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SCHOOL OF CIVIL & ENVIRONMENTAL ENGINEERING
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Optimum Utilization of Coal Ash in Cement Concrete Production

By

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in Structural Engineering

Advisor

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Declaration

I, the undersigned declare that this thesis entitled “**Optimum Utilization of Coal Ash in Cement Concrete Production**” is my original work, and has not been presented by any other person in this or any other university or Higher Educational Institute for an award of a degree. All sources of material used for this research have been duly acknowledged.

Kasahun Kifle

Signature_____

Date_____

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ABSRTACT

Coal ash is the waste that is left after coal is combusted (burned). It includes fly ash (fine powdery particles that are carried up the smokestack and captured by pollution control devices) as well as coarser materials that fall to the bottom of the furnace. Coal ash used as Portland cement constitutes or as ingredient of concrete will help in more sustainable cement production by lowering energy and raw material consumption.

This study aims to investigate the suitability of coal ashes produced in different factories of Ethiopia (AYKA Addis Textile factory and Dongfang Spinning and printing) as supplementary cementitious material in Cement Concrete production. The physical and chemical characteristics of coal ash and concrete raw materials were investigated to check their compliance with the requirements of standards and specifications.

Coal ashes taken from the factories were pulverized and sieved with 300 μ m sieve and fineness determined by air-permeability test, results 3385.57 cm²/g and 3788.9 cm²/g for FA-1 and FA-2 respectively. X-ray examination has shown that the fly ashes are mainly amorphous but there are also present crystal phases like feldspar, melilite, hematite, very little anhydrite, and quartz.

The substitution portions of fly ashes were made 10%, 15%, 20% and 25% by volume of cement for FA1 and 5%, 10%, 15% and 20% by volume of cement for FA2. Furthermore, two classes of concrete with a water-binder ratio of 0.4 and 0.6 were made to investigate the effect of coal ashes on the strength of concrete.

The performance of the concrete was evaluated by conducting compressive strength, flexural strength and water penetration tests. The results showed that both coal ashes possess sufficient pozzolanic characteristics to be used in the production of cement concrete, and the optimum cement replacement level by these ashes can range between 5-15% by volume.

Keywords: Coal ash, fly ash, bottom ash, pozzolanic, compressive strength, flexural strength, water penetration, cost-benefit analysis, Green House Gas

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ASTM	American Standard for Testing and Measurement
Bar	Barometer
BCAM	Benefit-cost Analysis Model
CaO	Calcium Oxide
CCPs	Coal Combustion Products
C ₃ A	Tri-Calcium Aluminate
CH	Calcium Hydroxide
C ₃ S	Tri-Calcium Silicate
C-S-H	Calcium-Silicate Hydrate
CTM	Compression Testing Machine
FA	Fly Ash
Fe ₂ O ₃	Ferrite
FM	Fineness Modulus
GGBFS	Ground granulated blast furnace slag
GHG	Green House Gas
gm/cm ³	Gram per a cubic centimeter
H ₂ O	Water
ITZ	Interfacial Transition Zone
K ₂ O	Potassium Oxide
LOI	Lose in Ignition
MgO	Magnesium Oxide
MnO	Manganese Oxide
MPa	Mega Pascal
Na ₂ O	Sodium Oxide
OH	hydroxyl
OPC	Ordinary Portland Cement
SCM	Supplementary cementitious material
SEM	Scanning Electron Microscope
SiO ₂	Silicon dioxide
SO ₃	Sulfate
SSD	Saturated Surface Dry
TiO ₂	Titanium dioxide
XRD	X-ray diffraction
0C	Degree Celsius
Ø	Diameter
µm	Micrometer
%	Percent

1 INTRODUCTION

1.1 Background

As a result of industrial development, the quantity of coal electric power plant wastes has increased very rapidly. Industrialization development and economic growth of countries associated with the use of energy.

In Ethiopia, great attention was given for the establishment of industries. The country has established a foundation for further growth of the strategic heavy industries which finally enable Ethiopia to become an industrialized country by 2025. The Ethiopian government has been building industrial parks in different cities of the country that are believed to enhance the industrialization, such as textile factories (Akter, 2017).

These industries most probably will use coal as an electric power source in addition to hydroelectric for their sustainable function and power demand. The basic problems with current known Ethiopian coal resources are the high ash content and occasionally high Sulphur content (Teferra, 1991).

In Ethiopia, the establishment of a coal-based urea fertilizer integrated with the 90MW coal-fired power plant for electrical energy source is in the Oromia regional state in the Ilubabor Zone in Yayu Wereda is expected to produce 75,000tons of coal ash annually. Furthermore, it is believed that there would be 32 million tons of coal potential in the Achebo area. Of the total, on average 70 tons have been extracted and supplied to AYKA Addis Textile and Investment Group PLC (Tadesse, 2016).

The coal reserves in different regions of the country are worth that can play an important role to facilitate the development of the national economy through industrial and agricultural development. Various researches suggest that coal has a greater potential to substitute the imported Heavy Fuel Oils to meet its ever-increasing energy demand. In this respect, it will play an important role in reducing the hard currency, secure better reliable supply and improve energy sources.

On the contrary, if the country gets industrialized, it would be grappling with the problem of expeditious and safe waste disposal. The resulted coal combustion by-products from industries can potentially cause irreparable damage to the environment and human health if strategically disposed

of. Hence, recycling coal combustion products very important in advance to reduce the emission of greenhouse gas and energy demand. The present investigation aims to analyze alternative use of coal combustion products as part of construction material like pozzolanic material in cement concrete production.

Cement Concrete is the most extensively used Construction material. When using Concrete in construction industry as main construction material, the addition of supplementary materials in cement has dramatically increased along with the development of concrete industry, due to consideration of cost-saving, energy-saving, environmental concerns both in terms of damages caused by extraction of raw materials and carbon dioxide emission during cement manufacture have brought pressure to reduce cement consumption.

Coal Combustion by-products are by-products of electric power generation produced by the combustion of coal. They are solid residues that remain after the combustion of coal within the furnace and are collected in the emission control process. Coal combustion products have been used in the construction industry since the 1930's. Although the utilization of these products was limited to small scale applications in the early days. The use of coal combustion products has gained increasing acceptance in the construction industry in the last few decades. The interest in coal combustion products significantly increased during the 1970's because of the rapid increase in energy costs and the corresponding increase in cement costs (Tadesse, 2016).

Coal combustion products are expected to continue to play a major role in the concrete market as supplementary cementitious material. Supplementary cementitious materials (SCM) are material that contribute to the properties of hardened concrete through hydraulic and pozzolanic activity. Fly ash is pozzolana that possess little or no cementitious properties by itself but in the presence of moisture, chemically react with calcium hydroxide at ordinary temperature to form compounds having cementitious properties. The use of concrete containing fly ash has recently gained popularity as a resource-efficient, durable and sustainable option for a variety of concrete applications.

The use of fly-ash and other supplementary cementitious material reduces greenhouse gas emissions. Cement production reaches 4 billion tones worldwide and responsible for 6% global warming CO₂ emission. It is one of the biggest challenges that the world faces in climate change. The production of Portland cement is not only costly and energy-intensive, but it also produces large amounts of carbon emissions. The production of one ton of Portland cement produces

approximately one ton of CO₂ in the atmosphere (Hanle, 2004). To decrease emission of CO₂, utilization of some industrial by-products such as coal fly ash, coal bottom ash, silica fume and granulated blast furnace slag as Portland cement constitute become very important. Likewise, their disposal in industrial residue in landfills will be avoided.

Coal ash application has been presented and studied by many researchers all over the world. However, the property of coal ash varies from one sample to the next depending on the source of the coal, cleaning and pulverization, condition during combustion, efficiency of an emission control device, storage, and handling of byproduct. Moreover, the effective crucial and economical application has been varying from place to place on the quality of coal ash produced and its intended use. In these circumstances, the optimize utilization of coal ashes is strongly desired from environmental, ecological and economic points of view.

It is proven that unoptimized utilization of fly ash in concrete may be encountered with extended setting time and slow strength development, leading to early age strength and delays in the rate of construction. Therefore, this study enables to develop and discover an optimum utilization of coal ash in the process of concrete production with the same effect in mechanical properties as standard concrete.

Therefore, this study aims to investigate the fly ash from the AYKA Addis Textile factory and Dongfang Spinning and Pringitn PLC. in partially replacing cement in concrete production.

1.2 Statement of the Problem

Coal ash is the waste that is left after coal is combusted (burned). It includes fly ash (fine powdery particles that are carried up the smokestack and captured by pollution control devices) as well as coarser materials that fall to the bottom of the furnace. Most coal ash comes from coal-fired electric power plants.

Depending on where the coal was mined, coal ash typically contains heavy metals including arsenic, lead, mercury, cadmium, chromium, and selenium, as well as aluminum, antimony, barium, beryllium, boron, chlorine, cobalt, manganese, molybdenum, nickel, thallium, vanadium, and zinc. If eaten, drunk or inhaled, these toxicants can cause cancer and nervous system impacts such as cognitive deficits, developmental delays, and behavioral problems. They can also cause heart damage, lung disease, respiratory distress, kidney disease, reproductive problems, gastrointestinal illness, birth defects, and impaired bone growth in children (US.EPA, 2010.).

The dumping of coal ash is becoming an increasing concern for many countries because of the increasing volume generated, the costs of operating landfill sites, and its potential hazardous effects. In AYKA Addis textile factory, more than a third is disposed in dry landfills, frequently at the power plant where the coal was burned. The disposal of coal ash in the future most likely would become a concern for Ethiopia. As industrialization increased in the country, the increasing volume of ash, the costs of operating landfill sites, and its potential hazardous effects would be great worry. Therefore, new applications of coal ash have become an interesting alternative to disposal.

At present day, coal ash (especially fly ash) commonly used as supplementary cementitious material all over the world. The properties of coal ash especially fly ash vary significantly with coal composition and plant operating conditions. Each fly ash from different places has different characteristics, where quality requirements for fly ash vary depending on the intended use. Therefore, this study envisioned to investigate the suitability of coal ashes produced in different factories of Ethiopia (AYKA Addis Textile factory and Dongfang spinning and printing) as supplementary cementitious material in Cement Concrete production.

1.3 Objectives of the study

1.3.1 General Objective

This study aims to investigate the suitability of coal ashes produced in different factories of Ethiopia as supplementary cementitious material in Cement Concrete production.

1.3.2 Specific Objective

The specific purposes of this study are

- ✓ Utilize waste coal ashes into a mixture of cement concrete which have the same mechanical properties as standard concrete.
- ✓ To estimate the volume replacement or optimal utilization of coal ash in the mixture of concrete.

1.4 Scope of the study

This study is limited to the effect of coal ash on mechanical properties of concrete; such as Compressive strength, Flexural Strength (i.e. Tensile Strength) and durability.

1.5 Significances of the study

Recycling of industrial waste as supplementary cementitious material (SCM) reduce cement consumption during concrete production, lower CO₂ emission and finally make waste management more efficient.

Fly ash looks to be a promising supplementary cementitious material for cement concrete. A possible lower cost, due to the reduction of cement cost itself may be advantages. Ethiopia is one of the countries that have large coal reserves which is about 179 million tons of coal in Yayo woreda only. This potential should be realized by all levels of society so that the optimal management of coal for the benefit of the nation. Researches indicate that most Ethiopian coal resources have high ash content and occasionally high Sulphur content.

The research was to apply the waste material of coal as constituent material or supplementary cementitious material in the production of concrete. Utilization of waste coal is one of the environmental conservation programs in the form of 3R (Reuse, Recycle and Reduce). So, this study can be used as a pilot project in the development and discovery of optimum utilization of coal ash in the process of concrete production with the same effect in mechanical property as standard concrete.

2 LITERATURE REVIEW

2.1 Concrete

In simple definition, Concrete is a mixture of sand and gravel held together by cement paste. It is the world's most widely-used man-made material. Concrete is the backbone of the world's infrastructure, used in vast amounts to make roads, buildings, bridges, and other structures. The process of concrete making at the microscopic scale is more complex. Due to its complexity there are still things that scientists do not know about the chemistry and microscopic structure, and there is still significant potential for improving concrete to make better and longer-lasting structures (Rachel, 1996).

2.2 Hydration Reaction of Cement

During concrete making process, cement react with water and form new solid phase called calcium-silicate hydrate (C-S-H) gel. The C-S-H gel grows out into the spaces between the particles, binding them together and giving the cement its strength. After continued hydration the formation of C-S-H gel decreases the amount of water-filled pore space, which makes the cement relatively impermeable to water and dissolved ions. The configuration of solid phases and pore space is called the microstructure. Microstructural features are generally too small to be seen without a microscope, but on the other hand they are much larger than the atoms or molecules that make up the fundamental chemical structure. In general, both the chemical structure and the microstructure of a material control its properties (Maso, 1996).

The major components of cement that react with water to produce reaction products are tricalcium silicate (C₃S), dicalcium silicate (C₂S), tricalcium aluminate(C₃A), and tetra calcium alumionferite (C₄AF). The important strength-developing hydration reactions are those of C₃S and C₂S. Typical hydration reactions would be (Oss, 2005):



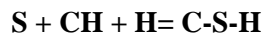
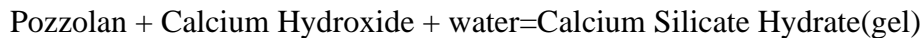
The C-S-H gel is not only the most abundant reaction product, occupying about 50% of the paste volume, but it is also responsible for most of the engineering properties of cement paste. Calcium hydroxide, also known by its mineral name portlandite, forms from C₃S and, to a lesser extent, C₂S. It occupies about 15% of the volume of a normal Portland cement paste. Calcium hydroxide

contributes slightly to the strength and impermeability of the paste, because it reduces the total pore volume by converting some of the liquid water into solid form. In this respect, it is much less important than the C-S-H.

2.3 Pozzolanic Reaction

The reaction between pozzolanic material and CH is called pozzolanic reaction. Blended cement pastes, have little or no CH, as the CH that forms from cement hydration is consumed along with the mineral admixtures to form additional C-S-H gel. CH is the most soluble of the hydration products, and thus is a weak link in cement and concrete from a durability point of view. If the paste is exposed to fresh water, the CH will leach out (dissolve), increasing the porosity and thus making the paste more vulnerable to further leaching and chemical attack.

Free lime in hardened concrete is also not particularly desirable because it increases the chemical reactivity of the surface (including along cracks) and can leach out in an unsightly fashion. It is available to react with any pozzolans that may have been added to the cement or concrete mix. This has beneficial effects on the strength and permeability (Oss, 2005).



Equation 2-3

Pozzolans contain active silica which combines with the alkalis in the paste (thus leaving less alkalis available to react with the aggregates), and significantly reduce the hardened concrete's porosity.

2.4 Coal Reserve and Classification

2.4.1 Formation of Coal

Coal is a fossil fuel formed from the remains of plants that lived and died hundreds of millions of years ago, when parts of the Earth were covered with huge swampy forests. The decayed vegetation was subjected to extreme temperature and crushing pressures. It took several hundred million years to transform the soggy peat into the solid mineral. 20 meters of compacted vegetation was required to produce 1-meter seam of coal. This is called as coalification or coal forming. The extent to which coalification has progressed determines the rank of coal. (Warrne, 2017).

2.4.2 Classification of Coal

There are various ways in which coal is grouped. Most of classifications are based on the results of chemical analysis and physical tests. Coal can be categorized by the coal type(rank), the presence of organic and inorganic matter, thickness and layering (banding), and fractures (cleats). The most common classification is based on rank, referring to the degree of coalification that has occurred. The rank of a coal is determined primarily by the depth of burial and temperature to which the coal was subjected over time.

With increasing temperature, peat is converted to lignite, a very soft and very low rank coal. Lignite is brown to black in color, woody structures and high moisture. With further increases in temperature lignite is transformed into subbituminous coal and then into bituminous coal. Bituminous coal is black in color and ignites fairly easily and burns with flame and smoke. At even higher temperature usually accompanied by intense deformation generated by the folding and faulting of the Earth's crust anthracites, the highest rank of coal, are produced. Anthracite is black in color and lustrous and difficult to ignite. It burns without flame. The increase in coal rank is accompanied by increases in the amount of fixed carbon and by decreases in the amount of moisture and other volatile material in the coal (Krishnan, 1996).

Table 2-1 Classification characteristics by coal rank (Tadesse, 2016)

Coal rank	Volatile matter (wt %)	Fixed Carbon (wt %)	Heating Value (MJ/Kg)
Lignite	27-35	65-73	26-28
Sub-bituminous	22-27	73-78	28-32
Bituminous	8-22	78-92	32-36
Anthracite	<8	>92	36-37

During coalification process the decayed vegetation was subjected to extreme temperature and crushing pressures. Type of coal depends on forming temperature and burial depth. Coal rank increases with burial depth. The degree of coalification undergone by a coal, as it matures from peat to anthracite, has an important bearing on its physical and chemical properties.

2.4.3 Coal Production and Reserves

According to World Coal Association report in 2018, it is estimated that there are over 1.04 trillion tons of proven coal reserves worldwide; which is enough to last more than 130 years at current rates of production.

Now a day it is believed that in every continent except Antarctica fossil fuels are the major source of energy generation. Industrialization development and economic growth of countries associated with the use of energy. In 2016 over 7,460 million tons of coal produced worldwide. China and India are the leading countries in the coal production and estimated about 3,411 and 692.4 million ton respectively. In Africa 92% of production coal was produced in South Africa and quantitatively about 251.3 million tons of coal produced annually (Craig, 2013).

The demand for coal production has been increasing rapidly due to increased economic growth and changing lifestyles. Coal is a major fuel for energy and steam production in coal-fired power plants across the globe. Coal currently supplies around 30% of primary energy and 41% of global electric generation. Coal use is forecasts to rise over 50% to 2030 with developing countries responsible for 97% of this increase, primarily to meet improved electrification rates (Hodge, 2014).

2.4.4 Coal Production in Ethiopia

It is well known that Ethiopia has a significant potential of coal resource at different places in the country. The nation should work more on the mining sector to unleash its potential of coal thereby save foreign currency expenditure. The coal mining provides multifaceted jobs. Besides the extract services, as a much-needed input to fertilizer factory, textile factory, the project helps to generate thermal power, cement factory and brisk production through substituting diesel oil. Coal resources appear to be quite widespread in Ethiopia. The most promising coal resource areas are found at Yayu, Debre birhan, Delbi Moye, Chilga, Mush Valley and Wuchale (Ahmed, 2007).

The Yayo Woreda alone endowed with over 229 million tons of coal potential. Provided that it is possible to produce 100,000 tons of coal per day. Furthermore, it is believed that there would be 32 million tons of coal potential in Achebo area. Of the total, on the average 70 tons have been extracted and supplied to AYKA Addis Textile and Investment Group PLC annually (Dawit, 2018).

Ethiopia imports over 750,000 tons of coal annually, of which more than three-fourths is for cement businesses, which heavily depend on carbon intensive fuels such as coal. In the case of Ethiopia, more than 50pc of the energy consumption of cement factories is fulfilled by coal (Samson, 2017).

The major applications which have got greater attention are the utilization of coal as a raw material for the production of fertilizer and as source of energy for power and heat generation, especially in cement industries. There are occurrences in different parts of the country that assure the country has more coal reserve that could serve as a bridge to build sustainable agricultural and industrial development on rational use of these reserves, with acknowledgment of the clean coal technologies (Demos, 2007).

2.5 Coal combusted Products

The combustion of pulverized coal in the furnace of power station boiler results in the production of a number of solid products traditionally regarded as wastes but more accurately classified as coal combustion products (CCPs) (Tharaniyil, 2004).

According to World Coal Ash Association 2018 report the worldwide production of coal combustion products was approximately 780 Million metric tons (Mt). The largest coal combustion product producing countries and regions were; China 395 Mt, North America 118Mt, India 105Mt, European union (EU15) 52.6Mt, Africa 31.1Mt and Middle East as minor contributor. In Africa 92% of production coal combustion products was produced in South Africa. From 780Mt of the global CCPs produced, some 415Mt or 53% were reported as utilized. Utilization rate varies widely from country to country depending on the quality of CCPs produced, technological capability and degree of awareness on utilization possibilities. Japan had the highest reported effective utilization rate of 96.4% and Africa with lowest at 10.5%.

Coal combustion products (CCPs) include fly ash, bottom ash, boiler slag, fluidized-bed combustion (FBC) ash, or flue gas desulfurization (FGD). The term coal ash is used interchangeably for different ash type. Fly ash is the fine ash produced in a coal-fired power station, which is collected using electro-static precipitators. Bottom ash is the coarse ash that falls to the bottom of a furnace.

2.5.1 Coal Ash Generation

In the production of fly ash, coal is first pulverized in grinding mills before being blown with air into the burning zone of the boiler. In this zone the coal combusts producing heat with temperatures reaching approximately 1500°C (2700°F). At this temperature the non-combustible inorganic minerals (such as quartz, calcite, gypsum, pyrite, feldspar and clay minerals) melt in the furnace and fuse together as tiny molten droplets. These droplets are carried from the combustion chamber of a furnace by exhaust or flue gases. Once free of the burning zone, the droplets cool to form spherical glassy particles called fly ash. The fly ash is collected from the exhaust gases by mechanical (bag house) and electrostatic precipitators. The heavier unburned material drops to the bottom of furnace is termed as bottom ash (Ian, 2004).

In electrostatic precipitators the flue gas is passed between electrically charged plates where the fly ash particles are then attracted to the plates. Bag houses can also be used to collect ash with bags that filter the fly ash out of the flue gas stream. The fly ash particles are periodically knocked off the plates or bags and fall into the hoppers located at the bottom of the electrostatic precipitators or bag houses. The fly ash is then pneumatically transported to storage silos. The storage silos are equipped with dry un loaders for loading dry bulk semi tankers or rail cars, and wet un loaders for conditioned ash or disposal applications.

Bottom ash is formed when ash particles soften or melt and adhere to the furnace walls and boiler tubes. These larger particles agglomerate and fall to hoppers located at the base of the furnace where they are collected and normally ground to a predominantly sand size gradation. Some bottom ash is transported to storage dry, but most is transported wet from the furnace bottom to dewatering bins where water is removed prior to unloading and transports to construction sites or storage stockpiles.

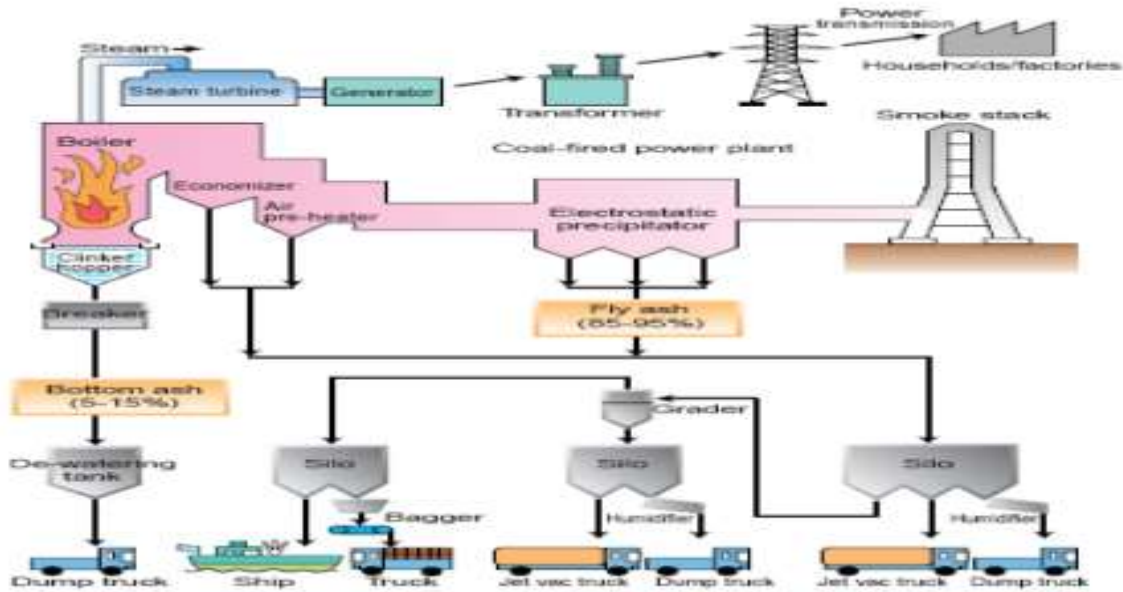


Figure 2-1: Schematic layout coal-fired electric generation station (Behera, 2010)

2.6 Pozzolanic Material

As per ACI 211.1-91 standard practice for selecting proportions for concrete, Binders are materials resembling or having some properties of cement. They are other than hydraulic cement often used in concrete in combination with Portland or blended cement for economy, reduction of heat of hydration, improved workability, improved strength and/or improved durability under the anticipated service environment. These materials include Coal fly ash, natural pozzolans, GGBF slag and silica fume.

ASTM C 618 specified that, pozzolans are siliceous or aluminous materials which in themselves possess little or no cementitious value, but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Pozzolanic material can be classified as Class N, Class F and Class C. Class N pozzolanic materials most customarily used during pozzolana Portland cement (PPC) production. They are raw or calcined natural pozzolans such as some diatomaceous earths, opaline cherts, shales, tuffs and volcanic ashes or pumicites, calcined or un calcined; and various materials requiring heating substance to a high temperature to induce satisfactory properties, such as some clays.

Class F and Class C are type of coal fly ashes and are finely divided residue that results from the combustion of ground or powdered coal. Class F coal fly ash normally produced from burning of anthracite or bituminous coal and has pozzolanic properties. Whereas, Class C coal fly ash normally produced from lignite or subbituminous coal. This class of fly ash, in addition to having pozzolanic properties, also has some cementitious properties. As a result, this material may be self-setting when mixed with water. Class C fly ash may contain lime (CaO) amounts higher than 10 percent.

2.6.1 Proportioning of Binder

ACI 211.1-91 recommends, in the absence of prior information and in the interest of preparing estimated proportions for a first trial batch or a series of trial batches the following general ranges are given based on the percentage of the ingredients by the total weight of Binder used in the batch for structural concrete:

Table 2-2 Recommended replacement range of pozzolanic material (ACI 232.2R, 2002)

No.	Pozzolanic Material		Proportioning Rate (%)
1	Coal Fly Ash	Class C	15-35
		Class F	15-25
2	Ground Granulated Blast Furnace Slag		25-70
3	Silica fume		5-15
4	Natural Pozzolans (Class N)		10-20

2.7 Properties of fly ash

2.7.1 Chemical Properties

ASTM C-618 classified fly ash into two types, Class C and Class F. The sum of the first three constituents (SiO_2 , Al_2O_3 , and Fe_2O_3) is required to be greater than 70 percent to be classified as an ASTM Class F fly ash, whereas their sum must only exceed 50 percent to be classified as an

ASTM Class C fly ash. Class C fly ashes generally contain more than 20 percent of CaO. Therefore, the sum of the SiO₂, Al₂O₃, and Fe₂O₃ may be significantly less than the 70 percent of Class F minimum limit (ACI 232.2R, 2002).

The LOI limit in ASTM C618 is 6% for Class F and Class C fly ash, however, the specification allows Class F fly ashes with up to 12% LOI to be approved by the user if either acceptable performance records or laboratory test results are made available.

Table 2-3: ASTM C-618 Specification for Fly Ash

Class	Source Coal type	Chemical Requirement	LOI (%)
F	Anthracite and Bituminous coal	SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃ ≥ 70%	≤6
C	lignite and Sub-bituminous coal	SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃ ≥ 50%	≤6

Table 2-4: Ranges of bulk chemical compositions of fly ash produced in North America (wt. %) (Siddique, 2011)

Oxide	Class F fly ash	Class C fly ash
SiO ₂	38-65	33-61
Al ₂ O ₃	11-33	8.0-26
Fe ₂ O ₃	3.0-31	4.0-10
CaO	0.6-13	14-37
MgO	0.0-5.0	1.0-7.0
Na ₂ O	0.0-3.1	0.4-6.4
K ₂ O	0.7-5.6	0.3-2.0
SO ₃	0.0-4.0	0.5-7.3
LOI*	0.1-12	0.2-1.4

LOI*=Loss on ignition

2.7.2 Mineralogical Composition

Mineralogical analysis of fly ash is determination of the crystalline and amorphous (glassy) phases. Most of this is done by X-ray diffraction (XRD). Developments in the techniques of quantitative X-ray diffraction (XRD) analysis have made it possible to determine the approximate amounts of crystalline and glassy material in fly ash (Colin, 2005).

On cooling from a disordered state such as gas or liquid, silica becomes ordered in crystals because that is its lowest energy state. However, when it is cooled rapidly it does not have time to order itself before solidifying, so that it solidifies in an amorphous structure (glass) or in a structure intermediate between crystalline and amorphous. Since this state has a higher free energy than the crystalline state, the silica is metastable and thus more reactive. Fly ash can be made to have a high degree of amorphousness by careful control of the temperature during burning process of the coal (Tadesse, 2016).

Crystalline composition: Generally fly ashes have 15-45% crystalline matter. The high-calcium ashes (Class C) contain larger amounts of crystalline matter ranging between 25 and 45%. Class C fly ash may contain quartz (SiO_2), mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$), ferrite spinel ($(\text{Mg,Fe})(\text{Fe,Al})_2\text{O}_4$), hematite (Fe_2O_3), anhydrite (CaSO_4), alkali sulfate ($(\text{Na,K})_2\text{SO}_4$), dicalcium silicate (Ca_2SiO_4), tricalcium aluminate ($\text{Ca}_3\text{Al}_2\text{O}_6$), lime (CaO), melilite ($\text{Ca}_2(\text{Mg,Al})(\text{Al,Si})$), merwinite ($\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$), periclase (MgO), and sodalite ($\text{Ca}_2(\text{Ca,Na})_6(\text{Al,Si})_{12}\text{O}_{24}(\text{SO}_4)$). Low-calcium fly ashes (Class F) are characterized by having only relatively chemically inactive crystalline phases, namely, quartz, mullite, ferrite spinel, and hematite (Siddique, 2011).

Amorphous Phases: they are the circular particles 1-5 μm in diameter. These particles are formed due to quenching of particles, resulting in disordered, lack of crystal structures, making them harder to characterize. This lack of crystal structure is due to “rapid cooling, network isomorphic substitution, and cation modification”. Parent coal with a low calcium results in aluminosilicate glass. Parent coal with higher level of calcium result in calcium aluminosilicate glass, a known reactive phase in Class C ashes. The presence of calcium aluminosilicate glass makes Class C ashes more reactive than class F ashes (Karla, 2013).

2.7.3 Physical Properties

The shape, fineness, particle-size distribution, and density of fly ash particles influence the properties of freshly mixed, unhardened concrete and the strength development of hardened concrete (ACI 232.2R, 2002).

Shape: Particle size and shape characteristics of fly ash are dependent upon the source and uniformity of the coal, the degree of pulverization prior to burning, the combustion environment (temperature level and oxygen supply), uniformity of combustion, and the type of collection system used (mechanical separators, baghouse filters, or electrostatic precipitators). SEM photographs of the ground coal bottom ash and coal fly ash shows surface of coal bottom ash has irregular particles, whereas coal fly ash is characterized by a more uniform distribution of spherical grains with a fairly smooth surface (Cristina, 2017).

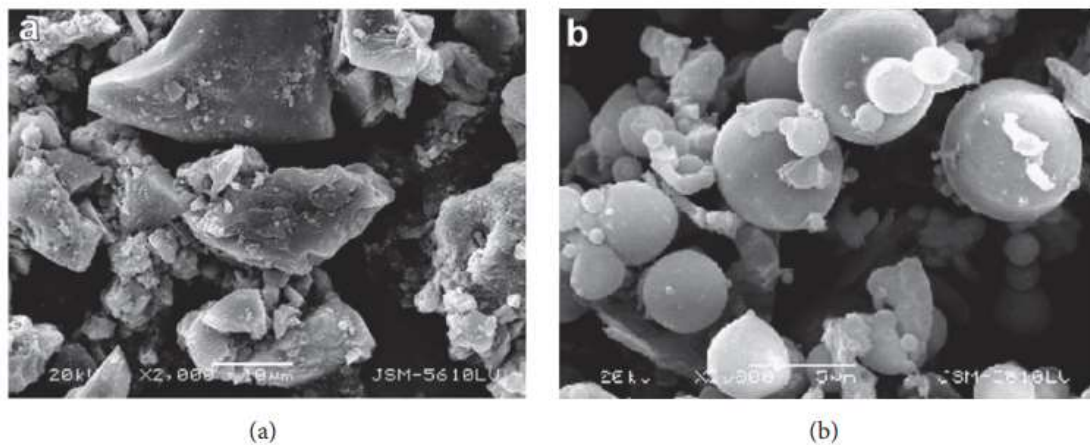


Figure 2-2: SEM images of coal bottom ash (a) and coal fly ash (b) (Cristina, 2017)

Fineness: Fineness is one of the important properties contributing to the pozzolanic reactivity of fly ash. Fineness of fly ash is a result of combustion process and collection system. In older plants where mechanical separators are used, the fly ash is coarser than in more modern plants which use electrostatic precipitators or bag filters. In addition to collection system fineness of fly ash is most closely related to the operating condition of the coal crushers and the grindability of the coal itself (Behera, 2010).

The surface area of fly ash particles varies from 2,000-10,000 cm^2/g depending on the proportion of fine particles in the fly ash (Plessis, 2005). These small glass spheres improve the fluidity and workability of fresh concrete.

Specific Gravity: Generally, density of solid fly ash particles ranges from 1.3 to 4.8 (Josh, 1970). The influence of specific gravity on pozzolanic activities with increasing order of reactivity is listed below;

Table 2-5: the influence of specific gravity on pozzolanic activities (Josh, 1970)

Specific gravity rang (g/cm ³)	Pozzolanic effect
>2.74	Rich in iron and less reactive
<2.1	Glassy and highly porous
2.1-2.5	Glassy particles of low porosity
2.5-2.74	Clear solid glassy spheres

2.7.4 Pozzolanic Activity

The property of fly ashes, possessing little or no cementing value to react with calcium hydroxide in the presence of water, and produce highly cementitious water insoluble products, is called pozzolanic reactivity. The pozzolanic activity of a fly ash depends upon its fineness, calcium content, structure, specific surface, particle size distribution, LOI content. Regarding, when fly ash is pulverized to increase fineness, its pozzolanic activity increases significantly. However, the effect of increase in specific surface area beyond 6,000 cm²/g is reported to be insignificant (Siddique, 2011)

In relation of the above, high silica content and high degree of amorphousness in fly ash makes it reactive. In the pozzolanic reaction the silica (SiO₂) in the fly ash react with calcium hydroxide (Ca (OH)₂) and water form calcium silicate hydrate, the main strength producing component of hydrated cement and concrete.

2.8 Effects of Fly Ash on Concrete

2.8.1 Effects on properties of fresh concrete

2.8.1.1 Workability

Workability is defined as the ease with which a freshly mixed concrete can be properly compacted, transported, placed, and finished. Workability is one of the governing factors of concrete mix

design. The use of good quality fly ash with a high fineness and low carbon content reduces the water demand of concrete. Generally spherical shape of fly ash particles normally permits the water in the concrete to be reduced for a given workability.

Coarser fly ashes or those with high levels of carbon generally produce a smaller reduction in water demand and some may even increase water demand. Owens (1979) reported that with the use of fly ash containing large fraction of particles coarser than $45\mu\text{m}$ or a fly ash with high amount of unburned carbon, exhibiting loss on ignition more than 1%, higher water demand was observed.

2.8.1.2 Setting Time

The rate of stiffening of cement paste is expressed in terms of setting time. Generally, the effect of fly ash on the setting time depends upon the characteristics and amount of fly ash used. The interacting effects of fly ash with other chemical and mineral admixtures may also influence the setting of concrete.

It is fairly well-established that low-calcium fly ashes extend both the initial and final set of concrete.

2.8.1.3 Heat of Hydration

The hydration or setting of Portland cement paste is accompanied by an evolution of heat that causes a temperature rise in fresh concrete. Replacement of cement by fly ash results in a reduction in the temperature rise in fresh concrete. This is of particular importance in mass concrete, where cooling following a large temperature rise can lead to cracking. The first major use of fly ash in concrete was in the construction of a gravity dam, where it was employed principally to control temperature rise.

2.8.2 Effects on properties of hardened concrete.

2.8.2.1 Strength development

The main factors determining strength in concrete are the amount of cement used and water/cement. In practice, these are established as a compromise between the needs of workability in the freshly mixed state, strength and durability in the hardened state, and cost.

Strength at any given age and rate of strength gain of concrete are affected by the characteristics of the particular fly ash, the cement with which it is used, and the proportions of each used in the concrete. The relationship of tensile strength to compressive strength for concrete with fly ash is

not different from that of concrete without fly ash. Class C fly ashes often exhibit a higher rate of reaction at early ages than Class F fly ashes (ACI 232.2R, 2002).

Particle size can influence strength development in two ways. First, particles less than 45 μ m appear to influence water requirement in an adverse way. They counteract the proportioning methods used to compensate for the slow rate of reaction of fly ash at early ages. Secondly, cementing activity occurs on the surface of solid phases and through heterogeneous processes of diffusion and dissolution of materials in concentrated pastes. Surface area of particles must play a considerable role in determining the kinetics of such processes (Ramezaniapour, 2014).

3 MATERIAL PROPERTIES

3.1 Introduction

The aim of this chapter is to discuss the physical and chemical properties of material used in this research. The properties of each material must comply with the requirements of standards and specifications. ASTM standards and specifications were used for checking of requirements in sampling method and testing.

Except for chemical test and XRD analysis of coal fly ashes, all laboratory tests on aggregate and concrete were carried out in the Material Testing Laboratory of Institute of Technology of AAU. A complete silicate analysis of coal ashes was conducted in the Geological Survey of Ethiopia. Fineness tests of cement and coal fly ashes were conducted in Chemical Engineering laboratory whereas XRD analysis was conducted in a Chemistry department laboratory.

3.2 Coal fly Ash

For this research, two coal ashes were used in which they were collected from two distinct factories of Ethiopia, namely: AYKA Addis Textile factory and Dongfang Spinning and Printing and Dying PLC. These two samples of coal ashes were designated by FA1 and FA2. Where;

FA1= Coal ash collected from AYKA Addis Textile factory

FA2= Coal ash collected from Dongfang Spinning and Printing and Dying PLC.

Both samples are by-product of the electric power generation plant. AYKA Addis Textile factory uses local coal which is extracted and supplied from the Achebo area whereas Dongfang Spinning and Printing and Dying PLC used imported coal from South Africa.

Fly Ash collected from AYKA Addis Textile factory (FA-1) is captured by particle filtration equipment (Bag filter) before the flue gases reach the chimneys. Figure 3-1 shows that schematic layout of AYKA Addis Textile factory electric power plant.



Figure 3-2: Disposed Coal ash in AYKA Addis Textile Factory

Fly ash from Dongfang Spinning Printing and Dying PLC(FA-2) is collected by a wet system of collection or disposal. Fly ash is mixed with bottom ash in slurry before transporting to the ash disposal area. This process of fly ash dumping is largely unsuitable for all purposes where pozzolanic properties are essential to use it.

According to ASTM C618, coal ash collected from AYKA is classified as Class C ash whereas coal ash from Dongfang is referred to as off-specification fly ash because it does not meet requirements for either Class C or Class F fly ashes in ASTM 618. The general properties of both coal ashes are summarized in Table 3-1.



Figure 3-3: Coal ash Collection in Dongfang Spinning Printing and Dying PLC.

3.2.1 Chemical Analysis

Complete silicate analysis of fly ashes was conducted in the Geological Survey center of Ethiopia and the results of which are given in Table 3-1. The full Chemical analysis of the ashes as reported by the Geological Survey of Ethiopia is attached in the appendix section of this study.

As shown in Table 3-1, the sum of the first three constituents (SiO_2 , Al_2O_3 , and Fe_2O_3) of coal ash collected from AYKA is greater than 70% which indicates that the sample fly ash classified as an ASTM Class F fly ash. As per ASTM C-618 recommendation LOI of the given fly ash should be below 12 so as the sample fly ash. On the other hand, fly ash collected from Dongfang is out of the specification of ASTM C-618. Its LOI value is 37.8% which shows a large amount of carbon content.

Table 3-1 Chemical composition Coal ash and Cement

Parameter	Chemical Composition Of Cement (%)	Chemical Composition Of AYKA Coal Ash (%)	Chemical Composition Of Dongfang Coal Ash (%)
SiO₂	22.82	52.54	30.96
Al₂O₃	5.41	34.66	18.86
Fe₂O₃	3.37	1.34	4.96
CaO	66.32	0.16	2.18
MgO	1.46	0.01	0.58
Na₂O	-	1.08	0.5
K₂O	-	0.01	0.4
MnO	-	0.01	0.06
P₂O₅	-	0.01	1
TiO	-	0.55	0.42
H₂O	-	4.25	2.56
LOI	-	6.85	37.8
SiO₂+ Al₂O₃+ Fe₂O₃	31.6	88.54	54.78
Classification		Class F	Off-spec

3.2.2 Particle Size Distribution

Samples taken from the factories were pulverized and sieved with 300µm sieve before any physical and chemical property has been determined. The particle size distribution of Coal ash samples sieved with 300µm sieve and that of cement showed as follows;

Table 3-2: Particle size distribution of Coal Ash and Cement

Sieve Size (µm)	Percentage Passing of FA-1	Percentage Passing of FA-2	Percentage Passing of Cement
150	63.4	92.9	99.5
125	49.41	88.55	99.1
75	21.62	76.5	94.9
63	4.11	46.5	83.9
32	0.59	1.1	1.4

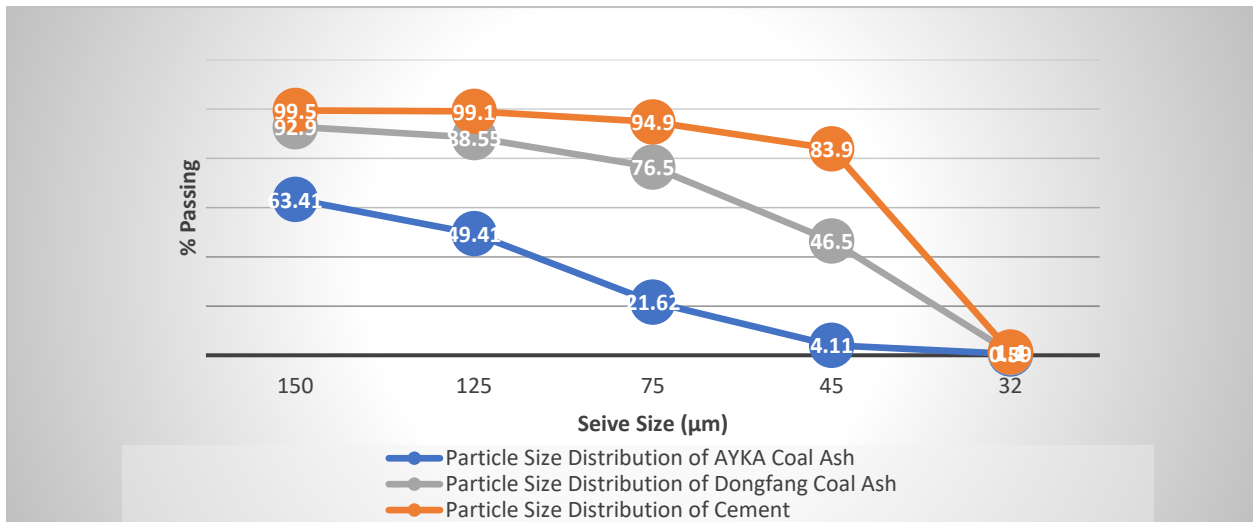


Figure 3-4: Particle size distribution of Coal Ash and Cement

3.2.3 Fineness of Fly Ash

Fineness of fly ashes were determined by air-permeability test according to ASTM C 204. The fineness of fly ashes is measured like cement as a specific surface area. The specific surface area is expressed as the total surface area in square meters of all the cement particles in one kilogram of cement. The higher the specific surface is, the finer cement will be. The principle of air permeability method is observing the time taken for a fixed quantity of air to flow through compacted cement bed of specified dimension and porosity. Figure 3-5; shows the Blain air Permeability apparatus used during this research.

The method is comparative rather than absolute and therefore a reference sample of known specific surface is required for calibration of the apparatus. Reference specific surface area of Ss, 3774

cm²/g was taken for calibration of the apparatus and the corresponding time interval of manometer drop for standard sample used in calibration of apparatus was T_s=37.9 sec.



Figure 3-5: Blain air Permeability apparatus

A bed of fly ash is prepared in a special permeability cell and has a porosity of $e = 0.5$. The weight of the fly ash in gram is calculated from:

$$m = 0.5\rho V \quad \text{Equation 3-1}$$

Where: -

ρ is the density of the cement [g/cm³]

V volume of the fly ash bed [cm³]

As per ASTM C-204, Specific surface area of fly ash is calculated using the following equation;

$$S = S_s \frac{\sqrt{T}}{\sqrt{T_s}} \quad \text{Equation 3-2}$$

Where: -

S = Specific surface of the test sample (m²/kg)

S_s = Specific surface of the standard sample used in calibration of apparatus (m²/kg)

T = Measured time interval of manometer drop for test sample (Seconds)

T_s = Measured time interval of manometer drop for standard sample used in calibration

Based on the above equation, the fineness of Coal ashes collected from the two factories and fineness of cement are summarized below in Table 3-3.

Table 3-3: Fineness of Coal Ash and Cement

Parameters	Cement	FA-1	FA-2
Density (g/cm ³)	3.15	2.51	2.13
Volume of bed (cm ³)	1.852	1.852	1.852
Mass of bed(g)	2.917	2.32	1.972
Time interval of manometer drop, T (seconds)	49.3	30.05	38.2
Specific surface area (cm ² /g)	4304.33	3385.57	3788.9
Mean Particle diameter (μm)	4.5	7.04	7.25

ACI 232.2R provides a relation between particle size and surface area based on various densities. Accordingly, the mean particle diameter of coal ash collected from AYKA and Dongfang would be 7.04μm and 7.25μm respectively.

3.2.4 XRD Analysis

Mineral properties of samples of fly ash from AYKA and Dongfang were determined by X-ray studies at the Laboratory of Chemistry department of Addis Ababa University Science Faculty. X-ray diffraction is a nondestructive experimental method based on the usage of the diffraction of X-rays with crystal lattice sized wavelengths. This method is primarily used for quality analysis, due to the fact that it enables the identification of present crystal components, type of crystal lattice, the presence of certain phases in the system, the deformation of a crystal lattice, the size of crystals. It can also be used for quantitative analysis, or more precisely, for an estimation of different components share in the content of the sample (Miloš, 2016).

All samples were tested on the powder diffractometer. The diffraction patterns (diagrams) were obtained with K-alpha radiation ($\lambda_1 = 1.54059 \times 10^{-10} \text{m}$ and $\lambda_2 = 1.54441 \times 10^{-10} \text{m}$), created in the X-ray tube at 15 mA and a voltage of 40 kV. Record the sample is performed in the range of 2θ from 5 to 55° with a step of 0.02°.

Analysis of XRD data was made by using Match software. Match software is a software that enables the identification of peaks of crystalline phases. In this research, the trial version of Match software was used to show the existence of common crystalline phases in the fly ash sample.

To identify crystalline phases in the fly ash, raw XRD data was recorded by '.asc' type file which can easily readable by match software. The software uses the default COD-Inorganic (Crystallography open database) reference database which is released January 12, 2018 (Putz, 2015). Reference databases typically contain thousands of peak lists (diffraction patterns of known phases). Figure 3-6; below shows the user interface of Match software during XRD analysis of the FA-1 sample.

Basis of Match software is the comparison of peak in a sample's powder diffraction pattern with peaks of known reference phases. Matching is calculated by numerical agreement value ('Figure of Merit', FoM) for every reference pattern. The reference phases are sorted according to their numerical agreement with the experimental pattern (FoM) so that the best matching phases are at the top.

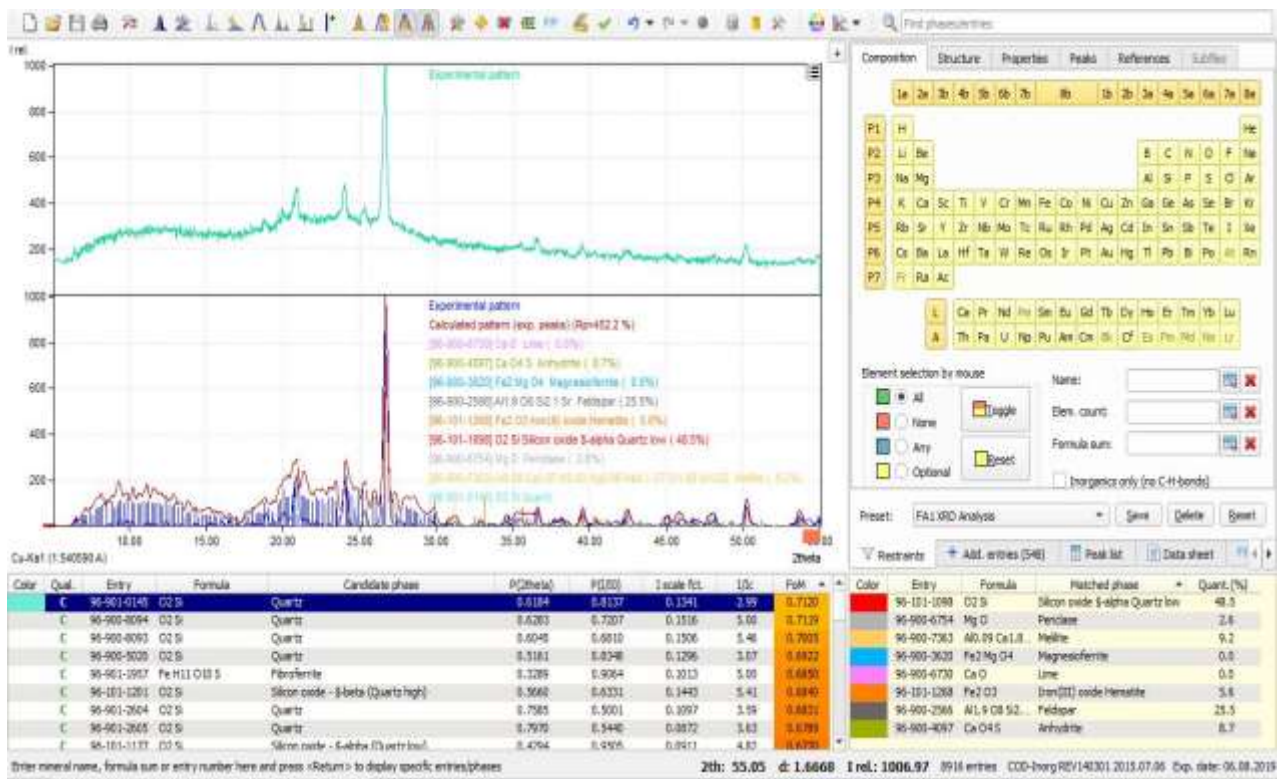


Figure 3-6: XRD analysis of FA-1 sample

The characteristic peaks of the mineral composition of FA-1 and FA-2 are shown below in Table 3-4. Details of Match phase analysis report are present in the appendix section of this report. X-ray examination has shown that the fly ash is mainly amorphous, but there are also present crystal phases feldspar, melilite, hematite, very little anhydrite, and quartz. As observed in Table 3-4; the most common minerals of fly ash are constituents of FA-1. Moreover, about 8.7 percent of the sample is Anhydrite. It plays a significant role in fly ash hydration behavior because it participates along with tricalcium aluminate and other soluble aluminates (Miloš, 2016).

Table 3-4: Crystalline phases of FA-1

Name of Mineral	Label of Mineral	Chemical formula	Amount (%)
Quartz	Qz	SiO ₂	48.5
Feldspar	f	Al _{1.9} O ₈ Si _{2.1} Si ₄	25.5
Melilite	M	Al _{0.09} Ca _{1.87} K _{0.02} Mg _{0.96} Na _{0.1} O ₇ Si _{1.98} Sr _{0.02}	9.2
Iron (III) oxide Hematite	He	Fe ₂ O ₃	5.6
Anhydrite	An	Ca SO ₄	8.7
Periclase	Pc	MgO	2.6
Unidentified peak area			24.7

3.3 Cement

Dangote Ordinary Portland Cement from the local market were used during this study. The cement used in this research was manufactured according to Ethiopian standard ES-1177-1-2005 and European standard EN-197-1-2000. Its physical and chemical composition clearly shown in Table 3-1, Table 3-2 and Table 3-3.

3.4 Aggregates

It is well recognized that coarse aggregate plays an important role in concrete. Coarse aggregate typically occupies 65-75% of the volume of concrete, and research indicates that changes in coarse aggregate can change the strength and fracture properties of concrete. In Concrete, aggregates generally serve as inert mineral filler material in which the cement paste binds together provides better durability and reduces volume changes.

All relevant laboratory tests required for proportioning and mix design were conducted. Gradation, bulk density, specific gravity and moisture content of the aggregate has tested to ensure that the material meets specification for concrete work and to determine processing requirements. Before the determination of properties of aggregate, it was thoroughly washed to make it free from impurities like silt, organic material, clay, and any other dust which degrades its quality and kept in moisture shielding sacks after it dried.

3.5 Fine Aggregate

As per ASTM C-125 definition, fine aggregates used in concrete are small size filler material that pass through 4.75mm sieve and retain on sieve 0.07mm sieve. River sand or machine sand (crushed stoned sand) are major sources of fine aggregate. For this study, locally available river sand passing through 4.75mm sieve was used.

After the fine aggregate is thoroughly washed and dried, relevant quality tests were conducted in Material and Testing Laboratory to check its compliance with the requirements of specification and standards. Accordingly, the following test results have been recorded;

3.5.1 Particle Size Distribution

Particle Size Distribution test has been conducted and checked as per ASTM C-136 sieve analysis. A sample of fine aggregate for sieve analysis is first surface dried and then sieved through the series of sieves, starting with 4.75mm. The material retained on each sieve after shaking represents the fraction of fine aggregate coarser than the sieve in question and finer than the sieve above. The summation of the material retained on the sieves divided by 100 is called the fineness modulus. It is used as an index to the fineness or coarseness and uniformity of aggregate supplied. The grading requirement for fine aggregate according to ASTM C-33 and the grain size distribution of the fine aggregate is as shown in Table 3-5.

Based on grain size distribution of fine aggregate, fineness modulus of fine aggregate would be 2.69 which conforms with the AASHTO M6 requirement of minimum 2.3 and maximum 3.1 for fine aggregate. Gradation curve for fine aggregate and standard fineness as per ASTM C-33 presents in Figure 3-7;

Table 3-5: Grain size distribution of fine aggregate

Sieve Size (mm)	Percentage passing by mass	Standard Passing As per ASTM C-33
9.5		100
4.75	100	95-100
2.36	95	80-100
1.18	80	55-85
0.6	44	25-60
0.3	10	5_30
0.15	2	0_10

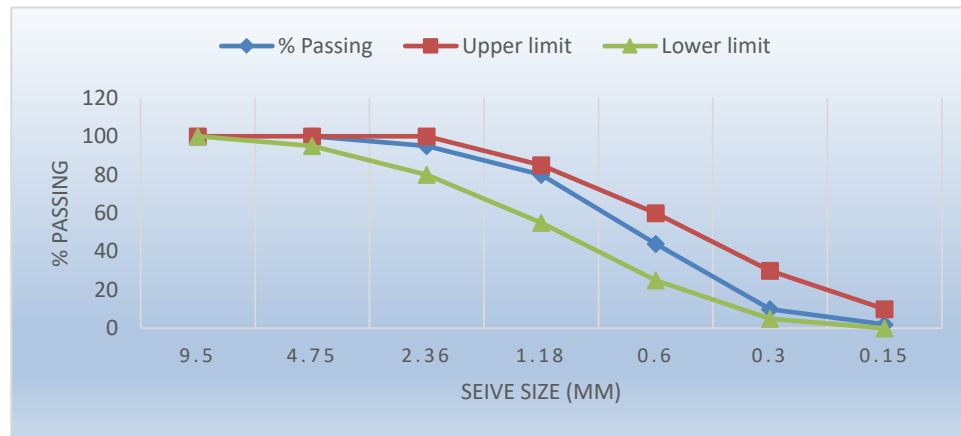


Figure 3-7: Gradation curve of fine aggregate

3.5.2 Specific Gravity and Absorption Capacity.

The specific gravity of sand is the ratio between the weight of the sand and that of the same volume of water. In this research, apparent specific gravity and Bulk specific gravity of fine aggregate was identified based on ASTM C-127 specification. Apparent specific gravity is the ratio of the weight in air of given volume fine aggregate plus impermeable pores or voids to the weight in air of an equal volume of distilled water. Bulk specific gravity is the ratio of the weight in air of a given volume of permeable sand including both its permeable and impermeable voids to the weight in

air of an equal volume of water. Bulk specific gravity (SSD basis) is the ratio of the weight in air of a permeable sand in a saturated surface dry condition to the weight in air of an equal volume of water. Absorption is the measurement of water that is in the concrete pores.

In this common understanding, the results obtained during the laboratory experiment is summarized as follows;

Bulk specific gravity = 2.49

Bulk specific gravity (SSD state) = 2.56

Apparent specific gravity = 2.69

Absorption capacity = 3.09%

3.5.3 Silt Content

The fine aggregate used for this research is natural river sand. The sand was washed before the silt content test. However, it may contain other materials such as dust, loam, and clay that are finer than sand. The presence of such materials in the sand used to make concrete or mortar decreases the bond between the materials to be bound together and hence the strength of the mixture. The finer particles do not only decrease the strength but also the quality of the mixture produced resulting in fast deterioration. Therefore, to make sure the quality of the sand it is necessary to make a test on the silt content and check against permissible limits. The silt content obtained from the test result is 1.66% which is below the Ethiopian Standard of 6%.

3.5.4 Moisture Content

It is well known that the water-binder ratio affects the workability and strength of concrete specimens. A design water-binder ratio is usually specified based on the assumption that aggregates are inert. However, in most cases, aggregates from different sources do not comply with this. Wet aggregates give water to the mix and dry aggregates take water from the mix. In both cases, it will affect the design water-binder ratio. To correct this inconsistency, the moisture content of the fine aggregates has to be determined.

In light of the above, moisture content of fine aggregate was determined and the obtained result is 1.01%.

3.5.5 Unit weight

The Dry-Rodded Unit Weight of an aggregate is the weight required to fill a container or a specified unit volume after it has been rodded to attain maximum packing. For this research, ASTM C29 was used to determine the dry-rodded unit weight that is also sometimes called the “bulk unit weight of aggregates” since the voids between the particles are included. It is important to note that the dry- rodded unit weight is not the same as specific gravity. Therefore, the unit weight of sample sand is 1593.34 Kg/m³

3.6 Coarse Aggregates

Crushed stone with a nominal size of 25mm from local source confirming ASTM C-33 was used for this study. For all laboratory experiments, the aggregate used similar and purchased once from the single source to avoid the variability of characteristics of aggregates. Several laboratory tests were carried out to identify the physical properties of the coarse aggregate and to be sure that the aggregate complies with specific requirements and standards. The physical properties of coarse aggregate used in this research are summarized and tabulated as follows;

Table 3-6: Physical Properties of coarse aggregate

No.	Test Description	Result	
1	Nominal Maximum Size	25mm	
2	Moisture Content	1.27%	
3	Unit Weight	1593.34Kg/m ³	
4	Absorption Capacity	1.52%	
5	Specific gravity	Bulk	2.61
		Bulk (SSD)	2.65
		Apparent	2.72

One of the most important factors for producing workable concrete is a good gradation of aggregate. Good grading implies that a sample of aggregates contains all standard fractions of aggregate in the required proportion such that the sample contains minimum voids. A good gradation secures an increased economy, higher strength, lower shrinkage, and greater durability. The grading or particle size distribution of aggregate is determined by a sieve analysis as per

ASTM C-136. As shown in Figure 3-7, each size of aggregate fall into the required range of standard passing as per ASTM C-33.

3.7 Water

Water is an important ingredient of concrete as it actively participates in the chemical reaction with cement. Moreover, the curing of concrete and washing of aggregate have been done by water. Therefore, as much as possible it should be free from impurities such as suspended solids, silt, clay, acids, alkalis, and organic matters and dissolved salts. Accordingly, the tap water supplied found in the laboratory was used in this study.

Table 3-7: Grain size distribution of coarse aggregate

Sieve Size (mm)	Percentage Passing by mass (%)	Standard Passing as Per ASTM C-33 (%)
37.5	100.00	100
25	96.17	95-100
19	49.9	40-85
12.5	26.7	25-60
9.5	7.4	0-15
4.75	0.2	0-10

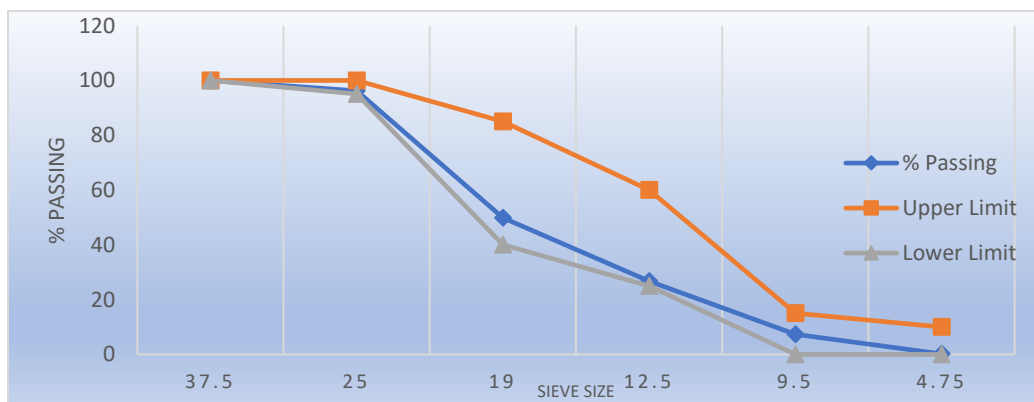


Figure 3-8: Gradation curve of coarse aggregate

4 EXPERIMENTAL PROGRAM

4.1 Introduction

The objective of this study is to investigate the suitability of coal ashes produced in different factories of Ethiopia, as supplementary cementitious material in cement concrete production and its optimum utilization. Two fly ashes designated by FA-1 and FA-2 were used as indicated in section 3.1 of this report.

The substitution portion of fly ash were made 10%, 15%, 20% and 25% by volume of cement for FA1 and 5%, 10%, 15% and 20% by volume of cement for FA2. It is obvious that Strength (compressive or flexural) and durability of concrete mostly affect by water to binder ratio. For this matter, two classes of concrete with a water-binder ratio of 0.4 and 0.6 were made to investigate the effect of coal ashes on the strength of concrete.

4.2 Mix Design

The selection of concrete proportions should be based on test data or experience with the materials actually to be used. Accordingly, four mix proportions were conducted to compare the rate of strength development and the difference in compressive and flexural strength values with age on two classes of concrete using Dangote OPC with different percentages of FA1 and FA2. They were made with cement content of 475kg/m³ and 316.67 kg/m³.

Based on material properties discussed in chapter 3, the concrete mix has proportioned for a water-binder ratio of 0.4 and 0.6. Accordingly, the coarse aggregate of well-graded, 25mm nominal maximum size (ASTM C33) with bulk specific gravity of 2.62, absorption of 1.52%, and oven dry rodded bulk density (unit weight) of 1599.97 kg/m³ was used. The laboratory sample for trial batching had a moisture content of 1.27%. The bulk volume of coarse aggregate recommended when using sand with fineness modulus of 2.86 is 0.664. Therefore, the oven dry mass of coarse aggregate for a cubic meter of concrete is $1599.97 \times 0.664 = 1062.4$ Kg.

Fine aggregate of Natural sand (ASTM C33) with an oven-dry specific gravity of 2.487 and absorption 3.09% was used. The laboratory sample moisture content is 1.57%. and the fineness modulus is 2.86%. The approximate amount of entrapped air in non-air-entrained concrete is 2%.

4.2.1 Concrete Mix Design for Water-binder ratio= 0.4

The cement content was determined based on the maximum water-binder ratio and the water content. Therefore, for a water-binder ratio of 0.4 and water content of 190Kg/m^3 , the required cement content become 475Kg .

The designed mix was proportioned based absolute volume method. The absolute volume of water, cement, and coarse aggregate is calculated by dividing the known mass of each by the product of their specific gravity and density of water. Volume computation as follows:

$$\begin{array}{lcl} \text{Water} & = \frac{190}{1 \cdot 1000} & = 0.190\text{m}^3 \\ \text{Cement} & = \frac{475}{3.15 \cdot 1000} & = 0.15\text{m}^3 \\ \text{Air} & = \frac{2}{100} & = 0.02\text{m}^3 \end{array}$$

In the absolute volume method, the volume of aggregate is determined by subtracting the absolute volumes of the known ingredients from 1 a cubic meter. The calculated absolute volume of aggregate is $1 - 0.36 = 0.64\text{m}^3$

Fine aggregate and coarse aggregate have proportioned to 0.42% and 0.58% of total aggregate content in order to balance the optimum volume of wet concrete. Therefore;

The mass of dry fine aggregate is $0.42 \times 0.64 \times 2.487 \times 1000 = 671.5\text{kg}$

The mass of dry coarse aggregate is $0.58 \times 0.64 \times 2.62 \times 1000 = 969.4\text{kg}$

The estimated batch weights for one cubic meter of concrete are revised to include aggregate moisture as follows:

$$\text{Mass of F. A} = 671.5 \cdot (1 + 0.0157) = 682.04\text{Kg}$$

$$\text{Mass of C. A} = 969.4 \cdot (1 + 0.0127) = 981.71 \text{ kg}$$

Water absorbed by the aggregates does not become part of the mixing water and must be excluded from the water adjustment. Surface moisture contributed by the coarse aggregate amounts to $1.27\% - 1.52\% = -0.25\%$; that contributed by the fine aggregate is, $1.57\% - 3.09\% = -1.52\%$. The estimated requirement for added water becomes;

$$\text{Mass of water} = 190 + 671.5 \cdot 0.0152 + 969.4 \cdot 0.0025 = 202.63 \text{ kg}$$

As per ACI 211.1, when pozzolanic materials are used in concrete, a water-to-cement plus pozzolanic materials ratio (or water-to-cement plus other Binders ratio) by weight must be considered in place of the traditional water-binder ratio by weight. This can be done either the equivalent weight of pozzolanic materials or the equivalent absolute volume of pozzolanic materials in the mixture.

The equations for converting a target water-binder ratio, w/c to a weight ratio of water to cement plus coal fly ash, w/(c + p) by weight equivalency is done base on ACI 211.1 recommendation.

$$\frac{w}{c+p} = \frac{w}{c} \quad \text{Equation 4-1}$$

Where:

$$\frac{w}{c+p} = \text{weight of water divided by weight of cement + Coal fly ash}$$

$$\frac{w}{c} = \text{target water binder ratio by weight}$$

Absolute Volume Equivalence

$$\frac{w}{c+p} = \frac{3.15 \frac{w}{c}}{3.15(1-F_v) + G_p F_v} \quad \text{Equation 4-2}$$

The Coal fly ash percentage by weight of total cement plus coal fly ash expressed as a decimal factor, is

$$F_w = \frac{P}{C+P} \quad \text{Equation 4-3}$$

Where:

F_w = coal fly ash percentage by weight, expressed as a decimal factor

p = weight of coal fly ash

c = weight of cement

The desired coal fly ash percentage factor by absolute volume F_v , is known, it can be converted to F_w as follows:

$$F_w = \frac{1}{1 + \left(\frac{3.15}{G_p}\right) \left(\frac{1}{F_v} - 1\right)} \quad \text{Equation 4-4}$$

Where

F_v = Coal fly ash percentage by absolute volume of the total absolute volume of cement
as a decimal factor

G_p = Specific gravity of coal fly ash

3.15= Specific gravity of Portland cement

In light of the above, the mix proportions for FA-1 and FA-2 with a water-binder ratio of 0.4 and each percentage of replacements are summarized below in Table 4-1 and Table 4-2;

Table 4-1: FA-1 and Cement proportion of a cubic meter of concrete for each percent of replacement and w/c=0.4

Fv(%)	Fw(%)	W/(C+P)	Weight of cement + Coal fly ash (Kg)	Weight of Cement (Kg)	Weight of Coal fly ash (Kg)
10	8.13	0.41	465.35	427.50	37.85
15	12.33	0.41	460.52	403.75	56.77
20	16.61	0.42	455.70	380.00	75.70
25	20.99	0.42	450.87	356.25	94.62

Table 4-2: FA-2 and Cement proportion of a cubic meter of concrete for each percent of replacement and w/c=0.4

Fv (%)	Fw (%)	$\frac{W}{C + P}$	Weight of cement + Coal fly ash (Kg)	Weight of Cement (Kg)	Weight of Coal fly ash (Kg)
5	3.44	0.41	467.31	451.25	16.06
10	6.99	0.41	459.62	427.50	32.12
15	10.66	0.42	451.93	403.75	48.18
20	14.46	0.43	444.24	380.00	64.24

4.2.2 Concrete Mix Design for Water-binder ratio= 0.6

A similar procedure was used to proportion a concrete mix with a water-binder ratio of 0.6. Accordingly, the mix proportion for FA-1 and FA-2 with a water-binder ratio of 0.6 and each percentage of replacements are summarized below in Table 4-3;

Table 4-3: FA-1 and Cement proportion of a cubic meter of concrete for each percent of replacement and w/c=0.6

Fv (%)	Fw (%)	W/(C+P)	Weight of Coarse aggregate (Kg)	Weight of Fine aggregate (Kg)	Weight of Water (Kg)	Weight of cement + Coal fly ash (Kg)	Weight of cement (Kg)	Weight of Coal fly ash (Kg)
10	8.13	0.61	1061.31	732.55	203.58	310.23	285.00	25.23
15	12.33	0.62	1061.31	732.55	203.58	307.02	269.17	37.85
20	16.61	0.63	1061.31	732.55	203.58	303.80	253.33	50.47
25	20.99	0.63	1061.31	732.55	203.58	300.58	237.50	63.08

Table 4-4: FA-2 and Cement proportion of a cubic meter of concrete for each percent of replacement and w/c=0.6

Fv (%)	Fw (%)	W/(C+P)	Weight of Coarse aggregate (Kg)	Weight of Fine aggregate (Kg)	Weight of Water (Kg)	weight of cement + Coal fly ash (Kg)	weight of cement (Kg)	weight of Coal fly ash (Kg)
5	3.44	0.61	1061.31	732.55	203.58	311.54	300.83	10.71
10	6.99	0.62	1061.31	732.55	203.58	306.41	285.00	21.41
15	10.66	0.63	1061.31	732.55	203.58	301.29	269.17	32.12
20	14.46	0.64	1061.31	732.55	203.58	296.16	253.33	42.83

4.3 Specimen Preparation

Based on the aforementioned mix design procedure mixes were done. Each mix batch was 45 liter in volume and was subjected to 1-minute dry mixing and 2 minutes wet mixing. Regarding placing and compaction, placing was started immediately and compacted in table vibrator for 30 seconds. To minimize error each sample should be mixed at a time. However, the capacity of the mixer at Material Test Laboratory is limited to 60liters but each sample required 12 units of 10cm cubes, 3 units of 15cm cubes and 12 units of 10cmx10cmx50cm flexure specimen which correspond to

about 99 liters. Hence, mixing was done in two or three batches and of course, this may contribute some errors among the test result of each cube within a sample.

After 24 hours of placing and compaction, samples were removed from their molds and placed into a water pond for twenty-eight days.

4.4 Experimental program for Compressive Strength

The test program considered the cast and testing of three concrete specimens of cube 100mm for each percentage of replacement and date of investigation. The average test result of three samples were taken.

For each mix, twelve cubes of size 100mm were cast and tested using Compression Testing Machine (CTM). The specimen placed on the platform of the CTM as shown in Figure 4-1. The load applied gradually with the rate of loading of 0.28Mpa/sec until the failure stage. The ultimate load in KN and compressive strength in MPa noted for each corresponding specimen.



Figure 4-1: Sample set up for compressive strength test

To evaluate and compare the rate of strength development among concretes of the same class (i.e. $w/c=0.4$ & $w/c=0.6$) produced by replacing cement by various percentages of fly ashes; FA-1 and FA-2, the test was conducted for each concrete at different ages (i.e. 3,7,28,56 days).

4.5 Experimental program for Flexural Strength

Beam samples measuring 500×100×100mm were molded and stored in water for 28days before the test for flexural strength. Three similar samples were prepared for each mix proportion. The

casting was made by filling each mold with freshly mixed concrete and compacted in table vibrator for 30 seconds. To determine the flexural strength of concrete ASTM C-78 (Standard Test Method for Flexural Strength of Concrete Using Simple Beam with Third-Point Loading) was used. The hardened beam was placed on the modified compressive testing machine simply supported over a span on a pair of supporting rollers. Two additional loading rollers were placed on top of the beam as shown in Figure 4-2.



Figure 4-2: Sample set up for flexural strength test

As per the ASTM C-78 specification, the load was applied at a constant rate to the breaking point. Application of the load was without shock at a rate that constantly increases the extreme fiber stress between 1.21 MPa/min until rupture occurs. Based on this principle, the rate of loading was fixed to 0.02 MPa/sec. The ultimate load was noted and the flexural strength of the corresponding specimen was calculated.

4.6 Experimental program for Water Penetration

The test was carried out according to BS EN 12390-8:2000 on concrete specimens of size 150x150x150 mm, at an age of 28 days. The test cell assembly being used had the provision for testing three cubes at a time as shown in Figure 4-3 below.



Figure 4-3: Water penetration test

Once the specimens were assembled in the test cells, a water pressure of 300KPa (3 bar), 500 KPa (5 bar) and 700Kpa (7 bar) was applied for 72 hours. Water pressure is applied using an arrangement consisting of a water tank connected to an air compressor through a valve, to adjust the pressure.

After the pressure had been applied for the specified time, the specimen was removed from the apparatus. The face on which the water pressure was applied was wiped to remove excess water. The specimen was then split in half, perpendicularly to the face on which the water pressure was applied. Figure 4-4; below shows a typical water penetrated sample just after splitting.



Figure 4-4: concrete sample just after splitting

Upon visual examination, the portion of the specimen into which water has penetrated appears darker than the rest, and immediately after splitting, this zone was marked and measurements were taken.

5 RESULTS AND DISCUSSION

5.1 Introduction

The experiments conducted for this study were performed because of the importance to be able to characterize fly ash collected from two factories in Ethiopia in a way that best predicts how it will perform in concrete with an emphasis on mechanical properties. Pozzolanic properties of the fly ash determined by the mechanical properties of concrete are the most important in the application of ash as a building material.

As described in the experimental program section of this report, two fly ashes with water-binder ratio of 0.4 and 0.6 were investigated employing compressive strength and flexural (tensile) strength starting from 3 days up to 56 days. To understand the effect of fly ash on the durability of concrete, the water penetration test of normal strength concrete (i.e. w/c=0.6) was conducted.

This chapter comes up with a summary of all experimental test results elucidated in the previous chapter. Moreover, discussion and analysis of all experimental test results will be presented and expounded.

5.2 Analysis and discussion on the Compressive strength test results

Compressive strength of concrete is commonly considered as the most valuable property, although, in many practical cases, other characteristics, such as durability and permeability, may be more important. Of the various properties of concrete, it is generally the compressive strength, which attracts the greatest interest since it is the property used in designing of building units of structural or load-bearing members. Besides, it has great practical and economic significance because the sections and sizes of the concrete structures are determined by it. Since most concrete structures are designed to resist compressive stress, it is this property that is usually prescribed by standards.

Compressive strength usually gives an overall picture of the quality of concrete because strength is directly related to the structure of the hydrated cement paste. Therefore, the main constituents of concrete that affect compressive strength are the cement quality. Moreover, the strength of concrete is almost invariably a vital element of structural design and is specified for compliance purposes.

In engineering practice, the strength of concrete at a given age and cured in water at a prescribed temperature is assumed to depend primarily on the water/cement ratio (Neville, 2011). Due to the

fact that, the effect of fly ash on the strength of concrete studied with different water-binder ratio. Accordingly, a water-binder ratio of 0.4 and 0.6 were used.

5.2.1 Effect of FA-1 on Compressive strength

Coal ash collected from the AYKA Addis Textile factory is designated by FA-1 for ease of reference and identification as indicated in section 3.1 of this report. This fly ash complies with ASTM class F fly ash and has a specific gravity of 2.51. A replacement percentage of 10, 15, 20 and 25 were used. These percentages of replacements were chosen based on ACI 232.2R report recommendation for class F fly ash.

The average compressive strength of three samples of concrete cubes in each percentage of replacement and at each day of investigation is summarized as shown in Table 5-1. The detail of the compressive strength test result of concrete samples are attached in the appendix section of this report.

As shown in Table 5-1 and Figure 5-1, for a water-binder ratio of 0.4, the effect of FA-1 in early age strength becomes maximum when the amount of fly ash added to the mix is 10% of the volume of cement. This is due to pozzolanic reaction (i.e. consumption of CH) of fly ash begin after three days.

Jeff. K.(1997) suggested that the calcium hydroxide contents in fly ash paste are similar to those of plain cement paste at 1 and 2 days, then begin to decrease gradually after 3 days. After 3 days, the decrease in calcium hydroxide content suggests the beginning of a pozzolanic reaction.

Accordingly, these test result shows that at three days pozzolanic reaction begins and the production of calcium hydroxide is depressed in the presence of fly ash, similar to the findings of Jeff. K.(1997). Even these results display the possibility of a pozzolanic reaction of fly ash at 3 days, but a significant reaction begins only after 7 days.

The average Compressive strength result for a 15% replacement ratio shows that the 28th day strength of concrete has an increment of 3.73% over the reference mix. Although the increment of strength is minor, it clearly shows that the strength at later ages has a larger strength increment than strength at an early age. So, one can understand from the result that compressive strength continued to increase with age, indicating pozzolanic action of fly ashes.

Table 5-1: Average Compressive strength of Concrete with FA-1 and w/c=0.4

Fly-Ash Content (%)	Water to Binder ratio	Average Compressive Strength (MPa)			
		Test Days			
		3 days	7 days	28 days	56 days
0	0.4	26.18	28.60	43.69	44.68
10	0.41	27.40	31.53	45.17	47.12
15	0.41	26.02	31.81	45.32	45.85
20	0.42	23.13	25.43	39.49	41.12
25	0.42	19.37	21.67	36.98	38.31

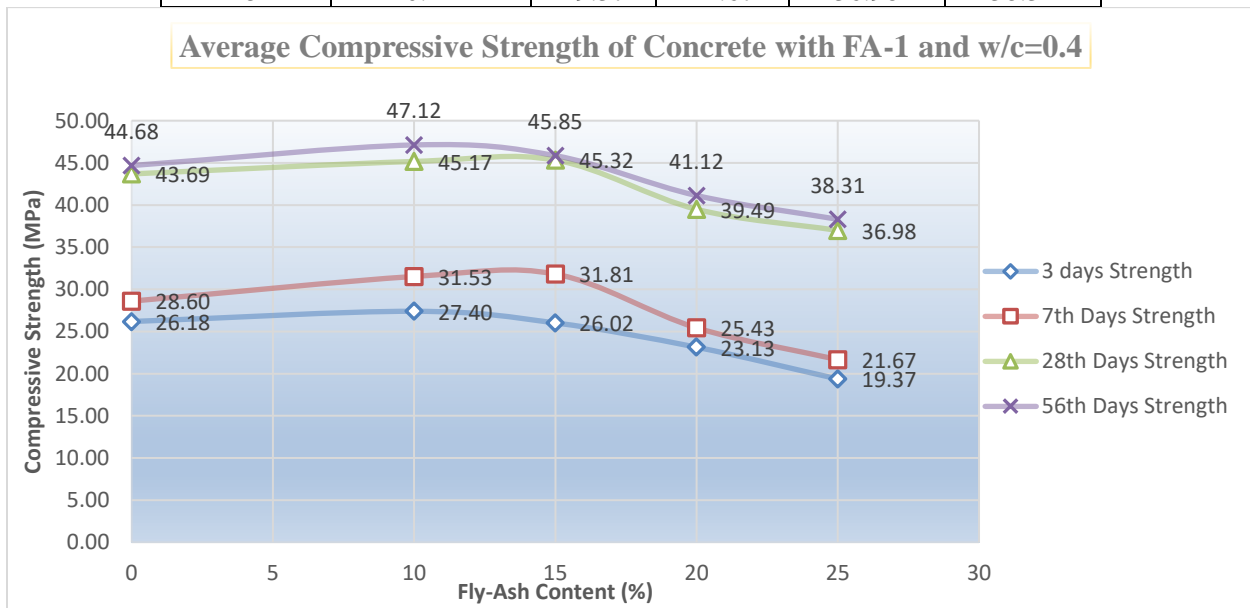


Figure 5-1: Average Compressive strength of Concrete with FA-1 and w/c=0.4

The probable reason for strength increment would be a denser cement paste matrix produced at the interfacial transition zone. Moreover, fly ash reacts with lime produced from a hydration reaction of binder. The additional binder resulting from its pozzolanic reaction provides a high strength matrix. Furthermore, lime accumulates at the interface between the matrix and the aggregate, reacts with pozzolanic material in these regions and creates dense transition zones with enhanced properties.

Golewski (2018) suggested that “Interfacial Transition Zone (ITZ) of coarse aggregate cement matrix is commonly regarded as the weakest element of concrete. In this phase, the first cracks in the material are initiated, and the process of destruction of the composite begins. An improvement of the ITZ properties are positively influenced by the mineral additives used for the composite. One of such a substitute for a binder is, potentially hazardous industrial waste, siliceous fly ash (FA).”

The average compressive strength of concrete mix made up of FA-1 and water-binder ratio of 0.6 shown in Table 5.2

Table 5-2: Average Compressive strength of Concrete with FA-1 and w/c=0.6

Fly-Ash Content (%)	Water to Binder ratio	Average Compressive Strength (MPa)			
		3 days	7 days	28 days	56 days
0	0.6	13.52	18.15	29.83	30.90
10	0.61	13.56	18.24	30.55	32.12
15	0.62	13.13	17.51	29.36	32.37
20	0.63	12.69	16.53	27.14	29.03
25	0.63	11.93	15.79	23.01	26.00

From the test results shown in Table 5.2 one can see that the effect of FA-1 in concrete, proportioned by water-binder ratio of 0.6 is quite similar to concrete proportioned by water-binder ratio of 0.4. However, unlike concrete mix with a water-binder ratio of 0.4, the maximum 3rd, 7th and 28th day compressive strength of concrete is obtained at a 10% replacement ratio of FA-1. The probable reason for the fact mentioned above is due to a decreased in cement content of concrete mix proportioned by water-binder ratio of 0.6. At later age (i.e. 56th day), up to 15%, FA-1 replacement results improved the compressive strength of concrete.

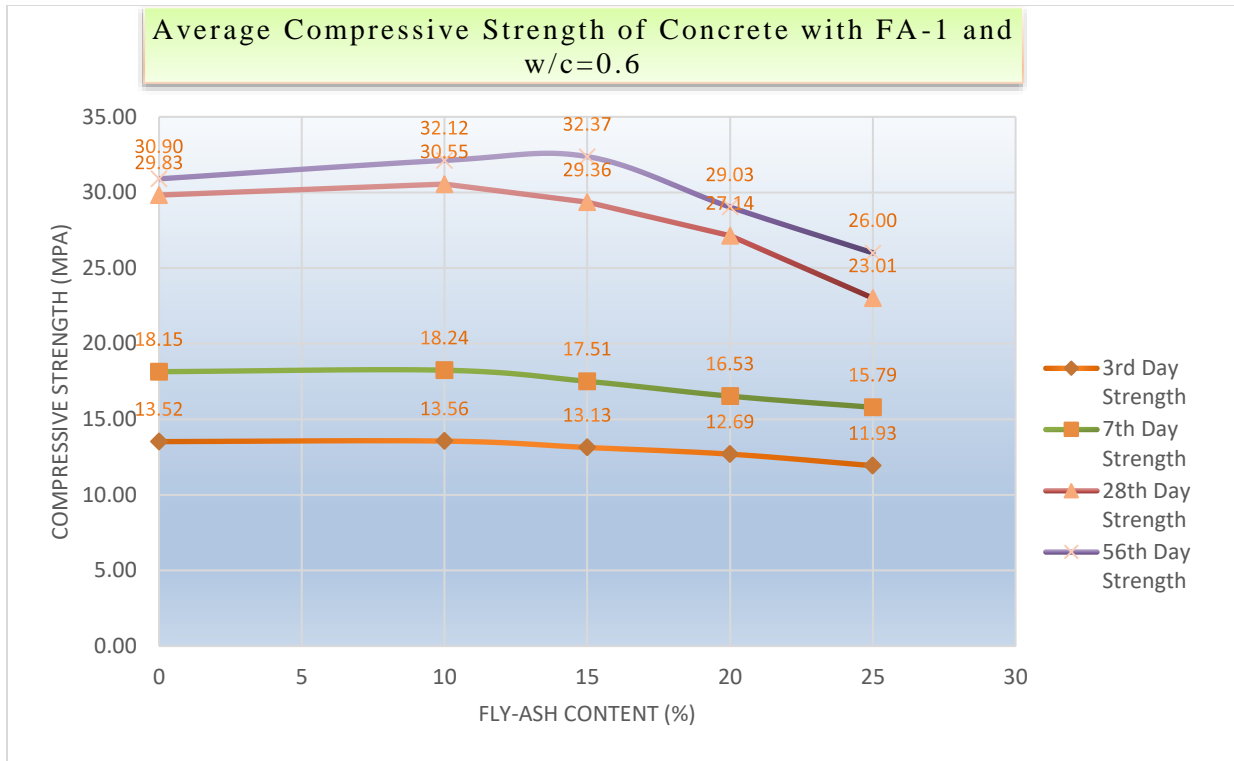


Figure 5-2: Average Compressive strength of Concrete with FA-1 and w/c=0.6

5.2.2 Effect of FA-2 on Compressive strength

FA-2 coal ash is collected from Dongfang Spinning and Printing PLC. This coal ash is not in compliance with either ASTM class C and class F fly ashes. A replacement percentage of 5, 10, 15 and 20 were used in this study. Since this coal ash is off-specification of ASTM C-618 Standard Specification for Coal Fly Ash, replacement has started from 5% to avoid any uncertainties.

Similar to FA-1, the average compressive strength of three samples of concrete cubes in each percentage of replacement and at each day of investigation is summarized as shown in Table 5-3. The detail of the compressive strength test result of concrete samples are attached in the appendix section of this report.

As shown in Table 5-3 and Figure 5-3, the result obtained for FA-2 follow a pattern similar to FA-1. The presented results contain FA-2 as supplementary cementitious material in concrete mix having a water-binder ratio of 0.4 show slightly strength degradation at an early age beyond 5% replacement.

Table 5-3: Average Compressive strength of Concrete with FA-2 and W/C=0.4

Fly-Ash Content (%)	Water to Binder ratio	Average Compressive Strength (MPa)			
		Test Days			
		3 days	7 days	28 days	56 days
0	0.4	26.18	28.60	43.69	44.68
5	0.41	26.85	30.83	44.09	46.29
10	0.41	26.06	31.91	45.47	46.97
15	0.42	24.13	26.61	40.86	42.02
20	0.43	20.89	22.46	38.67	39.74

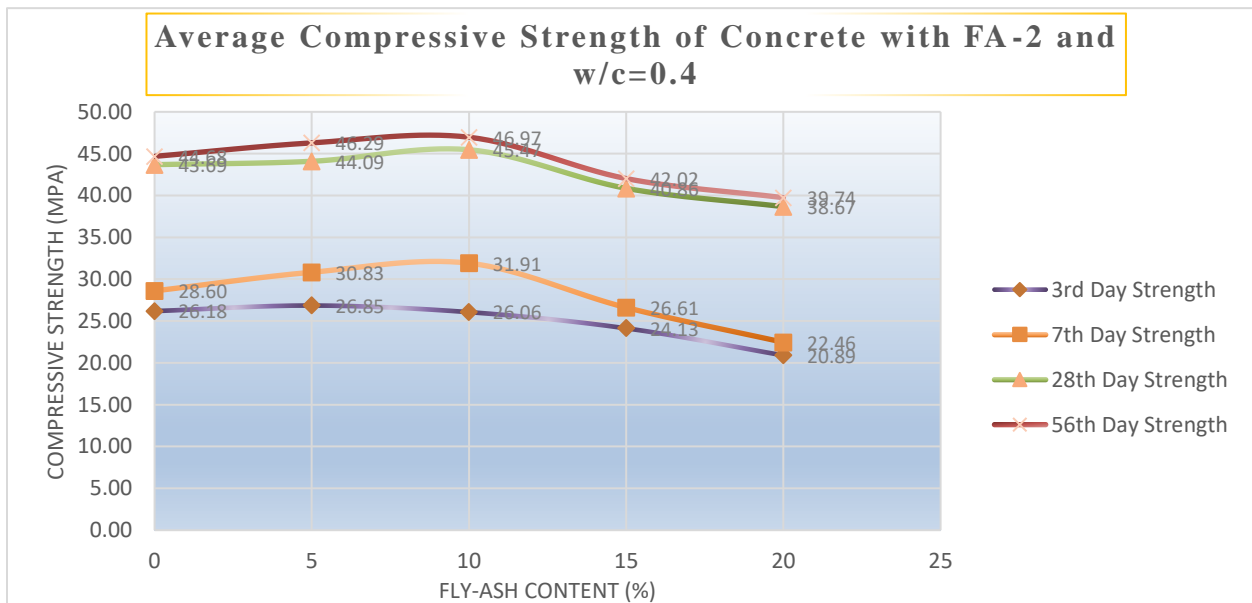


Figure 5-3: Average Compressive strength of Concrete with FA-2 and w/c=0.4

As indicated in the chemical analysis of FA-2 in section 3.2.1 of this report, its silica content is relatively low. So, it requires more time to undergo secondary hydration reactions. On the other hand, for a later age, as shown in Figure 5-3, the addition of FA-2 in the concrete had resulted in a higher compressive strength for 10% replacement. Even if FA-2 is out of various ASTM requirements, plentiful to meet strength requirements for later age.

(ACI 232.2R, 2002) states that the analytic bulk chemical composition used to determine compliance with ASTM C- 618 does not address the nature or reactivity of the particles. This type of analysis is used as a quality assurance tool. Minor variations in the chemical composition of a particular fly ash do not relate directly to the long-term performance of concrete containing that fly ash.

Table 5-4 and Figure 5-4 show the average compressive strength of concrete mix made up of FA-2 and water-binder ratio of 0.6.

Table 5-4: Average Compressive strength of Concrete with FA-2 and W/C=0.6

Fly-Ash Content (%)	Water to Binder ratio	Average Compressive Strength (MPa)			
		3 days	7 days	28 days	56 days
0	0.6	13.52	18.15	29.83	30.90
5	0.61	13.65	18.65	29.96	31.53
10	0.62	13.54	18.18	28.73	30.55
15	0.63	12.09	16.24	27.44	28.91
20	0.64	10.85	15.19	26.91	28.15

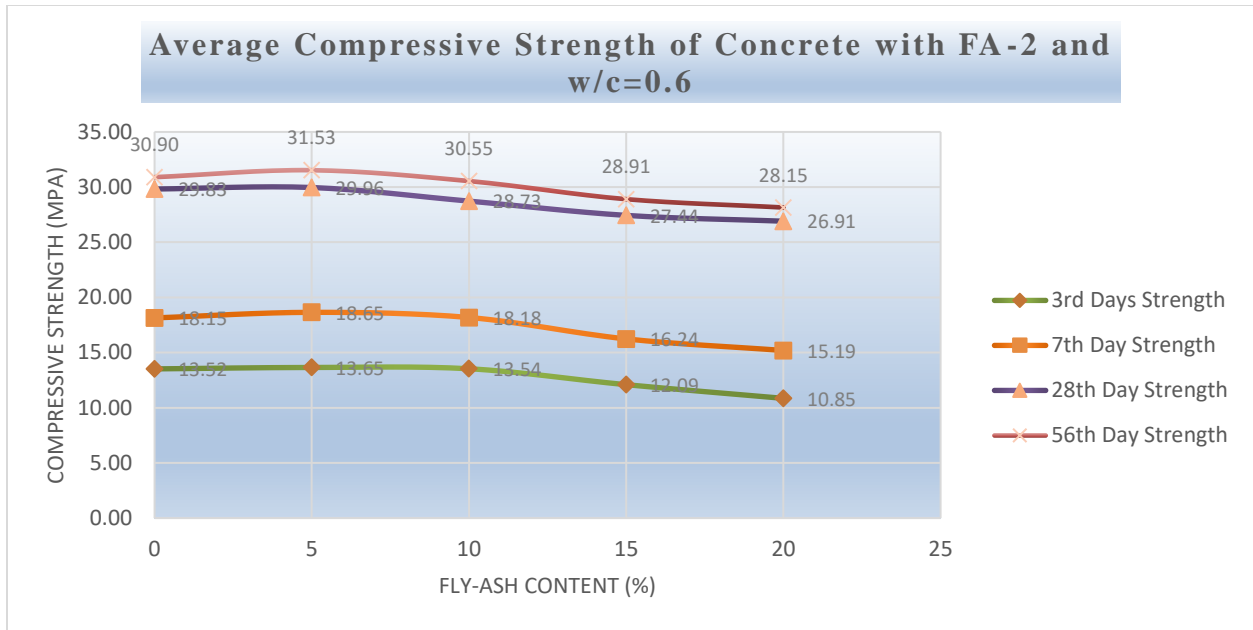


Figure 5-4: Average Compressive strength of Concrete with FA-2 and w/c=0.6

It can be seen in Figure 5-4; the maximum value of the uniaxial compressive strength is obtained for the sample with the cement replacement of 5 % for almost all ages. As the FA-2 amount in water-binder ratio 0.6 mix increases the compressive strength decreases. High replacement of cement by FA-2, thus reducing the cement content of the mixture which in turn causes a reduction in the hydration reaction.

5.3 Analysis and discussion on the Flexural strength test results

As described in chapter three, a three-point loading test procedure was used to measure the flexural strength of concrete. The load is applied at a constant rate of 0.02MPa/sec with the corresponding rate of increase in extreme fiber stress of 1.21MPa/sec until rupture occurs. For each percentage of replacement at each test day, three samples were prepared and the average of the three samples was taken as the flexural strength of that specific concrete type at that specific day.

All fractures were initiated in tension surface within the middle third of span length. The figure below shows the beam fractures inside the middle third of the span length.



Figure 5-5: Beam failure during flexure test

After the failure load of each sample properly recorded and the modulus of rupture of a specific specimen is calculated as follows:

$$R = PL/bd^2$$

Equation 5-1

Where:

R = modulus of rupture, MPa,

P = maximum applied load indicated by the testing machine, N,

L = span length, mm,

b = average width of specimen, mm,

d = average depth of specimen, mm.

ASTM C-78 recommends that the results of this test method may be used to determine compliance with specifications or as a basis for proportioning, mixing and placement operations. It is used in testing concrete for the construction of slabs and pavements.

Flexural strength of concrete is one way of estimating the tensile strength of concrete. The tensile strength of concrete develops more quickly than the compressive strength. As a result, shear strength and bond strength, which are strongly affected by the tensile strength of concrete, tend to develop more quickly than the compressive strength (James, 2005).

5.3.1 Effect of FA-1 on Flexural strength

The average flexural strength of three samples of a concrete specimen in each percentage of replacement and at each day of investigation is summarized as shown in Table 5-5. The detail of the flexural strength test result of concrete samples are attached in the appendix section of this report.

It is evident that, when the beam is loaded, the bottom fibers (below the neutral axis) are in tension and the upper fibers are in compression. Failure of the beam, if it is made of concrete, will be a tensile failure in the lower fibers, as concrete is much weaker in tension than in compression.

Table 5-5: Average Flexural strength of Concrete with FA-1 and W/C=0.4

Fly-Ash Content (%)	Water to Binder ratio	Average Flexural Strength (MPa)			
		3 days	7 days	28 days	56 days
0	0.4	2.77	3.85	4.45	4.48
10	0.41	2.78	4.20	4.55	4.70
15	0.41	2.68	4.23	4.58	4.75
20	0.42	2.32	3.48	4.13	4.42
25	0.42	2.20	3.18	3.93	4.17

The results in Table 5-5 and Figure 5-6 show that, with the increase of fly ash content, the tensile strength of Concrete mixed with water-binder ratio of 0.4 shows a trend of decrease after 15% replacement ratio of FA-1 at later age. In early age, the tensile strength shows a reduction after 10% of replacement ratio.

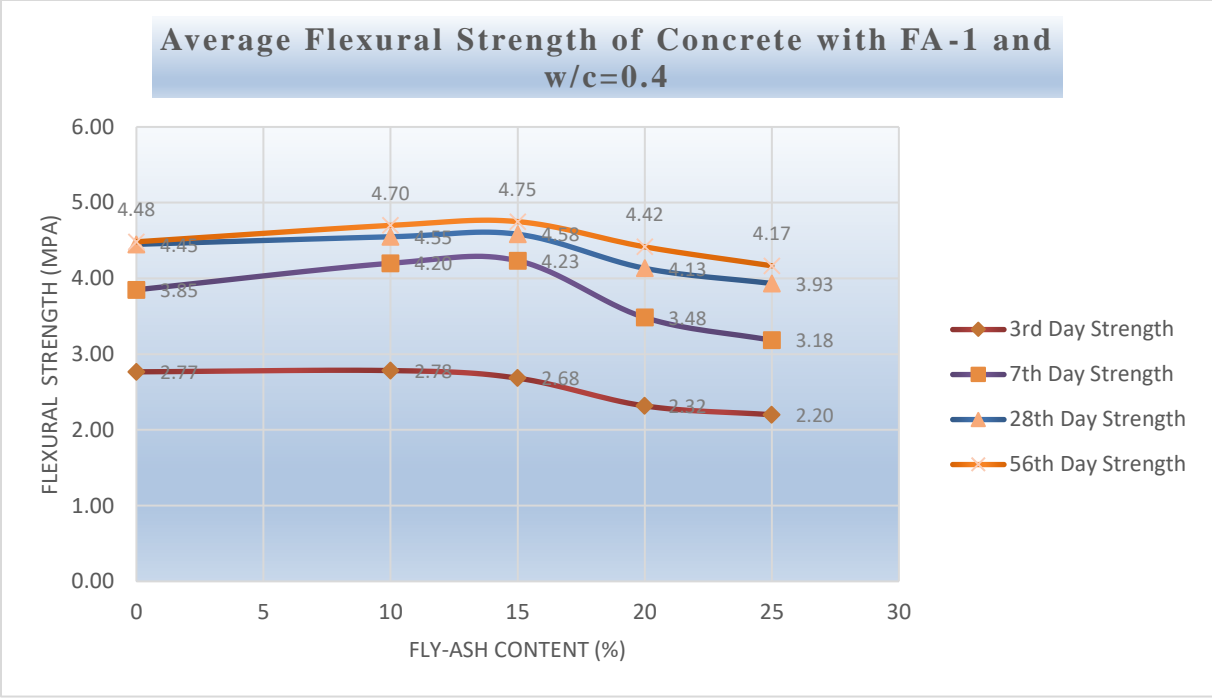


Figure 5-6: Average Flexural strength of Concrete with FA-1 and W/C=0.4

Wan Li (2015) suggests that fly ash mixed in the concrete produced micro aggregate effect, namely the fly ash of glass beads have the effect of the “ball bearing lubrication”, and it improved the density of concrete and reduced the internal porosity. With the increase of the content of fly ash, the matrix is more uniform and the structure of the differences between each section is relatively narrow, so the tensile strength and cracking strength showed a trend of increase first. As the continued increase of fly ash content, the cement content is reduced, thus reducing the hydration speed of cement, resulting in the weakening of matrix strength. It shows that there is a critical value of matrix strength with fly ash content, when more than the critical value, the fly ash micro aggregate effect is not obvious.

In this regard, the best content of fly ash for early age tensile strength is 10% and for later age strength is 15% is obtained in this experiment.

Below Table 5-6 and Figure 5-7 shows, the average tensile strength of concrete mix made up of FA-1 and water-binder ratio of 0.6. A similar trend has been observed in tensile strength for both concrete having a 0.4 and 0.6 water-binder ratio. As can be seen from Table 5-6 and Figure 5-7, the optimum content of fly ash for early age tensile strength is 10% and for later age strength is 15% .

Table 5-6: Average Flexural strength of Concrete with FA-1 and W/C=0.6

Fly-Ash Content (%)	Water to Binder ratio	Average Flexural Strength (MPa)			
		3 days	7 days	28 days	56 days
0	0.6	1.68	2.13	3.30	3.55
10	0.61	1.73	2.17	3.53	4.17
15	0.62	1.40	2.03	4.52	4.53
20	0.63	1.23	1.88	3.15	3.38
25	0.63	1.08	1.70	2.98	3.03

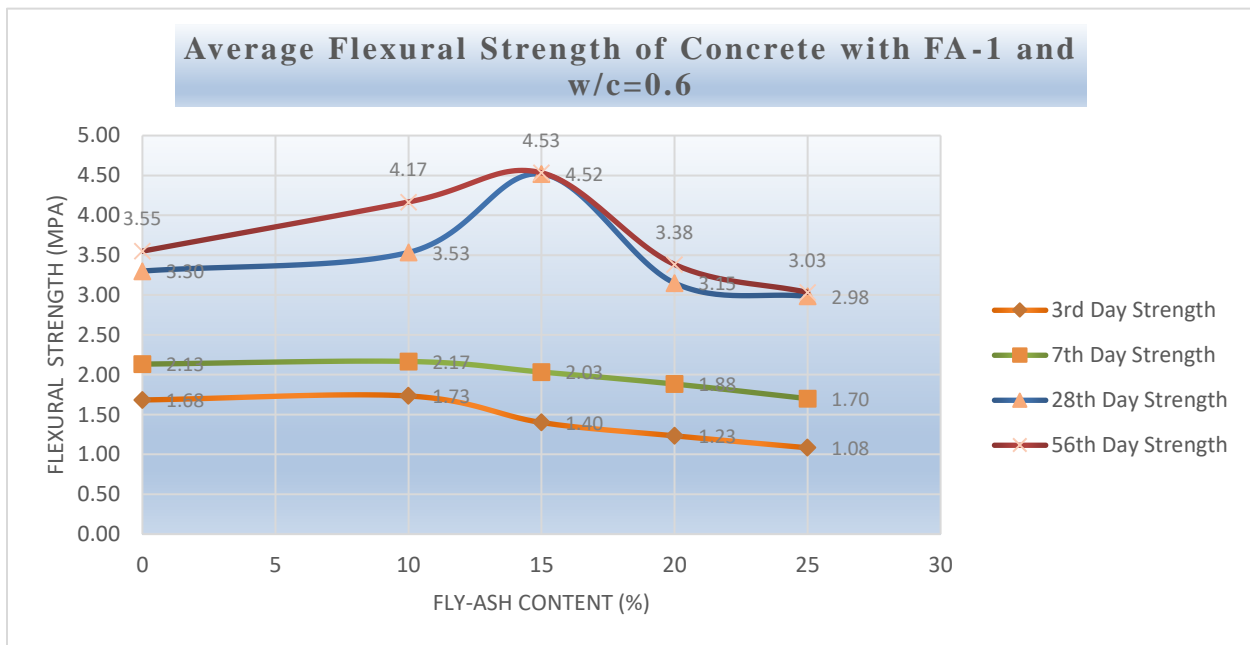


Figure 5-7: Average Flexural strength of Concrete with FA-1 and W/C=0.6

5.3.2 Effect of FA-2 on Flexural strength

Table 5-7 shows the average flexural strength value obtained for each percentage of replacement of FA-2 at each day of testing. The detail test result is attached to the appendix section of this report.

Table 5-7: Average Flexural strength of Concrete with FA-2 and W/C=0.4

Fly-Ash Content (%)	Water to Binder ratio	Average Flexural Strength (MPa)			
		3 days	7 days	28 days	56 days
0	0.4	2.77	3.85	4.45	4.48
5	0.41	2.90	4.22	4.77	4.98
10	0.41	3.10	4.40	5.05	5.37
15	0.42	2.67	3.82	4.38	4.52
20	0.42	2.48	3.32	4.03	4.27

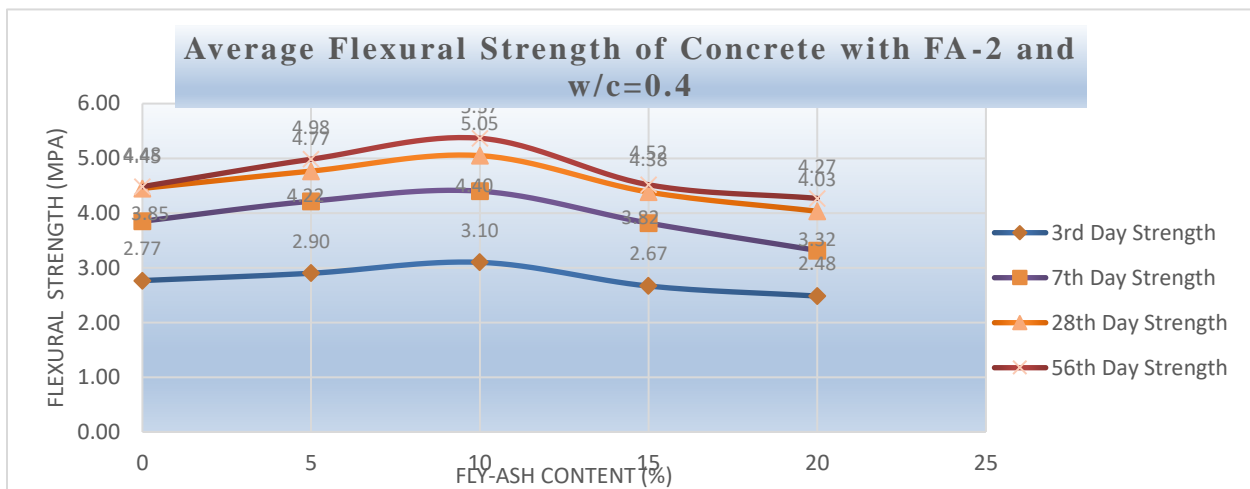


Figure 5-8: Average Flexural strength of Concrete with FA-2 and W/C=0.4

Table 5-8: Average Flexural strength of Concrete with FA-2 and W/C=0.6

Fly-Ash Content (%)	Water to Binder ratio	Average Flexural Strength (MPa)			
		3 days	7 days	28 days	56 days
0	0.6	1.68	2.13	3.30	3.55
5	0.61	1.77	2.27	3.67	4.23
10	0.62	1.92	2.83	3.98	4.37
15	0.63	1.58	2.55	3.42	3.95
20	0.63	1.23	1.73	2.62	2.92

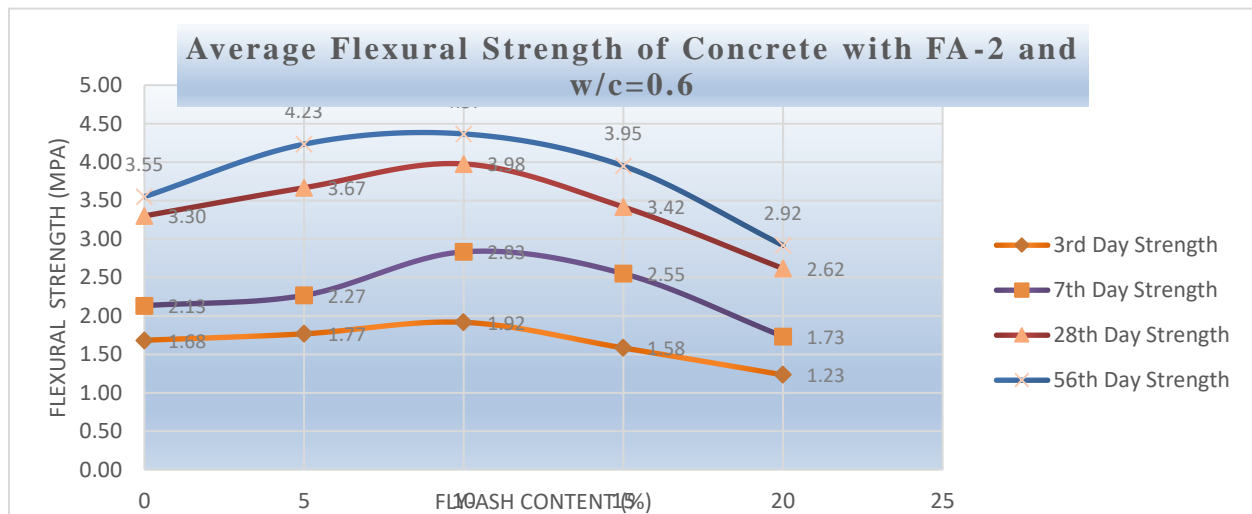


Figure 5-9: Average Flexural strength of Concrete with FA-2 and W/C=0.6

By shown in Figure 5-8 and Figure 5-9, with the increase of FA-2 content up to 10% both in water-binder ratio 0.4 and 0.6 mixes, the flexural strength increases. Although fly content 15% results lower flexural strength than fly ash content 10%, when it is compared with the reference mix, the resulted flexural strength is better. Therefore, up to 15% FA-2 replacement is possible without degrading the tensile properties of the reference mix.

5.4 Effect of FA-1 on Water penetration

The durability of concrete is one of its most important properties. Durability of concrete can be defined as its ability to resist weathering action, chemical attack, abrasion, or any other processes of deterioration and thereby retain its original shape, dimension, quality, and serviceability. One of the criteria, which determine concrete durability, is permeability (Biparva, 2005).

It is well known that permeability determines the vulnerability of concrete to external agencies, and in order to be durable, concrete must be relatively impervious. Concrete durability depends largely on the ease or difficulty with gases or fluids that can migrate through the hardened concrete mass.

Water is the most significant fluid that flows through concrete. In porous material water penetration usually determines the rate of deterioration. Water can be directly involved in the physical process leading to degradation, especially during the repeated freezing and thawing cycles. Besides, water also serves as the carrying agent for soluble aggressive ions that can be a source of chemical degradation.

As discussed in the experimental program, depth of penetration of the sample is determined by applying water under pressure to one surface of the specimen for 72 hours and then to split the specimen perpendicular to the injected face and determine visually the depth of penetration. Measurements were taken at 10mm intervals. The average and maximum water penetration depth of each concrete samples were measured from the split concrete pieces for each sample group are summarized below. The detail of water penetration test results of concrete samples are attached in the appendix section of this report.

As shown in Table 5 9, the average depth of penetration is minimum at FA-1 content of 10%. Pozzolanic materials such as fly ash is being used to enhance concrete properties. Experts have widely agreed for decades that the use of pozzolans under proper conditions and curing can reduce permeability (Biparva, 2005).

In this regard, 10% FA-1 in the mix reduces slightly penetration depth of the sample. This is due to the additional binder resulting from a pozzolanic reaction that provides a low permeability concrete. Besides, lime accumulates at the interface between the matrix and the aggregate, reacts with pozzolanic material in this region and creates dense transition zones with enhanced properties.

This shows that following proper curing the use of FA-1 with correct quantity (in this experiment 10%) has a positive influence on concrete durability.

Table 5-9: Water penetration test result of Concrete with FA-1 and w/c=0.6

Percentage replacement	Water Penetration depth (mm)	
	Average	Maximum
0	14.76	26
10	14.35	25
15	16.41	28
20	19.47	32

In general, fly ash also reduces the heat of hydration and water demand, densifies transition zone and in turn improves the durability of concrete. Furthermore, adding fly ash under proper curing conditions provides excellent water-tightness in concrete. When Portland cement hydrates, it forms calcium-silicate hydrate gel CSH and calcium hydroxide Ca(OH)_2 . CSH is the “glue” that provides strength and holds the concrete ingredients together. Compared to Ca(OH)_2 , CSH contributes more to strength and impermeability. Permeability is related to the proportion of CSH to Ca(OH)_2 in the cement paste. The higher CSH to Ca(OH)_2 , the lower the permeability of the concrete. This can be achieved when fly ash in concrete mixture reacts with Ca(OH)_2 to form additional CSH, which in turn lower the permeability of concrete (Biparva, 2005).

The depth of water penetration inside the specimen can be converted to its equivalent coefficient of water penetration using Valenta’s equation (Hossain, 2017):

$$k = \frac{e^2 v}{2ht} \text{ m/sec} \quad \text{Equation 5-2}$$

Where;

e = depth of penetration of concrete in meters,

h = hydraulic head in meters, (ranges between 0.1 to 0.7 MPa)

t = time under pressure in seconds, and

v = the fraction of the volume of concrete occupied by pores.

The value of ' v ' represents discrete pores, such as air bubbles, which do not become filled with water except under pressure and can be calculated from the increase in the mass of concrete during the test and typically ranges between 0.02 to 0.06 (Geremew, 2017).

Neville suggests that concrete with a depth of penetration of water less than 50 mm is classified as impermeable and concrete with a depth of penetration of water less than 30mm is considered as impermeable under aggressive conditions. Accordingly, all the samples under this investigation are impermeable under aggressive condition.

6 COST BENEFIT ANALYSIS

6.1 Introduction

Ordinary Portland Cement (OPC) is one of the most popularly used building materials in Ethiopia. However, even being as popular as it is, some disadvantages of OPC are still hard to overcome. The major drawbacks associated with OPC is energy consumption and emission of greenhouse gases. Cement production is one of the most energy-intensive of all industrial manufacturing processes. Moreover, one ton of Portland cement clinker production creates one ton of CO₂ and other greenhouse gases (GHGs) (Naik, 2005).

Recycling fly ash and using it to replace cement has positive impacts on the environment, such as conserving landfill spaces, conserving natural resources, reducing CO₂ emissions, and saving energy. A potential application of fly ash in concrete is investigated in this study based on the market needs and its advantages over OPC concrete. Fly ash, a waste byproduct material, can be recycled into making value-added products, in terms of both product quality and influence on the environment.

This chapter presents an examination of the Benefit-Cost Analysis Model (BCAM) to characterize the economic and environmental impact of cement concrete produced from fly ash and OPC. Output from BCAM includes the monetary value of GHG emissions, like; social costs of CO₂, SO₂, and NO_x.

6.2 Benefit-Cost Analysis Model (BCAM)

Benefit-cost analysis model is used to analyze the environmental impacts associated with Cement concrete (i.e. concrete made up of OPC only) and fly ash Concrete (i.e. concrete constituent fly ash) by converting them into monetary value for a comparative assessment. Accordingly, benefit-cost analysis model (BCAM) has made to quantify the range of potential costs and impacts for fly ash concrete in comparison to OPC concrete, including the impacts of emissions of carbon dioxide (CO₂), nitrogen oxides (NO_x) and sulfur dioxide (SO₂).

6.2.1 Methods

BCAM includes a variety of methods including identifying and examining alternatives, defining alternatives in a way that allows for fair comparison, calculating and placing a monetary value on issues that regularly do not have a monetary value present, and conducting sensitivity and risk analysis on the parameters in the benefit-cost analysis model. Savings on reducing greenhouse emissions and reducing raw materials of producing cement were considered in this model.

The raw materials and mixes used in BCAM is based on chapter 3 and 4 findings. The analysis considered two mixes to produce one-meter cube of concrete for each mix, and mix portions are presented in Table 6-1, Table 6-2 and Table 6-3.

Table 6-1: Mixes used for BCAM

Mix type	Material
Mix-1 OPC only	OPC, Fine aggregate, Coarse aggregate and Water
Mix-2 OPC with FA	10% FA, OPC, Fine aggregate, Coarse aggregate and Water

Table 6-2: Mix proportion for W/C=0.4

Mixes	Mix-1(OPC only)	Mix-2(OPC with FA)
Fly ash (Kg/m ³)	0	37.85
OPC(Kg/m ³)	475	427.5
Fine aggregate (Kg/m ³)	682.04	682.04
Coarse aggregate (Kg/m ³)	981.71	981.71
Water (Kg/m ³)	202.63	202.63
Total (Kg/m ³)	2341.38	2331.73

Table 6-3: Mix proportion for W/C=0.6

Mixes	Mix-1(OPC only)	Mix-2(OPC with FA)
Fly ash (Kg/m ³)	0	25.23
OPC(Kg/m ³)	316.67	285.00
Fine aggregate (Kg/m ³)	732.55	732.55
Coarse aggregate (Kg/m ³)	1061.31	1061.31
Water (Kg/m ³)	203.58	203.58
Total (Kg/m ³)	2314.11	2307.67

Based on the available data the following assumptions have been made. Only raw materials costs are considered, and all other factors in concrete manufacturing using fly ash or Portland cement are assumed the same and therefore cancel out in a comparative benefits analysis. Moreover, savings on reducing greenhouse emissions were considered as indirect costs in this study.

Table 6-4: Material price in ETB per m³ of Mix proportion for W/C=0.4

Mixes	Material price in ETB per m ³	
	Mix-1(OPC only)	Mix-2(OPC with FA-)
Fly ash (ETB/m ³)	0	0
OPC (ETB/m ³)	1425-1520	1282.5-1358
Fine aggregate (ETB/m ³)	164.54-191.96	164.54-191.96
Coarse aggregate (ETB/m ³)	187.35-224.82	187.35-224.82

*ETB means Ethiopian Birr

*This range of prices is adopted from different providers

Table 6-5: Material price in ETB per m³ of Mix proportion for W/C=0.6

Mixes	Material price in ETB per m ³	
	Mix-1(OPC only)	Mix-2(OPC with FA)
Fly ash (ETB/m ³)	0	0
OPC (ETB/m ³)	950.01-1013.34	855-912
Fine aggregate (ETB/m ³)	176.73-206.19	176.73-206.19
Coarse aggregate (ETB/m ³)	202.54-243.05	202.54-243.05

The impacts of using OPC and fly ash were obtained from different references as numbered in the Table 6-6. Table 6-6 shows the impacts of fly ash concrete and OPC concrete in terms of GHG emissions and its corresponding financial savings by category that were considered in BCAM.

The reductions in GHG emissions are primarily obtained by offsetting the production of conventional materials (e.g., the use of fly ash precludes the need to produce Portland cement). Economic benefits were calculated based on the monetary value of the environmental benefits.

Table 6-6: Impact of using OPC

Impact		Price in ETB per m ³
GHG Emission	CO ₂ emission from cement production	820 kg CO ₂ /ton cement ^[1] .
	Social cost of CO ₂	\$12/ton to \$60/ton ^[2] ETB342/ton to ETB1710.36/ton
	Average of NO _x emissions from wet kilns	4.4Kg/ton of clinker ^[3] 4.048Kg/ ton of cement
	Average of NO _x emissions from dry kilns	1.72Kg/ton of clinker ^[3]
	Social cost of NO _x	\$647/ ton of NO _x ^[1] ETB18443.38/ ton
	Average of SO ₂ emissions	1.79 Kg/ton of cement ^[1]
	Social cost of SO ₂	\$1,580/ton to \$1,670/ton of SO ₂ ^[1] ETB45,030/ton to ETB 47,595/ton

[1]. (Khaled, 2018)

[3]. (US.EPA, 2007)

[2]. (US EPA, 2013)

6.2.1.1 GHG Emissions

Particulate matter, nitrogen oxides (NO_x), sulfur dioxide (SO₂), carbon monoxide (CO), and CO₂ are the primary emissions in the manufacture of Portland cement. Small quantities of volatile organic compounds (VOC), ammonia (NH₃), chlorine, and hydrogen chloride (HCl), also may be emitted. Emissions may also include residual materials from the fuel and raw materials or products of incomplete combustion that are considered to be hazardous (Mummert, 2005).

6.2.1.2 Unit Exchange

Much of the original data used in this document were in different units. To facilitate comparisons of costs and efficiencies for the various control measures, units were converted to the International System of Units (SI) units when possible. Also, many measures were expressed in units per ton of raw feed to the kiln, clinker production or cement production. Conversions used in this process were as follows: 1.65 tons of raw feed/ton of clinker, 0.92 tons of clinker/ton of cement, and 1.52 tons of raw feed/ton of cement (US EPA, 2010). Costs of control measures expressed in dollars (\$) were converted to Ethiopian Birr (ETB) assuming ETB is 28.5/\$.

6.2.1.3 Social Cost of GHG

The Social cost of GHG is an estimate of the economic damages associated with a small increase in GHG emissions, conventionally one metric ton, in a given year. These dollar (the corresponding ETB) figure also represents the value of damages avoided for a small emission reduction (i.e. the benefit of GHG reduction). The Social cost of GHG is meant to be a comprehensive estimate of climate change damages and includes, among other things, changes in net agricultural productivity, human health, and property damages from increased flood risk (US EPA, 2013).

The social cost of carbon is the present value of future harm caused by an incremental ton of carbon dioxide emissions. It is difficult to estimate the social cost of carbon, because carbon emissions, climate change, and economic harm are related through complex processes that are not fully understood. Additionally, the rate at which to discount future harm is contentious and critical to the magnitude of the present value (Kyle, 2011).

6.2.1.4 Sensitivity Analysis

Sensitivity analysis is used to account for uncertainty in the estimation of direct and indirect costs. In this regard, sensitivity analysis has been made to account how uncertainty of social cost of GHG emission and direct cost of concrete ingredient material affect the cost of 1 m³ of concrete. Hence, there is no longer the need to reduce what is known about a variable to a single number. Instead, it has been included in all what has been known about the variable, including its full range of possible values and some measures of the likelihood of occurrence for each possible value.

Sensitivity analysis is one technique of risk analysis and has been recognized as powerful tools to help decision-makers successfully manage situations subject to uncertainty (Borgonovo, 2017). Sensitivity analysis has been conducted in order to determine which of the inputs has the greatest

effect on the cost of one cubic meter of concrete. Therefore, a sensitivity analysis was done to all involved parameters (direct cost and social cost of GHG, in each model, and it displayed the effect of each parameter on the entire model.

Based on the above discussion, the key results from the analysis are presented in the following tables and figures. Table 6-7 has financial data that was derived from Table 6-2 ,Table 6-4 and Table 6-6 and was calculated for one cubic meter of concrete made with OPC (Mix-1) and w/c=0.4.

Table 6-7: Direct and Indirect Cost per m³ of OPC Concrete (Mix-1) and w/c=0.4

Direct + Indirect Cost	Min (ETB)	Max (ETB)
OPC	1425.00	1520.00
Fine-aggregate	164.55	191.97
Course-aggregate	187.35	224.82
Social Cost of CO ₂	133.21	666.05
Social Cost of NO _x	35.46	35.46
Social Cost of SO ₂	38.29	40.47

Figure 6-1 shows the probability of the cost of one cubic meter of concrete made with OPC only (Mix 1). This is done, by normal distribution of 5000 randomly generated projection values between the minimum and maximum of the above-listed costs using Microsoft Excel 2016.

It has been indicated in Figure 6-1, the maximum, minimum and average probable cost in ETB of one cubic meter of concrete made with OPC and having a water-binder ratio of 0.4 is 2678.76, 1983.85 and 2332.97 respectively.

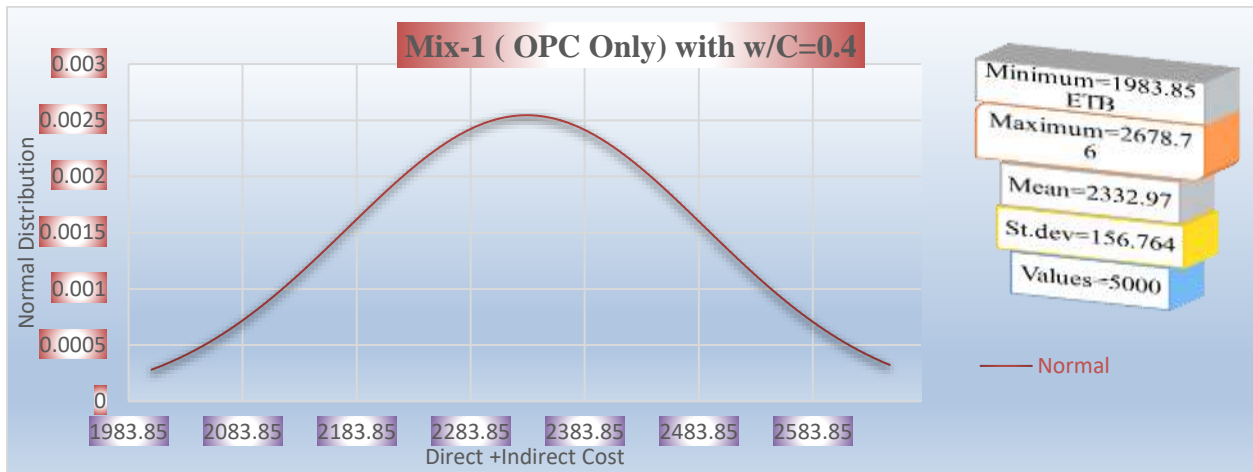


Figure 6-1: Probable Cost Concrete made with OPC only (Mix-1) and w/c=0.4

As shown in Figure 6-1, the probability of getting costs from ETB: 2019.44/m³ to ETB: 2646.50/m³ is 95% which is two standard deviations from the mean. There is only a 5% chance of having a cost of one cubic meter of Portland cement concrete with w/c=0.4 greater or less than this.

Table 6-8 represents a summary of the cost of one cubic meter of concrete made with OPC (Mix 1) and other statistical details.

Table 6-8: Summary Statistics for cost of one cubic meter of concrete made with OPC (Mix 1)

Statistics		Percentile	
Mean	2,332.97	5%	2087.52
Maximum	2,678.76	10%	2116.82
Minimum	1,983.85	20%	2172.38
Median	2,335.47	30%	2226.89
Standard deviation	156.764	40%	2279.20
Variance	24,574.88	60%	2387.26
Skewness	-0.019	70%	2442.74
Kurtosis	1.12	80%	2491.16

Table 6-9 has financial data calculated for one cubic meter of concrete made with OPC and fly ash (Mix-2) and w/c=0.4.

Table 6-9: Direct and Indirect Cost per m³ of Concrete made with OPC and fly ash (Mix-2) and w/c=0.4

Direct + Indirect Cost	Min (ETB)	Max (ETB)
OPC	1282.50	1368.00
Fine aggregate	164.55	191.97
Coarse aggregate	187.35	224.82
Social Cost of Co2	119.89	599.44
Social Cost of NOx	31.91	31.91
Social Cost of SO2	34.46	36.42

Figure 6-2 shows the probability of the cost of one cubic meter of concrete made with OPC and fly ash (Mix 2).

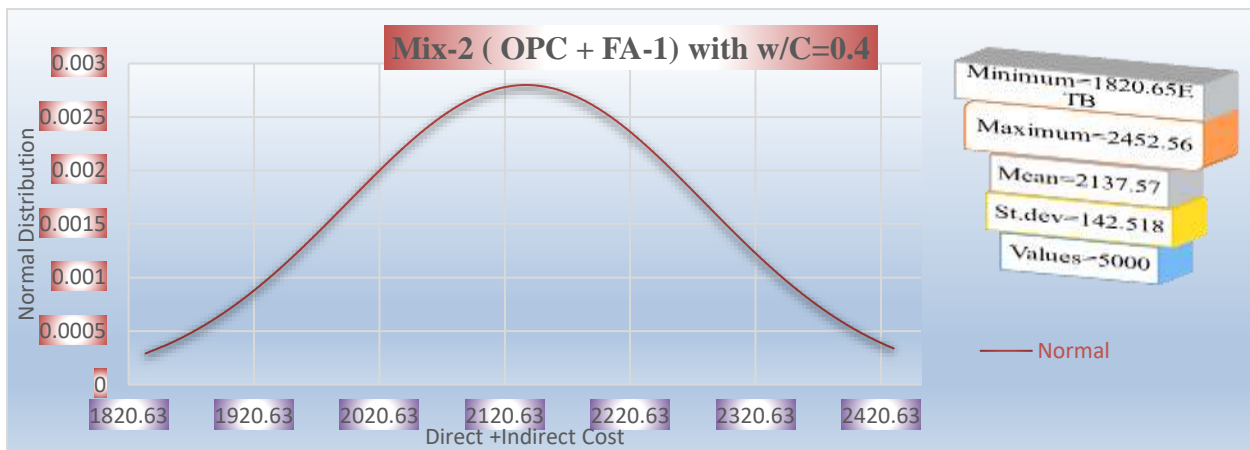


Figure 6-2: Probable Cost Concrete made with OPC plus fly ash (Mix-2) and w/c=0.4

As shown in Figure 6-2, the maximum, minimum and average probable cost of one cubic meter of concrete made with OPC plus fly ash and having a water-binder ratio of 0.4 is 2452.56, 1820.65 and 2137.57 respectively. The probability of getting costs from ETB: 1852.54/m³ to ETB: 2422.60/m³ is 95%. There is only a 5% chance of having a cost of one cubic meter of concrete using Portland cement plus fly ash and w/c=0.4 greater or less than this.

Table 6-10 represents a summary of the cost of one cubic meter of fly ash concrete (Mix 2) and other statistical details.

Table 6-10: Summary Statistics for cost of one cubic meter of concrete made with OPC (Mix 1)

Statistics		Percentile	
Mean	2,137.57	5%	1916.98
Maximum	2,452.56	10%	1943.55
Minimum	1,820.65	20%	1992.94
Median	2135.97	30%	2040.22
Standard deviation	142.51	40%	2087.52
Variance	20,307.41	60%	2187.92
Skewness	0.00704	70%	2235.13
Kurtosis	-1.11	80%	2283.36

The probability of cost of one cubic meter of OPC concrete and fly ash concrete having water-binder ratio of 0.6 is summarized as shown in Figure 6-3 and Figure 6-4.

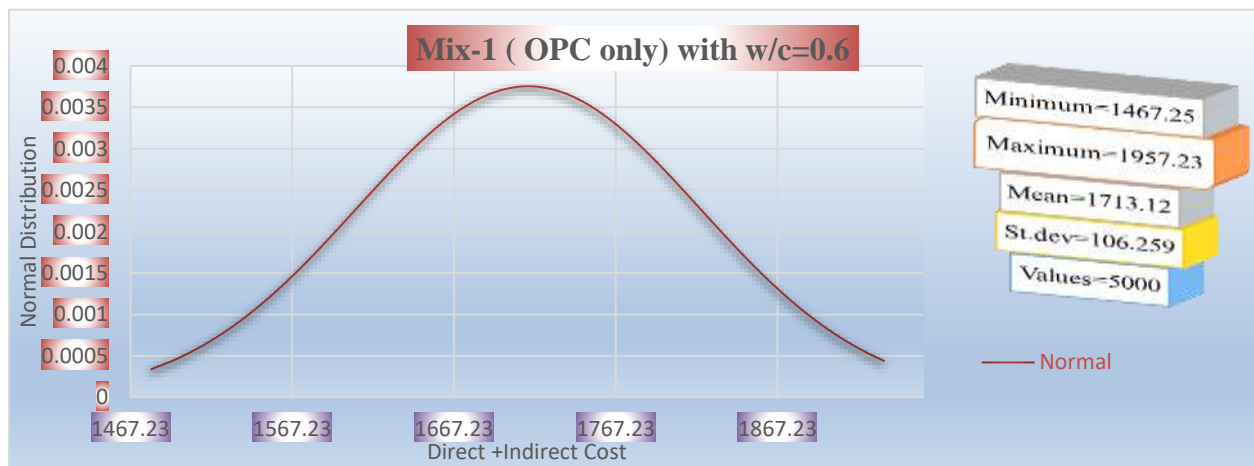


Figure 6-3: Probable Cost Concrete made with OPC only (Mix-1) and w/c=0.6

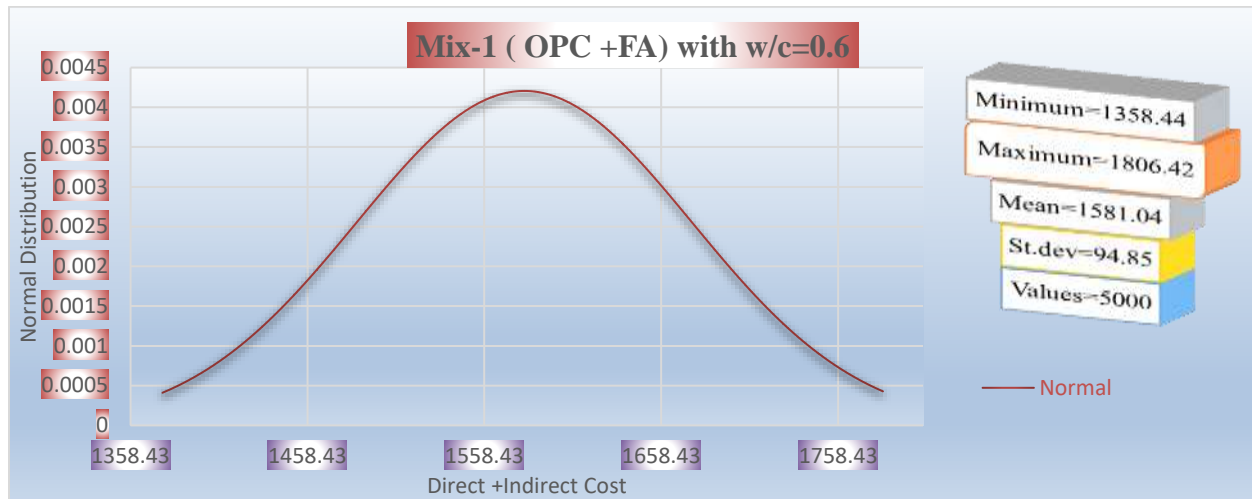


Figure 6-4: Probable Cost of Concrete made with OPC plus fly ash (Mix-2) and w/c=0.6

Therefore, from the aforementioned Benefit-cost analysis model (BCAM), an economic advantage can be attained by using coal ash as a cement replacing material. This study shows that there is great potential for fly ash concrete to reduce the environmental impacts of cement production. This analysis has found that the probable average cost (direct cost + indirect cost) of Mix-1 is ETB:2332.97 whereas the probable average cost of Mix-2 is ETB:2137.57 which has cost saving of ETB:195.4 per a cubic meter of concrete proportioned with a water-binder ratio of 0.4.

In the same manner, for concrete proportioned with a water-binder ratio of 0.6, the cost-saving of ETB: 132.08 per cubic meter can be achieved by substituting a 10% volume of cement by fly ash.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In this study, the suitability and optimum utilization of coal ash collected from AYKA Addis Textile factory and Dongfang Spinning Printing and Dying PLC in cement concrete production was investigated. The sample ash was pulverized and sieved by 300 μ m sieve. The properties of each material used in this study complied with the requirements of standards and specifications. Replacement ratio of 10%, 15%, 20% and 25% by volume of cement for FA1 and 5%, 10%, 15% and 20% by volume of cement for FA2 has been made. Each level of replacements in concrete was proportioned with water-binder ration of 0.4 and 0.6. Based on observations and trends determined from the results of this study, the following conclusions were made:

- ✓ The chemical and physical properties of the coal ash collected from the AYKA Addis Textile factory were suitable to use as pozzolanic material in cement concrete production based on ASTM C 618. The sum of the first three chemical constituents (SiO_2 , Al_2O_3 , and Fe_2O_3) of coal ash is greater than 70% and having LOI of below 12, which indicates that the sample fly ash classified as an ASTM Class F fly ash.
- ✓ On the other hand, fly ash collected from Dongfang Spinning Printing and Dying PLC is out of specification of ASTM C-618 by its LOI value of 37.8%, which shows a large amount of carbon content.
- ✓ The results of the compressive strength of FA-1 concrete proportioned by water-binder ratio of 0.4 revealed that 10% and 15% by volume replacement of cement is optimum in early and later age compressive strength of concrete respectively.
- ✓ The effect of FA-1 in concrete, proportioned by a water-binder ratio of 0.6 shows a similar trend to concrete proportioned by a water-binder ratio of 0.4. The maximum early age strength obtained at a 10% replacement ratio of FA-1. At later age (i.e. 56th day) up to 15% FA-1 replacement results improved the compressive strength of concrete.
- ✓ Compressive strength of concrete contains FA-2 as supplementary cementitious material and mixed with a water-binder ratio of 0.4 and 0.6 shows slightly strength degradation at an early age beyond 5% replacement. However, at later age and w/c 0.4, up to 10% replacement by volume of cement is possible.

- ✓ A similar trend has been observed in tensile strength for FA-1 concrete having both 0.4 and 0.6 water-binder ratios. The optimum content of fly ash for early age tensile strength is 10% and for later age strength is 15%.
- ✓ Flexural strength of FA-2 Concrete increases as FA-2 content increases up to 10% both in the water-binder ratio of 0.4 and 0.6 mixes.
- ✓ The water penetration test of the samples reveals that the average depth of penetration of water into concrete is minimum at FA-1 content of 10%. The depth of penetration of water in all samples is less than 30mm. Hence, all the samples under this investigation are impermeable under aggressive conditions according to Neville's suggestion.
- ✓ The benefit-cost analysis model (BCAM) reveals that there is a great potential for fly ash concrete to reduce the environmental impacts of cement production. A cost-saving of ETB:195.4 and ETB:132.08 per cubic meter of concrete can be achieved by substituting 10% volume cement by fly ash in concrete mix proportioned by water-binder ratio of 0.4 and 0.6 respectively.

7.2 Recommendations

- ✓ Since Ethiopia is one of the countries that have large coal reserves which is about 179 million tons of coal in Yayo woreda only, its potential utilization should be realized by all levels of society so that optimal management of coal for the benefit of the nation. If that so, its byproduct fly ash looks to be a promising supplementary cementitious material for cement concrete.
- ✓ The application of coal ash should be done in the form of slurry during mixing of coal ash with concrete rather than dry mixing in order to make uniform distribution of ash throughout the mix.
- ✓ This study focused only on the effect of coal ash collected from AYKA Addis Textile factory and Dongfang Spinning and Printing and Dying PLC on mechanical properties and durability of concrete. However, further studies are required on the following items:
 - I. The effect of coal ash on the thermal behavior of the concrete should be investigated.

- II. Investigation should be made on the effect of fineness of coal ash on mechanical and thermal behavior of concrete.
 - III. Activation of fly ash and its effect on cement properties should be studied.
- ✓ Due to financial resources limitation, this experiment was not covering some aspects. But this does not change the above test results. Therefore, the following test should be recommended in order to have further constructive information on coal ash collected from the two factories.
- I. SEM analysis in order to know the particle shapes of the ash and ITZ matrix of paste and aggregate.
 - II. Thermogravimetric analysis (TGA) in order to measure the consumption of calcium hydroxide during pozzolanic reaction.

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Appendix A

A-1 Compressive Strength of Concrete with FA-1 and w/c=0.4

No.	Test Age [Days]	0%		10%		15%		20%		25%	
		Failure Load (KN)	Compressive Strength (MPa)	Failure Load (KN)	Compressive Strength (MPa)	Failure Load (KN)	Compressive Strength (MPa)	Failure Load (KN)	Compressive Strength (MPa)	Failure Load (KN)	Compressive Strength (MPa)
1	3	265.2	26.52	269.8	26.98	255.3	25.53	225	22.5	182	18.2
2		259.8	25.98	268.1	26.81	261.7	26.17	231	23.1	195	19.5
3		260.5	26.05	284	28.4	263.5	26.35	238	23.8	204	20.4
Mean		261.83	26.18	273.96	27.4	260.16	26.02	231.33	23.13	193.67	19.37
1	7	301	30.1	307	30.7	308.9	30.89	254	25.4	223	22.30
2		292	29.2	312.5	31.25	330.3	33.03	242	24.2	201	20.10
3		265	26.5	326.3	32.63	315	31.5	267	26.7	226	22.60
Mean		286	28.6	315.26	31.53	318.06	31.81	254.33	25.43	216.67	21.67
1	28	431.8	43.18	456.8	45.68	445.8	44.58	400.1	40.01	370.2	37.02
2		436.7	43.67	450.1	45.01	457.1	45.71	394.5	39.45	364.1	36.41
3		442.1	44.21	448.1	44.81	456.8	45.68	390.2	39.02	375.2	37.52
Mean		436.86	43.69	451.66	45.17	453.23	45.32	394.93	39.49	369.83	36.98
1	56	445.6	44.56	468.3	46.83	456.2	45.62	408	40.8	375.6	37.56
2		440.1	44.01	472.2	47.22	450.1	45.01	410.5	41.05	382.4	38.24
3		454.6	45.46	473.2	47.32	469.2	46.92	415.2	41.52	391.2	39.12
Mean		446.76	44.68	471.23	47.12	458.5	45.85	411.23	41.12	383.07	38.31

A-2 Compressive Strength of Concrete with FA-1 and w/c=0.6

No.	Test Age [Days]	0%		10%		15%		20%		25%	
		Failure Load (KN)	Compressive Strength (MPa)	Failure Load (KN)	Compressive Strength (MPa)	Failure Load (KN)	Compressive Strength (MPa)	Failure Load (KN)	Compressive Strength (MPa)	Failure Load (KN)	Compressive Strength (MPa)
1	3	135.2	13.52	139.5	13.95	129.6	12.96	125.4	12.54	119.2	11.92
2		134.1	13.41	132.9	13.29	133.6	13.36	123.1	12.31	120.1	12.01
3		136.4	13.64	134.3	13.43	130.8	13.08	132.3	13.23	118.6	11.86
Mean		135.23	13.52	135.56	13.56	131.33	13.13	126.93	12.69	119.3	11.93
1	7	180.8	18.08	183.6	18.36	170.3	17.03	165.2	16.52	148	14.8
2		181.2	18.12	178.3	17.83	179.6	17.96	170.1	17.01	159.4	15.94
3		182.4	18.24	185.4	18.54	175.4	17.54	160.5	16.05	166.3	16.63
Mean		181.46	18.15	182.43	18.24	175.1	17.51	165.26	16.53	157.9	15.79
1	28	299.8	29.98	319.1	31.91	302.4	30.24	278.5	27.85	220.4	22.04
2		294	29.4	302.3	30.23	286.6	28.66	260.7	26.07	231.3	23.13
3		301	30.1	295.2	29.52	291.7	29.17	275.1	27.51	238.7	23.87
Mean		298.26	29.83	305.53	30.55	293.56	29.36	271.43	27.14	230.13	23.01
1	56	305	30.5	319.6	31.96	318.6	31.86	287	28.7	265.4	26.54
2		315	31.5	342	34.2	331.1	33.11	295	29.5	263.8	26.38
3		307	30.7	302	30.2	321.5	32.15	289	28.9	250.9	25.09
Mean		309	30.9	321.2	32.12	323.73	32.37	290.33	29.03	260.03	26

A-3 Compressive Strength of Concrete with FA-2 and w/c=0.4

No.	Test Age [Days]	5%		10%		15%		20%	
		Failure Load (KN)	Compressive Strength (MPa)	Failure Load (KN)	Compressive Strength (MPa)	Failure Load (KN)	Compressive Strength (MPa)	Failure Load (KN)	Compressive Strength (MPa)
1	3	266.3	26.63	262.7	26.27	237.6	23.76	195.2	19.52
2		265.1	26.51	258.9	25.89	241	24.1	223.5	22.35
3		274.1	27.41	260.2	26.02	245.2	24.52	208	20.8
Mean		268.5	26.85	260.6	26.06	241.26	24.13	208.9	20.89
1	7	305	30.5	312.4	31.24	262.8	26.28	232.5	23.25
2		310.1	31.01	329.3	32.93	256.3	25.63	211.5	21.15
3		309.8	30.98	315.7	31.57	279.1	27.91	229.8	22.98
Mean		308.3	30.83	319.133	31.91	266.067	26.61	224.6	22.46
1	28	440.1	44.01	458.2	45.82	411.3	41.13	389.5	38.95
2		432.4	43.24	449.2	44.92	406.2	40.62	377.1	37.71
3		450.2	45.02	456.8	45.68	408.2	40.82	393.6	39.36
Mean		440.9	44.09	454.733	45.47	408.567	40.86	386.733	38.67
1	56	470.1	47.01	475.9	47.59	435.4	43.54	392.5	39.25
2		462.4	46.24	482.6	48.26	409.6	40.96	412.6	41.26
3		456.2	45.62	450.5	45.05	415.7	41.57	387.1	38.71
Mean		462.9	46.29	469.667	46.97	420.233	42.02	397.4	39.74

A-4 Compressive Strength of Concrete with FA-2 and w/c=0.6

No.	Test Age [Days]	5%		10%		15%		20%	
		Failure Load (KN)	Compressive Strength (MPa)	Failure Load (KN)	Compressive Strength (MPa)	Failure Load (KN)	Compressive Strength (MPa)	Failure Load (KN)	Compressive Strength (MPa)
1	3	132.5	13.56	135.6	13.25	118.9	11.89	102.9	10.29
2		135.1	14.1	141	14.51	120.1	12.01	115.2	11.52
3		138.5	13.3	133	13.85	123.8	12.38	107.5	10.75
Mean		135.367	13.65	136.533	13.54	120.933	12.09	108.533	10.85
1	7	189.4	18.94	184.1	18.41	160.6	16.06	145.2	14.52
2		189.1	18.91	178.4	17.84	164.3	16.43	160.1	16.01
3		181	18.1	183	18.3	162.3	16.23	150.5	15.05
Mean		186.5	18.65	181.833	18.18	162.4	16.24	151.933	15.19
1	28	302	30.2	289.4	28.94	268.4	26.84	261.2	26.12
2		295.5	29.55	285.8	28.58	274.5	27.45	278.5	27.85
3		301.4	30.14	286.7	28.67	280.2	28.02	267.6	26.76
Mean		299.633	29.96	287.3	28.73	274.367	27.44	269.1	26.91
1	56	323	32.3	306	30.6	292.1	29.21	283.7	28.37
2		308	30.8	299.6	29.96	285.6	28.56	279.3	27.93
3		315	31.5	310.9	31.09	289.5	28.95	281.5	28.15
Mean		315.333	31.53	305.5	30.55	289.067	28.91	281.5	28.15

Appendix B

B-1 Flexural Strength of Concrete with FA-1 and w/c=0.4

No.	Test Age [Days]	0%		10%		15%		20%		25%	
		Failure Load (KN)	Flexural Strength (MPa)	Failure Load (KN)	Flexural Strength (MPa)	Failure Load (KN)	Flexural Strength (MPa)	Failure Load (KN)	Flexural Strength (MPa)	Failure Load (KN)	Flexural Strength (MPa)
1.00	3.00	5.20	2.60	5.00	2.50	5.90	2.95	4.50	2.25	4.30	2.15
2.00		5.60	2.80	6.30	3.15	4.90	2.45	5.10	2.55	4.80	2.40
3.00		5.80	2.90	5.40	2.70	5.30	2.65	4.30	2.15	4.10	2.05
Mean		5.53	2.77	5.57	2.78	5.37	2.68	4.63	2.32	4.40	2.20
1.00	7.00	8.20	4.10	8.50	4.25	7.90	3.95	6.20	3.10	5.80	2.90
2.00		7.30	3.65	8.60	4.30	8.90	4.45	7.60	3.80	6.80	3.40
3.00		7.60	3.80	8.10	4.05	8.60	4.30	7.10	3.55	6.50	3.25
Mean		7.70	3.85	8.40	4.20	8.47	4.23	6.97	3.48	6.37	3.18
1.00	28.00	8.90	4.45	9.90	4.95	9.20	4.60	8.60	4.30	7.80	3.90
2.00		8.60	4.30	9.10	4.55	9.40	4.70	8.20	4.10	8.20	4.10
3.00		9.20	4.60	8.30	4.15	8.90	4.45	8.00	4.00	7.60	3.80
Mean		8.90	4.45	9.10	4.55	9.17	4.58	8.27	4.13	7.87	3.93
1.00	56.00	9.30	4.65	9.60	4.80	9.80	4.90	8.90	4.45	8.30	4.15
2.00		9.10	4.55	9.80	4.90	9.60	4.80	9.10	4.55	8.60	4.30
3.00		8.50	4.25	8.80	4.40	9.10	4.55	8.50	4.25	8.10	4.05
Mean		8.97	4.48	9.40	4.70	9.50	4.75	8.83	4.42	8.33	4.17

B-2 Flexural Strength of Concrete with FA-1 and w/c=0.6

No.	Test Age [Days]	0%		10%		15%		20%		25%	
		Failure Load (KN)	Flexural Strength (MPa)	Failure Load (KN)	Flexural Strength (MPa)	Failure Load (KN)	Flexural Strength (MPa)	Failure Load (KN)	Flexural Strength (MPa)	Failure Load (KN)	Flexural Strength (MPa)
1.00	3.00	3.60	1.80	3.50	1.75	3.00	1.50	2.50	1.25	2.20	1.10
2.00		3.40	1.70	3.30	1.65	2.90	1.45	2.80	1.40	2.00	1.00
3.00		3.10	1.55	3.60	1.80	2.50	1.25	2.10	1.05	2.30	1.15
Mean		3.37	1.68	3.47	1.73	2.80	1.40	2.47	1.23	2.17	1.08
1.00	7.00	3.90	1.95	4.30	2.15	3.60	1.80	3.80	1.90	3.30	1.65
2.00		4.60	2.30	4.20	2.10	4.00	2.00	3.80	1.90	3.10	1.55
3.00		4.30	2.15	4.50	2.25	4.60	2.30	3.70	1.85	3.80	1.90
Mean		4.27	2.13	4.33	2.17	4.07	2.03	3.77	1.88	3.40	1.70
1.00	28.00	6.90	3.45	7.20	3.60	8.40	4.20	6.20	3.10	6.60	3.30
2.00		6.60	3.30	7.50	3.75	9.40	4.70	5.80	2.90	5.40	2.70
3.00		6.30	3.15	6.50	3.25	9.30	4.65	6.90	3.45	5.90	2.95
Mean		6.60	3.30	7.07	3.53	9.03	4.52	6.30	3.15	5.97	2.98
1.00	56.00	7.40	3.70	8.50	4.25	8.80	4.40	6.40	3.20	6.10	3.05
2.00		7.00	3.50	8.20	4.10	8.50	4.25	7.00	3.50	5.30	2.65
3.00		6.90	3.45	8.30	4.15	9.90	4.95	6.90	3.45	6.80	3.40
Mean		7.10	3.55	8.33	4.17	9.07	4.53	6.77	3.38	6.07	3.03

B-3 Flexural Strength of Concrete with FA-2 and w/c=0.4

No.	Test Age [Days]	0%		5%		10%		15%		20%	
		Failure Load (KN)	Flexural Strength (MPa)	Failure Load (KN)	Flexural Strength (MPa)	Failure Load (KN)	Flexural Strength (MPa)	Failure Load (KN)	Flexural Strength (MPa)	Failure Load (KN)	Flexural Strength (MPa)
1.00	3.00	5.20	2.60	6.20	3.10	6.50	3.25	5.60	2.80	5.40	2.70
2.00		5.60	2.80	5.30	2.65	5.60	2.80	5.10	2.55	4.90	2.45
3.00		5.80	2.90	5.90	2.95	6.50	3.25	5.30	2.65	4.60	2.30
Mean		5.53	2.77	5.80	2.90	6.20	3.10	5.33	2.67	4.97	2.48
1.00	7.00	8.20	4.10	8.80	4.40	8.80	4.40	7.50	3.75	6.50	3.25
2.00		7.30	3.65	8.20	4.10	8.90	4.45	7.80	3.90	5.90	2.95
3.00		7.60	3.80	8.30	4.15	8.70	4.35	7.60	3.80	7.50	3.75
Mean		7.70	3.85	8.43	4.22	8.80	4.40	7.63	3.82	6.63	3.32
1.00	28.00	8.90	4.45	9.80	4.90	10.30	5.15	8.90	4.45	7.70	3.85
2.00		8.60	4.30	9.60	4.80	10.50	5.25	9.20	4.60	8.10	4.05
3.00		9.20	4.60	9.20	4.60	9.50	4.75	8.20	4.10	8.40	4.20
Mean		8.90	4.45	9.53	4.77	10.10	5.05	8.77	4.38	8.07	4.03
1.00	56.00	9.30	4.65	9.70	4.85	9.90	4.95	9.10	4.55	9.02	4.51
2.00		9.10	4.55	10.70	5.35	11.50	5.75	9.50	4.75	8.69	4.35
3.00		8.50	4.25	9.50	4.75	10.80	5.40	8.50	4.25	7.90	3.95
Mean		8.97	4.48	9.97	4.98	10.73	5.37	9.03	4.52	8.54	4.27

B-4 Flexural Strength of Concrete with FA-2 and w/c=0.6

No.	Teat Age [Days]	0%		5%		10%		15%		20%	
		Failure Load (KN)	Flexural Strength (MPa)	Failure Load (KN)	Flexural Strength (MPa)	Failure Load (KN)	Flexural Strength (MPa)	Failure Load (KN)	Flexural Strength (MPa)	Failure Load (KN)	Flexural Strength (MPa)
1.00	3.00	3.60	1.80	3.90	1.95	3.80	1.90	3.10	1.55	2.90	1.45
2.00		3.40	1.70	3.40	1.70	4.10	2.05	2.90	1.45	2.40	1.20
3.00		3.10	1.55	3.30	1.65	3.60	1.80	3.50	1.75	2.10	1.05
Mean		3.37	1.68	3.53	1.77	3.83	1.92	3.17	1.58	2.47	1.23
1.00	7.00	3.90	1.95	4.00	2.00	5.90	2.95	5.10	2.55	3.20	1.60
2.00		4.60	2.30	5.10	2.55	5.60	2.80	4.90	2.45	3.50	1.75
3.00		4.30	2.15	4.50	2.25	5.50	2.75	5.30	2.65	3.70	1.85
Mean		4.27	2.13	4.53	2.27	5.67	2.83	5.10	2.55	3.47	1.73
1.00	28.00	6.90	3.45	7.20	3.60	8.36	4.18	6.50	3.25	4.90	2.45
2.00		6.60	3.30	7.50	3.75	7.60	3.80	7.20	3.60	5.20	2.60
3.00		6.30	3.15	7.30	3.65	7.90	3.95	6.80	3.40	5.60	2.80
Mean		6.60	3.30	7.33	3.67	7.95	3.98	6.83	3.42	5.23	2.62
1.00	56.00	7.40	3.70	8.10	4.05	8.40	4.20	7.50	3.75	5.90	2.95
2.00		7.00	3.50	8.50	4.25	8.70	4.35	8.00	4.00	6.50	3.25
3.00		6.90	3.45	8.80	4.40	9.10	4.55	8.20	4.10	5.10	2.55
Mean		7.10	3.55	8.47	4.23	8.73	4.37	7.90	3.95	5.83	2.92

Appendix C

Water Penetration Test Result

FA-1												
W/C=0.6												
		0%			10%			15%			20%	
Penetration depth measured at 10mm interval	Points	1	2	3	1	2	3	1	2	3	1	2
	1	11	5	7	4	13	8	9	6	5	26	12
	2	12	2	5	8	14	16	8	7	6	16	9
	3	14	6	4	15	12	8	12	5	6	17	11
	4	12	9	15	21	13	11	14	11	8	14	28
	5	22	12	21	23	11	15	22	19	21	18	30
	6	18	15	26	21	9	13	18	21	22	19	30
	7	13	17	16	22	19	21	24	19	18	19	16
	8	21	25	17	18	24	25	28	24	17	15	18
	9	17	21	17	17	21	17	23	28	17	29	19
	10	6	23	18	12	22	13	22	26	13	29	14
	11	3	12	8	9	21	7	17	14	11	21	11
	12	9	14	8	8	16	14	19	16	9	19	28
	13	5	13	7	10	5	13	14	14	19	16	32
	14	11	19	11	11	6	11	9	12	11	19	27
	15	15	20	14	14	6	8	7	11	9	15	21
	16	16	13	5	12	8	9	5	7	19	10	17
Maximum		22	25	26	23	24	25	28	28	22	29	32
Average		13.4	14.8	13.2	14.6	14.4	13.8	16.4	15.8	13.7	19.5	20.9