash to measured head loss. During the experiments solid concentration (C_w) of coal ash was fixed i.e 60 % (by weight). The slurry was continuous circulate in pipeline till the experimentation was completed at different flow velocity. After completion of experiment slurry was drain by open drain valve. The water was supply from water tanks to clean the test loop to avoid and blockage by solid ash in loop. The head loss measured from test loop is presented as a function of flow velocity in terms of mWc/m of pipeline.

6.2.1 Range of parameters

The present study is carried out with pilot plant test loop of 60 meter length and 100mm diameter. The experiments of head loss were conducted for the flow of fly and bottom ash slurry at 60% (by weight) solid concentrations. The effect of addition of additive (Sodium bi-carbonate) on head loss was also determined by changing solid concentration of additive from 0.2-0.6% (by weight). Measurements of head loss was measured for flow velocities in the range of 0.5 to 4.5 ms^{-1} .

6.3 Mathematical method for prediction of head loss

The friction factor can be considered as primary factor for prediction of head loss in pipeline flow. The flow characteristics of any solid liquid flow can be divided into three sections such as laminar,

transition, and turbulent flow. The flow behavior of a fluid depends upon its Reynolds number while fanning friction factor for transition and turbulent flow depends on empirical relations. The experimental value required to for prediction of head loss was taken from Table 5.2 and 5.3. The experimental value of viscosity, yield stress and density was used in model for predict head loss in horizontal slurry pipe line. Darby and Melson (1981) developed an analytical correlation to predict the head loss in slurry pipeline. Friction factor was calculated with the help of a relation between Bingham Reynolds number (Re_b) and Hedstorm number (H_{ed}) given by Buckingham (1912) as:

$$\frac{f}{16} - \frac{H_{ed}}{6R_{eb}^2} + \frac{H_{eb}^4}{3f^3R_{eb}^8} = \frac{1}{R_{eb}} \quad (6.1)$$

$$H_{ed} = \frac{D^2 \tau_{yb} \rho_s}{\mu_s^2} \quad (6.2)$$

$$R_{eb} = DV \frac{\rho_s}{\mu_s} \quad (6.3)$$

For modified Reynolds number, friction factor is written as $f = \frac{16}{R_{e\text{ mod}}}$ (6.4)

$$R_{e\text{ mod}} = \frac{6R_{eb}^2}{6R_{eb} + H_{ed}} \quad (6.5)$$

The critical value of Reynolds number (Re_{bc}) is shown in equation (6.6):

$$R_{ebc} = \frac{H_{ed}}{8X_{cs}} \left(1 - \frac{4}{3}X_{cs} + \frac{1}{3}X_{cs}^4 \right) \quad (6.6)$$

$$\frac{X_{cs}}{(1-X_{cs})^3} = \frac{H_{ed}}{16800} \quad (6.7)$$

Darby and Melson (1981) developed a correlation of Fanning friction factor is shown in equation (6.8):

$$f_t = 10^c (R_{eb})^{-0.193} \quad (6.8)$$

$$c = -1.378(1 + 0.146 \times \exp(-2.9 \times 10^{-5} \times R_{eb})) \quad (6.9)$$

Darby and Melson (1921) modified the above discussed equations to measure the friction factor for flow regimes as given by:

$$f = (f_l^m + f_t^m)^{\frac{1}{m}} \quad (6.10)$$

$$m = 1.7 + \frac{40000}{R_{eb}} \quad (6.11)$$

The head loss in circular pipeline was predicted for fly and bottom ash suspensions using equation (6.12):

$$\Delta p = f \frac{l}{d} \times \frac{\rho V^2}{2} \quad (6.12)$$

6.4 Results and discussion

Experimental investigation was carried out to determine the head loss of fly and bottom ash slurry with and without addition of additive at 60% (by weight) solid concentration. Sodium bi-carbonate is used as an additive for fly and bottom ash slurry with concentration range of 0.2-0.6% (by weight). The head loss is measured for varying velocities from 0.5 to 4.5 ms⁻¹ at 60% (by weight) solid concentration.

6.4.1 Effect of flow velocity on head loss characteristics of fly and bottom ash slurry

Head loss in horizontal pipeline was also investigated for fly and bottom ash with additive. Figure 6.2 the variation in head loss with flow velocity ranging from 0.5 to 4.5 ms⁻¹ at 60% (by weight) solid concentration for fly ash slurry. The head loss was increased from 2.91 to 5.12 mWc/m as the flow velocity was increased from 0.5 to 1.5 ms⁻¹ whereas head loss increase from 5.12 to 11.28, 11.28 to 20.25 and 20.25 to 32.50 mWc/m as flow velocity increases from 1.5 to 2.5, 2.5 to 3.5 and 3.5 to 4.5 ms⁻¹ respectively. Experimental results reveals that head loss was increased with increase in flow velocity. However, results also indicated that at higher flow velocity (2.5 to 4.5 ms⁻¹), the rate of increase in head loss was quite higher as compared to lower flow velocity (0.5 to 1.5 ms⁻¹). This may attribute that flow behaviour in slurry pipeline was shifted from laminar to turbulent with change in flow velocity. The experimental results found to be good aggregate with the results reported by researchers (Verma et al. 2006; Chandel et al. 2009). Figure 6.3 shows the

head loss of bottom ash slurry suspension with change in flow velocity. The head loss in slurry pipeline was increased from 1.43 to 4.39, 4.39 to 9.65, 9.65 to 18.14 and 18.14 to 28.08 mWc/m as flow velocity increases from 0.5 to 1.5, 1.5 to 2.5, 2.5 to 3.5 and 3.5 to 4.5 ms⁻¹ respectively. Head loss characteristics of bottom ash slurry in pipeline shows similar trend as fly ash slurry. Experimental results also reveal that head loss for fly ash slurry suspension is higher as compared to bottom ash at same experimental condition.

6.4.2 Effect of addition of additive on head loss for fly and bottom ash slurry

The addition of additive improve the rheological characteristics of fly and bottom ash slurry is already discussed in Chapter 5. In order to measure the head loss fly and bottom ash slurry suspension with additive, a separate experimentation was performed. The additive (Sodium bi-carbonate) with dosage proportion 0.2, 0.4 and 0.6% (by weight) was added in fly and bottom ash slurry. The effect of addition of additive at different flow velocities of fly and bottom ash slurry suspension is shown in Figure 6.2-6.3. The head loss results shows that addition of additive significantly affect the head loss. The head loss was increased as the flow velocity increases. Moreover, considerable reduction in head loss was observed with addition of additive. In other words, the head loss was decreases with increase in concentration of additive in both fly and bottom ash slurries. The addition of additive in coal ash slurry tends to increase the pH of the slurry suspension and also highly soluble into water. The addition of additive in slurry suspension reduce the inter-particle particle friction. This should considerably effect on head loss in slurry pipeline. The reduction in head loss for fly ash slurries was found as 13.05, 23.17 and 9.15% with addition of 0.2, 0.4 and 0.6% additive whereas 11.16, 19.02 and 7.27% for bottom ash slurry respectively. The experimental results found to be good aggregate with the results reported by researchers (Chandel et al. 2002; Seshadri et al. 2008; Kumar et al.2017). For a given solid concentration, suspension of fly and bottom ash slurry suspension maximum reduction in head loss was found with addition of 0.4% additive.

6.4.3 Experimental versus predicted head loss

Head loss in a straight horizontal circular pipeline of diameter 100 mm have been calculated by using the Darby and Melson (1981) model which is discussed in Section 6.3. To attain better precision, experimental data of head loss was compared to the predicted values obtained from

model. Thus, the deviation of head loss for experimental and predicted values obtained for the fly as well as bottom ash slurry suspension. With the help of experimental value of viscosity and yield stress, computations was performed to determine the head loss in slurry pipe line of 100 mm diameter by Darby and Melson (1981) method. The comparison between predicted and experimental values of head loss for fly and bottom ash slurry at 60% solid concentration at different flow velocity i.e 0.5, 1.5, 2.5, 3.5 and 4.5 ms^{-1} is represented in Figure 6.4-6.5. From figures it is noticed that the experimental data point of head loss falls closely to predicted values, which supports the prediction methodology. The experimental versus predicted head loss data with fly and bottom ash slurry at 60% solid concentration. Predicted head loss values ideally match with experimental results line. A reasonable agreement has been noticed. That is realistic for design purposes, as various uncertainties involved in the predicted and experimental procedures.

6.5 Head loss prediction by using theoretical approach

In present work, an effort has been made to predict the head loss in slurry pipeline for the flow of fly and bottom ash slurries at solid concentrations ranging from 10 to 60% (by weight) with and without addition of additives. Sodium bi-carbonate was used as an additive for fly and bottom ash slurry with concentration range of 0.2-0.6% (by weight). The head loss was determined at varying velocities from 0.5 to 4.5 ms^{-1} .

6.5.1 Effect of solid concentration on head loss characteristics of fly and bottom ash

Head loss prediction was made in 100 mm diameter pipe with fly and bottom ash slurry for concentration (C_w) varying from 10-60% (by weight). At each concentration, the head loss was calculated in meter of water column pipeline. Figure 6.6 represents the influence of solid concentration on head loss for the flow of fly ash suspension. It was found that the increase in solid concentration tends towards the increase in head loss at a specified velocity. This was due to fact that the increase in solid concentration results in step increase in density and viscosity of the slurry. Similar type of phenomenon was observed by investigators (Verma et al. 2006; Seshadri et al. 2008; Chandel et al. 2009; Senapati et al. 2010; Kumar et al. 2017). It was seems that head loss increased from 11.16 to 13.70, 13.70 to 19.10, 19.10 to 24.52, 24.52 to 27.43 and 27.43 to 30.44 mWc/m with increase in value of C_w from 10 to 20, 20 to 30, 30 to 40, 40 to 50 and 50 to 60 % at a flow velocity of 4.5 ms^{-1} respectively. Head loss versus solid concentration (C_w) curve of bottom ash suspension follows similar trend as for fly ash suspension. The variation of head loss at

different concentration for bottom ash suspension is shown in Figure 6.7. It observed that head loss increased from 9.66 to 11.40, 11.40 to 18.12, 18.12 to 21.35, 21.35 to 23.01 and 23.01 to 26.46 mWc/m with increase in value of C_w from 10 to 20, 20 to 30, 30 to 40, 40 to 50 and 50 to 60 % at a flow velocity of 4.5 ms^{-1} . Maximum value of head loss was found at $C_w=60\%$ while least at $C_w=30\%$ for given velocity 4.5 ms^{-1} of both fly as well as bottom ash suspensions.

6.5.2 Effect of velocity on head loss characteristics of fly and bottom ash

Head loss in slurry pipeline has been determined for the range of flow velocity $0.5\text{-}4.5 \text{ ms}^{-1}$ at different solid concentration (C_w) upto 60% (by weight). It was observed that head loss increased with increase in slurry velocity for a given solid concentration. In addition, it may be attributed that higher velocity leads to high head loss as compared to low flow velocities. It can be noticed that lower velocities (0.5 to 1.5 ms^{-1}) showed laminar flow while higher flow velocities showed turbulent flow. Similar observations are drawn by investigators (Verma et al. 2006; Chandel et al. 2009). It was noticed that head loss was increased from 2.23 to 4.87, 4.87 to 10.54, 10.54 to 19.33 and 19.33 to 30.44 mWc/m with increase in flow velocity from 0.5 to 1.5 , 1.5 to 2.5 , 2.5 to 3.5 and 3.5 to 4.5 ms^{-1} respectively at 60% solid concentration. Head loss characteristics of fly ash slurry in pipeline shows similar trend as bottom ash slurry whereas the head loss attains higher values for the flow of fly ash as compared to bottom ash. It is also found that the head loss is increased from 0.80 to 3.63, 3.63 to 9.14, 9.14 to 16.80 and 16.80 to 26.46 mWc/m with increase in velocity from 0.5 to 1.5 , 1.5 to 2.5 , 2.5 to 3.5 and 3.5 to 4.5 ms^{-1} respectively at 60% solid concentration. Maximum value of head loss is found at velocity 4.5 ms^{-1} while least value is observed at flow velocity 0.5 ms^{-1} for a given solid concentration of both fly as well as bottom ash suspensions.

6.5.3 Head loss characteristics of fly and bottom ash with additives

The discussion about change in rheological properties of slurry by the addition of additives has already discussed in Chapter 5. Sodium bicarbonate was used as an additive with proportion of 0.2, 0.4 and 0.6% (by weight). The effect by addition of additive was investigated by comparing head loss results for slurry suspensions with and without addition of additive. Results reveal that addition of additive significantly affects the head loss at higher concentrations. Head loss drop for fly and bottom ash suspension with additive at solid concentrations 60% (by weight), are shown in Figure 6.8-6.9. It was found that the value of head loss increases with increase in flow velocities and solid concentration for fly as well as bottom ash slurry suspension. However, a remarkable reduction in head loss was observed with addition of additive. In other words, the head loss

decreases with increase in proportion of additive in slurry suspensions. This may be attributed that addition of additive in slurry suspension reduced the inter particle friction and surface tension among the particles of ash which leads to decrease in head loss. Similar observations are also drawn by investigators (Chandel et al. 2002; Seshadri et al. 2008; Kumar et al.2017).The reduction in head loss for fly ash slurries was observed as 30.44 to 30.09, 30.09 to 29.40 and 29.40 to 29.10 mWc/m with addition of additive in 0.2, 0.4 and 0.6% (by weight) with 60% solid concentration at 4.5ms^{-1} whereas it was found 26.46 to 26.01, 26.01 to 25.68 and 25.68 to 25.43 respectively for bottom ash suspension. For a given solid concentration, suspension of bottom and fly ash slurry shows maximum reduction in head loss by adding the additive in weightage of 0.4% whereas marginal reduction in head loss is observed with addition of additive in propitiation of 0.2 and 0.4% for bottom as well as fly ash slurry suspensions.

6.6 Reflection

In the present investigation, head loss characteristics of bottom and fly ash suspension have been measured. Pilot plant loop has been used for experimental investigation of head loss while Darby and Melson (1981) model is used to calculate predicted head loss in slurry pipeline. Experimental and predicted results are compared and following conclusion are drawn:

- Maximum reduction in head loss was noticed with addition of additive in weight age of 0.4%.
- Experimental and predicted head loss results shows reasonable agreement for bottom and fly ash slurry suspension.

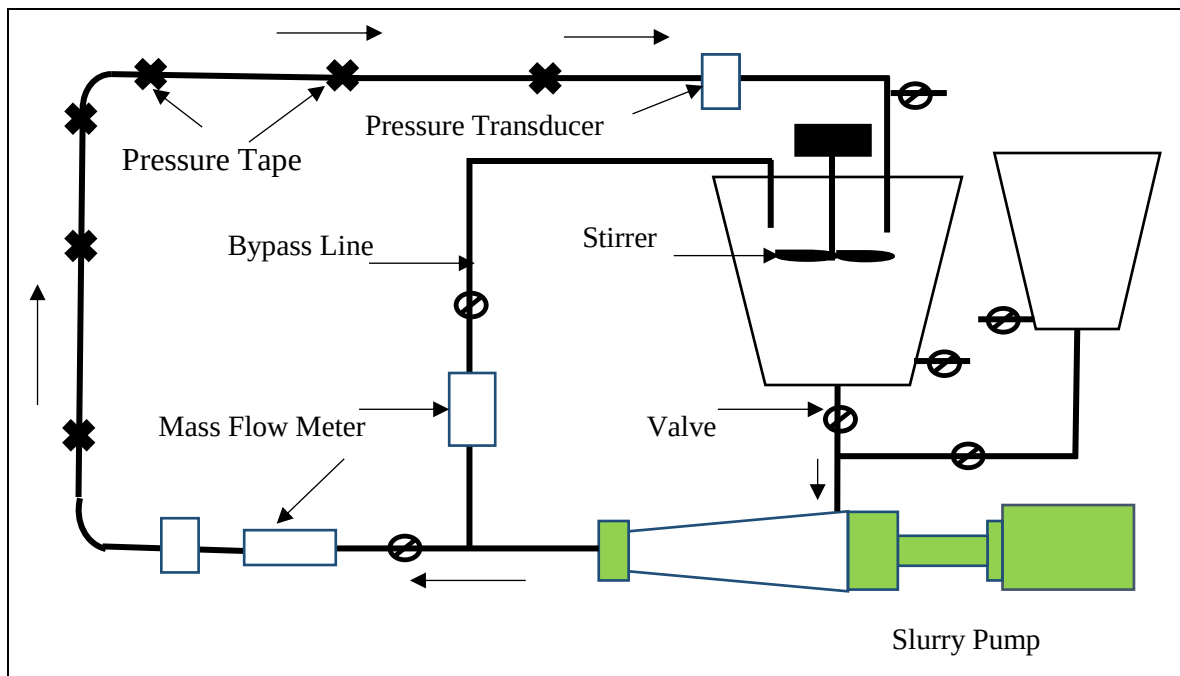


Figure 6.1: Schematic diagram of pilot plant test loop

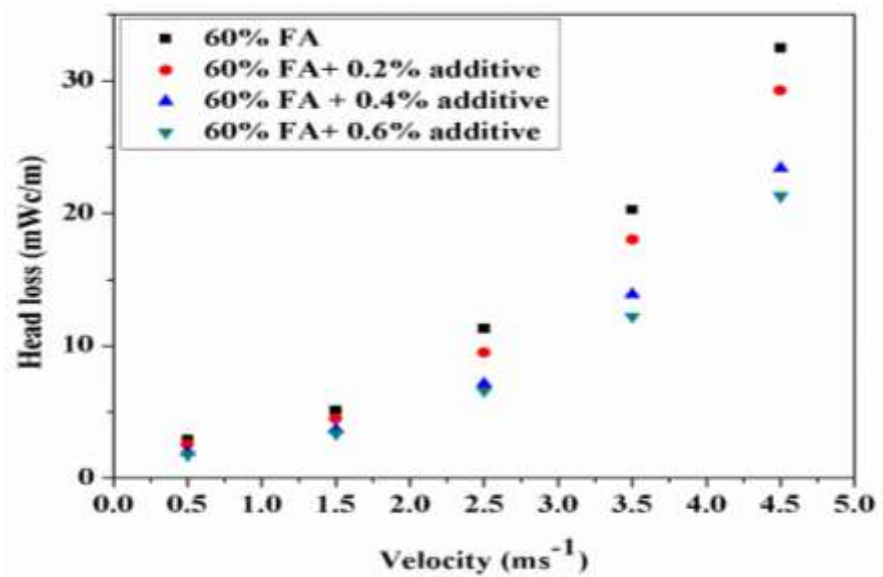


Figure 6.2: Experimental results of head loss fly ash slurry suspension with and without additive

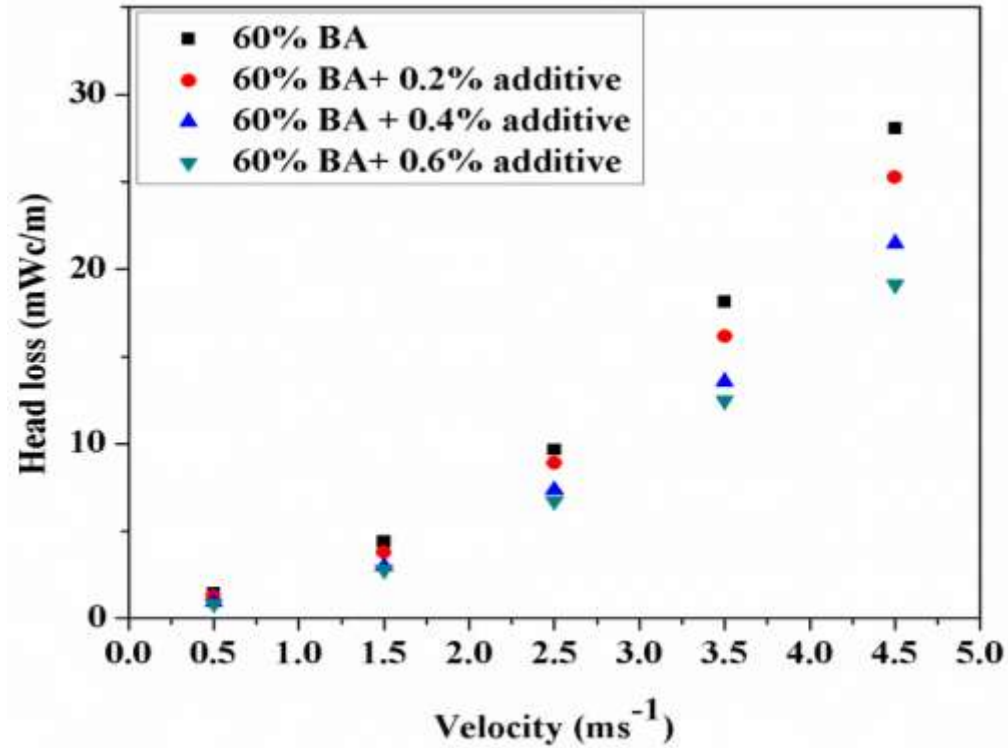


Figure 6.3: Experimental results of head loss bottom ash slurry suspension with and without additive

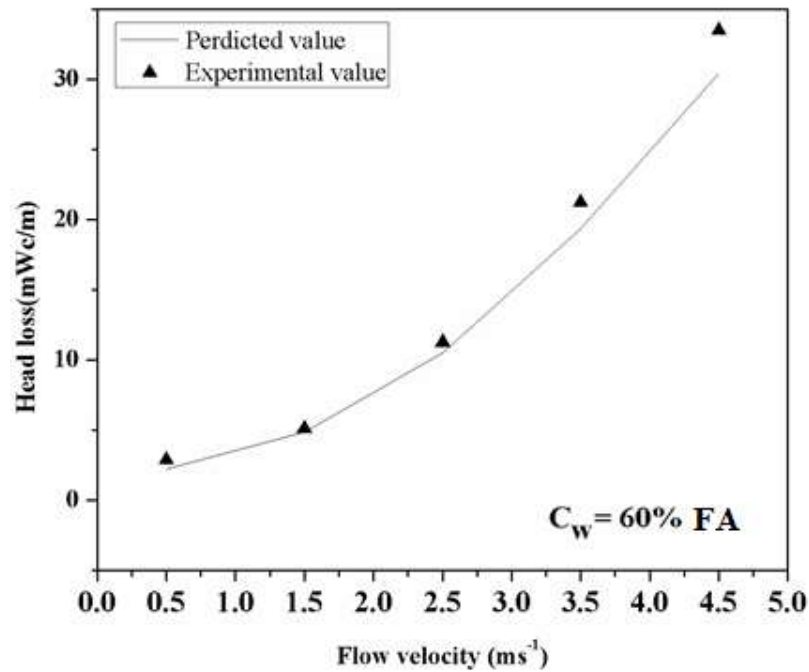


Figure 6.4: Comparison between experimental and predicted values of head loss for fly ash slurry suspension

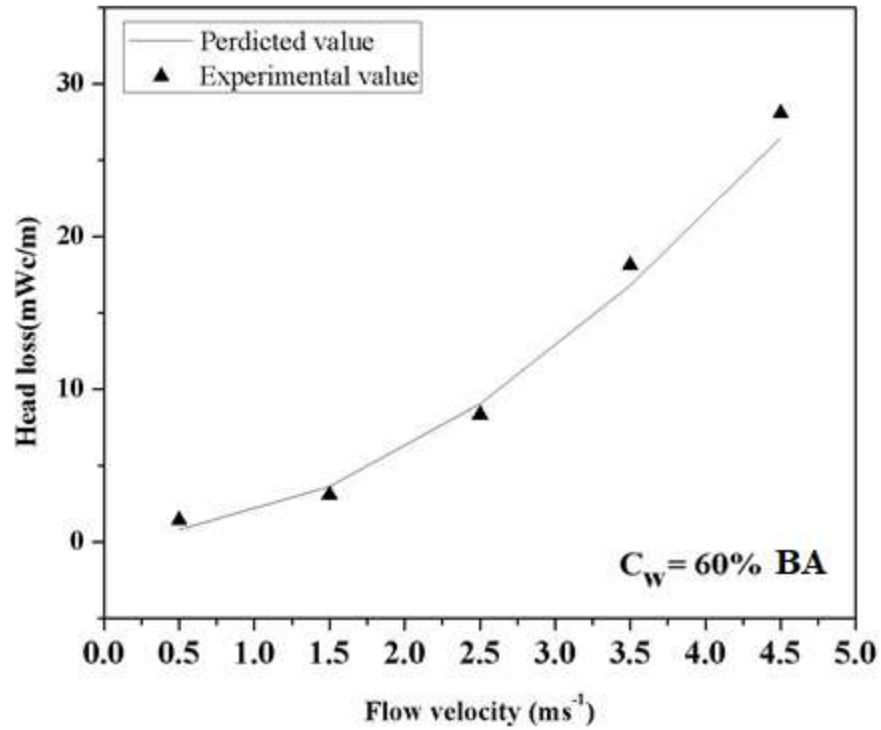


Figure 6.5: Comparison between experimental and predicted values of head loss for bottom ash slurry suspension

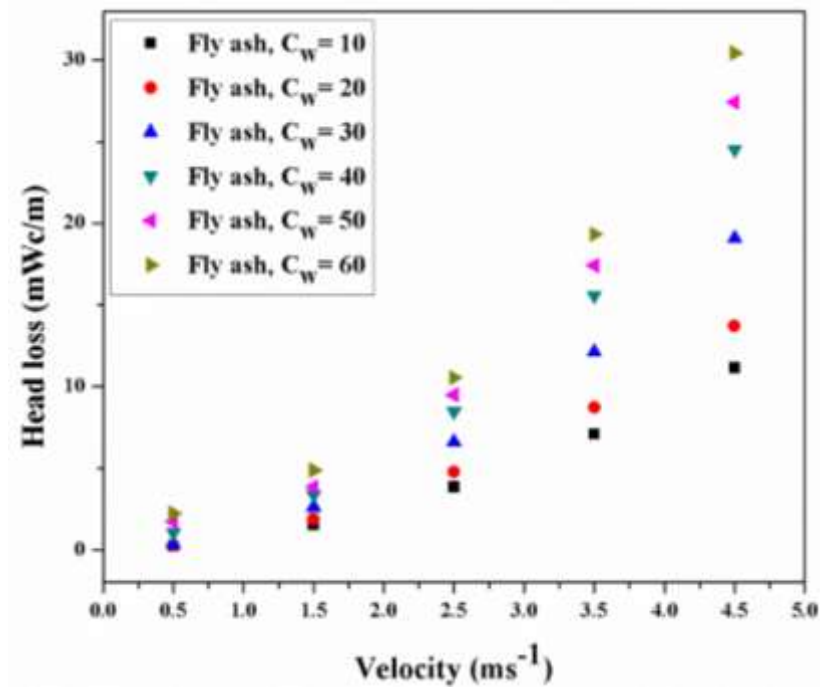


Figure 6.6: Effect of solid concentration on head loss for fly ash suspension

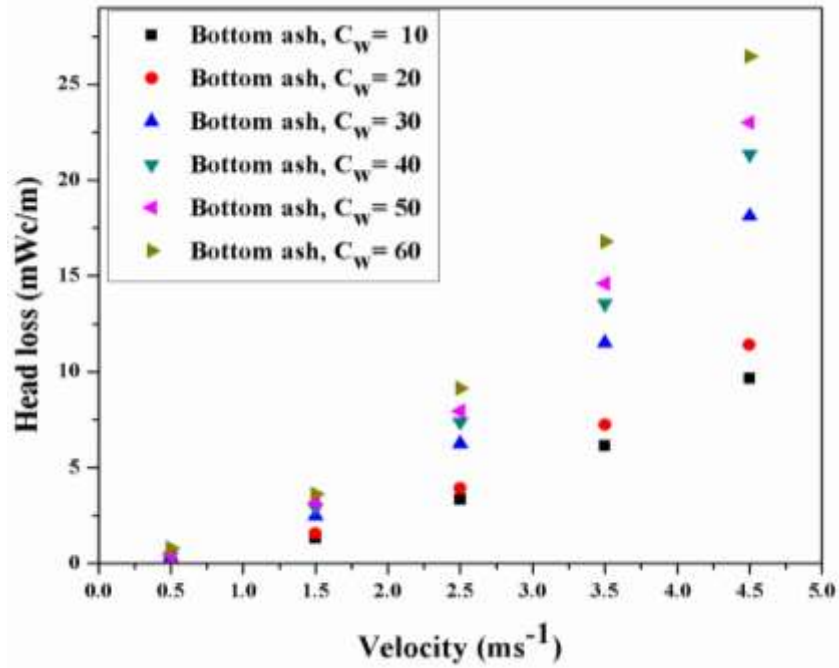


Figure 6.7: Effect of solid concentration on head loss for bottom ash suspension

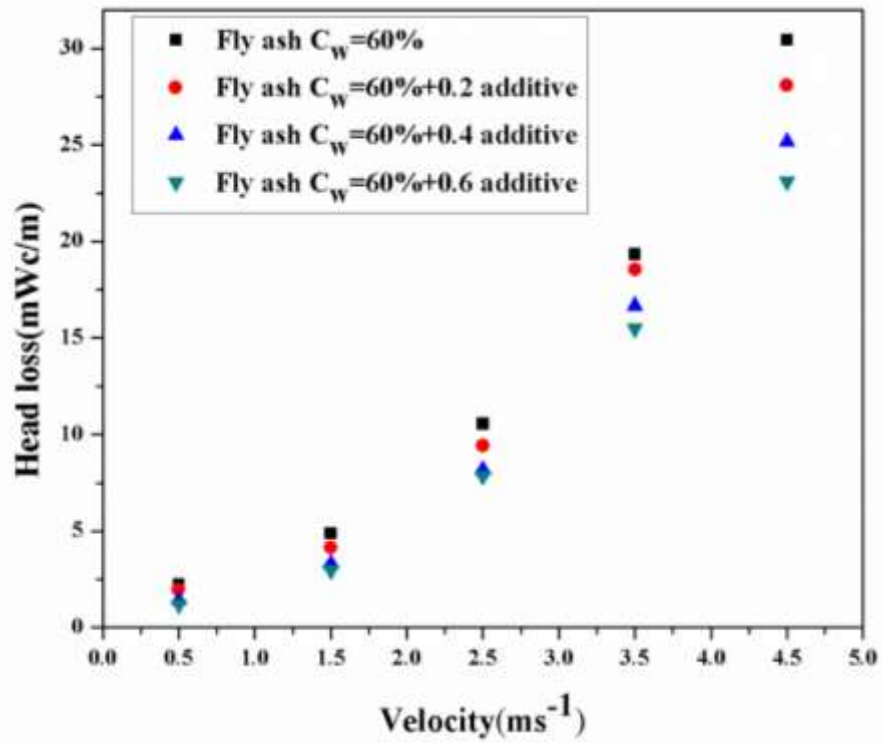


Figure 6.8: Effect of addition of additive on head loss for fly ash suspension

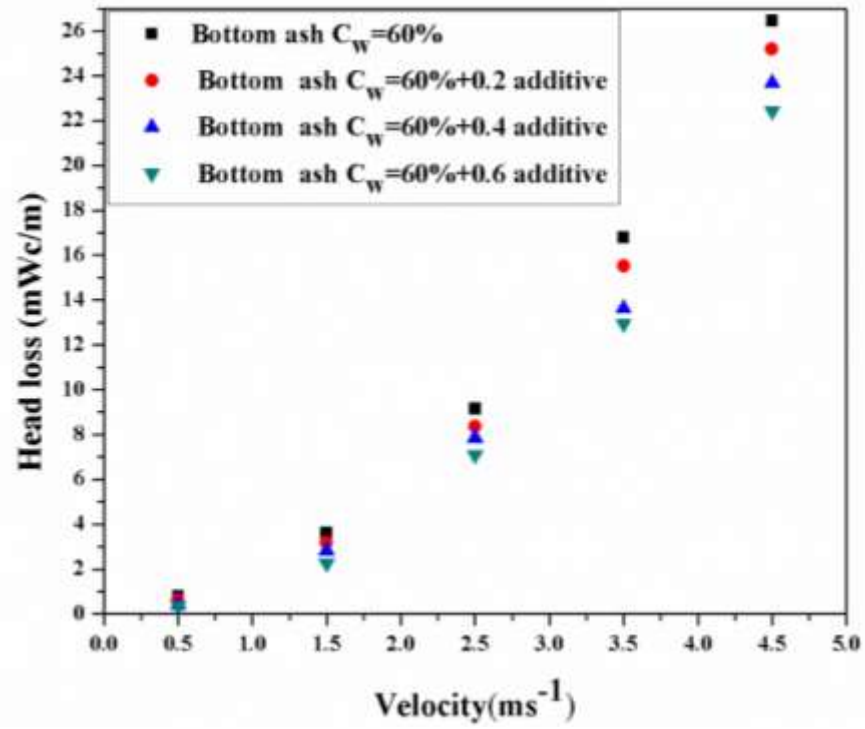


Figure 6.9: Effect of addition of additive on head loss for bottom ash suspension

Chapter 7

CONCLUSIONS AND FUTURE SCOPE

The investigation on “Investigation of rheological and leaching characteristics of ash at higher concentrations” was carried out using the fly and bottom ash samples procured from different thermal power plant situated in Punjab and Haryana namely Guru Nanak Dev thermal power plant, Bhatinda, Punjab, Guru Gobind Singh Super Thermal Power Plant, Ropar, Punjab, Guru Hargovind Singh thermal power plant, Lehra Mohabbat, Punjab and Deenbandhu Chhotu Ram thermal power plant, Yamuna nagar, Haryana. The present study deals with physical, chemical, mineralogical, rheological as well as leaching characteristics of fly and bottom ash slurries at high solid concentration. Based on study, the specific conclusion drawn have already been mentioned in individual chapter. Hence only generic conclusions are listed here:

- All fly ash samples shows higher settled concentration as compared to bottom ash sample. The cenospheres of the fly ash having lightweight as compared to bottom ash.
- The pH value of both fly and bottom ash samples decreases with increase in solid concentration. Fly ash shows acidic nature while bottom ashes have non-reactive nature.
- The quartz and mullite were found as major crystalline phases present in all fly and bottom ash samples while hematite phase was observed only in bottom ash sample BA-I. It was also observed that diffraction intensities peaks for quartz and mullite were stronger in fly ash samples as compared to bottom ash samples.
- The presence of high proportion of silica and alumina improves the strength and CaO improves the strength and structural properties which tends the bulk utilization of fly ash and bottom ash in the field of civil engineering, geotechnical and cement materials etc. The F type fly ash possesses very good pozzolanic properties, favorable for stowing in coal mines.
- The leachate concentration of trace elements in both fly and bottom ash was found higher with TCLP method as compared to ASTM and EP method.
- Trace elements of present in fly ash show higher leachability than bottom ash. Leachate concentration increased with increase in liquid to solid ratio, time duration and temperature of fly and bottom ash samples.

- The concentration of heavy metal elements Zn, Mo and Co is within the permissible limits of Indian standard while elements of concentrations of elements Mg, Cr, Pb, Mn, Ni, Cu and Fe have crossed the standard limits. These may cause many harmful effects on the human health. Potential utilization of fly ash helps to reduce the transportation cost as well as reduces environmental hazard.
- Bottom ash slurry suspension showed Newtonian behavior up to 40% solid concentration (by weight) beyond which it followed non-Newtonian flow characteristics. Whereas fly ash slurry suspension showed Newtonian behavior up to 30% solid concentration (by weight) and beyond this it depicted non-Newtonian flow characteristics.
- Addition of sodium bicarbonate as an additive improved the rheological as well as leaching characteristics of fly and bottom ash slurries and resulted in substantial saving in energy consumption.
- The optimum value of additive was found as 0.4% (by weight) for reduction of viscosity as well as leaching rate of fly and bottom ash slurries.
- The additive also helps to reduce the trace element concentration of fly and bottom ash. This aspect of the study will also suggest the improvement in ash disposal system of thermal power plant to minimize the environment impact. It will be also helpful for design and operation of high concentration slurry handling and disposal systems.

7.1 Future scope

The further work needs to be carried for better understanding of the flow mechanism of highly concentrated slurry through pipes. Some probable work that could be done in coming future by researchers is listed below:

- To study detailed flow field analysis of the solid-liquid flow through slurry pipeline using sophisticated instrument like laser Doppler velocimeter (LDV) etc.
- To study the performance characteristics of progressive cavity screw pump with solid materials of different properties so as to establish the relationship between particle size distribution and head-to-efficiency ratio of screw pump.
- To study the shut-down/re-start characteristics of the slurry pipeline and pump at higher concentration.

- To study the wear characteristics of different pump and piping materials with help of erosion wear tester.
- Disposal of fly ash slurries at high concentrations through pipeline to ash ponds should include the study of deposition characteristics of the fly ash slurry at the ash lagoons.

References

- Ahn, J.W., Cho, H.C., Han, G.C., You, G.S., Um, N., Characteristic of Cu and Pb leaching behavior of municipal solid waste incineration bottom ash. *Geosystem Engineering*, 9(1), (2006) 11-14.
- Aggarwal, P., Aggarwal, Y., Gupta, S.M., Effect of bottom ash as replacement of fine aggregates in concrete. *Asian journal of civil engineering (building and housing)*, 8, (2007) 49-62.
- Akar, G., Polat, M., Galecki, G., Ipekoglu, U., Leaching behavior of selected trace elements in coal fly ash samples from yenikoy coal-fired power plants. *Fuel Processing Technology*, 104, (2012) 50-56.
- Alexander, J., Ford, M., hydrogeology and contaminant fate/transport. Groundwater pollution: liabilities and engineering implications east midlands geotechnical group (EMGG) *University of Nottingham, October 1993, Jones, R.H., Roger, C.D.F and Holden, J.M.W(eds)1994.*
- Amouroux, J., Siffert, P., Massue, J. P., Cavadias, S., Trujillo, B., Hashimoto, K., Rutberg, P., Dresvin, S., Wang, X. Carbon dioxide: a new material for energy storage. *Progress in Natural Science; Materials International*, 24, (2014) 295–304.
- Antiohos, S.K., Tsimas, S., A novel way to upgrade the coarse part of a high calcium fly ash for reuse into Cement Systems. *Waste Management*, 27, (2007) 675-683.
- Asokana, P., Saxena, M., Asolekar, S.R., Coal combustion residues-environmental implications and recycling potentials. *Resources, Conservation and Recycling*, 43, (2005) 239–262.
- Assefa, K.M., Kaushal, D.R., Experimental study on the rheological behaviour of coal ash slurries. *Journal of Hydrology and Hydromechanics*, 63, (2015) 303–310.
- Assi, L., Ghahari, S.A. Deaver, E.E., Leaphart, D., Ziehl, P. Improvement of the early and final compressive strength of fly ash-based geopolymers concrete at ambient conditions. *Construction and Building Materials*, 123, (2016) 806–813.
- Baba, A., Gurdal, G., Sengunalp, F. Leaching characteristics of fly ash from fluidized bed combustion thermal power plant: Case study Çan (Çanakkale-Turkey). *Fuel Processing Technology*, 91, (2010) 1073–1080.
- Baba, A., Kaya, A., Leaching characteristics of solid wastes from thermal power plants of western Turkey and comparison of toxicity methodologies. *Journal of Environmental Management*, 73, (2004) 199–207.

- Badoga, S., Pattanayek, S.K., Kumar, A., Pandey, L.M., Effect of polymer–surfactant structure on its solution viscosity. *Asia-Pacific Journal of Chemical Engineering*, 6, (2011) 78–84.
- Baite, E., Messan, A., Hannawi, K., Tsobnang, F., Prince, W., Physical and transfer properties of mortar containing coal bottom ash aggregates from Tefereyre (Niger). *Construction and Building Materials*, 125, (2016) 919–926.
- Bakoshi, T., Kohno, K., Kawasaki, S., Yamaji, N., Strength and durability of concrete using bottom ash as replacement for fine aggregate. *ACI Special Publication*, SP-179 (10), (1998) 159–172.
- Bialuchan, R., Leaching standard for quality control of aggregates waste materials in construction. The science and engineering of recycling for environment protection wascon 2000, *Waste management series (1) Walley, G.R. Goumans, J.J.J.M. and Wainwright P.J. (eds) Elsevier Science, Amsterdam 2000.*
- Biswas, A., Gandhi, B.K., Singh, S.N., Seshadri, V., Characteristics of coal ash and their role in hydraulic design of ash disposal pipelines, *Indian Journal of Engineering and Material Science*, 7 (2000) 1-7.
- Blissett R, Rowson N. A review of the multi-component utilization of coal fly ash. *Fuel*, 97, (2012) 1-23.
- Bournonville, B., Nzihou, A., Rheology of non-Newtonian suspensions of fly ash: effect of concentration, yield stress and hydrodynamic interactions. *Powder Technology*, 128, (2002) 148–158.
- Boylu, F., Dincer, H., Atesok, G., Effect of coal particle size distribution, volume fraction and rank on the rheology of coal–water slurries. *Fuel Processing Technology*, 85, (2004) 241– 250.
- Buranasrisak, P., Narasingha, M.H., Effects of particle size distribution and packing characteristics on the preparation of highly-loaded coal-water slurry. *International Journal of Chemical Engineering and Applications*, 3, (2012) 31-35.
- Chandel, S., Singh, S.N., Seshadri, V., Deposition characteristics of coal ash slurries at higher concentrations. *Advanced Powder Technology*, 20, (2009) 383–389.
- Chandel, S., Seshadri, V., Singh, S.N., Effect of additive on pressure drop and rheological characteristics of fly ash slurry at high concentration. *Particulate Science and Technology*, 27, (2009) 271-284.

- Chen, L., Duan, Y., Liu, M., Zhao, C., Slip flow of coal water slurries in pipelines. *Fuel*, 89, (2010) 1119-1126.
- Cheng, Y.W.C., Hong, F.Y.U., Hui, F.Z. Extraction of aluminum by pressure acid-leaching method from coal fly ash. *Transactions of Nonferrous Metals Society of China*, 22, (2012) 2282-2288.
- Chindaprasirt, P., Rukzon, S., Sirivivatnanon, V., Resistance of chloride penetration of blended Portland cement mortar containing palm oil fuel ash, rice husk ash and fly ash. *Construction and Building Materials*, 22(5), (2008) 932.
- Conner, J.R., chemical fixation and solidification of hazards wastes. *Van Nostrand reinhold*. 1990.
- Das, D., Effect of organized assemblies part 4 formulation of highly concentrated coal-water slurry using a natural surfactant. *Energy & Fuels*, 22, (2008) 1865-1872.
- Dhadse, S., Kumari, P., Bhagia, L.J. Fly ash characterization and government initiatives in India a review. *Journal of scientific and Industrial Research*, 67, (2008) 11-18.
- Dutta, B.K., Khanra, S., Mallick, D., Leaching of elements from coal fly ash: assessment of its potential for use in filling abandoned coal mines. *Fuel*, (2009) doi:10.1016/j.fuel.2009.01.00.
- Erol, M., Kuçukbayrak, S., Ersoy-Meriçboyu, A., Comparison of the properties of glass, glass–ceramic and ceramic materials produced from coal fly ash. *Journal of Hazardous Materials*, 153, (2008) 418-425.
- Fallman, A.M., Characterization of residues release of contaminants from slags and ashes. *PhD dissertation Linkoping studies in science and technology No. 486 department of physics and measurement technology Linkoping University*, 1997.
- Gahlot, V.K., Studies on the effect of particle size distribution and material properties on the rheological parameters of slurries and the performance of slurry pumps. Ph. D. Thesis, Department of Applied Mechanics, IIT Delhi (1987).
- Gahlot, V.K., Seshadri, V., Malhotra, R.C., A method for the experimental determination of the rheological parameters of multi-sized coarse particulate slurries, International symposium on hydraulic transportation of coal and other minerals, IIT Delhi, (1988) 283-295.
- Gahlot, V.K., Seshadri, V., Malhotra, R.C., Effect of density, size distribution, and concentration of solid on the characteristics of centrifugal pumps, *Transaction of ASME, Journal of Fluid Engineering*, 114, (1992) 386-389.

- Gandhi, B.K. Singh, S.N., Seshadri, V., Improvement in the prediction of performance of centrifugal slurry pump handling slurries, *Proceeding of Intuition Indian Journal of Mechanical Engineers*, 214(A), (2000) 473-486.
- Gandhi, B.K., Singh, S.N., Seshadri, V., Performance characteristics of centrifugal slurry pumps. *Transaction actions of ASME, Journal of Fluid Engineering*, 123, (2001) 271-280.
- Gandhi, B.K., Singh, S.N., Seshadri, V., Effect of speed on the performance characteristics of a centrifugal slurry pump, *Transaction actions of ASCE, Journal of Hydraulic Engineering*, 128, (2002) 225-233
- Garcia-Lodeiro, I., Carcelen-Taboada, V., Fernandez-Jimenez, A., Palomo, A. Manufacture of hybrid cements with fly ash and bottom ash from a municipal solid waste incinerator. *Construction and Building Materials*, 105, (2016) 218–226.
- Gentzis, T., Goodarzi, F., Chemical fractionation of trace elements in coal and coal ash. *Energy Sources*, 21(3), (1999) 233-256.
- Georgakopoulos, A., Anestis, F.A., Fournaraki, A.K., Turiel, J.L.F., Liorens, J.F., Mousty, F., Leachability of major and trace elements of fly ash from Ptolemais power station, Northern Greece. *Energy Sources*, 24, (2002) 103-113.
- Ghafoori, N., Najimi, M., Diawara, H., Islam, M.S. Effects of class F fly ash on sulfate resistance of Type V Portland cement concretes under continuous and interrupted sulfate exposures. *Construction and Building Materials*, 78, (2015) 85–91.
- Ghanta, K.C., Purohit, N.K., Effect of particle size distribution (psd) on the viscosity of suspension of bi-dispersed particles. *Proceedings Hydro transport 15, (Cranfield, Bedford), England*, (2002) 299-313.
- Gillies, R.G., Shook, C.A., Xu, J., Modelling Heterogeneous Slurry Flows at High Velocities. *The Canadian Journal of Chemical Engineering*, 82, (2004) 1060-1065.
- Gitari, W.M., Fatoba, O.O., Petrik, L.F., Vadapalli, V.R.K., 2009. Leaching characteristics of selected South African fly ashes: Effect of pH on the release of major and trace species. *Journal of Environmental Science and Health Part A*. 44(2), (2009) 206–220.
- Ghosh, C.N., Mondal, P.K., Suitability of fly ash as a stowing material for underground coal mines - some studies. *Proceeding 1st Asian Mining Congress. Kolkata, India*, (2006) 113–123.

- Gonzalez, A., Navia, R., Moreno, N. Fly ashes from coal and petroleum coke combustion: current and innovative potential applications. *Waste Management and Research*, 27(10), (2009) 976–987.
- Heywood, N.I., Mehta, K.B., Poplar, D., Moore, C..D., Assesment of the flow characteristics of pulverised fuel ash slurries at higher concentration. *12th International conference on slurry handling and pipeline transport, Hydrotransport-12, Belgium*, (1993).
- Hower, J.C., Sakulpitakphon, T., Trimble, A.S., Thomas, G.A., Schram, W.H., Major and Minor Element Distribution in Fly Ash from a Coal-Fired Utility Boiler in Kentucky. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 28(1), (2006) 79-95.
- Huggins, F.E., Rezaee, M., Honaker, R.Q., Hower, J.C. On the removal of hexavalent chromium from a Class F fly ash. *Waste Management*, 51, (2016) 105-110.
- Jing-yong, L., Shui-yu, S., Effect of solid additive on heavy metal vaporization of fly ash from co-incineration of MSW with sludge at high temperature. *Journal of Fuel Chemistry and Technology*, 40(12), (2012) 1512-1520.
- Jose, L., Pastor, J., Ortega, M., Flor, M., Lopez, M.P., Sanchez, I., Climent, M.A. Microstructure and durability of fly ash cement grouts for micropiles. *Construction and Building Materials*, 117, (2016) 47–57.
- Kim, B. J., Prezzi, M., Salgado, R., Geotechnical properties of fly and bottom ash mixtures for use in highway embankments. *Journal of Geotechnical and Geoenvironmental Engineering*, 131(7), (2005) 914–924.
- Kim, H. K., Lee, H. K., Use of power plant bottom ash as fine and coarse aggregates in high-strength concrete. *Construction and Building Materials*. 25(2), (2011) 1115-1122.
- Komonweeraket, K., Cetin, B., Aydilek, A.H., Benson, C.H., Edil, T.B., Effects of pH on the leaching mechanisms of elements from fly ash mixed soils. *Fuel*, 140, (2015) 788–802.
- Kurama, H., Kaya, M., Usage of coal combustion bottom ash in concrete mixture. *Construction and Building Materials*, 22, (2008) 1922–1928.
- Kumar, K., Kumar, S., Gupta, M., Garg, H.C., Singh, G., Measurement of flow characteristics for multiparticulate bottom ash-water suspension with additives. *Journal of Residual Science and Technology*, 14(1), (2017) 11-17.

- Kumar, S., Singh, G., Mohapatra, S.K. An assessment of the physical, mineral, and rheological properties of fly ash for stowing in coal mines. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 38(20), (2016) 2955-2962.
- Kumar, S., Singh, G., Mohapatra, S.K., Leaching characteristics of heavy metal in bottom ash from Indian thermal power plant. *Journal of Scientific and Industrial Research*, 76, (2017) 255-258.
- Kumar, S., Mohapatra, S.K., Gandhi, B.K. Performance characteristics of centrifugal slurry pump with multi-sized particulate bottom and fly ash mixtures. *Particulate Science and Technology*, 32, (2014) 466-476.
- Kumar, U., Gandhi, B.K., Singh, S.N., Seshadri, V., Gupta, V.K., Performance characteristics of demonstration unit for transportation of solid-liquid flow at high concentration setup at NCPP, Dadri, *Proceedings International Seminar on Material handling Systems Indian Institute of Plant Engineers (Delhi-Haryana Chapter)*, November 16-18, New Delhi, 126-136 (2000).
- Latifi, N., Marto, A., Safuan, A., Rashid, A., Yii, J.L.J.Y., Strength and physico-chemical characteristics of fly ash–bottom ash mixture. *Arabian Journal for Science and Engineering*, 40(9), (2015) 2447–2455.
- Lee, J.K., Shang J.Q., Jeong, S., Thermo-mechanical properties and microfabric of fly ash-stabilized gold tailings. *Journal of Hazardous Materials*, 276, (2014) 323-31.
- Li, L., Usui, H., Suzuki, H., Study of pipeline transportation of dense fly ash-water slurry. *Coal Preparation*, 22(2), (2002) 65-80.
- Lin, C.Y., Yang, D.H., Removal of pollutants from wastewater by coal bottom ash. *Journal of Environmental Science and Health. Part A, Toxic/Hazardous Substances & Environmental Engineering*, 37, (2002) 1509–1522.
- Loya, M.I.M., Rawani, A.M., Promising applications for utilization of fly ash: a review. *International Journal of Advanced Technology in Engineering and Science*, 2(7), (2014) 143-149.
- Mahale, N.K., Patil, S.D., Sarode, D.B., Attrade, S.B., Effect of fly ash as an admixture in agriculture and the study of heavy metal accumulation in wheat wheat (*Triticum aestivum*), mung bean(*Vigna radiata*) and urad beans (*Vigna mungo*). *Polish Journal of Environmental Studies*, 21(6), (2012), 1713-1719.

- Mathur, A.K., Kumar, R., Mishra, M., An investigation of radon exhalation rate and estimation of radiation doses in coal and fly ash samples. *Applied Radiation and Isotopes* 66(3), (2008) 401–406.
- Malhotra, V.M., Painter. K.E., Early-age strength properties, and freezing and thawing resistance of concrete were incorporating high volume of ASTM Class F Fly ash. *International Journal of Cement Composites and Lightweight Concrete* 11(1): (1995) 38–46.
- Mamol, G., Savastano, H, Monzo, J.M., Soriano, M.V.B.L., Paya, J. Portland cement, gypsum and fly ash binder systems characterization for lignocellulosic fiber-cement. *Construction and Building Materials*, 124, (2016) 208–218.
- Mika, L., Rheological behaviour of low fraction ice slurry in pipes and pressure loss in pipe sudden contractions and expansions. *International Journal of Refrigeration*, 35, (2012) 1697-1708.
- Min-Hao, W., Wei-Chieh, H., Chiou-Liang, L., Jin-Wen, C. Heavy metals leaching from the incinerator bottom ash used for road pavement. *Journal of Residuals Science & Technology*, 12(1), (2015) 11-15.
- Mishra, U.C., Environmental impact of coal industry and thermal power plants in India. *Journal of Environmental Radioactivity*, 72, (2004) 35–40.
- Mosa, E.S., Saleh, A.M., Taha A. Taha, El-Molla, A.M., Effect of chemical additives on flow characteristics of coal slurries. *Physicochemical Problems of Mineral Processing*, 42, (2008), 107-118.
- Naik, H.K., Mishra, M.K., Rao Karanam, U.M., Deb, D. Evaluation of the role of a cationic surfactant on the flow characteristics of fly ash slurry. *Journal of Hazardous Materials*, 169, (2009) 1134–1140.
- Naik, H.K., Mishra, M.K., Rao, K.U.M. Rheological characteristics of fly ash slurry at varying temperature environment with and without additive. *World of coal ash conference*, (2009) Lexington, KY, USA.
- Naik, H.K., Mishra, M.K., Rao, K.U.M., Evaluation of flow characteristics of fly ash slurry at 40% solid concentration with and without additives. *World of Coal Ash Conference, May 9-12, Denever, U.S.A*, (2011) 1-15.
- Naik, T.R., Singh, S.S., Permeability of flowable slurry materials containing foundry sand and fly ash. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, 123(5), (1997) 446–52.

- Naik, T.R., Kraus, R.N. MPU Ash as a Potential Source for Construction Materials. 2001.
- Nawaz, I., Disposal and utilization of fly ash to protect the environment. *International Journal of Innovative Research in Science, Engineering and Technology*, 2(10), (2013) 5259–5266.
- Nayak, A.K., Rajaa, R., Rao, K.S., Shukla, A.K., Mohanty, S., Shahid, M., Tripathi, R., Panda, B.B, Bhattacharyya, P., Kumar, A., Lal, B., Sethi, S.K., Puri, C., Nayak, D., Swain, C.K. Effect of fly ash application on soil microbial response and heavy metal accumulation in soil and rice plant. *Ecotoxicology and Environmental Safety*, 114, (2015) 257-262.
- Nikbin, I.M., Rahimi, S., Allahyari, H., Damadi. M., A comprehensive analytical study on the mechanical properties of concrete containing waste bottom ash as natural aggregate replacement. *Construction and Building Materials*, 121, (2016) 746–759.
- Noushini, A., Farhad, A., Castel, A., Gilbert, R. I. Foster, S. Compressive stress-strain model for low-calcium fly ash-based geopolymer and heat-cured Portland cement concrete. *Cement and Concrete Composites*, 73, (2016) 136-146.
- Padhya, R.N., Nayakb, N., Dash-Mohinia, R.R., Ratha, S., Sahu, R.K. Growth, metabolism and yield of rice cultivated in soils amended with fly ash and cyanobacteria and metal loads in plant parts. *Rice Science*, 23(1), (2016) 22–32.
- Panda, D., Pradhan, B., Hydraulic transport of fly ash and fly ash- bottom ash mixtures at high concentrations. *International Journal of Chemical Engineering and Applied Sciences*, 4(1), (2014) 1-4.
- Pani, G.K., Rath, P., Maharana, L., Barik, R., Senapati, R.K., Assessment of heavy metals and rheological characteristics of coal ash samples in presence of some selective additives. *International Journal of Environmental Science and Technology*, 13, (2016) 725–731.
- Pavithra, P., Srinivasula, R.M., Dinakar, P., Hanumantha, R.B., Satpathy, B., Mohanty, A. A mix design procedure for geopolymer concrete with fly ash. *Journal of Cleaner Production*, 133(1), (2016) 117-125.
- Pavel, V., Zdenek, C., Effect of particle size distribution and concentration on flow behaviour of dense slurries. *Particulate Science and Technology*, 29, (2011) 53-65.
- Popovic, A., Djordjevic, D., pH-Dependent leaching of dump coal ash retrospective environmental analysis. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 31, (2009) 1553-1560.

- Popovic, A., Djordjevic, D., Polic, P., Leaching of trace and major elements from coal ash dumps, *Toxicological & Environmental Chemistry*, 75(3-4), (2000) 141-150.
- Popovic, A., Djordjevic, D., Relic, D., Associations and pollution potential of selected trace and major elements in filter lignite ash from the “Nikola Tesla A” power plant (Obrenovac, Serbia) (I) Leaching Experiments. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 35, (2013) 529-537.
- Popovic, A., Djordjevic, D., Relic D., Zelic, A.M., Speciation of trace and major elements from coal combustion products of serbian power plants (ii) Obilic power plant. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 33, (2011) 2309-2318.
- Prasad, B., Mondal, A.H., Heavy metals leaching in Indian fly ash. *Journal of Environmental Science and Engineering*, 50(2), (2008) 127-132.
- Quijorna, N., Miguel, G.S., Andres, A. Incorporation of waelz slag into commercial ceramic bricks: a practical example of industrial ecology. *Journal of Industrial and Engineering Chemistry* 50 (9), (2010) 5806–5814.
- Rabinovich, E., Kalman, H., Threshold velocities of particle-fluid flows in horizontal pipes and ducts: Literature review, *Reviews in Chemical Engineering*, 27(5), (2011) 215-239.
- Rani, R., Jain, M.K., Effect of bottom ash at different ratios on hydraulic transportation of fly ash during mine fill. *Powder Technology*, 315, (2017) 309–317.
- Risto, P., Nurmesniemi, H., Keiski, R.L. Chemical, physical and leaching studies of bottom ash from a medium-sized (32MW) municipal district heating plant for assessing its suitability for an earth construction agent and for a fertilizer used in agriculture and in forestry. *Journal of Residuals Science & Technology*, 5(1), (2008) 13–21.
- Sahoo B.K., De, S., Carsky, M., Meikap, B.C., Enhancement of rheological behavior of Indian high ash coal-water suspension by using microwave pretreatment. *Industrial and Engineering Chemistry Research*. 49, (2010) 3015–3021.
- Sarkar, A., Rano, R., Water holding capacities of fly ashes: effect of size fractionation. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 29(5), (2007) 471-482.
- Sarkar, A., Rano, R., Mishra, K.K., Sinha, I.N., Particle size distribution profile of some Indian fly ash a comparative study to assess their possible uses. *Fuel Processing Technology*, 86, (2005) 1221– 1238.

- Sarode, D.B., Jadhav, R.N., Khatik, V.A., Ingle, S.T., Attarde, S.B., Extraction and leaching of heavy metals from thermal power plant fly ash and its admixtures. *Polish Journal of Environmental Studies*, 19(6), (2010) 1325-1330.
- Senapati, P.K., Das, D., Nayak, A., Mishra, P.K., Studies on preparation of coal water slurry using a natural additive. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 30, (2008) 1788-1796.
- Senapati, P.K., Mohapatra, R., Pani, G.K., Mishra, B.K. Studies on rheological and leaching characteristics of heavy metals through selective additive in high concentration ash slurry. *Journal of Hazardous Materials*, 229–230, (2012) 390–397.
- Senapati, P.K., Mishra, B.K., Parida, A., Modeling of viscosity for power plant ash slurry at higher concentrations: Effect of solids volume fraction, particle size and hydrodynamic interactions. *Powder Technology*, 197, (2010) 1–8.
- Senapati, P.K., Panda, D., Parida, A., Predicting viscosity of limestone–water slurry. *Journal of Minerals and Materials Characterization and Engineering*, 8(3), 2003, 203-221.
- Senapati, P.K., Panda, D., Parida, A., Studies on high concentration fly ash -bottom mixture slurry. *Bulk Solid Handling*, 25(6), (2005) 386-290.
- Senapati, P.K., Mishra, B.K., Parida, A., Analysis of friction mechanism and homogeneity of suspended load for high concentration fly ash & bottom ash mixture slurry using rheological and pipeline experimental data. *Powder Technology*, 250 (2013) 154-163.
- Seshadri, V, Singh, S.N., Jain, K.K., Verma, A.K., Effect of additive on head loss in the high concentration slurry disposal of fly ash. *IE(I) Journal–MC*, (2008) 3-10.
- Seshadri, V., Singh, S.N., Jain, K.K., Verma, A.K. Effect of additive on head loss in the high concentration slurry disposal of fly ash. *Journal Institution of Engineers India Part ME Mechanical Engineering Division*, 89, (2009) 3-10.
- Shafigh, P., Nomeli, M.A., Alengaram, U.J., Mahmud, H.B., Jumaat, M.Z. Engineering properties of lightweight aggregate concrete containing limestone powder and high volume fly ash. *Journal of Cleaner Production*, 135 (1), (2016) 148–157.
- Sharma, N.K., Mitra, S., Sehgal, V., Mishra, S., An assessment of physical properties of coal combustion residues w.r.to their utilization aspects. *International Journal of Environmental Protection*, 2, (2012) 31–38.

- Sheoran, H.S., Duhan, B.S., Kumar, A. Effect of fly ash application on soil properties: a review. *Journal of Agroecology and Natural Resource Management*, 1(2), (2014) 98-103.
- Singh, G., Kumar, S., Mohapatra, S.K., Kumar, K., Comprehensive characterization of grounded bottom ash from Indian thermal power plant. *Journal of Residuals Science & Technology*, 14, (2017) 1-10.
- Singh, G., Kumar, S., Singh, M.K., Mohapatra, S.K. Environmental impact assessment of ash disposal system of a thermal power plant. *International Journal of Hydrogen Energy*, 41, (2016) 15887-15891.
- Singh, M.K., Ratha, D., Kumar, S., Kumar, D., Influence of particle size distribution and temperature on rheological behaviour of coal slurry. *International Journal of Coal Preparation and Utilization*, 36, (2016) 44-54.
- Singh, R.K., Gupta, N.C., Guha, B.K., The leaching characteristics of trace elements in coal fly ash and an ash disposal system of thermal power plants. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. 34, (2012) 602–608.
- Snigdha, S., Batra, V.S., Analysis of fly ash heavy metal content and disposal in three thermal power plants in India. *Fuel*, 85, (2006) 2676–2679.
- Slatter, P., The role of rheology in the pipelining of mineral slurries. *Mineral Processing and Extractive Metallurgy Review*, 20(1), (2000) 281-300.
- Steward, N.R., Slatter, P., The transport of fly ash pastes through pipelines. *Australian Bulk Handling Review*, 8(1), (2009) 206-215.
- Stanislav, V., Vasilev, V., Christina, G., Vassileva methods for characterization of composition of fly ashes from coal-fired power stations: a critical overview. *Energy and Fuels*, 19, (2005) 1084-1098.
- Sultana, P., Das S., Bagchi B., Bhattacharya, A., Basu, R., Nandy, P. Effect of size of fly ash particle on enhancement of mullite content and glass formation. *Building Materials and Science Processing*, 34, (2011) 1663–1670.
- Sushil, S., Batra, V.S., Analysis of fly ash heavy metal content and disposal in three thermal power plants in India. *Fuel*, 85, (2006) 2676–2679.
- Tang, S.W., Yao, Y., Andrade, C., Li, Z.J., Recent durability studies on concrete structure. *Cement and Concrete Research*, 78, (2015) 143–154.

- Tsiridis, V., Samaras, P., Kungolos, A., Sakellaropoulos, G.P., Application of leaching tests for toxicity evaluation of coal fly ash. *Environmental Toxicology* (2006) DOI 10.1002/tox 409-416. 2006.
- Ugurly, A., Leaching characteristics of fly ash. *Environment Geology*, 46, (2004) 890–895.
- Usui, H., Li, L., Suzuki, H., Rheology and pipeline transportation of dense fly ash-water slurry Korea-Australia. *Rheology Journal*, 13, (2001) 47-54.
- Verma, A.K., Singh, S.N., Seshadri, V., Pressure drop for the flow of high concentration solid liquid mixture 90° horizontal conventional circular pipe bends. *Indian Journal of engineering and Material Science*, 13, (2006) 477-483.
- Viji, R., Prasanna, P.R., Assessment of water holding capacity of major soil series of Ialugudi Trichy. *Indian Journal of Environmental Research Development*, 7(1), (2011) 393–398.
- Vlasak, P., Chara, Z., Effect of particle size and concentration on flow behavior of complex slurries, In *Proceedings of the Seventh (2007) ISOPE Ocean Mining (& Gas Hydrates) Symposium*. Cupertino, California: International Society of Offshore and Polar Engineers, 188-196.
- Vlasak, P., Chara, Z., Conveying of solid particles in Newtonian and non-Newtonian fluids. *Particulate Science and Technology*, 27(5), (2009) 428-443.
- Wei L., Utilization of coal combustion by products for masonry production. *M.S. Thesis University of Wisconsin Milwaukee*, (1992).
- Xie, J., Kayali, O. Effect of superplasticiser on workability enhancement of Class F and Class C fly ash-based geopolymers. *Construction and Building Materials*, 122, (2016) 36–42.
- Yongfan, G., Yonghao, F., Preparation of belite cement from stockpiled high-carbon fly ash using granule-hydrothermal synthesis method. *Construction and Building Materials*, 111, (2016) 175–181.
- Zhao, J., Wang, D., Liao, S., Effect of mechanical grinding on physical and chemical characteristics of circulating fluidized bed fly ash from coal gangue power plant. *Construction and Building Materials*, 101, (2015) 851–860.
- Zhang, H., Shao, P.J., Li, M., Li, X.J., Leaching behavior of heavy metals from municipal solid waste incineration bottom ash and its geochemical modeling. *Journal of material cycles and waste management*, 101, (2008) 7–13.

Zheng, D.D., Ji, T., Wanga, C.Q., Sun, C.J., Lin, X.J., Hossain, K.M.A. Effect of the combination of fly ash and silica fume on water resistance of magnesium–potassium phosphate cement. *Construction and Building Materials*, 106, (2016) 415–421.

Zhipeng, T., Bingru, Z., Chengjun, H., Rongzhi, T., Huangpu, Z., Fengting, L. The physiochemical properties and heavy metal pollution of fly ash from municipal solid waste incineration. *Process Safety and Environmental Protection*, 98, (2015) 333–341.

www.cea.nic.in/reports/monthly/executivesummary/2017/exe_summary-01.pdf www.cea.nic.in/
Central Electricity Authority, New Delhi report.

LIST OF PUBLICATION

Kumar, S., Singh, G., Mohapatra, S.K., An assessment of the physical, mineral, and rheological properties of fly ash for stowing in coal mines. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 2016, 38(20), 2955-2962 **(SCI Indexed)**.

Kumar, S., Singh, G., Mohapatra, S.K., Leaching characteristics of heavy metal in bottom ash from Indian thermal power plant. *Journal of Scientific and Industrial Research*, 2017, 76(4), 255-258 **(SCI Indexed)**.

Singh, G., Kumar, S., Mohapatra, S.K., Influence of pH and liquid to solid (L/S) ratio on leaching characteristics of fly ash. *International Conference on Engineering, Technology and Science in Muthayammal Engineering Institutions Rasipuram ICEST'17*

Singh, G., Kumar, S., Mohapatra, S.K., Potential environmental hazardous due to disposal of ash from Indian thermal power plants, *15th International Conference on Environmental Science and Technology, Rhodes, Greece*.