Journal of Ceramics and Concrete Technology
Volume 6 Issue 1
ISSN: 2457-0826 (Online)

# Chloride and Sulfate Resistance of Brick Aggregate Concrete Containing Fly Ash

**Abdur R. Kaoser[1*], Khan M. Amanat[2], Munaz A. Noor[3]**
*Ph.D. Student[1], Professor[2, 3]*
*Department of Civil Engineering*
*Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh*
**Corresponding Authors' Email id:** *kaoser_rhd@yahoo.com[1*], kmamanat@gmail.com[2]*

**Abstract**

*This paper presents the influence of fly ash on durability properties of brick aggregate concrete. Two types of durability tests were evaluated. One is chloride ion penetration and another is sulfate resistance property of fly ash concrete. A lot of tests were done about chloride ion permeability and sulfate resistance properties of fly ash concrete all over the world. In those experiments, stone chips were generally used as coarse aggregate. In this experiment, locally available materials such as burnt clay brick chips as coarse aggregate, sand and fly ash available in Bangladesh (Indian fly ash) were used. Chloride ion penetration test was done as per British standard whereas a non-standard test method was adopted for checking sulfate resistance of fly ash concrete. For both chloride ion permeability and sulfate ion resistance test of fly ash concrete, three different types of concrete specimens based on percentages of fly ash replacement (0%, 15% and 30%) were prepared. Test samples were submerged in three different chloride-ion concentrated solutions such as 0.10 mol/L, 0.35 mol/L and 0.70 mol/L for chloride ion penetration test and three different sulfate-ion concentrated solutions such as 0.01 mol/L, 0.10 mol/L and 0.50 mol/L for sulfate degradation test of fly ash concrete. All tests were performed at three different ages such as 14, 28 and 90 days. It was observed from the experiment that concrete with fly ash exhibited better resistance to chloride ion penetration and sulfate degradation of concrete. Thus fly ash increases the durability of concrete. Fly Ash is low cost material and use of fly ash in concrete reduces* *the amount of cement required. Thus fuel cost, needed for production of cement and emission of harmful gas like CO2 into air, during manufacturing of cement also reduce. Thus using fly ash in concrete is economical and also environmental friendly.*

***Keywords**: - Compressive strength, durability, fly ash, w/c ratio, hydration, chloride concentration, sulfate ion concentration*

***Notations**: - A = Cross sectional area of concrete sample, CA = Coarse aggregate,* $C_3A$ *= Tricalcium aluminate,* $C_4AF$ *= Tetra calciumalumino ferrite,* $C_2S$ *= Dicalcium silicate,* $C_3S$ *=Tricalcium silicate,* $C_U$ *= Co-efficient of uniformity,* $C_z$ *= Curvature co-efficient,* $D_{10}$ *= Particle size corresponding to 10 percent finer,* $D_{30}$ *= Particle size corresponding to 30 percent finer,* $D_{60}$ *= Particle size corresponding to 60 percent finer, FA = Fine aggregate, FM = Fineness modulus,* $f_{c'}$ *= Compressive strength of concrete, P = Load applied to the sample, w/c = Water/cement ratio,* $\gamma$ *= Unit weight of concrete, hcp = hydrated hardened cement paste.*

## INTRODUCTION

In modern world, almost all structures are made of concrete which is a mixture of sand, cement, water and coarse aggregate. But manufacturing of cement is expensive and sometimes troublesome as raw materials needed for cement are not enough compare to its demand. On the other hand, some industrial by-products like fly ash, silica fume, slag etc. has some cementitious properties. These materials can be used in concrete as a partial replacement of cement and reduce the cost of production to a great extent. These materials also cause huge environmental problems if left exposed and unattended. Therefore, their utilization in concrete mix is not only cost effective, but also eco-friendly in nature. Thus, a lot of experiments all over the world were done to evaluate the properties of fly ash in order to use it as a component of concrete.

Fly ash, very fine in nature, coming from combustion of ground or powdered coal and transported from firebox through gas-pipe is known as pulverized fuel ash in UK (ACI 116R). Fly ash is primarily of volcanic or sedimentary origin. Fly ash has pozzolanic property. A pozzolona is a siliceous and aluminous material. Generally a pozzolanic material has little or no cementitious value. But in finely divided form and in presence water, it may gain cementitious property by chemically reacts with calcium hydroxide at ordinary temperature. Recently, in many countries of the world, pozzolon like fly ash is being used as an ingredient of the Portland cement concrete.

Historically, fly ash is used as a partial replacement of cement in many parts of the world. About 2000 years ago the Romans mixed volcanic ash, called “Pulvis Puteolanus” (later changed to “Pozzolana”) with lime to produce cement and mortar (Vitruvius 1960, in interpretation).

In 1984, America used fly ash firstly at large scale during construction of Hungry Horse dam. Cement was replaced by fly ash approximately 30 percent by weight. Fly ash was then used in Canyon and ferry dams. In India, during construction of Rihand dam, 15 percent fly ash was used by weight of cement. Physical as well as chemical properties of fly ash are to be considered for use as a partial replacement of cement in concrete (Chatterjee 1999).

It is well known that the properties of concrete are closely related to its microstructure and products of hydration (Jiang 1998, Ramachandran *et al.* 1981, Ben-Bassat *et al.* 1990). The microstructure and products of hydration of concrete depend on its reaction and progress of hydration. It is important to know about the characteristics of hydration in fly ash concrete binder. The water cement ratio is an important control parameter in concrete mix proportioning. The properties controlled by w/c ratio in conventional concrete, are workability and durability. Concrete durability is normally specified in terms of bulk properties relating to strength, which can readily be applied in practice (ACI 318, 1989). It was proposed (Dhir *et al.* 1987) that the permeation properties (Absorption, diffusion and permeability) of concrete relate more specifically to durability than strength.

A lot of experiments about the tensile and compressive strength of fly ash concrete were done all over the world in the last few decades. Recently durability properties of fly ash concrete also were tested throughout the world. As the application of high performance concrete in high-rise buildings, bridges and other structure increases, the demand of durability of high performance concrete has also been important. In case of durability of concrete, chloride diffusion is largely concerned. A reinforced concrete structure is to be corroded significantly by chloride ion, resulting very high repairing cost (Berke *et al.* 1988).

Another analysis on the strength and durability properties of fly ash concrete was conducted by Thomas and Matthews (1993). The study reports the results of an analysis of existing concrete structures designed using fly ash concrete. The systems include two reinforced concrete road bridges, a water-retaining framework of reinforced concrete, three large concrete dams, a sea protection wall, and base blocks of reinforced concrete. The structures ranged in age from 2 to 33 years. Comparable ordinary Portland cement (OPC) concrete was eligible for sampling at all the locations selected, in addition to fly ash concrete. On concrete cores taken from these structures, measurements of a variety of properties were made. In contrast with similar OPC concretes, the fly ash concretes usually displayed enhanced properties. These enhancements include increased strength, decreased permeability, increased resistance to chloride ingress and alkali silica reaction suppression. Two years old concrete containing fly ash was carbonated from the same structure to a greater degree than OPC concrete, but variations in older structures were slightly less marked.

Saricimen *et al.* (1995) performed permeability and durability tests of plain and blended cement concretes that were cured in field and laboratory conditions. The effects of field and laboratory curing on the permeability and durability characteristics of plain and pozzolanic cement concrete have been studied in their investigation. For 7 days, the field specimens were subjected to moist-curing, while the laboratory specimens were subjected to water-curing before processing. As indicators for cement concrete permeability, water penetration and absorption tests were used. By performing an accelerated chloride permeability test, the durability output of the field and laboratory-cured specimens was determined. Cement type (i.e., plain and fly ash mixed cements), specimen size, and curing conditions were included in the research variables. Results showed that longer moist-curing in both plain and mixed cements is helpful in producing dense and permeable concrete. In thick sections, water permeability was lower than in thin specimens. After around 1 week of curing, fly ash cement concrete exhibited lower permeability than plain cement concrete, regardless of the curing method followed. These results indicate that the use of properly characterized pozzolans in cement concrete can give rise to technical and economic benefits, even in situations where, due to high evaporation rates, cement concrete cannot be adequately cured.

Cement replacement by fly ash has been found to increase porosity but decrease the average pore size of the pastes at the ages of 28 and 56 days. The further cement substitution by up to 5% silica fume didn't drastically adjust the appropriation of pore size and porosity of either the plain cement paste or the fly ash cement paste. However, inclusion of fly ash and silica fume in the mortars made a great effect on interfacial porosity. Interfacial porosity was reduced significantly by adding fly ash and silica fume. The interfacial porosity better describes the effects of a chloride diffusion examination of the fly ash and silica fume concrete in most situations compared with the porosity and average pore size of the pastes and mortars. However, the decrease in ionic concentration of the pore solution appears to be more responsible for the low coulomb result passed in the test at 28 days for concrete with 55 percent fly ash replacement (Poon *et al.* 1999).

An experiment has done on evaluation of diffusion coefficient of chloride ion in concrete ion from mobility (Otsuki *et al.*1999). In that experiment the absolute mobility, basis theory related to ion diffusion has been calculated from electrochemical measurement.

Wee *et al.* (2000) have made an experiment on rapid chloride permeability of concrete. In their experiment the co-relation between the charged passed data derived from chloride permeability test and the chloride penetration test and mineral admixtures is elucidated.

Another research was performed by Bouzoubaa *et al.* (2002) on mechanical and durability properties of concrete containing high volume fly ash (HVFA). The test results obtained for HVFA concrete were compared with the control concrete made by using ASTM Type I cement. The 28-day compressive strength was compared between control concrete and the concrete made with the HVFA blended cement. It was found that a high-range water-reducing admixture and an air-entraining admixture (AEA) are required to obtain similar slump and air content for HVFA blended cement than that of control concrete. This resulted in a certain pause in the concrete initial and final setting periods. The compressive strength and flexural strength of HVFA blended cement were found lower than that of ASTM Type I cement at early age, before 28 days. But later, after 28 days HVFA blended cement gained higher strengths. The concrete provided a 1-day compressive strength of 13 MPa (compared to 19 MPa for the control concrete) to develop the HVFA blended cement, which was considered more than adequate for the removal of formwork. Durability characteristics of the concrete were greatly improved by using HVFA mixed cement; the only exception, as calculated in the ASTM C 672 test, was the deicing salt scaling resistance.

Jerath and Hanson conducted an analysis of the impact of fly ash content and aggregate gradation on concrete durability (2007). Eight concrete mixtures were cast. Among eight mixes, four mixtures were made of aggregates as per current specifications and four mixtures were made by dense graded aggregates. Different fly ash replacement levels of 30, 35, 40 and 45 percent for Portland cement were used for each of these two gradations. The 6 percent air content and 25-38 mm (1 to 1 1/2 in.) slump for the freshly mixed concrete is planned for all mixtures. The study found that the 30 to 45 percent rise in fly ash content improved the durability of concrete mixtures without the loss of compressive and bending capabilities. Concrete of dense graded and higher percentage of fly ash showed the lower water content requirement that reflected the beneficial effects of using it. The permeable pore space decreased in the specific gravity, absorption and voids in hardened concrete tests when the fly ash content in the concrete mixtures was increased from 30 to 45 percent. The electrical charge passing through the layers decreased in the rapid permeability test and the spacing factors were found lower in the microscopic determination of air-void tests suggested the great advantages of using fly ash. The advantage of using greater fly ash content in concrete has been demonstrated by these experimental findings. It also proved advantageous to use thick graded aggregates.

Sengul and Tasdemir (2009) conducted another experiment on the compressive strength and rapid chloride permeability of concrete containing fly ash and slag. Finely ground fly ash (Blaine specific surface: 604 $m^2$ /kg) and finely ground granulated blast furnace slag (Blaine specific surface: 600 $m^2$ /kg) were partly replaced by Portland cement. Two sets of concrete were developed with water/binder ratios of 0.60 and 0.38 and Portland cement was substituted by: (i) 50 percent fly ash, (ii) 50 percent blast furnace slag and (iii) 25 percent fly ash + 25 percent blast furnace slag for both water/binder ratios. Compressive strengths of the concretes with the pozzolan were weaker compared to those of the Portland cement concrete at the high water/binder ratio. However, these strength reductions were lower at the low water/binder ratio compared to the high water/binder ratio, and the compressive strength of the concrete made with 50 percent slag was also higher than the cement concrete from Portland. The test results showed that the penetration of chloride ion into concrete was reduced substantially by using ground fly ash and ground granulated blast furnace slag in concrete. It was concluded that pozzolan inclusion was more effective than reducing the water/cement ratio in order to decrease the chloride permeability of concrete.

By minimizing $CO_2$ emissions from cement manufacturing, the use of fly ash as a supplementary cement material added sustainability to concrete. Class F fly ash and control concrete specimens were determined for compressive strength, drying shrinkage, sorptivity and rapid chloride permeability. The samples of fly ash concrete indicated less drying shrinkage than the samples of plain concrete. Fly ash inclusion dramatically decreased sorptivity and chloride ion permeation at 28 days, and further decreased at 6 months. The incorporation of fly ash as partial cement substitute had typically increased the performance characteristics of concrete (Nath and Sarker 2011).

The effect of fly ash additives on the properties of concrete was studied by Marthong and Agrawal (2012). They noticed that the use of fly ash in concrete as a partial cement substitute gained tremendous significance, primarily due to the enhancement of concrete's long-term durability combined with ecological benefits. In the construction industry, three grades of ordinary Portland cement (OPC) are widely used: 33, 43 and 53 as graded by the Bureau of Indian Standard (BIS). A comparative research on the effects of concrete properties was recorded in the study, where OPCs of various grades were partially replaced by fly ash. The key variable investigated in this analysis was a 10 percent, 20 percent, 30 percent and 40 percent difference in the dosage of fly ash.

It primarily studied the compressive strength, durability and shrinkage of concrete. It was found from the experiment, that the using of fly ash up to a certain percentage improved concrete properties in all OPC grades.

Filho *et al.* (2013) did another experiment on chloride diffusion in fly ash concrete. They noticed in their experiment that fly ash affects the paste microstructure and can improve the durability of concrete. With 50 percent of the cement by weight, substituted with fly ash, calcium hydrated lime was applied to concrete with the goal of removing some of the calcium hydroxide absorbed by the pozzolanic activity. Three mix designs were prepared. One was concrete with high early strength cement (HESC), another was concrete with 50% HESC and 50% fly ash and the third one was concrete with 50% HESC, 50% fly ash, and an additional 20% hydrated lime. They were then tested in conjunction with ASTM C1202, but with the application of a 35 h voltage of 30 V. Results showed that concrete containing fly ash and hydrated lime had a lower accumulated charge density and chloride diffusion coefficient than the reference HESC concrete.


***Figure 1: Some images of chloride ion contaminated concrete in coastal region***

Rajamane and Ambily (2013) conducted a study to assess the impact of fly ash on concrete strength and durability characteristics, partially replaced by sand. There was a lower density and production cost of this type of fly ash concrete, a lower coarse aggregate material, a lower degree of permeability and greater durability than that of cement concrete. Also better strength-weight ratio (more concrete weight efficiency) and strength-energy ratio (more eco-friendly and less energy-intensive constructions) had been achieved by fly ash concrete.

An experiment on the strength and durability of class F fly ash concrete was made by Saha (2018). He found that, relative to the control samples, the compressive strength of fly ash samples showed low early compressive strength, but later, at 360 days, fly ash concrete gained almost equal strength to concrete control. He also found that the addition of fly ash as a binder decreased the concrete's porosity. As a result, lower water sorptivity and chloride permeability were exhibited in the fly ash concrete. Furthermore, a substantial decrease in sorptivity and chloride permeability between the curing periods of 28-180 days was observed for fly ash concrete. In order to determine the explanation behind the improved durability characteristics, the micro structural morphology of fly ash samples was investigated.

Moini *et al.* performed a report on the durability of concrete mixtures containing supplementary cement materials such as fly ash, slag, etc. in the rapid chloride permeability test (2019). In their testing, in the RCP and freezing-and-thawing tests, the performance of 54 concrete mixtures containing three types of water-reducing mixtures, two types of aggregates and two levels of cement content was evaluated, and the air void structure of the selected mixtures was analyzed. The use of supplementary cement materials (SCMs) has been found to significantly improve the efficiency of concrete mixtures in the RCP test. Moreover, in both RCP and freezing-and-thawing (F-T) tests, mixtures containing up to 30 percent of Class C fly ash and 50 percent slag content achieved outstanding durability efficiency. For mixtures containing Class F fly ash and poly-carboxylate ether (PCE) admixture, 'very-low' RCP values were found.

Portland cement concrete is affected considerably by sulfate attack which exists in soils, ground waters or sewage waste in form soluble ion. In recent years, it has become evident that some fly ashes increase the sulfate resistance of concrete while other fly ashes encourage the deterioration of concrete in a sulfate environment. Current ACI recommendation (ACI 226, 3R-92) for selecting fly ash to be used in sulfate resistant concrete are based on research performed at the United States Bureau of Reclamation (Dunstan 1980, Dikeou 1985).

Ghafoori and Zhang (1998) conducted a report on sulfate tolerance of plane and fly ash roller compacted concrete (RCC). This investigation used a total of 12 simple fly ash concretes, 24 cement substituted, and 12 fine aggregate substituted fly ash concretes. Laboratory-made RCC specimens were prepared and manufactured in compliance with ASTM C 1170, Procedure A at their maximum moisture content. The test samples were initially moist-cured for 28 days after casting, prior to immersion in a solution of 5 percent sodium sulfate. The test specimens were exposed to very severe sulfate attack to evaluate the length change, mass loss, and compressive strength of concrete at that situation. The tests were performed at 180 days. Also the bulk characteristics and sulfate resistance of mixture variables (cement, coarse aggregate, and fly ash content) were observed in that situation. The study showed that the use of Type V Portland cement with or without low-calcium fly ash could achieve strong sulfate-resistant roller-compacted concrete. With rises in cement or coarse aggregate content, the resistance to sulfate attack improves, as concrete becomes denser and more impermeable. With the rising immersion age, the length change of RCC samples increases and stabilizes within 3 to 4 months after the initial contact. No concrete residue mass has been identified for any specimens examined in this report. However, RCC mixtures with a cement content of 12% or less (by mass of total dry solids) experienced a small decrease in strength after six months of immersion in a sodium sulfate solution. A replacement of cement with low calcium fly ash by 20 to 40 percent increases the sulfate resistance of RCC samples (excluding mixtures made with 9 percent cement binder and 20 percent fly ash), whereas a replacement of 10 percent has the opposite effect. Mixtures replacing Class F fly ash with 10 to 20 percent fine aggregate show lower sulfate expansion and greater compressive strength than those of compacted concretes substituted for plain and cement fly ash rollers.

A laboratory research by Tikalsky and Carrasquillo (1992) studied the sulfate resistance of concrete containing fly ash. Concrete specimens were constantly immersed for 18 months in a 10 percent sodium sulfate solution. Eighteen fly ashes and two other pozzolans in a regular 4000 psi mix configuration were used as a partial substitute for Type II Portland cement. The chemical and mineralogical composition of each pozzolan was calculated in accordance with ASTM C 311 and X-ray diffraction (XRD) techniques. The study investigated the effects of the degree of fly ash replacement, slump, air content, cement form, and moist curing time, in addition to the effects of fly ash composition on the sulfate resistance of concrete. The findings of this research program showed that the physical effects of fly ash on the sulfate resistance of the concrete are controlled by the compositional effects of fly ash.

Another experiment on the sulfate resistance of fly ash concrete was made by Tikalsky and Carrasquillo (1993). Several assessment methods were tested in their research to predict the sulfate resistance of concrete containing fly ash. Both the bulk chemical composition and the measured amorphous glass composition of fly ash are based on these techniques. Of the 18 fly ashes used in this research, 9 were fly ashes of ASTM Class F and 9 were fly ashes of ASTM Class C. In addition, one silica fume source and one blast furnace slag source were used. The findings indicate a strong connection between the chemical and mineralogical composition of a fly ash source and the concrete containing the fly ash's sulfate resistance. Some fly ash increased concrete's resistance to sulfate attack, while other fly ash sources accelerated the rate of damage due to sulfate attack. In order to assist in selecting the fly ash source for concrete that can be exposed to a sulfate environment, a two-step assessment technique is proposed.

Siddamreddy and Chandrasekharar (2013) carried out a comprehensive analysis on the strength and durability of concrete. Ordinary Portland cement (OPC) was one of the primary materials used in the civil construction industry for the manufacture of concrete and was a versatile and relatively high-cost material. On the one hand large-scale cement manufacturing causes environmental issues and on the other, the loss of natural resources. This ecological challenge has led researchers to use agricultural goods in the manufacture of concrete as additional cementation material. The key parameter investigated in this study is M20 grade concrete with 0, 5, 10, 15 and 20 percent partial replacement of cement by fly ash. This paper presents a detailed experimental analysis at the age of 7 and 28 days on compressive force, split tensile strength. Acid attack durability research had also been studied, and the percentage of weight loss was comparable to standard concrete. Test findings showed that the use of fly ash in concrete had increased concrete efficiency in terms of strength as well as durability.

An experiment to test the effect of high volume fly ash on concrete strength and durability properties was performed by Nokken *et al.* (2014). Two forms of fly ash in combination with four cements were investigated in this study. The cements, with and without the blended silica fume, were both high and low alkali. Mortar and concrete mixtures containing 0 to 80 per cent fly ash replacement had been prepared. As well as sulfate, chloride, and alkali resistance, standardized tests were carried out for compressive strength. In sulfate and alkali resistance, high replacement levels performed reasonably well but poorly regarding compressive strength and chloride resistance. 40 percent fly ash replacement from these mixtures was found to have the best overall value from a durability perspective. Standardized research methods were comparative in nature and as such, the difficulty of concrete mixtures and their exposure conditions could not be replicated; higher substitutes had been used effectively in practice.

An investigation on the behaviors of high grade concrete containing fly ash was conducted by Uma and Shameem (2015). They utilized 30% fly ash and 50% of artificial sand in their analysis. Better compressive strength of concrete and high durability against acid action was found for concrete with fly ash and artificial sand over the traditional mix.

The Strength and durability properties of concrete blocks containing fly ash were tested by Robert and Deepa (2015). In this examination, fine aggregate (river sand) was replaced by fly ash. From the test, it was observed that the building blocks containing fly ash accomplished a significant improvement in the strength and durability properties over the conventional concrete.

Sahoo *et al.* (2017) researched the acid, alkali and chloride resistance properties of concrete composed of low carbonated fly ash. For different water curing ages, the impact of chemical exposure cycles (30, 60, 90, and 120 days) on the compressive strength and weight of concrete with low volume (25%) cement replacement was investigated (90 ,56 ,28, and 180 days). There was also a comparative evaluation of low volume (25 percent cement replacement) fly ash concrete and control concrete. The results indicated that low volume carbonated fly ash concrete demonstrated a significant improvement in compressive strength. Weight loss against salt, sulfate, and acid attack was observed substantially improved by using fly ash in concrete. To evaluate appropriate parameters for simultaneous minimization of strength loss and weight loss under chemical exposure, gray relation-based analysis was performed. In might be concluded that fly ash could be adopted as a partial replacement of cement in concrete due to its cost-effectiveness, fast processing, and environmentally friendly nature.

Another experiment on the sulfate resistance efficiency of fly ash concrete was made by Liu et al. (2018). The aim of this test was to investigate the relationship between calcium hydroxide (CH) content, gypsum formation and compressive strength, as well as the relationship between ettringite formation, pore structure and expansion properties at long-term sulfate attack, up to 1,110 days, in blended cement paste. The results showed that the pozzolanic fly ash reaction strengthened the pore structures and decreased the degree of ettringite super saturation by preventing external sulfate ions from entering.

*Figure 2: Some images of sulfate ion degraded concrete in coastal region*

In developed countries, many tests were done on the properties of fly ash concrete. In those experiments fly ash with stone chips as coarse aggregate were generally used. Bangladesh has a limited source of stone. In most cases, stone aggregate is imported from abroad which is expensive and time consuming. But brick is available and cheap here. This is why brick aggregate concrete structure is most common in Bangladesh. Moreover, recently in Bangladesh many contractors are using fly ash as cementitious material. But the quality of fly ash concrete is not checked. The experimental research program outlined in this study was carefully designed to investigate the effects of fly ash on durability properties of brick aggregate concrete. Two types of durability tests were performed. One was chloride ion penetration and another was sulfate resistance of fly ash concrete.

Thus in this study, burnt clay brick chips as coarse aggregate were used in concrete. Other materials were cement, sand (Sylhet) and fly ash available in Bangladesh (Indian fly ash). The study carefully investigated the effect of fly ash on chloride ion penetration and sulfate resistance of brick aggregate concrete.

**RESEARCH SIGNIFICANCE**

Reinforced cement concrete (RCC) structures are most common in construction field in Bangladesh. But Bangladesh has a severe shortage of cement as raw materials needed for manufacturing cement is not available here. Every year Bangladesh imports a lot of raw materials from abroad for production of cement which is expensive. Also during production of cement, a huge amount of $CO_2$ is added to green-house gasses by burning coals which causes environmental pollution. Moreover, emission of $CO_2$ causes climate change of Bangladesh increasing air temperature. To reduce the construction cost and to make the environment eco-friendly, a suitable substitute of cement is searching throughout the country. A part of this, use of fly ash, silica fume, slag etc. as a partial replacement of cement in concrete is being studied in recent time in Bangladesh. In this study, fly ash was used in concrete as a partial replacement of cement to observe its effects on durability properties of brick aggregate concrete. Two types of durability tests were performed. One was chloride ion penetration and another was sulfate resistance of fly ash concrete. This study was done to observe the effects of fly ash on durability properties of brick aggregate concrete.

 

Journal of Ceramics and Concrete Technology
Volume 6 Issue 1
ISSN: 2457-0826 (Online)

**Following tests were performed:**

a) Effect of fly ash on chloride ion permeability in brick aggregate concrete at constant w/c ratio using locally available materials such as brick aggregate, ordinary Portland cement, sand and fly ash available in Bangladesh.

b) Effects of fly ash on sulfate resistance of brick aggregate concrete at constant w/c ratio using locally available materials such as brick aggregate, ordinary Portland cement, sand and fly ash available in Bangladesh.

## OUTLINE OF METHODOLOGY

Effects of fly ash on durability of brick aggregate concrete were examined in this study. Ordinary Portland Cement (OPC) and fly ash, available in Bangladesh were the main materials. The other components were local sand, well-graded brick aggregate and potable water. The physical properties of coarse and fine aggregate and both physical and chemical properties of cement and fly ash were evaluated. The testing procedures were followed according to ASTM codes.

### Physical Properties of Coarse and Fine Aggregate

Different physical properties of both fines and coarse aggregate were tested according to different ASTM codes. Fineness modulus, unit weight, voids, moisture content, specific gravity and absorption capacity of fine aggregate were tested according to ASTM C117, ASTM C136, ASTM C29 and ASTM C128 respectively. The values of fineness modulus, unit weight, voids, moisture content, bulk specific gravity and absorption capacity of fine aggregate were 2.47, 1660 kg/m³, 37%, 0.30% 2.64 and 0.95% respectively.

For coarse aggregate fineness modulus, unit weight, voids, moisture content, specific gravity and absorption capacity were tested according to ASTM C117, ASTM C136, ASTM C29 and ASTM C127 respectively. The values of fineness modulus, unit weight, voids, moisture content, bulk specific gravity and absorption capacity of coarse aggregate were 7.62, 990 kg/m³, 47%, 0.33%, 1.87 and 9.7% respectively.

As a part of physical properties of fine and coarse aggregate, gradations of fine aggregate, coarse aggregate and combined aggregate were also determined before preparing test samples.

Journal of Ceramics and Concrete Technology
Volume 6 Issue 1
ISSN: 2457-0826 (Online)

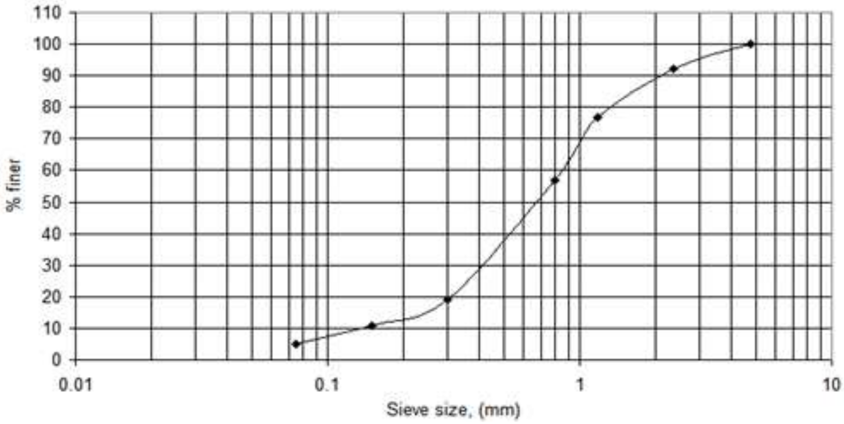


***Fig. 3: Gradation chart of fine aggregate***

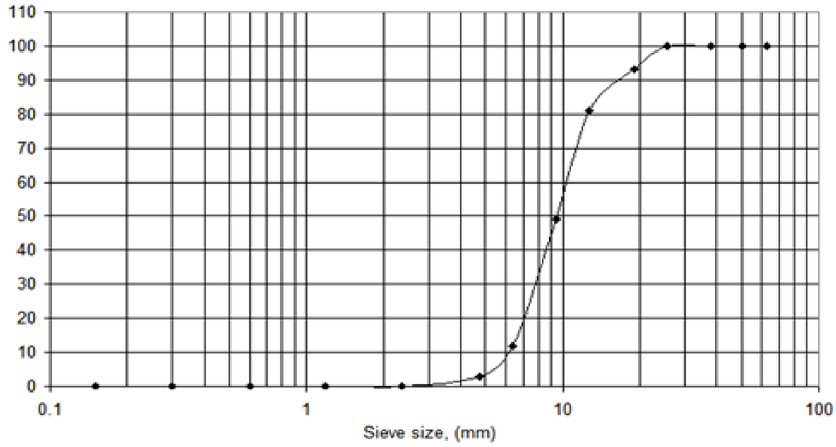


***Fig. 4: Gradation chart of coarse aggregate***

Gradation chart of fine aggregate is shown in Fig. 3. From this figure the values of $D_{10}$, $D_{30}$ and $D_{60}$ are 0.14, 0.4 and 0.85 respectively. The values of uniformity coefficient, $C_u$ ($C_u = D_{60}/D_{10}$) and curvature coefficient, $C_z$ ($C_z = D_{30}^2/ D_{60}$ x D10) are calculated and are found 6.07 and 1.34 respectively. As Cu is greater than 6 and Cz is between 1 and 3, the aggregate is well-graded (Pech, Hanson and Thornburn, 1974).

Gradation chart of coarse aggregate is shown in Fig. 4. From this figure the values of D10, D30 and D60 are 6.2, 7.8 and 10.5 respectively; where D10, D30 and D60 are the particle size corresponding to 10, 30 and 60 percent finer respectively. The values of uniformity coefficient, Cu (Cu = D60/D10) and curvature coefficient, Cz (Cz = $D30^2$/ D60 x D10) are 1.69 and 0.93 respectively. As Cu is not greater than 4 and Cz is not in between 1 and 3, the aggregate is not well graded but uniformly graded aggregate (Pech, Hanson and Thornburn, 1974).

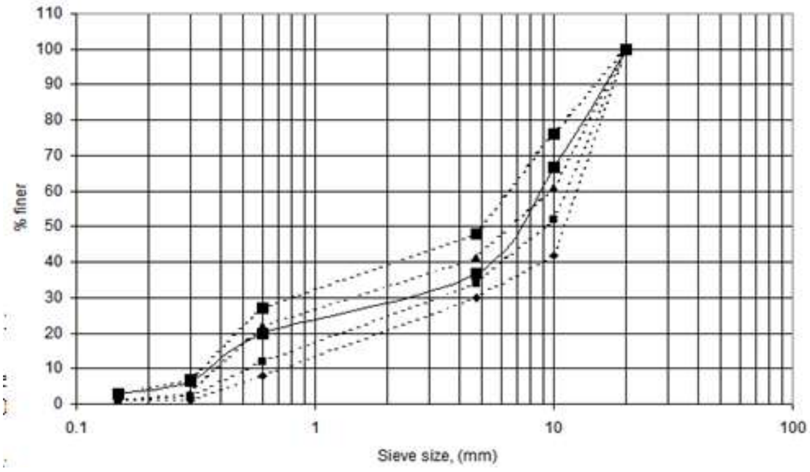


***Fig. 5: Gradation chart of combined aggregate***

Gradation chart of combined aggregate has been drawn as per IS383-1970. Fig. 5 shows the gradation chart of combined aggregate.

The figure shows that combined gradation chart lies mainly in middle zone and a small portion in upper zone. It indicates that major portion of aggregate used in this research is medium grade aggregate. The temperature of the air in the vicinity of the mixing bowl was maintained between 68 and 81.5ºF or (20 and 27.5ºC). The relative humidity of the laboratory was less than 50%.

**Physical and Chemical Properties of Cement and Fly Ash**

Physical properties like fineness, setting time and compressive strength of both cement and fly ash were tested according to ASTM C115, ASTM C191 and ASTM C150 respectively. The chemical compositions of OPC and fly ash were tested according to ASTM C618. Table 1 shows the physical properties of cement and fly ash and Table 2 shows the chemical properties of cement and fly ash. Moreover water is an important ingredient of concrete as it actively participates in the chemical reaction with cement. Water, used in this experiment was conformed to standard code.

***Table 1: Physical properties of cement and fly ash***

| **Physical Properties** | **Cement** | **Fly ash** |
| --- | --- | --- |
| Fineness, m²/kg | 348 | -- |
| Initial setting time, min | 85 | -- |
| Final setting time, min | 250 | -- |
| Compressive strength, MPa | | |
| 1-day | 6.9 | -- |
| 3-day | 13.78 | -- |
| 7-day | 23.8 | -- |
| 28-day | 31.5 | -- |

***Table 2: Chemical properties of cement and fly ash***

| **Chemical Compounds** | **Cement** | **Fly ash** |
|---|---|---|
| Silicon dioxide,$SiO_2$ | 21.5 | 53 |
| $Al_2O_3$ | 5.3 | 27.6 |
| Ferric oxide,$Fe_2O_3$ | 2.5 | 6.2 |
| $NH_4$-hydroxide group | 7.8 | 33.8 |
| Sulfur trioxide,$SO_3$ | 2.7 | 2.6 |
| Calcium oxide, CaO | 64.5 | 5.0 |
| MgO | 1.2 | 3.0 |
| Loss on ignition | 1 | 0.8 |
| Others | 1.3 | -- |

### Preparation and Testing of Samples

Two types of durability tests were performed in this research. One was chloride ion penetration test and another was sulfate-resisting test.

#### *Method for Determination of Chloride Ion Penetration in Concrete*

Chloride ion penetration test in concrete was performed according to BS 812-117. AgNO3, KSCN, HNO3, Ammonium Iron (III) Sulfate Indicator etc. were used for testing. Three different types of concrete specimens, each of 4-inch diameter and 8 inch height were tested based on percentages of fly ash replacement. Table 3 and Table 4 show the material properties and mix design of brick aggregate concrete used for chloride ion penetration test respectively.

***Table 3: Materials properties for durability test (both chloride ion penetration and sulfate resistance)***

| **Materials** | **Sources** | **Properties** | |
|---|---|---|---|
| Cement | Ordinary Portland cement | Fineness ($^2$/kg) | 348 |
| FA | Locally available fine aggregate | Specific gravity<br>Fineness modulus<br>Absorption (%) | 2.64<br>2.47<br>0.95 |
| CA | Locally available crushed brick chips. | Maximum Size (mm)<br>Fineness modulus<br>Specific gravity<br>Absorption (%) | 20<br>7.62<br>1.87<br>9.70 |

***Table 4: Mix design of concrete specimens for durability test***

| **Mix type** | **w/c ratio** | **% of fly ash** |
|---|---|---|
| Type 1 | 0.5 | 0% |
| Type 2 | 0.5 | 15% |
| Type 3 | 0.5 | 30% |

After casting concrete specimens were cured in water at 20°C for 28 days. After 28 days water curing, concrete specimens were immersed into chloride-salt solutions with three different concentrations (Table 5). The concentration of solution was kept constant during the test. To perform this, concentration of solution was measured by silver nitrate titration and adjusted concentration by adding salt of required amount.

ISSN: 2457-0826 (Online)

***Table 5: Concentration of chloride solution***

| Solution | Concentration (mol/L) | Temperature (°C) |
|---|---|---|
| Chloride ion solution | 0.70 | 20±3 |
| | 0.35 | |
| | 0.10 | |

***Determination of deterioration of concrete due to sulfuric acid attack***

A non-standard method was adopted for determining the deterioration of concrete due to sulfuric acid attack. The goal of this study was to establish a durability-checking method of concrete under the attacks of chemical environments. This research was to examine experimentally how various factors (such as percentage fly-ash replacement, material property) influence the deterioration of concrete by Sulfuric acid attack and to discuss the relationship between degradation of concrete and percent fly-ash replacement. The size of concrete specimens was 40cm×10cm×10cm. The concrete specimens were cured in water at 20ºc for 28 days. Table 3 shows the properties of materials and table 4 shows the mix design of concrete specimens used in this test.

After 28 days water curing, concrete specimens were immersed into sulfuric acid solutions with three different concentrations (Table 6). The pH of sulfuric acid solutions was kept constant during the test.

***Table 6: Concentration of sulfuric acid solution***

| $H_2SO_4$ Conc. (mol/L) | Measured pH | Temperature (°C) |
|---|---|---|
| 0.50 | 0.3 | 20±3 |
| 0.10 | 1.0 | |
| 0.01 | 2.0 | |

The moisture content of room conformed to the requirements of specification ASTM C511. Results were evaluated at three different ages such as 14, 28 and 90 days for both tests.

## RESULT AND DISCUSSION

***Effects of Chloride Ion on Fly Ash Concrete and Discussion***

Fig. 6 and Fig. 7; Fig. 8 and Fig. 9; Fig. 10 and Fig. 11 show the influences of fly ash on chloride ion penetration in concrete at 0.1, 0.35 and 0.7 mol/L chloride ion concentrated solution respectively. The below figures show that both chloride ion penetration depth and percent chloride ion penetration are almost same for concrete without fly ash and fly ash concrete at early ages like 14 and 28 days. But later fly ash performs well against chloride ion penetration in concrete.

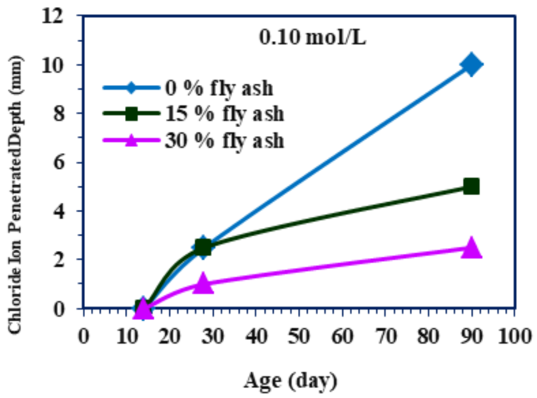


*Fig. 6: Effect of fly ash on chloride ion penetration depth (0.10 mol/L chloride concentration)*

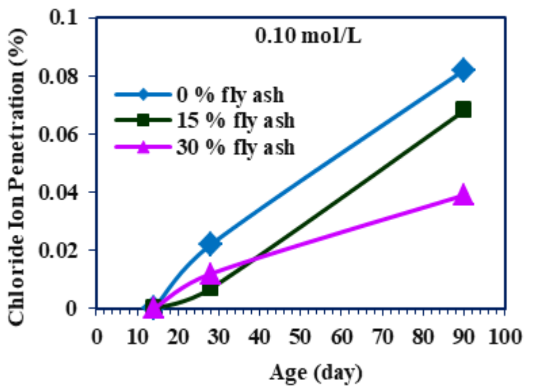


*Fig. 7: Effect of fly ash on percent chloride ion penetration (0.10 mol/L chloride concentration)*

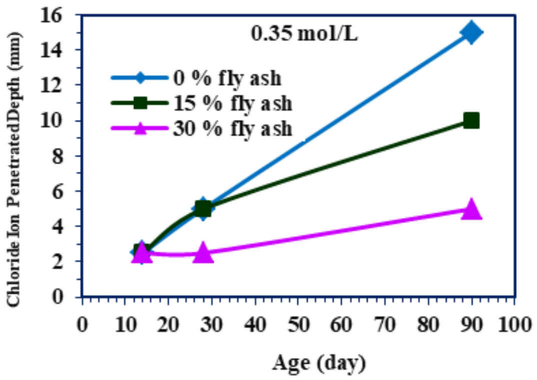


*Fig. 8: Effect of fly ash on chloride ion penetration depth (0.35 mol/L chloride concentration)*

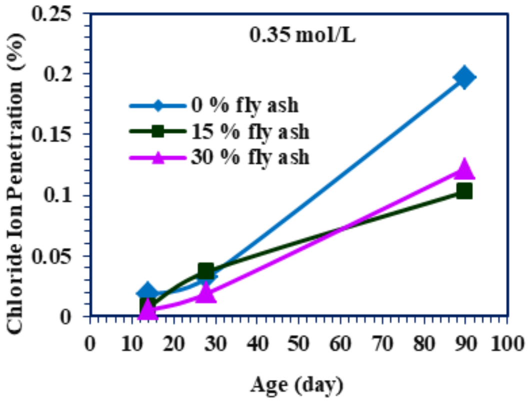


*Fig. 9: Effect of fly ash on percent chloride ion penetration (0.35 mol/L chloride conc.)*

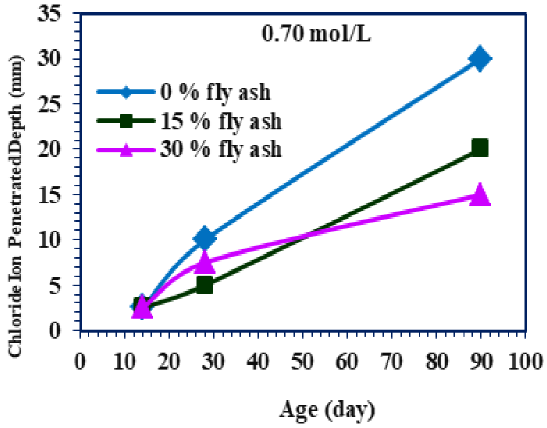


*Fig. 10: Effect of fly ash on chloride ion penetration depth (0.70 mol/L chloride concentration)*

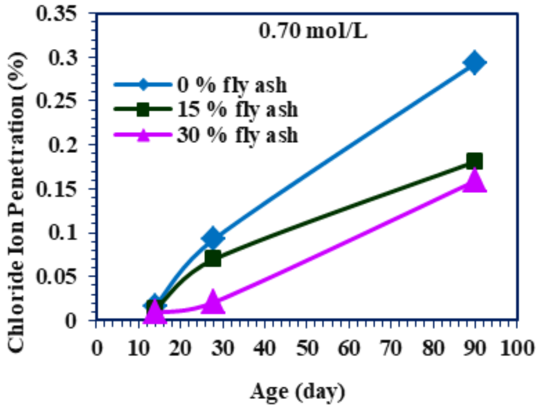


*Fig. 11: Effect of fly ash on percent chloride ion penetratio (0.70 mol/L chloride conc.)*

At 90 days, average chloride ion penetration depth and percent chloride ion penetration in concrete are 39 and 34 percent respectively higher for concrete without fly ash than 15 percent fly ash concrete. Similarly at 90 days, average chloride ion penetration depth and percent chloride ion penetration in concrete are 64 and 46 percent respectively higher for concrete without fly ash than 30 percent fly ash concrete.

Fig. 12, Fig. 13, Fig. 14 and Fig. 4.15 show the effect of fly ash replacement on strength of concrete at 0, 0.1, 0.35 and 0.7 mol/L chloride ion concentrated solution respectively. The above figures show that average gained strength of concrete without fly ash at 14 days is 21 percent higher than 15 percent fly ash concrete and 29 percent higher than 30 percent fly ash concrete. At 28 days, average gained strength of concrete without fly ash is 12 percent higher than 15 percent fly ash concrete and 20 percent higher than 30 percent fly ash concrete. So, at 28 days the difference of gained strength between concrete without fly ash and fly ash concrete is reduced. And at 90 days, average gained strength of concrete without fly ash is 2 percent higher than 15 percent fly ash concrete and 3 percent higher than 30 percent fly ash concrete. Thus at 90 days fly ash concrete gains almost same strength as concrete without fly ash.

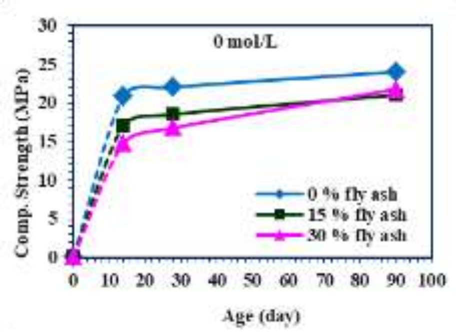


*Fig. 12: Strength of fly ash concrete (no chloride contamination)*

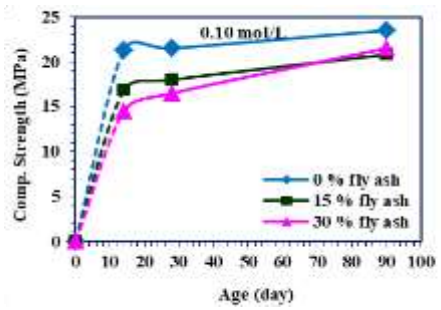


*Fig. 13: Strength of chloride contaminated fly ash concrete (0.10 mol/L chloride concentration)*

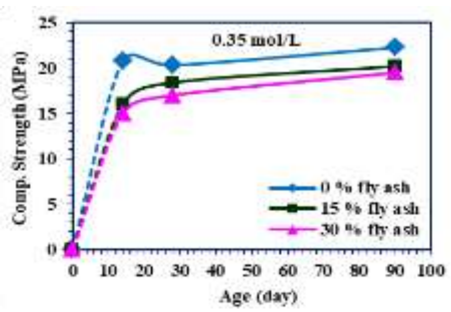


*Fig. 14: Strength of chloride contaminated fly ash concrete (0.35 mol/L chloride concentration)*

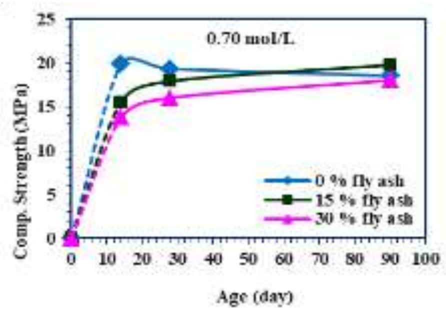


*Fig. 15: Strength of chloride contaminated fly ash concrete (0.70 mol/L chloride concentration)*

 

Journal of Ceramics and Concrete Technology
Volume 6 Issue 1
ISSN: 2457-0826 (Online)

It should be noted here that many experiments about effects of fly ash on chloride ion penetration in stone aggregate concrete were done all over the world. In those experiments, almost similar results were found for stone aggregate concrete like brick aggregate concrete using fly ash as a partial replacement of cement. i.e., at initial stage fly ash concrete gains lower strength than that of plain concrete and effect of fly ash on chloride ion penetration in concrete is not remarkable. But later, later fly ash concrete gains higher strength, almost equal strength as plain concrete and fly ash plays an important role against chloride ion penetration in concrete. The reason is, fly ash does not have cementitious property by itself which is responsible for strength generation. But in presence of water fly ash reacts with free lime obtained from hydrated products (C2S andC3S) which help in attaining the strength. As the fly ash is very fine in nature, it fills more voids of concrete and provides superior pore structures. So fly ash reduces the permeability of chloride ion in concrete. Thus fly ash increases the durability of concrete against chloride ion attack (Nath and Sarkar, 2011; Sama, Lalwani, Shukla and Sofi, 2014; Saha, 2018)

**Sulfate Resistance of Fly Ash Concrete and Discussion**

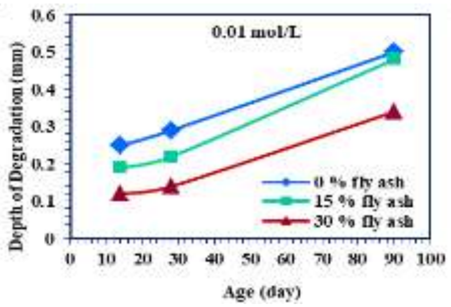


***Fig. 16: Effect of fly ash on degradation of concrete due to sulfuric acid attack (0.01 mol/L concentration)***

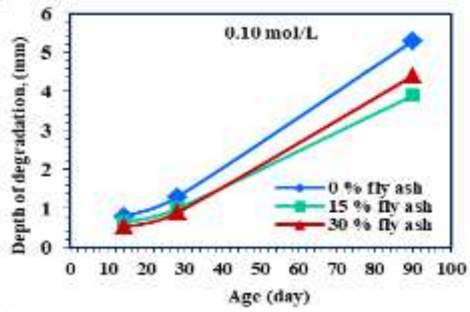


***Fig. 17: Effect of fly ash on degradation of concrete due to sulfuric acid attack (0.10 mol/L conc.)***

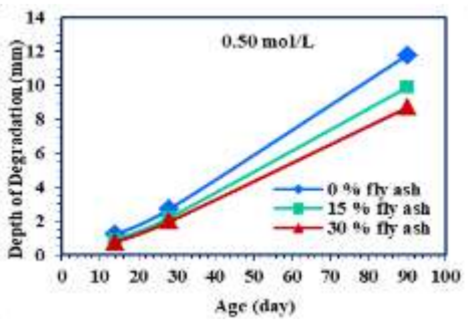


***Fig. 18: Effect of flyash on degradation of concrete due to sulfuric acid attack (0.50mol/L concentraion***

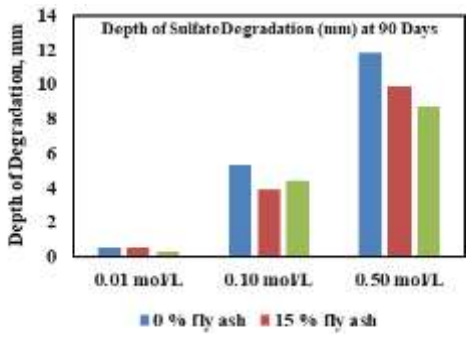


***Fig. 19: Sulfate resistance of fly ash concrete at 90 Days***

Fig.16, Fig.17 and Fig.18 show the influence of fly ash on degradation of concrete at 0.01 mol/L, 0.10 mol/L and 0.50 mol/L sulfuric acid concentrated solution respectively. These three figures show that average degradation depth of concrete without fly ash at 14 days is 22 percent higher than 15 percent fly ash concrete and 41 percent higher than 30 percent fly ash concrete. At 28 days average degradation depth of concrete without fly ash is 22 percent higher than 15 percent fly ash concrete and 36 percent higher than 30 percent fly ash concrete. And at 90 days average degradation depth of concrete without fly ash is 14 percent higher than 15 percent fly ash concrete and 24 percent higher than 30 percent fly ash concrete. Fig. 4.14 shows the bar diagram of sulfate resistance of fly ash concrete at 90 days. It is observed from fig.19, fly ash exhibit better resistance to sulfuric acid attack. Thus it is concluded that fly ash reduces the sulfate degradation of concrete.

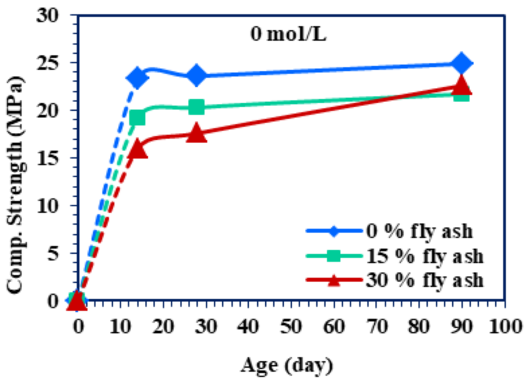


*Fig. 20: Strength of fly ash concrete (no sulfate attack)*

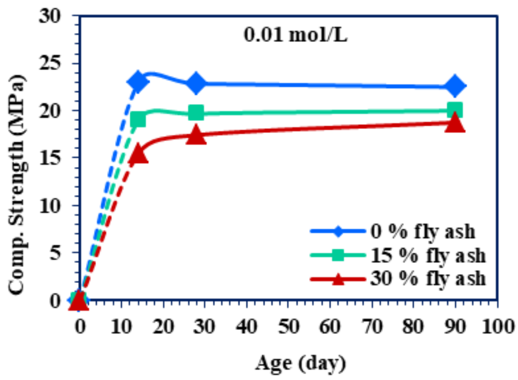


*Fig. 21: Strength of sulfuric acid degraded fly ash concrete (0.01 mol/L acid concentration)*

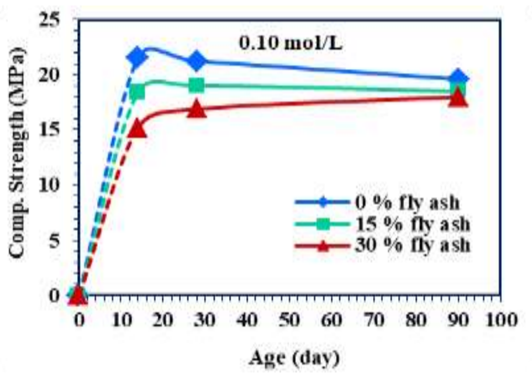


*Fig. 22: Strength of sulfuric acid degraded fly ash concrete (0.10 mol/L acid concentration)*

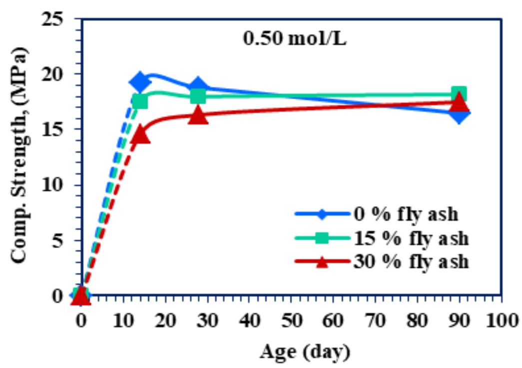


*Fig. 23: Strength of sulfuric acid degraded fly ash concrete (0.50 mol/L acid concentration)*

Fig. 20, Fig.21, Fig. 22 and Fig. 23 show the effect of fly ash replacement on strength of concrete at 0, 0.01, 0.1 and 0.5 mol/L sulfate ion concentrated solution respectively. At 14 days, average gained strength of concrete without fly ash is 14.5 and 29 percent higher than 15 and 30 percent fly ash concrete respectively. At 28 days, average gained strength of concrete without fly ash is 11 and 21 percent higher than 15 and 30 percent fly ash concrete respectively. And at 90 days, average gained strength of concrete without fly ash is 5 and 6.5 percent higher than 15 and 30 percent fly ash concrete respectively.

It should be mentioned here that many experiments about effects of fly ash on sulfate degradation of stone aggregate concrete were done all over the world. In those experiments, almost similar results were found for stone aggregate concrete like brick aggregate concrete using fly ash as a partial replacement of cement. In those experiments, it was found that the addition of fly ash as partial replacement of cement improves durability of concrete when exposed to sulfate environment. Because cement paste containing fly ash favored the formation of expansive salts. Addition of fly ash to cement converts the leachable calcium hydroxide into insoluble non-leachable cementitious products. The increase in sulfate resistance may be due to the contained reaction of fly ash with hydroxides in concrete to form additional calcium silicate hydrate (C-S-H), which fills in capillary pores in the cement paste, reducing the permeability and the ingression of harmful ions like sulfate into concrete. Thus fly ash increases the durability of concrete against sulfuric acid attack (Ghafoory and Zhang, 1998; Marthong and Agrawal, 2012; Siddamreddy and Chandrasekhar, 2013; Uma and Shameem, 2015).

## CONCLUSIONS

The data on chloride-ion penetration resistance suggests that cement-replaced fly ash concrete samples perform better than that of concrete samples without fly ash because fly ash reduces the permeability of chloride ion into concrete structures. Rate of chloride-ion penetration for 15 percent and 30 percent fly ash concrete is lower than that of concrete without fly ash. The data also suggests that where durability of reinforced concrete (against chloride ingress) is the primary criterion, fly ash can be used as an admixture to produce dense concrete.

It was found in the experiment that pozzolanic material like fly ash performs better against the sulfate attack. The pozzolanic material like fly ash is responsible for impermeability of concrete. Fly ash makes concrete too dense to ingress sulfate-ion in it. Thus cement-replaced fly ash concrete reduces sulfate-ion deterioration rate and increases the durability of concrete.

It should be mentioned here that since pozzolanic reaction can just continue on the presence of water, enough moisture should be accessible for long time. Subsequently, fly ash mortar and concrete should be water-cured for longer period. In this sense, fly ash mortar and concrete for submerged structures, like dams or structures where early strength isn't essential such as footing, column, retaining wall, plastering work, fly ash will deliver full advantages of accomplishing improved long-term strength and water-tightness. Moreover fly ash is cheaper than OPC and using fly ash in concrete reduces the heat of hydration in concrete mix. Thus use of fly ash in concrete structure is eco-friendly and also economical.

## RECOMMENDATIONS FOR FUTURE WORKS

The followings are the recommendations for future research works.

1) Class F and class C fly ash may be used to observe the effect on strength of both brick and stone aggregate concrete at w/c ratio varying from 0.3 to 0.5.

2) Fly ash meeting the requirements of ASTM C 618 and containing higher percent (30 to 50) by weight of cement may be used to evaluate the influence of chloride and sulfate resistance of concrete at w/c ratio varying 0.3 to 0.5.

## ACKNOWLEDGEMENT

The author expresses his heartiest gratitude and profound indebtedness to Dr. Ashraf Ali,, Professor, Department of Civil Engineering, BUET, for his supervision, guidance and encouragement at all stages of the work. His keen interest in this topic, valuable suggestions and advice were the sources of inspiration to the author. The author also expresses his grateful thanks to all his friends for their helpful activities and suggestions. Finally gratitude is also expressed to all the related staffs of the Concrete laboratory, SM laboratory and Transportation laboratory for their co-operations.

## REFERENCES

I. ACI 226, 3R (1992), “Use of Fly Ash in Concrete”

II. ACI Committee 318, (1989), “Building Code Requirements for Reinforced Concrete Construction and Commentary (ACI 318-89/ACI 318R-89),” American Concrete Institute, Detroit, PP.347.

III. ASTM C39-96, “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens”.

IV. ASTM C150-98, “Standard Specification for Portland Cement”.

V. ASTM C191-99, "Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle”.

VI. ASTM C618-98, “Standard Specification for Coal, Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete”

VII. Ben-Bassat, M., Nixon, P. J., Hard Castle, J., (1990), “The Effect of Differences in Composition of Portland Cement on Properties of Hardened Concrete,” Magazine of Concrete Research, V.42, No.151, PP>59-66.

VIII. Berke, N. S.; Pfeifer, D. W. and Weil, T. G., (1988), “Protection Against Chloride-Induced Corrosion,” Concrete International, V.10, No.12, PP.45-55.

IX. Berke, N. S., (1988), “Chloride-Induced Concrete Corrosion,” Concrete International, V.10, No. 12, PP. 55-57.

X. Bouzoubaa, N.; Fournier, B.; Malhotra, V. M. and Golden, D. M. (2002), “Mechanical Properties and Durability of Concrete Made with High Volume Fly Ash Blended Cement Produced in Cement Plant” ACI Materials Journal, V. 99, No. 6.

XI. BS 812: Part 117:1988: Method for determination of water-soluble chloride salts.

XII. Chatterjee, A. K., (1999), “History of Pozzolanic Materials in Concrete.”

XIII. Dhir, R. K.; Hewlett, P. C. and Chan, Y. N., (1987), “Near-Surface Characteristics of Concrete: Assessment and Development of In-Situ Test Methods,” Magazine of Concrete Research, London, V.39, No.141, PP.183-195.

XIV. Dikeou, J. T., (1985), “Effect of Fly Ash on Concrete,” Research Report No. 23, USBR, Denver.

XV. Dunstan, E. R. Jr., (1980), “Possible Method for Identifying Fly Ashes That Will Improve

Sulfate Resistance", Cement, Concrete and Aggregates, CCAGDP, V.2, No.1, PP.20-30.

XVI. Dunstan, M. R. H., (1983), "Long Term Strength Development of High Fly Ash Cement Concrete," Institute of Civil Engineers (London), Part1, V.74, PP.495-513.

XVII. Dunstan, E. R., (1984), "Fly Ash and Fly Ash Concrete," Bureau of Reclamation, Denver, Colorado.

XVIII. Filho, J. H.; Medeiros, M. H. F.; Pereira, E.; Helene, P. and Isaia, G. C. (2013), "High-Volume Fly Ash Concrete with and without Hydrated Lime: Chloride Diffusion Coefficient from Accelerated Test" Journal of Materials in Civil Engineering © ASCE, J. Mater. Civ. Eng., 2013, 25(3): 411-418.

XIX. Ghafoori, N., and Zhang, Z., (1998), "Sulfate Resistance of Roller Compacted Concrete," ACI Materials Journal, V.96, No.4, PP.347-355.

XX. Jerath, S. and Hanson, N. (2007), "Effect of Fly Ash Content and Aggregate Gradation on the Durability of Concrete Pavements" Journal of Materials in Civil Engineering © ASCE, J. Mater. Civ. Eng., 2007, 19(5): 367-375.

XXI. Jiang, L. H., (1998), "Studies on Hydration, Microstructure, and Mechanism of High Volume Fly Ash Concrete," Ph.D. thesis, Hohai University, Nanjing, China.

XXII. Liu, K.; Sun, D.; Wang, A.; Zhang, G.; Tang, J., (2018), "Long-Term Performance of Blended Cement Paste Containing Fly Ash against Sodium Sulfate Attack" Journal of Materials in Civil Engineering © ASCE, J. Mater. Civ. Eng., 2018, 30(12): 04018309.

XXIII. Marthong, C., Agrawal, T. P., (2012), "Effect of Fly Ash Additive on Concrete Properties," Varanasi, Uttar Pradesh, India, 221005.

XXIV. Moini, M.; Sobolev, K.; Vivian, I. F.; Muzenski, S.; Pham, L. T.; Cramer, S.; Beyene, M., (2019), "Durability of Concrete Mixtures Containing Supplementary Cementitious Materials in Rapid Chloride Permeability Test" ACI Materials Journal, V. 116, No. 5.

XXV. Nath, P.; Sarker, P., (2011), "Effect of Fly Ash on the Durability Properties of High Strength Concrete."

XXVI. Nokken, M. R.; Salloum, T.; Idle, A.; Martinez Ramos, L. A., (2014), "Standardized Testing for

 

Determining the Durability of High Volume Fly Ash Mixtures" Journal of Materials in Civil Engineering © ASCE, J. Mater. Civ. Eng., 2014, 26(1): 206-210.

XXVII. Otsuki, N., Hisada, M., Otani, T., and Maruyama, T., (1999), "Theoretical Evaluation of Diffusion Coefficient of Chloride Ion in Mortar from Mobility," ACI Materials Journal, V.96, No.4-6, PP.627-633.

XXVIII. Pech, R. B., Hanson, W. E., Thornburn, T. H., (1974), "Foundation Engineering."

XXIX. Poon, C. S.; Lam, L. and Wong, Y. L. (1999), "Effect of Fly Ash and Silica Fume on Interfacial Porosity of Concrete", Journal of Materials in Civil Engineering, pg-197 -205.

XXX. Rajamane, N. P. and Ambily, P. S., (2013), "Fly Ash as a Sand Replacement Material in Concrete - A Study" Indian Concrete Journal, July 2013.

XXXI. Ramachandan, V. S.; Feldman, R. F. and Beaudoin, J. J., (1981), "Concrete Science," Heyden and Son Ltd., London.

XXXII. Robert, V. T; Deepa, G. N., (2015), "Fly Ash as a Fine Aggregate Replacement in Concrete Building Blocks" International Journal of Engineering and Advanced Research Technology (IJEART) Volume-1, Issue-2.

XXXIII. Sahoo, S.; Das, B. B.; Mustakim, S., (2017), "Acid, Alkali, and Chloride Resistance of Concrete Composed of Low-Carbonated Fly Ash" Journal of Materials in Civil Engineering © ASCE, J. Mater. Civ. Eng., 2017, 29(3): 04016242.

XXXIV. Saha, A. K., (2018), "Effect of class F fly ash on the durability properties of concrete," Department of Civil Engineering, Curtin University, Perth WA 6102, Australia.

XXXV. Saricimen, H.; Maslehuddin, M.; Al-Tayyib, A. J. and Al-Mana, A. I. (1995), "Permeability and Durability of Plain and Blended Cement Concretes Cured in Field and Laboratory Conditions" ACI Materials Journal, V. 92, No. 2.

XXXVI. Sengul, O. and Tasdemir, M. A. (2009), "Compressive Strength and Rapid Chloride Permeability of Concretes with Ground Fly Ash and Slag", Journal of Materials in Civil Engineering © ASCE, J. Mater. Civ. Eng., 2009, 21(9): 494-501.

XXXVII. Siddamreddy Anil Kumar Reddy, Dr. K. Chandrasekhar Reddy, (2013), "Effect of Fly Ash on Strength and Durability Parameters of Concrete."

XXXVIII. Thomas, M. D. A. and Matthews, J. D. (1993), "Performance of Fly Ash Concrete in U.K. Structures" ACI Materials Journal, V. 90, No.6.

XXXIX. Tikalsky, P. J. and Carrasquillo, R. L. (1992), "Influence of Fly Ash on the Sulfate Resistance of Concrete" ACI Materials Journal, V. 89, No. 1.

XL. Tikalsky, P. J. and Carrasquillo, R. L. (1993), "Fly Ash Evaluation and Selection for Use in Sulfate Resistant Concrete" ACI Materials Journal, V. 90, No.6.

XLI. Uma, M.; Shameem Banu, S., (2015), "Strength and Durability Studies on Concrete with Fly Ash and Artificial Sand."

XLII. Vitruvius, P., (1960), "The Ten Books of Architecture", Translated from the Latin by Morgan, M. J., Dover Publications, New York.

XLIII. Wee, T. H., Suryavanshi, A. K., and Tin, S. S., (2000), "Evaluation of Rapid Chloride Permeability Test (RCPT) Results for Concrete Containing Mineral Admixtures," ACI Materials Journal, V.97, No.1-3, PP.221-226.