A Valuable Industrial Waste (Coal Fly Ash): Properties and Its Applications in Civil Engineering Construction

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ABSTRACT: Large number of innovative alternate building materials and low cost construction techniques developed through intensive research efforts during last three to four decades satisfies functional as well as specification requirements of conventional materials/techniques and provide an avenue for bringing down the construction cost. Fly ash, a industrial by-product from Thermal Power Plants with current annual generation of approximately 112 million tones and its proven suitability for variety of applications as admixture in cement/concrete/mortar, lime pozzolana mixture (bricks/blocks) etc. is such an ideal material which attracts the attention of everybody. Fly ash utilization in the civil engineering construction materials have many advantages like cost effectiveness, environmental friendly, increases in strength and conservation of other natural resources and materials.Fortunately, its useful properties have now begun to be known as raw material for various applications as an outcome of their efforts, Fly Ash is being very effectively and economically used in building components such as bricks, cement, doors, door-frames, etc. Fly Ash is also being used in construction of roads and embankments with some design changes. The trend is clear, Fly Ash will soon be considered as a resource material and its potential will be fully exploited. Through development & application of technologies, Fly Ash has shifted from "Waste Material" category to "Resource Material" category. Thus fly ash management is a cause of concern for the future. This article attempts to highlight the management of fly ash to make use of this solid waste and its beneficial potential in application of civil engineering construction as well as others to reduce the environmental pollution.

Keywords: Fly ash, compressive, Eco-friendly, Construction material, efficient concrete

I. INTRODUCTION

Electricity is the key for development of any country. Coal is a major source of fuel for production of electricity in many countries in the world. In the process of electricity generation large quantity of fly ash gets produced and becomes available as a byproduct of coal-based power stations. It is a fine powder resulting from the combustion of powdered coal - transported by the flue gases of the boiler and collected in the Electrostatic Precipitators (ESP). Conversion of waste into a resource material is an age-old practice of civilization. The process of coal combustion results in coal ash, 80% of which is very fine in nature and thus known as fly ash. High ash content is found to be in range of 30% to 50% in Indian coal **[1].** The quantum of fly ash produced depends on the quality of coal used and the operating conditions of thermal power plants. Presently the annual production of fly ash in India is about 112 million tonnes with 65000 acre of land being occupied by ash ponds and is expected to cross 225 million tonnes by the year 2017 **[2].** The fly ash, solid waste from coal–fired thermal power plants, is becoming a serious concern to the environmentalists.

Fly ash is an extremely fine powder consisting of spherical particles less than 50 microns in size and produced approximately 420 million tons per year globally **[3].** It consists of silica, alumina, iron oxide, lime, magnesia and alkali in varying amounts with some unburned activated carbon **[4].** There are two ways that the fly ash can be used: one way is to intergrind certain percentage of fly ash with cement clinker at the factory to produce Portland pozzolona cement (PPC) and the second way is to use the fly ash as an admixture at the time of mixing the concrete at the site of work. Fly ash is one of the construction industry's most commonly used pozzolans. Pozzolans are siliceous or siliceous/alumino materials possessing the ability to form cementitious compounds when mixed with lime (calcium hydroxide, or $Ca(OH)_2$,) and water. Due to environmental regulations, new ways of utilizing fly ash have to be explored in order to safeguard the environment and provide cost effective ways for its bulk utilization. Now, there is an urgent and imperative need to adopt technologies for gainful utilization and safe management of FA on sustainable basis. FA has a number of useful applications that serves to utilise some of the large amount being produced all over the world. Main applications of FA are in the field of manufacturing of cement and other construction materials **[5-6].**

A huge volume of Fly Ash produced from coal-based thermal power plants may bring several problems from environmental point of view. Fly Ash particles ranging in size from 0.5 to 300 micron in equivalent diameter, being light weight, have potential to get airborne easily and pollute the environment. If not managed properly fly ash disposal in sea/rivers/ponds can cause damage to aquatic life also. It can also contaminate the under-ground water resources with traces of toxic metals present in fly ash. Huge investments/ expenditures are made just to get Fly Ash out from the thermal power plants and dump it in the ponds. If understood and managed properly, it can prove to be a valuable resource material. Every year a crude estimation of more than 300 billion tones of fly ash is generated in the world **[7]** and is being consumed in the production of building construction materials, in agriculture, metal recovery, in water and atmospheric pollution control, etc. **[8].** These applications could succeed up to some extent to consume the huge amount of fly ash. The paper also discusses some of the economic drivers which determine the degree of commercial success. Simply deposing of waste materials in concrete products is unlikely to succeed except in unusual situations. This paper deals with detail study of used of fly ash in civil engineering construction with partial replacement of cement and providing eco-friendly (Green Concrete) construction material to make use of this solid waste, in order to save our environment.

II. CHEMISTRY OF COAL FLY ASH

Fly ash is complex material having wide range of chemical, physical and mineralogical composition. The chemistry of fly ash depends on the type of coal burnt in boiler furnace, temperature of furnace, degree of pulverization of coal, efficiency of ESP etc Fly ash consists of fine, non plastic and powdery particles that are predominantly spherical in shape, either solid or hollow and mostly glassy (amorphous) in nature. The carbonaceous material in fly ash is composed of angular particles. The specific gravity of fly ash usually ranges from 2.1 to 3.0, while its specific surface area may range starts from 170 m2/ kg to 1000 m2/ kg **.** The particle size distributions of most bituminous coal fly ashes are generally similar to that of silt **(less than a 0.075 mm or No. 200 sieve***)*. Sub-bituminous coal fly ashes are also silt-sized; they are generally slightly coarser than bituminous coal fly ashes. In **Table 1**, normal ranges of chemical composition of Indian fly ash are given:

Table 1: Normal range of chemical composition of Indian fly ash produced from different coal types (expressed as percent by weight).

Component	Bituminous	Subbituminous	Lignite
SiO_2 (%)	20-60	40-60	15-45
Al_2O_3 (%)	5-35	20-30	20-25
Fe_2O_3 (%)	10-40	4-10	4-15
CaO (%)	1-12	5-30	15-40
LOI (%)	0-15	0-3	0-5

A. Production

Fly ash is produced from the combustion of coal in electric utility or industrial boilers. There are four basic types of coal-fired boilers: pulverized coal (PC), stoker-fired or traveling grate, cyclone, and fluidized-bed combustion (FBC) boilers. The PC boiler is the most widely used, especially for large electric generating units. The other boilers are more common at industrial or cogeneration facilities. Fly ashes produced by FBC boilers are not considered in this document. Fly ash is captured from the flue gases using electrostatic precipitators (ESP) or in filter fabric collectors, commonly referred to as bag houses. The physical and chemical characteristics of fly ash vary among combustion methods, coal source, and particle shape.

B. Physico-chemical properties of fly ash

The physical characteristics of fly ash depend on a number of factors. Chemical composition and pH values of fly ash possess a wide range of depending on the nature of coal and process of coal burnt. Due to low sulfur content of coal and presence of hydroxides and carbonates of calcium and magnesium the pH of fly ash 6.52 which generally highly alkaline **[9-10]**. In physical properties of fly ash, Colour is one of the important in terms of estimating the lime content qualitatively. It gives us a suggestion that darker colour suggest high organic content while lighter colour indicate the presence of high calcium oxide. Specific gravity another important physical property needed for the geotechnical use of fly ash. In general, the specific gravity of coal ashes lays around 2.0 but can vary to a large extent (1.6 to 3.0) .Fly ash containing a relatively slighter specific gravity than the normal soils **[11].** Specific gravity of fly ash depends considerably upon its carbon and iron content. More carbon content decreases its specific gravity, whereas presence of iron content increases the specific gravity **[12-13]**. **Table 2** shows the typical physical characteristics of fly ash

The X-ray Fluorescence test given the idea about the chemical compositions of fly ash. The investigation for an Indian fly ash demonstrates that all the fly ash contains silica, alumina, iron and calcium oxide. In fly ash silica content is between 38 and 63%, alumina content ranges between 27 and 44%, calcium oxide is in the range of 0 to 8% **[14-19].** In the fly ash, the elements present in declining order of their plenty are O, Si, Al, Fe, Ti, K, Ca, P and Mg. Moreover, trace quantity of Mn, Cr, Ni and Cu are identified in some of the fly ash (**Table 2).**

Table 2: Physico-chemical Characteristic of Fly ash

Physical properties		Chemical composition	
Structure	fine, powdery particles	**SiO_2**	38 – 63%
Shape	Spherical, either solid or hollow	**Al_2O_3**	27 – 44%
Nature	mostly glassy (amorphous)	**TiO_2**	0.4 – 1.8%
Particle size	1 µm to 150 µm (less than a 0.075 mm or No. 200 sieve)	**Fe_2O_3**	3.3 – 6.4%
specific gravity	2.1 to 3.0	**MnO**	0.1 – 0.5%
specific surface area	170 to 1000 m2/kg	**MgO**	0.01 – 0.5%
Porosity	44 – 55%	**CaO**	0.2 – 8.0%
PH	6.0-11.0	**K_2O**	0.04 – 0.9%
Colour	tan to gray to black (colour intensity varies from light to dark	**Na_2O**	0.07 – 0.43%

	with increased amount of carbon content)		

C. *Classification of coal fly ash*

On the basis of silica, alumina, and iron content the fly ash can be classified into two classes: (**Table 3)**

Table 3. Differences between class F and class C fly ash.

Class F	Class C
❖ Class F fly ash produces by burning of harder anthracite and bituminous coal.	❖ Class C fly ash produces by burning of younger lignite or sub bituminous coal.
❖ This class of fly ash contains less than 20 % of lime.	❖ This class of fly ash contains more than 20 % of lime.
❖ Alkali and sulfate contents are generally lower in class F.	❖ Alkali and sulfate contents are generally higher in class C.
❖ The quantities of Si, Fe & K oxides are higher in Class F.	❖ The quantities of Si, Fe & K oxides are lower in Class C.
❖ The CaO, MgO, SO_3 & Na_2O quantities are lower in Class F.	❖ While CaO, MgO, SO3 & Na_2O quantities are higher in Class C
❖ Class F fly ash has been rarely cemetitious when mixed with water.	❖ Class C fly ash usually has cementitious properties in addition to pozzolanic properties.
	

III. ENVIRONMENTAL PROBLEMS

Environmental pollution by the coal based thermal power plants all over the world is cited to be one of the major sources of pollution affecting the general aesthetics of environment in terms of land use, health hazards and air, soil and water in particular and thus leads to environmental dangers. The greatest part of the radioactivity in coal remains with the ash but some of the fly ash from coal-fired power plants escapes into the atmosphere. Air pollution in the vicinity of a coal fired thermal power station affects soil, water, vegetation, the whole ecosystem and human health.

IV. ENVIRONMENTAL BENEFITS OF FLY ASH USE IN CIVIL ENGINEERING CONSTRUCTION

Fly ash utilization, especially in concrete, has significant environmental benefits including:

- Increasing the life of concrete roads and structures by improving concrete durability,
- Net reduction in energy use and greenhouse gas and other adverse air emissions when fly ash is used to replace or displace manufactured cement,
- Reduction in amount of coal combustion products that must be disposed in landfills, and
- Conservation of other natural resources and materials.

V. ENGINEERING PROPERTIES

Some of the engineering properties of fly ash that are of particular interest when fly ash is used as an admixture or a cement addition to PCC mixes include fineness, LOI, chemical composition, moisture content, and pozzolanic activity. Most specifying agencies refer to ASTM C618 when citing acceptance criteria for the use of fly ash in concrete.

A. *Fineness*:

Fineness is the primary physical characteristic of fly ash that relates to pozzolanic activity. As the fineness increases, the pozzolanic activity can be expected to increase. Current specifications include a requirement for the maximum allowable percentage retained on a 0.045 mm (No. 325) sieve when wet sieved. ASTM C618 specifies a maximum of 34 percent retained on a 0.045 mm (No. 325) sieve. Fineness can also be assessed by methods that estimate specific surface area, such as the Blaine air permeability test commonly used for Portland cement **[20].**

B. *Pozzolanic Activity (Chemical Composition and Mineralogy)*:

Pozzolanic activity refers to the ability of the silica and alumina components of fly ash to react with available calcium and/or magnesium from the hydration products of Portland cement. ASTM C618 requires that the pozzolanic activity index with Portland cement, as determined in accordance with ASTM C311 be a minimum of 75 percent of the average 28-day compressive strength of control mixes made with Portland cement.

C. *Loss on Ignition*:

Many state transportation departments specify a maximum LOI value that does not exceed 3 or 4 percent, even though the ASTM criteria is a maximum LOI content of 6 percent. This is because carbon contents (reflected by LOI) higher than 3 to 4 percent have an adverse effect on air entrainment.

Fly ashes must have a low enough LOI (usually less than 3.0 percent) to satisfy ready-mix Concrete producers, who are concerned about product quality and the control of air Entraining admixtures. Furthermore, consistent LOI values are almost as important as low LOI values to ready-mix producers, who are most concerned with consistent and predictable quality.

D. *Moisture Content*:

ASTM C618 specifies a maximum allowable moisture content of 3.0 percent.Some of the properties of fly ash-concrete mixes that are of particular interest include mix workability, time of setting, bleeding, pumpability, strength development, heat of hydration, permeability, resistance to freeze-thaw, sulfate resistance, and alkali-silica reactivity.

E. *Workability*:

At a given water-cement ratio, the spherical shape of most fly ash particles permits greater workability than with conventional concrete mixes. When fly ash is used, the absolute volume of cement plus fly ash usually exceeds that of cement in conventional concrete mixes. The increased ratio of solids volume to water volume produces a paste with improved plasticity and more cohesiveness.

F. *Time of Setting*:

When replacing up to 25 percent of the Portland cement in concrete, all Class F fly ashes and most Class C fly ashes increase the time of setting. However, some Class C fly ashes may have little effect on, or possibly even decrease, the time of setting. Delays in setting time will probably be more pronounced, compared with conventional concrete mixes, during the cooler or colder months.

G. *Bleeding*:

Bleeding is usually reduced because of the greater volume of fines and lower required water content for a given degree of workability.

H. *Pumpability*:

Pumpability is increased by the same characteristics affecting workability, specifically, the lubricating effect of the spherical fly ash particles and the increased ratio of solids to liquid that makes the concrete less prone to segregation.

I. *Strength Development*:

Previous studies of fly ash concrete mixes have generally confirmed that most mixes that contain Class F fly ash that replaces Portland cement at a 1:1 (equal weight) ratio gain compressive strength, as well as tensile strength, more slowly than conventional concrete mixes for up to as long as 60 to 90 days. Beyond 60 to 90 days, Class F fly ash concrete mixes will ultimately exceed the strength of conventional PCC mixes. For mixes with replacement ratios from 1.1 to 1.5:1 by weight of Class F fly ash to the Portland cement that is being replaced, 28-day strength development is approximately equal to that of conventional concrete.

VI. FLY ASH APPLICATIONS IN CIVIL ENGINEERING

Fly ash can be used as prime material in blocks, paving or bricks; however, one of the most important applications is PCC pavement. PCC pavements use a large amount of concrete and substituting fly ash provides significant economic benefits. Fly ash has also been used for paving roads and as embankment and mine fill, and it's gaining acceptance by the Federal government, specifically the Federal Highway Administration.

A. Fly Ash in Cement Industries

Fly ash is considered to be stronger, more environmental friendly and durable cement as compared to Portland cement. It is the most widely used construction material in the world. It consists of cement, aggregates (fine and course) and water. In the concrete, cement chemically reacts with water and produces binding gel that binds other component together and creates stone type of material by a process called 'hydration', along with formation of some amount of lime [$Ca(OH)_2$]. The coarse and fine aggregates act as filler in the mass. Thus, the fly ash in Concrete could be an expensive replacement for Portland cement in concrete and using it, improves strength, segregation and ease of pumping concrete.

Advantages of Fly Ash in Concrete

Fly Ash improves concrete workability and lowers water demand. Fly Ash particles are mostly spherical tiny glass beads. Ground materials such as Portland cement are solid angular particles. Fly Ash particles provide a greater workability of the powder portion of the concrete mixture which results in greater workability of the concrete and a lowering of water requirement for the same concrete consistency.

Fly Ash generally exhibit less bleeding and segregation than plain concrete. This makes the use of Fly Ash particularity valuable in concrete mixtures made with aggregates deficient in fines.

Sulphate and Alkali Aggregate Resistance. Class F and a few Class C Fly Ashes impart significant sulphate resistance and alkali aggregate reaction (ASR) resistance to the concrete mixture.

Fly Ash has a lower heat of hydration. Portland cement produces considerable heat upon hydration. In mass concrete placements the excess internal heat may contribute to cracking. The use of Fly Ash may greatly reduce this heat buildup and reduce external cracking.

Fly Ash generally reduces the permeability and adsorption of concrete. By reducing the permeability of chloride ion egress, corrosion of embedded steel is greatly decreased. Also, chemical resistance is improved by the reduction of permeability and adsorption.

Fly Ash is economical. The cost of Fly Ash is generally less than Portland cement depending on transportation. Significant quantities may be substituted for Portland cement in concrete mixtures and yet increase the long term strength and durability. Thus, the use of Fly Ash may impart considerable benefits to the concrete mixture over a plain concrete for less cost.

B. *Fly ash in Portland cement concrete*

Fly ash can be used in Portland cement concrete to enhance the performance of the concrete. Portland cement is manufactured with calcium oxide (CaO), some of which is released in a free state during hydration. As much as 20 pounds of free lime is released during hydration of 100 pounds of cement. This liberated lime forms the necessary ingredient for reaction with fly ash silicates to form strong and durable cementing compounds, thus improves many of the properties of the concrete. Some of the resulting benefits are: be disposed in landfills, and conservation of other natural resources and materials. Typically, 15 to 30 % of the Portland cement is replaced with fly ash **[21-23].**

C. Fly ash as Fill Material

Large scale use of ash as a fill material can be applied where

- ❖ Fly ash replaces another material and is therefore in direct competition with that material.
- ❖ Fly ash itself is used by the power generating company producing the fly ash to improve the economics of the overall disposal of surplus fly ash.

Fly ash disposal is combined with the rehabilitation and reclamation of land areas desecrated by other operations. Fills can be constructed as structural fills where the fly ash is placed in thin lifts and compacted. Structural fly ash fills are relatively incompressible and are suitable for the support of buildings and other structures. Non-structural fly ash fill can be used for the development of parks, parking lots, playgrounds and other similar lightly loaded facilities.

D. Fly ash for Roads

Fly ash can be used for construction of road and embankment. This utilization has many advantages over conventional methods.

- ❖ Saves top soil which otherwise is conventionally used
- ❖ Avoids creation of low lying areas (by excavation of soil to be used for construction of embankments)
- ❖ Avoids recurring expenditure on excavation of soil from one place for construction and filling up of low lying areas thus created.
- ❖ Does not deprive the nation of the agricultural produce that would be grown on the top soil which otherwise would have been used for embankment construction.
- ❖ Reduces the demand of land for disposal/deposition of fly ash that otherwise would not have been used for construction of embankment **[24].**

E. Fly ash Bricks

Fly ash products are also environment-friendly. A case in point is fly ash bricks. The manufacture of conventional clay bricks involves the consumption of large amounts of clay **[20]**. This depletes topsoil and degradation of agricultural land. Fly ash bricks do not require clay and serve two purposes; preservation of topsoil and constructive utilization of fly ash **[25].**

Fly ash bricks are made up of fly ash, sand and cement. In these bricks fly ash is used as the primary filler and sand is added as secondary filler. Cement is used to binder, which helps in holding all the raw material together. Bricks can be mainly grouped into two categories:

- ❖ Fly ash bricks using cement as a binder: Raw materials include: fly ash, cement and sand.

- ❖ Fly ash brick using lime as a binder: Raw materials include: fly ash, lime gypsum and sand.

F. Fly ash Product-Mosaic tile

Mosaic tile are manufactured utilizing the fly ash. The process involves preparing the mix for two layers: the wearing layer and the base layer. The wearing layer consists of a plastic mix of mosaic chips, cement, and fly ash and dolomite powder. The base layer consists of a semi-dry mix of fly ash, cement and quarry dust. The tiles are pressed in the tile-making machine and air-dried for 12 hours or more. They then undergo curing in water tanks for 15 days. The tiles are then polished and stacked for supply.

G. Light Weight Aggregates

Worldwide, many technologies have been developed for the production of artificial aggregates from fly ash. Only two of them have reached the commercial status-the sintering process Lytag and the cold-bonded process Aardelite. Aggregates from fly ash produced can be used for a variety of applications in the construction industry, including masonry elements, precast concrete elements, ready-mix concrete for buildings up to five floors and bituminous concrete for road foundation.

H. Earthwork material

Fly ash can be effectively used for an embankment or reinforcement material since it is lighter than common earthwork materials. In recent years, therefore, various technology development efforts have been made, resulting in a number of applications. Among these is an application using fly ash in its original powder state with cement added as a solidifier to coal ash, as well as fly ash's utilization as a stabilizing material. It is also granulated or processed in other ways for different applications. Review is also underway for the intended commercialization of fly ash as a soil stabilizer or a construction sludge conditioner due to its pozzolanic activation as well as its self-hardening property. Meanwhile, basic research of the elution of coal ash's trace elements is continuing since fly ash's use in earthwork must be in harmony with the environment.

VII. CONCLUSIONS

Various approaches are cited for the effective utilization of fly ash mainly limited to limited quantity. Therefore bulk utilization of fly ash is recommended to resolve the issue of storage and handling of fly ash in huge volume. Fly ash has become an important raw material for the various industrial and construction material and finds a numerous application in the cement industries, construction industry, and polymer industries and in pollution control. It is widely used in civil engineering construction of bricks, cement, asbestos-cement products and road/embankments. Fly ash produced as waste materials can be a good construction material for highway or expressway embankments. Fly ash has been successfully used in more than ten highway embankments construction projects across the country. The paper focuses on the current utilization fly ash in civil engineering construction industry.

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