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Utilization of natural resources for sustainable development: Role of Bangladeshi fly ash

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Abstract

Coal fired power stations around the world produce enormous quantities of power coal ash (internationally known as Coal Combustion Products) every year. Volume of this product continues to grow consistent with increased consumer and industry energy demands. Marketers of coal ash are making significant inroads into increasing effective utilization of its portion of the worldwide coal ash production. In the year 2006, two units of 125 MW coal based power plant has started generation in Boropukuria, Bangladesh and also recently another plant of 1320 MW capacity is going to set up at Rampal, Bagerhat, Bangladesh. The power sector master plan of Bangladesh projects a high growth in coal based power generation although there is lack in strategy on the use of generated fly ash. The utilization of fly ash in concrete as partial replacement of cement is gaining immense importance today, mainly on account of the improvements in the long term durability of concrete combined with ecological benefits as well as reduction of huge dumping problem. This study aimed to explore the possibility of using Boropukuria fly ash in concrete construction. Three different grades of concrete M38, M33 and M28, each with seven different fly ash replacement level, 10, 20, 30, 40, 50, 60 and 70% were used for the experimental program. Ordinary Portland cement (OPC) concrete was also used as reference concrete. Evaluations of compressive strength, coefficient of permeability as well as rapid chloride penetration resistance of concrete specimens were carried out over the period of 180 days. Test results show that permeability of concrete decreases with the increase of fly ash level up to an optimum value and then start to increase, whereas strength of concrete increases with the increase of fly ash up to an optimum level and then starts to decrease. The optimum amount of cement replacement level is reported to be around 30%, which provides around 16% lower permeability, 40% lower rapid chloride penetration resistance and 13% higher compressive strength as compared to ordinary Portland cement concrete.

Keywords: Cement, Concrete, Fly ash, Strength, Water permeability, Rapid chloride penetration.

1. Introduction

Concrete is the most widely used man-made material in the world. Almost three tones of concrete per person are produced in the world, twice as much as the rest of all other materials together, including wood, steel, plastics and aluminium. Concrete is the second most consumed substance on Earth after water and is an essential product in the building sector. Portland cement is the prime ingredients in concrete. Cement is a fine grey powder and constitutes 7 to 15% by weight of concrete's total mass. The net cement production in the world is increased from about 1.4 billion tones in 1995 to almost 3 billion tones in the year 2010, expected to be around 5 billion tones in the year of 2040. CO_2 emission is in the range of 0.72–0.98 ton CO_2 per ton of cement (IEA, 2006) from which 50–70% comes from calcinations, 30–40% from fuel combustion and around 10% from transportation and other ancillaries (Barker, 2009). According to IPCC (Metz, 2007) and IEA (2006) 5 to 7% of worldwide CO_2 emissions are caused by the cement industry and adding the greenhouse gas equivalent to 330 million cars driving 12,500 miles per year. The considerable energy consumption, 4–5 GJ per ton of cement (IEA, 2006), is mainly due to fuel combustion. The cement industry represents around 20% of industrial carbon emissions (Allwood, 2010), with growing production that has gained importance in the last few years (ECA, 2007). Sustainable development can be defined as development which meets the needs of people living today without compromising the ability of future generations to meet their own needs. It requires a long-term vision of industrial progress, preserving the foundations upon which human quality of life depends: respect for basic human needs and local as well as global ecosystems. Sustainability issue in construction sector came forward in last two decades due to concerns regarding using virgin materials as well as emission of greenhouse gases from production of raw materials.

Almost all industry owners know that in order to continue to meet the demands of a growing world population, they must become smarter to use, reuse and recycle raw material. Using by product from other industries as raw material is a huge opportunity for the cement industry to reduce its environmental impact. There are a number of mineral by-products produced by the mining and power generation industries that contain useful materials that can be extracted for use in cement production, or in making concrete. Being emission a key issue to attain sustainability in construction industry, supplementary cementitious materials (SCM) are gaining interest and numerous researches has shown potential of using SCMs for instance pulverized fuel ash (fly ash) from coal combustion, GBBS from iron industry, Silica Fume and Metakaolin (Duran, 2011). These SCMs provide duel benefits in concrete construction, reduce the emission of CO_2 in material production and improve several properties of fresh and hardened concrete. It is generally agreed that with the proper selection of SCMs, mixture proportioning and curing, durability and strength property can be noticeably improved (Zichao, 2003). Recently there has been a growing trend for the use of SCMs in the production of composite cement because of ecological, economical and diversified product quality reason.

1.1 Use of Fly ash as supplementary cementitious material

Fly ash is one of the most common pozzolan and is being used quite extensively. Nowadays the utilization of fly ash in concrete as partial replacement of cement has increased rapidly. Fly ash contains high amount siliceous and aluminous compounds and has high potential for use as pozzolanic material to partially replace cement in concrete (Sarkar, 1995)**.** Through pozzolanic activity, fly ash chemically combines with water and calcium hydroxide, forming additional cementitious compounds which result in denser as well as higher strength concrete. The calcium hydroxide chemically combined with fly ash is not subject to leaching, thereby helping to maintain high density. The conversion of soluble calcium hydroxide to cementitious compounds decreases bleed channels, capillary channels and void spaces and thereby reduces permeability. Depending on the location of each power plant, the unused fly ash is disposed at the ponds, lagoons or landfills. When unused fly ash and bottom ash is disposed from coal combustion power plants, it makes major negative environment effects such as air pollution and groundwater quality problem due to leaching of metals from the ashes, specially unused fly ash which has very small particle size (Janos, 2002). The cement content in concrete mixture can be reduced by using fly ash as a replacement of cement, inconsequence, decreasing both energy and CO_2 from the production of cement. This CO_2 is a major contributor to the greenhouse effect as well as responsible for global warming of the planet (Ferreira, 2003). The fineness or particle size of fly ash is an important factor in developing the strength of concrete. According to the ASTM 618, the fly ash is suitable for use in concrete when not more than 34 percent of the particle is retained on the No. 325 (45μm) sieve. Fineness of ground disposed fly ash plays very important role on compressive strength of concrete. However, the ground disposed fly ashes which have particle sizes retained on sieve No. 325 less than 5% by weight can be used as good pozzolanic material (Cheerarot, 2004). Fly ash is primarily a silicon-aluminous material capable of reacting with calcium hydroxide at room temperature to form compounds with cementitious properties. ASTM C618 defines two classes of fly ash, Class F and Class C, based upon the origin of the coal used and the resulting chemical and mineralogical composition. According to ACI Committee 226(1987), Class F fly ash, also referred to as low calcium fly ash, is usually produced by burring anthracite of bituminous coals, while Class C fly ash is normally produced by burning sub bituminous coal or lignite. Both types of fly ash contain a substantial amorphous phase and each class of fly ash may constitute particles of varying morphology, size distribution, glassy phase and type of crystalline matter. Class F fly ashes are pozzolanic but Class C fly ash also exhibits cementitious properties because of high calcium content. Other forms of classification are based on carbon content, SiO_2 reactivity, solubility or pozzolanic activity etc.

Class F fly ashes are low in CaO. They are predominantly (>70%) noncrystalline silica, which is the determining factor for pozzolanic activity. Their crystalline minerals are generally composed of quartz, mullite, hermatitie, magnetite or ferrite spinel (Roy, 1984). Class C ashes may contain more than 20% CaO. Class C fly ash contains predominantly calcium alumino-silica glass, which is highly reactive. Crystalline phases in Class C ash include quartz, lime, mullite, gehlenite, anhydrite and cement minerals such as C_3A, C_2S and C_4AF. It is also reported to contain calcium sulfate and alkali sulfate (Mehta, 1989). Alkali sulfate may be derived from additions to improve fly ash resistivity and hence precipitator performance. The concentration of important minerals is found in fly ashes made from bituminous coals, as reported by Alonso and Wesche (1992). Other minerals that could also be present in small amounts are wustite, goethite, pyrite, calcite, anhydrite and periclase. Class C fly ash often reacts with water to form cementitious phase such as C-S-H, calcium hydroxide, and ettringite. Class F fly ash contains large proportions of silica glass. Wide ranges exist in the amounts of the three principal constituents: SiO_2 (20% to 65%), Al_2O_3 (10 to 30%) and Fe_2O_3 (5 to 25%). In a Class F fly ash, the total content of these three components must be 70 percent or greater. For Class C fly ash, these three constituents must constitute more than 50 percent of the mass, as Class C fly ash generally contains significant percentages of calcium compounds reported as CaO. The level of alkali oxides expressed as Na_2O equivalent is generally less than 5% in Class F fly ashes but may be up to about 10% in Class C fly ashes. Fly ashes for use in concrete must have less than 6% loss on ignition. The loss on ignition is primarily depends on the presence of free “unburned” carbon, carbonates and combined water in residual clay mineral. Unburned CaO particles sometimes constitute up to 16% of a fly ash by mass, depending on the nature of the coal, its degree of pulverization, the rate and temperature of combustion, and the fuel to air ratio (Alonso, 1992). Fly ash containing excessive unburned carbon, usually due to a boiler malfunction, is sometimes recycled as a part of the boiler fuel. The beneficial use of coal based power plant fly ash in concrete has increased the interest of researcher for the evaluation of the performance of such concrete. The relevant studies indicate that the percentage of cement replaced with fly ash and their relative proportion for making concrete is very important. Concrete mixes made by replacing cement with fly ash are reported to show better results for compressive, tensile as well as flexural strength, freezing and thawing resistance, shrinkage, permeability and abrasion resistance than conventional concrete mixes (Tarun, 1996). Fly ash has dual effects in concrete i.e. as a micro-aggregate and as a pozzolana. Fly ash improves the interfacial bond between the paste and the aggregates in concrete (Poon, 2000). According to Malhotra (2000), the concrete incorporating moderate and high volumes of fly ash showed superior resistance against strength deterioration, rebar corrosion and the penetration of chloride ions compared to the control concrete specimen.

Compressive strength is the most important design parameter for any types of concrete structures. This critical parameter drives the design process and can influence the cost of a structure as well as a project. Through the use of certain mineral admixtures, the cost of concrete can be reduced and also enhance the properties of mortar or concrete. The ACI Committee, 232 reported that the properties of freshly mixed, unhardened concrete and the strength of hardened concrete are influenced by the shape, fineness, particle size distribution and density of fly ash particle. With help of these pozzolan, less permeability and a denser calcium silicate hydrate (C–S–H) concrete can be obtained as compared with Portland cement (Oner, 2005). Fly ash replacement in concrete would be remarkable cement saving as well as cost minimizing steps for the construction of concrete structures without sacrificing the strength of concrete. The pozzolanic reaction in fly ash converts the calcium hydroxide into more CSH, thus leading to reduce permeability and increase strength. With the use of fly ash, the ingress of moisture, oxygen, chlorides, and aggressive chemicals are slowed significantly, thus improving durability and serviceability. The major aim of this investigation is to evaluate and explore the suitability of the use of fly ash in structural concrete and its efficiency in enhancing the concrete durability performance as well as strength characteristics through improvement of the concrete microstructure.

1.2 Permeability characteristics

Permeability is defined as the coefficient representing "the rate at which water is transmitted through a saturated specimen of concrete under an externally maintained hydraulic gradient" (HWR, 2011). Permeability is the most important aspect of concrete durability. To be durable, concrete must be relatively impervious (Berry, 1986). In general, lower permeability means greater durability (Joshi, 1997). The reduced permeability of fly ash concrete can decrease the rate of ingress of water, corrosive chemicals, and oxygen (ACI Committee 232, 2003). This leads to enhanced durability because aggressive agents cannot attack the concrete nor the reinforcing steel embedded in it (Bremner, 2004).

The single parameter that has the largest influence on permeability/durability is w/c ratio. As the w/c ratio is decreased, the porosity of the paste is decreased and the concrete become more impermeable. Clearly, the permeability of concrete plays an important role in durability because it controls the rate of entry of moisture that may contain aggressive chemicals and the movement of water during heating or freezing. This leads to enhanced durability because aggressive agents cannot attack the concrete nor the reinforcing steel embedded in it.

1.3 Rapid chloride permeability characteristics

Chloride attack on concrete differs from the other modes of environmental attack. It is the chloride-induced corrosion of steel reinforcement that causes damage to the concrete. The presence of chloride ions in the pore solution of concrete by itself does not lead to damage. The extent of chloride attack on reinforced concrete is therefore dependent on the rate of chloride penetration and the corrosion rate of steel reinforcement. Comparing cementitious materials in terms of resistance to chloride attack involves evaluating these two factors. Although both factors affect service life, resistance to chloride ion penetration is often considered the most significant property for reinforced concrete structures in a marine environment. Fly ash concretes have been known to have higher resistance to chloride ion penetration than Portland cement concretes. This beneficial characteristic of concrete containing fly ash is influenced by the source of the fly ash, its rate of addition and the Portland cement type. The pore refinement effect of fly ash in concrete is the main contributor to this characteristic. The better chloride binding capacity of fly ash blended cement may also contribute. In a corroding situation, while everything else is similar, the corrosion rate of steel will be less in concrete having high resistivity and resistance to ionic movement. Concretes containing fly ash are known to have higher resisitivity and higher resistance to ionic movement than equivalent Portland cement concrete. In conjunction with higher resistance to chloride ion penetration, the corrosion rate of steel at a given level of chloride contamination is likely to be less in fly ash concrete in comparison with Portland cement concrete. The service life to fly ash concrete is likely to be longer than that of equivalent Portland cement concrete in aggressive environment.

The rapid chloride permeability test (RCPT) designated as ASTM C-1202 is an electrical test in which the test result is a direct function of the resistance of the test specimen. In principle, the use of electrical properties to measure the ionic transport properties of concrete is affected by two aspects of the concrete: the connectivity of the capillary pore system and the electrolytic capacity (ionic concentration) of the pore solution. The capillary pore system is of primary interest with respect to assessing the durability of concrete. Capillary absorption, hydrostatic pressure, and diffusion are the means by which chloride ions can penetrate concrete. The most familiar method is diffusion, the movement of chloride ions under a concentration gradient. For this to occur, the concrete must have a continuous liquid phase and there must be a chloride ion concentration gradient. A second mechanism for chloride ingress is permeation, driven by pressure gradients. If there is an applied hydraulic head on one face of the concrete and chlorides are present, they may permeate into the concrete. As a concrete surface is exposed to the environment, it will undergo wetting and drying cycles. When water (possibly containing chlorides) encounters a dry surface, it will be drawn into the pore structure though capillary suction. A more common transport method is absorption and is driven by moisture gradients. Typically, the depth of drying is small, however, and this transport mechanism will not, by itself, bring chlorides to the level of the reinforcing steel unless the concrete is of extremely poor quality and the reinforcing steel is shallow. It does serve to quickly bring chlorides to some depth in the concrete and reduce the distance that they must diffuse to reach the rebar (Thomas, 1996). RCPT has been used to evaluate the chloride permeability of hardened cement mortars and concretes made with special cements or supplementary cementing materials (Alhozaimy, 1996). In one study (Thomas, 1996), a replacement of 10% cement with class F fly ash can even significantly reduce the chloride permeability of cement mortars at 7 days. The RCPT data can be used only for preliminary assessment of chloride permeability. The transport of chloride ions into concrete is a complicated and multi-mechanistic phenomenon and at the present time, this is the only test method that is widely accepted by the concrete industry. Important traditional means to improve concrete durability are through reduction of water to cement ratio and/or increase of the moist curing period. Recently, many new materials and techniques have been developed to control corrosion by reduction of penetrable aggressive species. Partial replacement of Portland cement with supplementary cementitious materials has been used widely in aggressive environmental applications. It is generally recognized that the introduction of pozzolan in blended cements improves concrete protection against chloride-induced corrosion of steel reinforcement by reducing its permeability/diffusivity, particularly to chloride ion transportation and increasing the resistivity of the concrete (Thomas, 1999). The Mineral admixtures having high fineness react with the product liberated at early ages during hydration and form secondary C-S-H gel (also referred as tobermorite gel) which is less denser and has more volume than primary C-S-H gel. Therefore, it fills all the pores inside concrete and makes the concrete more impermeable thereby reducing the risk of chloride and sulfate induced deterioration.

Previous studies (Hossain, 2004) have shown that use of cement replacement materials such as fly ash, silica fume, blast-furnace slag, etc. may reduce greatly the probability of steel corrosion as well as the permeability of concrete. The monitoring of concrete resistance to chloride penetration is also possible on the basis of electrical resistivity measurements. The electrical resistivity of concrete structure exposed to chloride indicates the risk of early corrosion damage, because a low resistivity is related to rapid chloride penetration and to high corrosion rate (Ampadu, 2002). The current is carried by ions dissolved in the pore liquid. Increased pore saturation (wet concrete) as well as increased number of larger diameter pores (higher water-to-cement ratio) decrease resistivity (Polder, 2001).

For constant moisture content, the resistivity is increased by longer curing (hydration), lower w/c ratio and by addition of reactive materials such as alternative cementing materials: fly ash, blast furnace slag, metakaoline and silica fume (Antiohos, 2005). The use of supplementary cementing materials such as ground blast furnace slag, silica fume, metakaoline, coal fly ash and natural pozzolan can have a very significant effect on the pore solution chemistry of concrete, depending on the dosage and composition of these materials. Supplementary cementing materials with low alkali content will incorporate more alkalis into hydration products than they release to the pore solution, which results in a lower alkali concentration or lower pH value in the pore solution. This is the basis for the use of those supplementary cementing materials to decrease the alkalinity of pore solution in concrete materials down to a safe level to suppress alkali-aggregate expansion of concrete.

1.4 Source of Fly ash in Bangladesh

In 2006, two units of 125 MW coal based power plant has started generation in Barapukuria, Bangladesh. Currently one million ton of coal is being produced per annum from this mine of which 65% is being supplied to the 250 MW thermal power plants and other 35% is being used in brick field and other domestic industries. At present, on an average 65 thousand tons of fly ash is being produced from those thermal power plants. Another coal based power plant of 1350 MW capacity is proposed to be installed very soon in Rampal, Bangladesh.

Use of these fly ash as partial replacement of cement may also ensures the proper utilization of fly ash, in an effective way which otherwise been dumped making environmental hazard. Very limited studies are reported to carry out to investigate the strength and permeability/transport properties of Boropukuria fly ash concrete as obtained by partial replacement of cement. This experimental investigation was carried out with a view to study the effects of inclusion of different quantities of Boropukuria fly ash with cement on concrete permeability as well as strength. The outcome of study would definitely lead to the effectively utilization of these waste materials in concreting work, especially in aggressive environment.

2. Experimental program

The experimental program was planed to study the effect of Boropukuria fly ash as partial replacement of cement on the strength and permeability characteristics of hardened concrete at different curing ages. The details of the program including different materials used and the various test conducted is summarized below:

2.1 Materials used

(a) Cement: ASTM Type-I Portland Cement was used as binding material. Chemical compositions of OPC are given in Table 1.
(b) Fly ash: Fly ash collected from Boropukuria Power Plant, Bangladesh was used as supplementary cementitious material. Chemical compositions of fly ash obtained by using X-ray fluorescence (XRF) study is shown in Table 1.
(c) Aggregate: 12.5 mm downgraded crushed stone, with fineness modulus 6.58 and specific gravity 2.7, was used as coarse aggregate. Locally available natural sand passing through 4.75 mm and retained on 0.075 mm sieve with fineness modulus 2.58 and specific gravity 2.61 was used as fine aggregate.

Table 1
Chemical composition (%) of ordinary Portland cement and fly ash

Constituents	Composition	OPC	FA
Calcium Oxide	CaO	65.18	0.65
Silicon Di-Oxide	SiO_2	20.80	51.49
Aluminum Oxide	Al_2O_3	5.22	31.60
Ferric Oxide	Fe_2O_3	3.15	2.80
Magnesium Oxide	MgO	1.16	0.28
Sulfur Tri-Oxide	SO_3	2.19	0.19
Sodium Oxide	Na_2O	--	0.18
Loss on Ignition	--	1.70	4.2
Insoluble Residue	--	0.6	--

2.2 Mix design and sample preparation

Three different grades of concrete namely M38, M33 and M28 were used in the program. Seven different replacement level of cement by fly ash i.e. cement fly ash mix ratio (90:10, 80:20, 70:30, 60:40, 50:50, 40:60, 30:70) were used as binding material. Plain concrete specimens i.e. Cement fly ash mix ratio of 100:0 were also cast as reference concrete. Fly ash concrete means the concrete made by using cement and fly ash as cementitious material with sand, stone chips and water. Relevant information of different concrete mixes is given in Table 2.

A total of 200 no's of cylindrical specimen of size 150 mm diameter and 175 mm high and 500 no's of cubical specimens of 100 mm size from eight different types of fly ash concretes were cast from different mix proportion as per need for water permeability and strength test. Another 200 no's of cylindrical specimen of size 100 mm diameter and 50 mm height were also prepared for Rapid chloride permeability test. The specimens were demoulded after 24 hours of casting and cured in plain water at 27±2°C. The concrete test specimens were designated keeping concrete grade and replacement level as variable. Thus M33FA70 concrete means grade of concrete is M33 and cement fly ash mix ratio is 30:70.

Table 2
Mix proportions and properties of fresh concrete

Mixture constituent & properties	Grade of Concrete		
	M38	M33	M28
Cement (kg/m^3)	500	480	435
Water (kg/m^3)	218	224	218
Sand (kg/m^3)	520	530	545
Stone Chips (kg/m^3)	1120	1130	1150
water/cement Ratio	0.44	0.47	0.50
Slump (mm)	60	63	68
Air content %	1.1	1.2	1.3

2.3 Test conducted

2.3.1 Strength test

Compressive strength of the relevant concrete specimens was tested at the ages of 3, 7, 28, 56, 90 and 180 days in accordance with the BS EN 12390-3:2009. Reported compressive strength is taken as the average of three tests results.

2.3.2 Rapid chloride penetration tests

Cylindrical sample of 100 mm diameter and 200 mm height were prepared in accordance with ASTM C39. After specific curing period they were cut into 50 mm thick slices. The cut cylinders were left to dry in laboratory condition for 24 hrs before application of epoxy coatings. All specimens were epoxy coated around the cylindrical surface. At the ages of 28, 56, 90 and 180 days, the prepared cut cylinders were tested according to the procedures described in the ASTM C1202. The average result of three test specimens was taken as the representative data.

2.3.3 Water permeability test

Water permeability test were carried out for different types of concrete specimens at the ages of 28, 56, 90 and 180 days. These specimens were dried in the oven at 105°C. Then specimens were coated with epoxy coating around the circular side to prevent water leakage from the side during the test. After placing the specimen in the apparatus, a water pressure of (500 ±50) kPa was applied for (72 ± 2) hours. After the specimen gets saturated, the flow rate reading was taken from burette by measuring the change of volume of water with time. During the test, the appearance of the surfaces of the test specimen not exposed to the water pressure was observed periodically to note the presence of water. Coefficient of permeability is calculated by using the following equation, $k = (QL/AH)$
where, k = permeability coefficients (m/s), Q = flow rate (m^3/s), A = area (m^2), L = depth of specimen (m), H = head of water (m). Depth of water penetrated in the test specimen was calculated in accordance with the EN 12390-8.

3. Results and discussions

The test specimens after definite exposure period were subjected to various test and results were analyzed to predict the different aspects of the fly ash concrete.

3.1 Compressive strength

The compressive strength of OPC and fly ash concrete of three different grades M38, M33 and M28 has been graphically presented in Fig.1, Fig.2 and Fig.3. Also for the ease of comparison, the relative compressive strengths are plotted in Fig.4, Fig.5 and Fig.6. At early ages of curing, OPC concretes achieve relatively higher compressive strength as compared to fly ash concrete. Test result shows that 7 days compressive strength for M38 grade OPC concrete is around 9%, 16%, 26%, 34%, 43% and 59% higher than M38FA10, M38FA20, M38FA30, M38FA40, M38FA50 and M38FA60 concrete respectively. At initial age of curing, upto 56 days compressive strength is seen to decrease with the increase of fly ash content in concrete when compared with no fly ash concrete with a variation of 10%. 56 days compressive strength test result of the specimens up to 40% replacement level are very similar to OPC concrete. After that compressive strength of fly ash concrete starts to increase compared to OPC concrete. 90 days compressive strength test result of the specimens up to 40% replacement level are slightly higher than OPC concrete. Compressive strength is higher by 6%, 9%, 12% and 8% for M38FA10, M38FA20, M38FA30 and M38FA40 concrete respectively; whereas the same strength for M33FA10, M33FA20, M33FA30 and M33FA40 concrete is reported to be higher by 5%, 4%, 9% and 6% respectively when compared with no fly ash concrete. Cement normally gains its maximum strength within 28 days. During that period, lime produced from cement hydration remains within the hydration product. Generally, this lime reacts with fly ash and imparts more strength. For this reason, concrete made with fly ash will have slightly lower strength than cement concrete at early ages of curing and higher strength at the later ages of curing. Yamato and Sugita (1983) found that the later age strength of fly ash concrete was higher than that of the control concrete. 180 days compressive strength data shows almost similar trend. 180 days compressive strength for M33FA10, M33FA20, M33FA30, M33FA40 and M33FA50 concrete are respectively 7%, 8%, 12%, 10% and 2% higher than no fly ash concrete; whereas the same value for M33FA60 and M33FA70 concrete are lower by 28% and 44% than OPC concrete. Similar strength values for M38FA10, M38FA20, M38FA30, M38FA40 and M38FA50 concrete are respectively 8%, 11%, 16%, 13% and 2% higher and for M38FA60 and M38FA70 concrete are respectively 25% and 39% lower than OPC concrete.

Rate of strength gaining for different types of concrete is observed to vary with the grade of concrete and is higher for the higher grade of concrete. Among all the concrete studied, 90 days relative compressive strength is about 103%, 98%, 106% and 99% for concrete M28FA10, M28FA20, M28FA30 and M28FA40 respectively as compared to OPC concrete; whereas the same value is around 105%, 104%, 109% and 105% for concrete M33FA10, M33FA20, M33FA30 and M33FA40 respectively; 106%, 109%, 112% and 108% for concrete M38FA10, M38FA20, M38FA30 and M38FA40 respectively compared to the strength of no fly ash concrete. Also for longer period of curing relative strength was observed to be higher for the higher grade concrete. In case of 180 days of curing, relative compressive strength compared to 28 days of curing of similar concrete was observed that 131%, 132%, 137%, 132% and 125% for M28FA10, M28FA20, M28FA30, M28FA40 and M28FA50 concrete, 124%, 125%, 130%, 128% and 119% for M33FA10, M33FA20, M33FA30, M33FA40 and M33FA50 concrete and 125%, 128%, 134%, 130% and 118% for M38FA10, M38FA20, M38FA30, M38FA40 and M38FA50 concrete. At the end of 180 days curing period, the overall strength gaining for M38 grade concrete is around 3% and 4% higher as compared to M33 and M28 grade concrete respectively. Thus it is seen that strength gaining is relatively faster for higher grade concrete as compared to lower grade concrete.

3.2 Water permeability

Permeability characteristics of M38, M33 and M28 grade concrete for various curing period are graphically presented in Fig.7, Fig.8 and Fig.9. At the initial age of curing, OPC concrete shows relatively better resistance against water permeability. But at later age of curing, reverse trend was observed. Coefficient of permeability value for M28FA10, M28FA20, M28FA30, M28FA40, M28FA50, M28FA60 and M28FA70 concrete are respectively 5%, 12%, 17%, 27%, 35%, 49% and 59% higher as compared to M33FA0 concrete for 28 days curing period; where as the same value is 6%, 13%, 16%, 26%, 34%, 50% and 55% higher respectively for M38FA10, M38FA20, M38FA30, M38FA40, M38FA50, M38FA60 and M38FA70 concrete compared to M38FA0 concrete. But these value for fly ash concrete of cement replacement level 10%, 20%, 30%, 40% and 50% at 90 days curing period are observed respectively 5%, 8%, 11%, 12% and 9% lower for M28 grade concrete and 10%, 12%, 13%, 16% and 14% lower for M38 grade concrete.

Fly ash has high fineness and can react with the products liberated during hydration. It forms secondary C-S-H gel that fills all the pores inside concrete specimen that makes the concrete dense, compact and as a result coefficient of permeability decreases with the increase of fly ash content upto certain level. Test result shows that fly ash concrete has higher resistance against water permeability as compared to OPC concrete. Overall observation shows that for 90 days curing period, coefficient of permeability value decreases around 16% for OPC concrete; whereas the same value decreases around 22%, 24%, 26%, 28% and 25% for 10%, 20%, 30%, 40%, and 50% cement replaced fly ash concrete respectively as compared to 28 days OPC concrete.

In case of 180 days of curing, relative coefficient of permeability is about 92%, 90%, 87%, 85% and 86% for M28FA10, M28FA20, M28FA30, M28FA40 and M28FA50 concrete respectively as compared to OPC concrete; whereas the same parameter is around 89%, 88%, 84%, 82% and 85% for M33FA10, M33FA20, M33FA30, M33FA40 and M33FA50 concrete respectively, 85%, 84%, 82%, 80% and 81% for M38FA10, M38FA20, M38FA30, M38FA40 and M38FA50 concrete respectively as compared to no fly ash concrete. Thus at the end of 180 days curing period, the overall value of coefficient of permeability for M38 grade concrete is around 5% and 7% lower as compared to M33 and M28 grade concrete respectively.

The progressive decrease in permeability may be connected to the micro voids dispersed in the mortar matrix of the concrete. As the hydration of cement progresses, crystallization of compounds take place as a result of which the concrete micro voids keep on getting subdivided into capillary micro pores of increasingly smaller sizes. Many of the micro pores lose their connectivity with the passage of time. The reduction in pore sizes coupled with the loss of pore connectivity result in a substantial progressive decrease in the permeability. Among all the fly ash concretes studied upto 180 days curing period, 30%, 40% and 50% cement replaced fly ash concrete shows better result from permeability point of view.

3.3 Rapid chloride penetration

Rapid chloride penetration value for OPC and fly ash concrete are graphically presented in Fig.10, Fig.11 and Fig.12. At the initial age of curing RCPT values are higher for fly ash concrete compared to OPC concrete. In case of OPC concrete, amount of passing charge is observed as 4240, 5330 and 6295 coulombs for M38, M33 and M28 grade concrete; whereas the same value for fly ash concretes of cement replacement level of 20%, 30%, 40% and 50% are 4512, 4621, 4766 and 5280 coulombs for M38 grade concrete, 5995, 6022, 6232 and 6520 coulombs for M33 grade concrete and 7295, 7465, 7870 and 8013 coulombs for M28 grade concrete at the curing age of 28 days. But for longer age of curing, fly ash concrete show better resistance against chloride ion penetration.

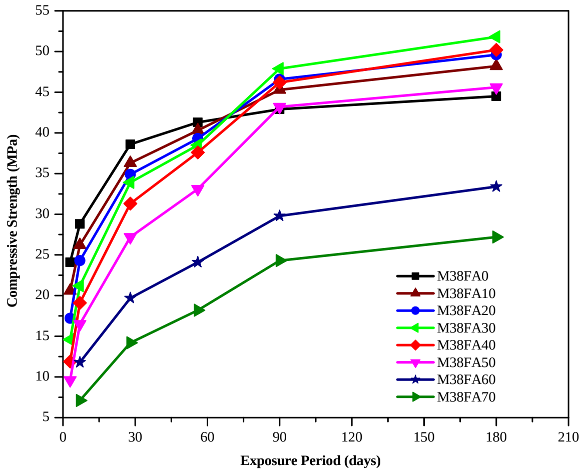

Fig.1 : Compressive Strength - Exposure Time Relation for M38 Fly Ash Concretes

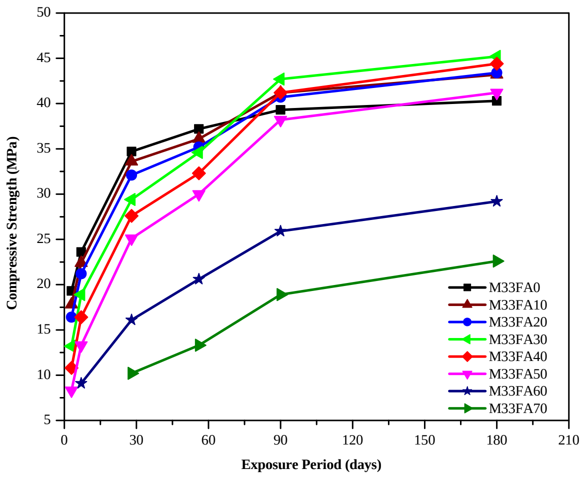

Fig.2 : Compressive Strength - Exposure Time Relation for M33 Fly Ash Concretes

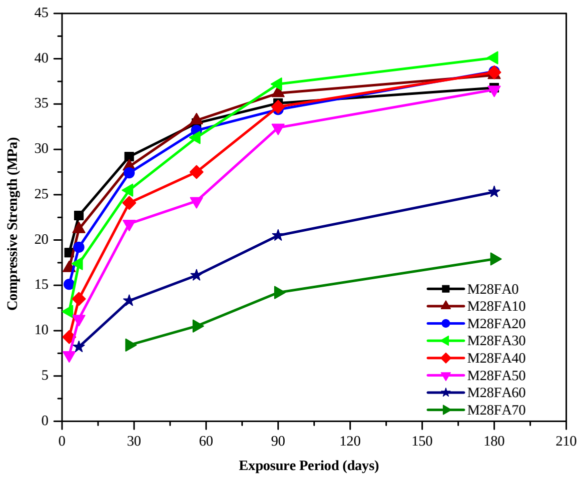

Fig.3 : Compressive Strength - Exposure Time Relation for M28 Fly Ash Concretes

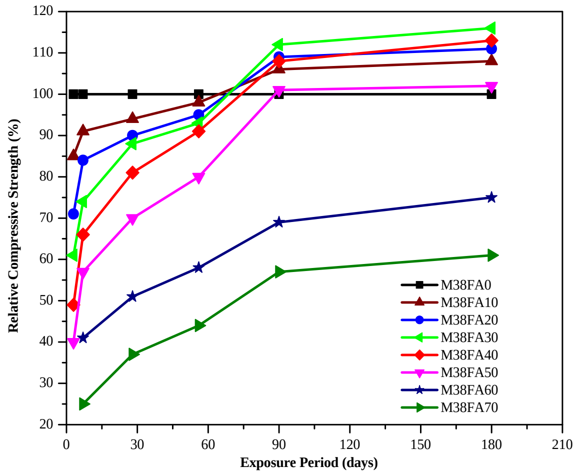

Fig.4 : Relative Compressive Strength - Exposure Time Relation for M38 Fly Ash Concretes

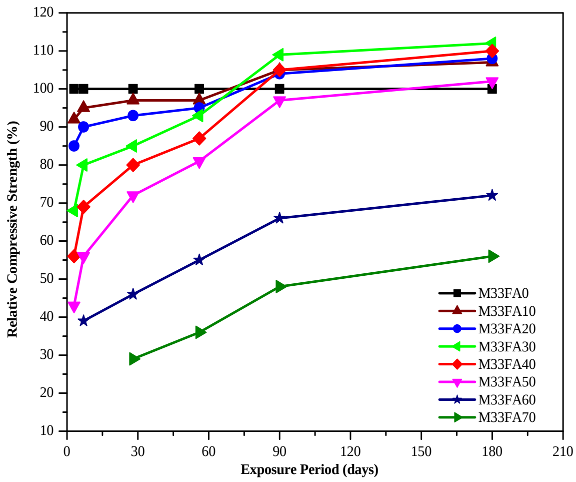

Fig.5 : Relative Compressive Strength - Exposure Time Relation for M33 Fly Ash Concretes

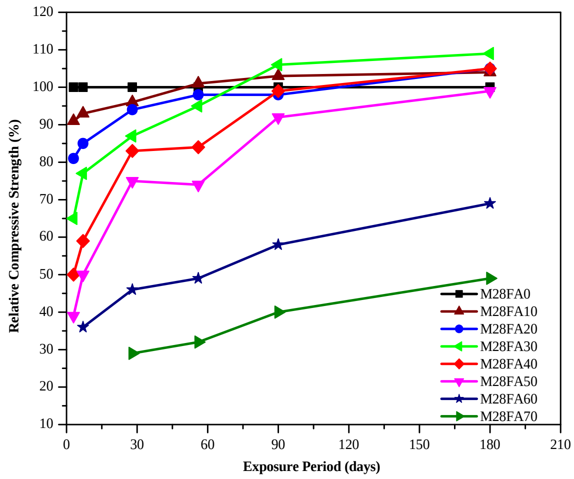

Fig.6 : Relative Compressive Strength - Exposure Time Relation for M28 Fly Ash Concretes

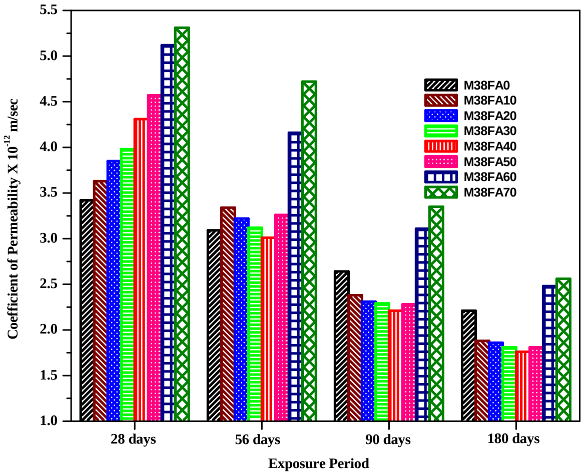

Fig.7 : Permeability - Exposure Time Relation for M38 Fly Ash Concretes

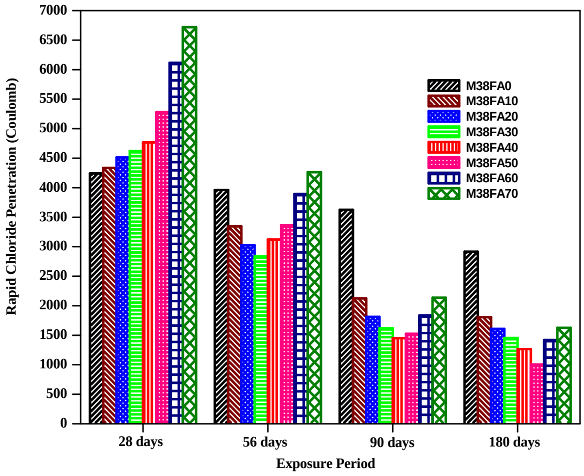

Fig.10 : Rapid Chloride Penetration - Exposure Time Relation for M38 Fly Ash Concretes

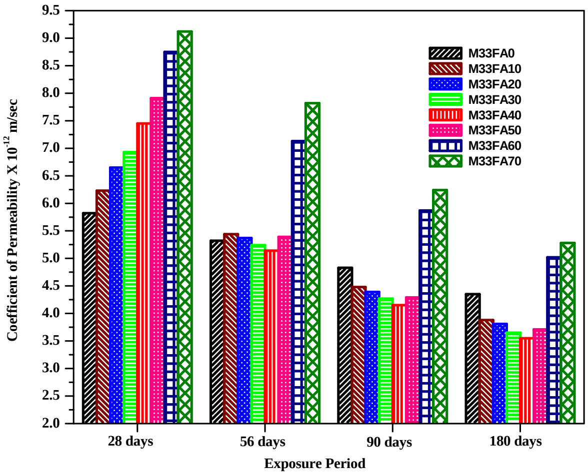

Fig.8 : Permeability - Exposure Time Relation for M33 Fly Ash Concretes

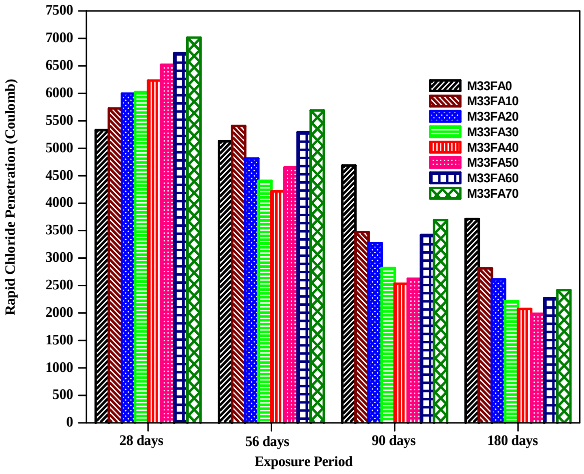

Fig.11 : Rapid Chloride Penetration - Exposure Time Relation for M33 Fly Ash Concretes

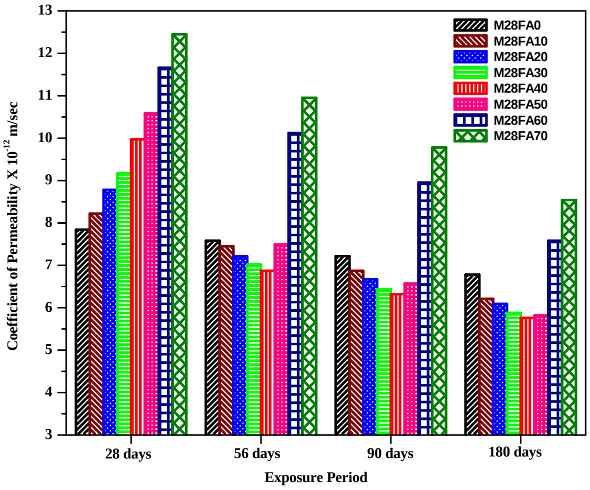

Fig.9 : Permeability - Exposure Time Relation for M28 Fly Ash Concretes

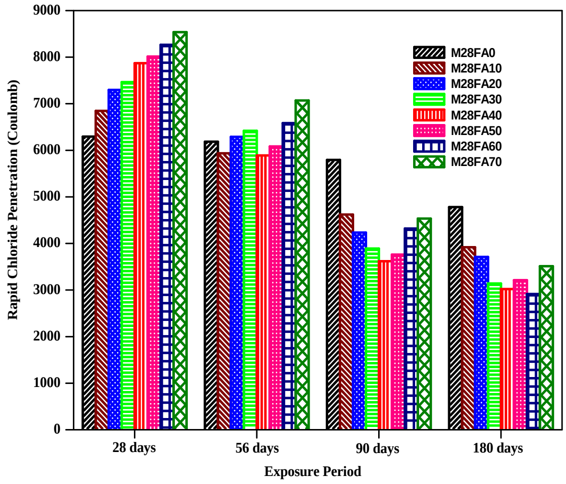

Fig.12 : Rapid Chloride Penetration - Exposure Time Relation for M28 Fly Ash Concretes

After 90 days of curing, rapid chloride penetration values are respectively 50%, 48%, 38%, 34%, 36% for M38FA10, M38FA20, M38FA30, M38FA40, M38FA50 concretes; 65%, 61%, 53%, 48%, 49% for M33FA10, M33FA20, M33FA30, M33FA40, M33FA50 concretes and 73%, 67%, 62%, 58%, 60% for M28FA10, M28FA20, M28FA30, M28FA40 and M28FA50 concretes respectively as compared to the 28 days RCPT values of OPC concrete of similar grade. Thus it is seen that the incorporation of pozzolanic materials has improved the resistance to chloride penetration of concrete and similar result is also confirmed by other researchers (Janotka, 2000).

Relative RCPT values of fly ash concrete compared to OPC concrete is observed to vary with the grade of concrete and replacement level of cement with fly ash. At an age of 180 days of curing, rapid chloride penetration values are 62%, 55%, 50%, 43%, 34% for M38FA10, M38FA20, M38FA30, M38FA40, M38FA50 concretes respectively; 76%,70%, 60%, 56%, 53% for M33FA10, M33FA20, M33FA30, M33FA40, M33FA50 concretes respectively and 82%, 78%, 66%, 63%, 67% for M28FA10, M28FA20, M28FA30, M28FA40, M28FA50 concretes respectively as compared to OPC concrete of similar grade. This is due to high fineness of fly ash which can react with the products liberated during hydration, forming secondary C-S-H gel that fills all the pores inside concrete and makes it more impermeable. So it reduces the amount of charge passed thorough the concrete. It was also observed that at the end of 180 days curing period, the overall RCPT values for M38 grade concrete is around 9% and 17% lower as compared to M33 and M28 grade concrete respectively.

3.4 Correlation equation

The experimental data were utilized to develop a correlation equation between compressive strength and coefficient of permeability. The correlation equation can be expressed by the following single formula:

$$Y = AX+B$$

Where, Y = Coefficient of Permeability
X = Compressive Strength
A and B are the constants.

The constants A and B, were obtained through the regression analysis of the data and the relationship has been in presented in Fig.13, Fig.14 and Fig.15. The best-fit curves and the values of constants A and B and the regression coefficient, R^2, are given in Figures.

Fig.13., Fig.14. and Fig.15. shows the plot of compressive strength against coefficient of permeability for the OPC and fly ash concretes over the period of 180 days, the relationship between compressive strength, X in (MPa) and coefficient of permeability Y in (m/s) is expressed in the form: Y = -0.206X + 11.435 with R^2 = 0.959 for M38 grade OPC concrete, Y = -0.088X + 6.339 with R^2 = 0.769 for M38 grade FA concrete, Y = -0.251X + 14.60 with R^2 = 0.971 for M33 grade OPC concrete, Y = -0.142X + 10.17, with R^2 = 0.794 for M33 grade FA concrete, Y = -0.134X + 11.85 with R^2 = 0.916 for M28 grade OPC concrete, Y = -0.190X + 13.27 with R^2 = 0.857 for M28 grade FA concrete. The coefficient of correlation is founding 0.825 which indicate a strong linear relationship between the two parameters and hence the coefficient of permeability can be predicted from the compressive strength for OPC and fly ash blended concrete.

A regression coefficient (R^2) having more than 0.85 indicates an excellent correlation between the fitted parameters (Montgomery, 1982). Therefore, the correlation expression for all grade of plain concrete M38, M33 and M28 indicate a good relationship between the compressive strength and permeability coefficient. However, in the case of fly ash concretes, the degree of curve fitting between the compressive strength and coefficient of permeability was on the lower side i.e. R^2 values for M38, M33 and M28 grade concretes are 0.769, 0.794 and 0.857 respectively. Among all the fly ash concrete, M28 grade concrete shows excellent correlation.

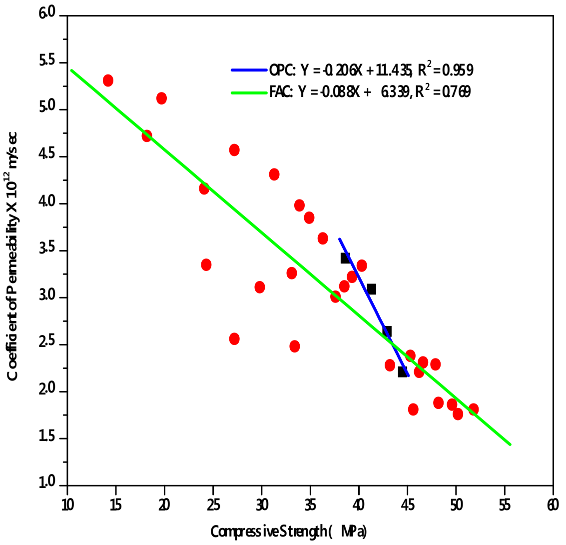

Fig 13: Permeability - Compressive Strength Relation for OPC and FA Concretes of Grade M38

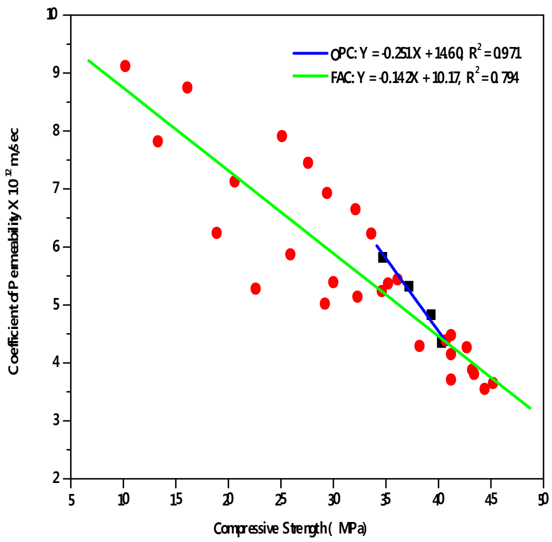

Fig.14: Permeability - Compressive Strength Relation for OPC and FA Concretes of Grade M33

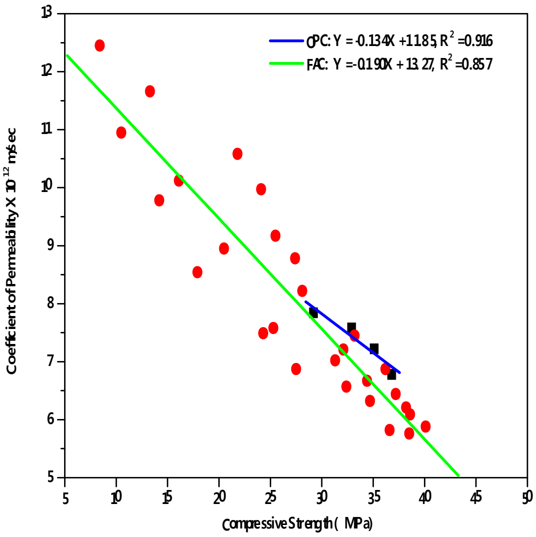

Fig.15: Permeability - Compressive Strength Relation for OPC and FA Concretes of Grade M28

It may be noted that the correlation equations relating compressive strength and coefficient of permeability for OPC and fly ash concretes, developed in the present work, would help the concrete mix designer to adjust the compressive strength and the permeability property simultaneously so as to get durable concrete. Predictions of the permeability properties of concrete in an existing structure may also be possible by only measuring the compressive strength using core specimens. However, it should be noted that the relationships reported in this paper were developed for concretes containing fly ash that were cured upto 180 days and hence such similar relationships may need to be developed for other curing conditions and curing ages for practical application.

4. Conclusions

Bangladesh has a vast resource of fly ash generated at Boropukuria and in near future the same will be extended. The proper use of this material can solve the major problems of fly ash disposal and reduce the use of cement, the production of which consumes lot of energy and natural resources. This experimental exercise has helped to study the various properties of fly ash concrete made with different percentage of fly ash as partial replacement of cement. Based on the result of the investigation, following conclusions can be drawn:

(1) At early ages of curing fly ash mix concrete achieve relatively lower strength compared to reference concrete without fly ash. However, after 56 days of curing, the fly ash mix concrete exhibited a higher rate of strength gaining than the reference mix.

(2) The study reveals that, 30% mixing of fly ash exhibited the best results with respect to compressive strength. Fly ash concrete with 30% cement replacement shows around 13% higher compressive strength than OPC concrete after 180 days curing. All the fly ash mix concrete up to 50% cement replacement indicated adequate strength for structural applications.

(3) Resistance to water permeability of concrete is significantly increased with the incorporation of fly ash. Permeability values are seen to reduce for fly ash concrete upto 50% cement replacement level after 90 days of curing. Fly ash concrete with 30% cement replacement showed around 16% lower coefficient of permeability as compared to OPC concrete.

(4) Chloride penetration resistance for fly ash concrete is observed to be improved as compared to OPC concrete. After 180 days, 30%, 40% and 50% fly ash mix concrete attained excellent resistance to chloride penetration, while the remaining mix exhibited good resistance to chloride penetration.

(5) Higher grade concrete showed higher rate of strength gaining, decrease in both coefficient of permeability value and rapid chloride penetration as compared to lower grade concrete.

(6) A good correlation between permeability and compressive strength was found for the different types of concrete studied which may be helpful for mix design of durable concrete.

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