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Durability Properties of Fly Ash Concrete
A Critical Review

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Abstract

Concrete structure is the most common all over the world. Cement is the major ingredient of concrete. Though the raw materials needed for manufacture of cement are available in most parts of the world, many countries have severe shortage of cement, although their needs are vast. The search for suitable substitute for cement, either partially or fully, has thus become a challenge for planning the development of many of the third world countries. At the same time, large-scale industrialization has led to newer environment problems related to disposal of industrial byproducts like fly ash. The thermal power stations existing in the world produce million tons of fly ash worldwide every year. There are large numbers of other industries, which also use coal for firing their boilers, producing large amounts of fly ash, which are generally collected by mechanical collectors. A large amount of land is being wasted for disposal of fly ash, which can otherwise be used for housing, agricultural, industrial or some other essential purposes. Moreover, during production of cement, a huge amount of CO2 is added to green-house gasses by burning coals which causes environmental pollution. It is well known that fly Ash is low cost material and use of fly ash in concrete reduces the amount of cement required. Thus use of fly ash in concrete minimizes the construction cost and improves the environment quality by reducing the emission of harmful gas like CO2 into air that caused during manufacturing of cement. In addition to economic and environmental benefits, the use of fly ash improves the durability, workability and fire resistance of concrete. It is observed from the previous researches that fly ash collected from electrostatic

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precipitator of thermal power plants is very much suitable for use in production of high performance concrete. This review paper focuses on the various durability properties of fly ash concrete.

***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, γ = 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 to 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

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chemically reacts with calcium hydroxide at ordinary temperature.

Recently, in many countries of the world, pozzolanic materials like fly ash is being used as an ingredient of the Portland cement concrete. It is essential to check the properties of fly ash before use it in concrete. In this regard, a lot of experiments on the properties of fly ash were conducted all over the world to observe the effects of fly ash on concrete. Based on the previous researches, different durability properties of fly ash concrete are reviewed in this study.

SCOPE OF THE STUDY

Reinforced cement concrete (RCC) structures are most common in construction field all over the world. Cement is one of the major ingredients of concrete. But many countries have a severe shortage of cement as raw materials needed for manufacturing cement is not available there. Every year they have to import 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 those countries increasing air temperature. To reduce the construction cost and to make the environment safe, a suitable substitute of cement is searching throughout the world for the last few decades. A part of this, use of fly ash, silica fume, slag etc. as a partial replacement of cement/sand in concrete is being studied in recent time in many parts of the world.

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-Bassatet al. 1990). The microstructure and products of hydration of concrete depend on its reaction and progress of hydration. The water cement ratio is another 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 318-89). It was proposed (Dhir et al. 1987) that the permeation properties (absorption, diffusion and permeability) of concrete relate more specifically to durability than strength. Durability of concrete is largely affected by permeability of chloride and sulfate ion into concrete. It was found from the previous researches that

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the reinforced steel losses its strength with time in contact with chloride and sulfate ion available in the ground water. Chloride ion reacts with steel and corrodes it where sulfate ion degrades the concrete, weakens it, sometimes collapses the structure. This phenomenon is not common all over the world but in the saline region of the world where chloride and sulfate ion concentration of water is relatively high, deterioration of concrete due to chloride and sulfate attack is remarkable. In these areas longevity of RCC structure relatively very low. To solve this problem a lot of studies/experiments/researches were done. As fly ash is finer than cement, it reduces the porosity of concrete and makes the concrete dense.

In the above circumstances, very recently, many concrete industries in the world are using fly ash as a partial replacement of cement/sand to reduce construction cost and to make eco-friendly structures. But the quality of fly ash concrete is to be checked properly before using it in the concrete. In this review paper different durability properties of fly ash concrete are discussed based on the previous researches to know the significance of using fly ash in concrete as a partial replacement of cement/sand.

SOURCE, PROPERTY AND CLASSIFICATION OF POZZOLANIC MATERIAL

Source

Historically the Romans used a consolidated volcanic tuff /ass in cement and mortar found in Pozzouli near Vesuvius in Italy. This was very much similar to the materials of volcanic origin found in another part of Italy, Spain and France. Later, the term pozzolan was employed throughout Europe to designate any material irrespective of its origin, which possessed similar properties (Efrent 1973). Another source of volcanic ash is the the Aegean island of Santorini. Different types of pozzolanic materials such as pumicites, opaline shales, diatomaceous are found in many parts of the United States such as California, Nevada, Arizona and Okalahoma. Now pozzolanic materials like fly ash are available in many parts of the world.

Pozzolanic Properties

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

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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 and produces cementitious material (ACI 116R -85). Recently, in many countries of the world, pozzolon like fly ash is being used as an ingredient of the Portland cement concrete. The reaction can be shown as:

$$\text{Pozzolan} + Ca(OH)_2 + \text{Water} = C - S - H \text{ (Gel)}$$

The above reaction is called pozzolanic reaction. The characteristic feature of pozzolanic reaction is firstly slow, with the result that heat of hydration and strength development will accordingly be slow. The reaction involves the consumption of $Ca(OH)_2$ which makes the cement paste dense and impervious. Thus it improves the durability of cement paste.

Classification of Pozzolanic Materials

Pozzolanic materials are mainly divided into two groups such as natural pozzolana and artificial pozzolana (ASTM C618, 1998).

Natural pozzolan

This type of pozzolan is present on the earth's surface. Volcanic ash, opaline shale, diatomaceous earth, pumicite and tuff are very common types of natural pozzolan. These materials are collected and processed such as calcining, grinding, drying etc to make it usable in concrete. These types of pozzolans are used in under water structures such as dams and bridges to lower the heat of hydration. They also perform better against sulfate degradation of concrete and control the alkali-silica reaction (ASTM C618, 1998).

a) Artificial pozzolan

The most common artificial pozzolan is fly ash. It is produced during the burning process of pulverized coal in the electric power plants. There are mainly two types of fly ash are available in the world; one is class C fly ash and another is class F fly ash (ASTM C618, 1998).

b) Artificial pozzolan

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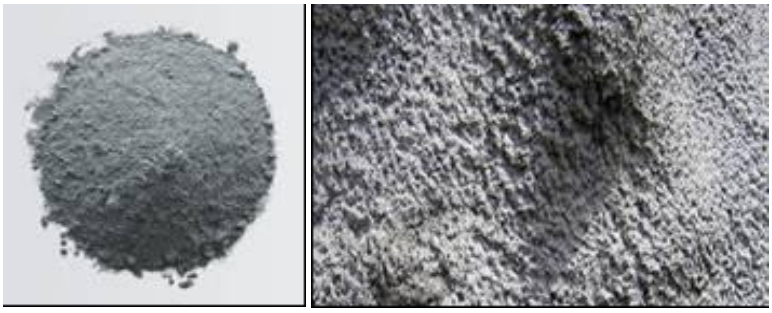


Image of fly ash

Class C fly ash possesses both pozzolanic and cementitious properties where class F fly ash has pozzolanic properties only. The chemical compositions of both types of fly ash are shown below:

Table 1 Chemical properties of Class C and Class F fly ash (ASTM C618)

ASTM Class C fly ash			**ASTM Class F fly ash**		
Sl no.	Chemical composition	Percent	Sl no.	Chemical composition	Percent
01.	SiO_2 plus Al_2O_3 plus Fe_2O_3, min	50	01.	SiO_2 plus Al_2O_3 plus Fe_2O_3, min	70
02.	SO_3, max	5	02.	SO_3, max	5
03.	Moisture content, max	3	03.	Moisture content, max	3
04.	Loss on Ignition, max	6	04.	Loss on Ignition, max	6

REVIEW ON THE DURABILITY PROPERTIES OF FLY ASH CONCRETE

Historically, fly ash is used as a partial replacement of cement in many parts of the world. About 2000 years ago the Greeks and the Romans mixed volcanic ash, called "PulvisPuteolanus" (later changed to "Pozzolana") with lime to produce cement and mortar (Vitruvius 1960, in interpretation). Such cementing materials were employed in the construction of aqueducts, arches, bridges etc.

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).

Different durability properties of fly ash concrete were examined in the last few decades all over the world. Among them freezing-thawing, rapid chloride ion penetration, water permeability,

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carbonation, sulfate degradation and acid-alkali reactions of fly ash concrete are discussed below from the previous researches.

Freezing and thawing

An experiment on the freezing and thawing durability property of concrete with or without fly ash was performed by ACI committee 226 in 1987. The committee found that the durability property like freezing and thawing of concrete was greatly influenced by the sufficiency of the air-void system, rate of hydration, soundness of aggregate, curing period, age and strength of cement paste (Fig. 2). As the rate of development of the strength of concrete containing class F fly ash was slower, it was required to use more cementitious material (cement with fly ash) to get comparable maturity at early age (28 days) in that experiment. It was also noticed, that the required amount of air-entraining admixtures were increased with increasing the cementitious materials per unit volume of concrete. The report acclaimed that the impact of pozzolans on the freezing and thawing durability of concrete is incredibly affected by the curing conditions of concrete (ACR 226.3R-87).

The air entraining system and the strength of cement paste were observed as the two major controlling factors of the freeze-thaw resistant of concrete (Fig. 3). It was noticed that the organic-based air-entraining admixtures were absorbed by carbon particles available in fly ash which affected the air system in concrete.

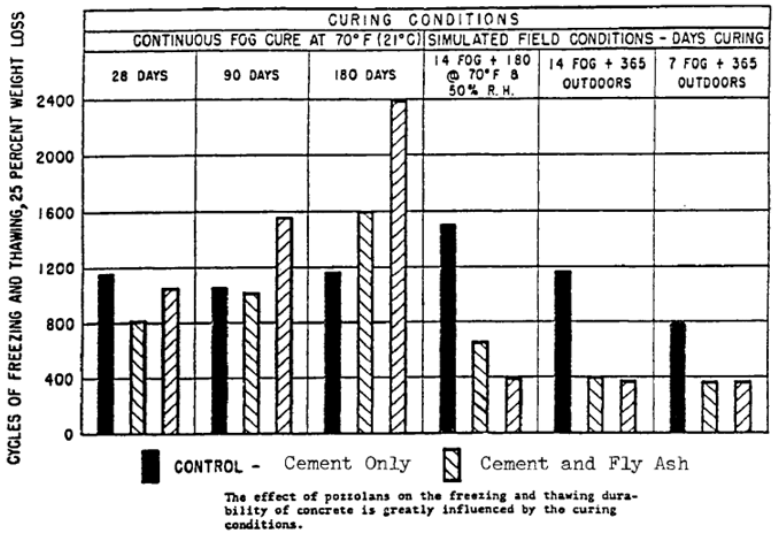


Fig. 2: The effect of pozzolans on the freezing and thawing durability of concrete (ACR 226.3R-87).

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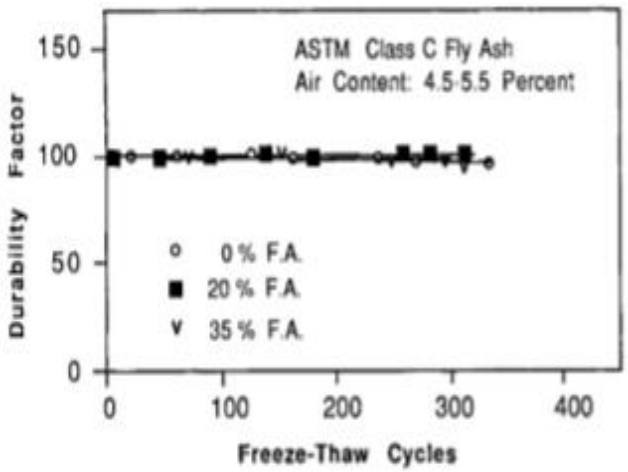


Fig. 3: Freeze-thaw durability of fly ash concrete (Tikalsky et al. 1988)

In this regard, to compensate the loss of admixture, additional amount of air-entraining admixture might be essential for fly ash cement paste and concrete (Tikalsky et al. 1988). In this study, the requirements of additional amount of air-entraining admixtures were sometimes found as double depending on the percent of fly ash replacement and the type of fly ash used in concrete mix. Adequate freeze-thaw resistance of concrete could be gained by ensuring adequate air content in concrete.

Moreover, excellent resistance to freezing and thawing cycling was found by using high volume fly ash in concrete, and there was no difficulty in entraining air into the device (Bisaillon et al. 1994, Bilodeau et al. 1994).

Rapid chloride permeability

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).

Thomas and Matthews (1993) conducted an experiment on different durability properties of concrete including chloride ion penetration. The study reported 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

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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 resistance to chloride ion ingress and decreased permeability of concrete. The evaluation of diffusion coefficient of chloride ion in concrete from mobility was performed by 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) derived a co-relation between the charged passed from chloride permeability test and the chloride penetration test and mineral admixtures is elucidated.

The inclusion of fly ash and silica fume in the mortars made a great effect on interfacial porosity by reducing it significantly. The interfacial porosity better described 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 appeared 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). Jerath and Hanson (2007) conducted an analysis of the impact of fly ash content and aggregate gradation on concrete durability. Different fly ash replacement levels of 30, 35, 40 and 45 percent for Portland cement were used. 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.

Sengul and Tasdemir (2009) conducted another experiment on the rapid chloride permeability of concrete containing fly ash and slag. Finely ground fly ash (Blaine specific surface: 604 m^2 /kg) and finely

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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. 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. Rapid chloride permeability and sorptivity of Class F fly ash concrete along with control concrete were tested by Nath and Sarker (2011).

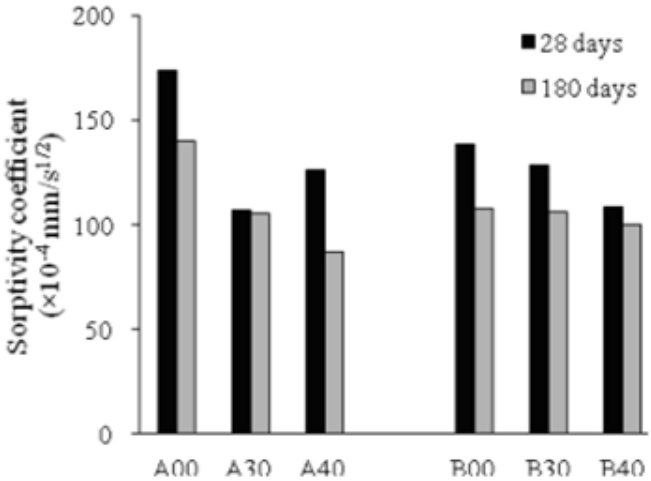


Fig. 3: Comparison of sorptivity coefficients (Nath and Sarker 2011)

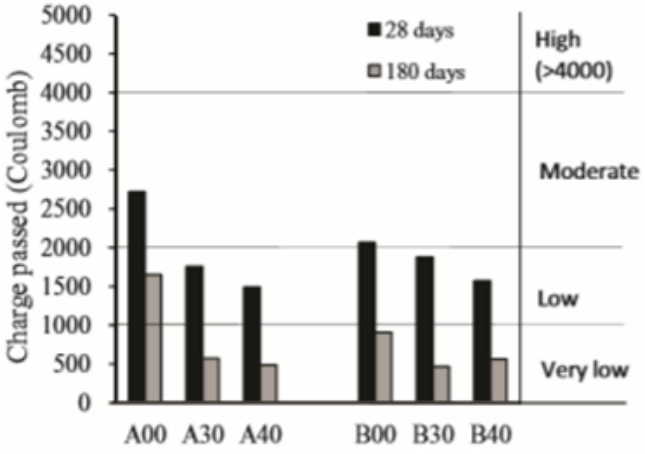


Fig. 4: Chloride permeability results (Nath and Sarker 2011)

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The test specimens were divided into two series marked as Series A and Series B based on fly ash content, super-plasticizer and water-binder (w/b) ratios. In series A, fly ash content and w/b ratio were taken 0%, 30%, 40% and 0.41, 0.32, 0.31 respectively and samples were denoted as A00, A30 and A40 accordingly. In series B, fly ash content was considered as 0%, 30% and 40% keeping w/b ratio constant and samples were denoted as B00, B30 and B40 respectively. The test result showed that the use of fly ash in concrete reduced the water sorptivity in both series (Fig. 3). Similar result was found by Saha (2018). For rapid chloride permeability test, it was found that Cl- penetration in concrete was reduced from 35% to 45% at 28 days by incorporating fly ash in concrete which were then 65% to 70% at 180 days in Series A. On the other hand, Cl- penetration was reduced up to 24% and 48% at 28 days and 180 days respectively for the concretes of Series B (Fig. 4).

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. Rajamane and Ambily (2013) also noticed that fly ash had better resistance against chloride ion penetration into concrete. In their experiment, fly ash was used as a partial replacement of sand.

Moini et al. (2019) 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. In their testing, 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

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of supplementary cement materials (SCMs) has been found to significantly improve the efficiency of concrete mixtures in the rapid chloride penetration RCP test. Moreover, the concrete mixtures containing up to 30 percent of Class C fly ash and 50 percent slag content achieved outstanding durability efficiency.

Water permeability

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.

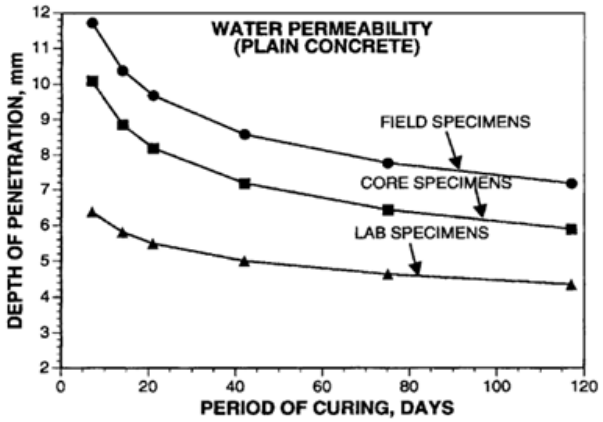


Fig. 5: Water permeability in plain cement concrete (Saricimen et al. 1995)

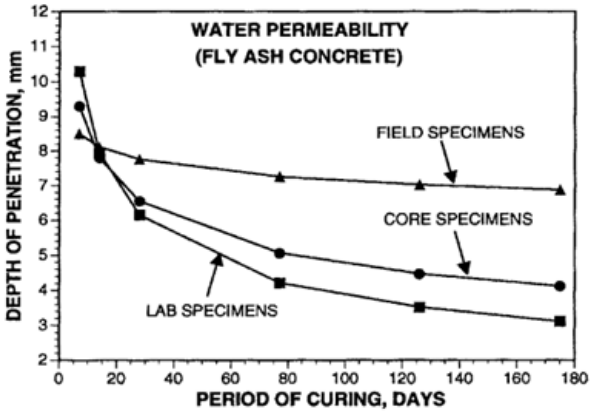


Fig. 6: Water permeability in fly ash cement concrete (Saricimen et al. 1995)

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The laboratory specimens were subjected to water-curing before processing. As indicators for cement concrete permeability, water penetration and absorption tests were used. 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. The depth of water penetration in plain concrete was calculated 1.13 to 1.38 times the fly ash cement concrete. Because fly ash concrete specimens were found denser than plain concrete in all curing process.

Moreover, it was observed that water permeability decreased with curing time in all cases. The decreasing rate was faster at 28 days, slowed down gradually up to 100 days and finally after100 days became almost constant. 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.

The pozzolanic properties of fly ash depends on its physical, chemical and mineralogical composition. Depending on these properties fly ash cement concrete takes longer curing period to attain similar properties of plain concrete. There, for quality of fly ash should be properly checked before utilization of it in concrete. Similarly early denseness and greater impermeability of fly ash concrete were reported by Haque and Kayyali (1989) and Haque (1990).

Carbonation

Zhang et al. (2016) studied the feasibility of carbonation curing of precast fly ash concrete. The relation between pozzolanic reaction and carbonation reaction was observed in this study. Cement reaction was assessed through the equivalent non evaporable water content, and the fly ash reaction degree was examined through a specific acid dissolution test. In all cases, different carbonation curing periods and different percentages of fly ash contents were considered. It was found that the early carbonation reaction hindered the pozzolanic reaction of fly ash.

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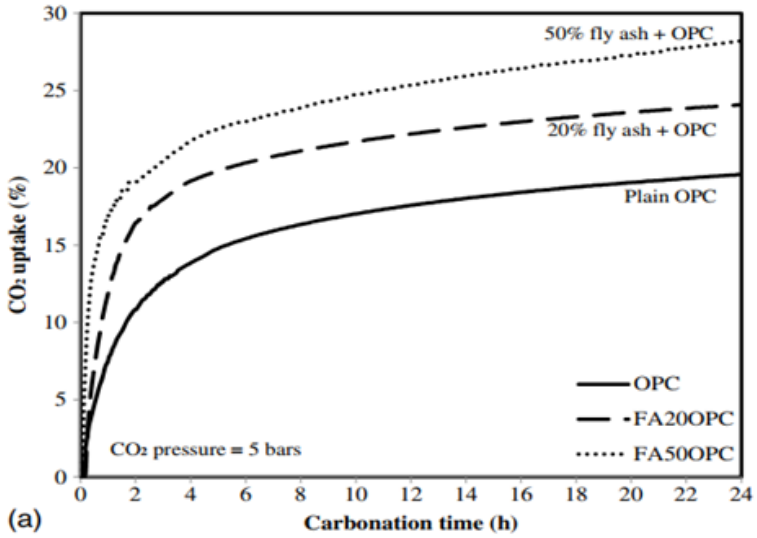


Fig. 7: CO_2 uptake mass curves of OPC and FA-OPC pastes (Zhang et al. 2016)

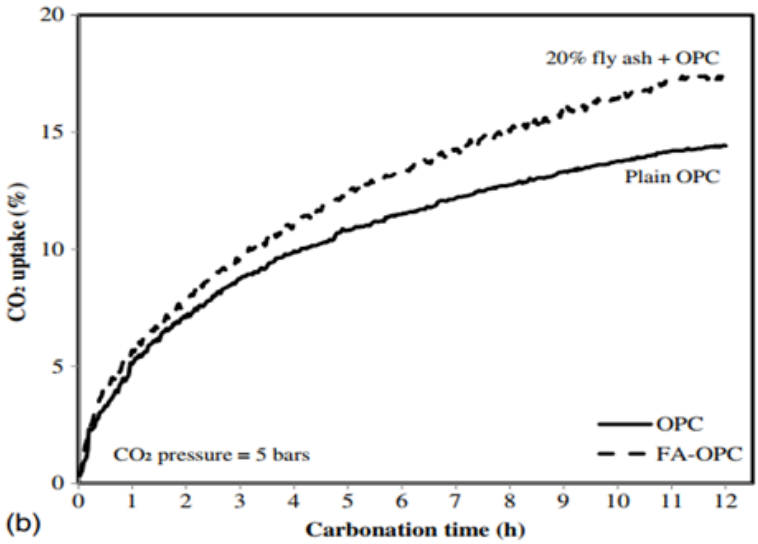


Fig. 8: CO_2 uptake mass curves of OPC and FA-OPC concretes (Zhang et al. 2016)

The pozzolanic reaction of fly ash was found lower at early higher carbonation rate. Also with compare to the plain cement paste, fly ash-OPC paste was found more reactive with CO2 (Fig. 7). Consequently, controlled carbonation at an early age is important to reduce the emission of carbon in air. The investigation showed that the higher early strength of concrete could be achieved by restricted the content of fly ash to 20% and limited the carbonation curing period to 12 hours (Fig. 8). In this way, better durability and reduction of carbon emission up to 36% could be attained. Therefore, carbonated fly ash concrete could have a pH value equivalent with the hydration reference and could be utilized in precast RCC concrete.

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Sulfate degradation

Portland cement concrete is affected considerably by sulfate attack which exists in soils, ground waters or sewage waste in form soluble ion. 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 (Dikeou 1985, Dunstan 1980).

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. 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.

Ghafoori and Zhang (1998) conducted a report on sulfate tolerance of plane and fly

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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, 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 (Fig. 9).

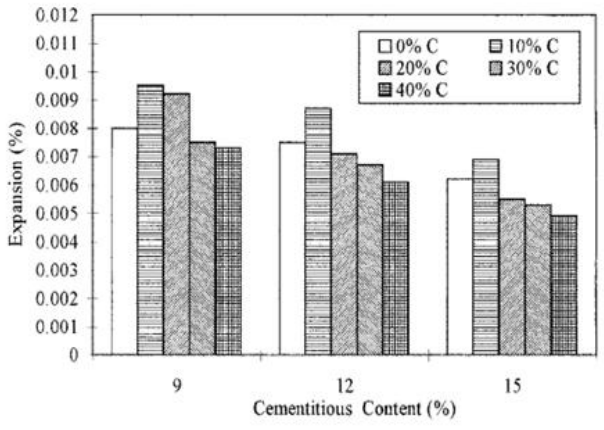


Fig. 9: Influence of fly ash on sulfate expansion of RCC specimens (Ghafoori and Zhang 1998)

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Mixtures replacing Class F fly ash with 10 to 20 percent fine aggregate show lower sulfate expansion than those of compacted concretes substituted for plain and cement fly ash rollers.

It was 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 (Marthong and Agrawal 2012). 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 was found from the experiment, that the using of fly ash up to a certain percentage improved durability of concrete against sulfate salt in all OPC grades.

Sahoo et al. (2016) 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 loss and weight loss under sulfate attack. To evaluate appropriate parameters for simultaneous minimization of strength loss and weight loss under sulfate 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 [CaSO4.2H2O] formation and compressive strength. Moreover relationship between ettringite [Ca6Al2(SO4)3(OH)12.26H2O] formation, pore structure and expansion properties at long-term sulfate attack, up to 1,110 days in fly ash cement paste were observed.

They noticed that the sulfate degradation of cement paste was happened after formation of ettringite. when cement paste/cement concrete was immersed into sodium sulfate solution, the external sulfate ions ingressed into cement paste.

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These ingressed sulfate ions reacted with the Al-phase such as C-A-H and mono-sulfate and produced ettringite.

These ingressed sulfate ion reacted with the Al-phase such as C-A-H and mono-sulfate and produced ettringite. At the initial stage, the ettringite was formed at a small amount only in the surface of cement paste and created a small crack only in the surface or corner, which was not severe. Thus the deterioration of concrete due to sulfate attack was not significant at the initial stage. But later, with continuous reaction, additional ettringite was formed which provided the energy for expansion. Thus significant degradation of concrete was caused at later stage.

Degradation of concrete due to sulfate attack was reduced by incorporating of fly ash in cement paste. The pozzolanic reaction of fly ash improved the pore structures by reducing the porosity of concrete. The lower porosity of concrete reduced the penetration of external sulfate ion and also reduced the formation of ettringite, which decreased the crystallization pressure. Thus fly ash reduced the sulfate expansion of concrete at later age (Fig. 10).

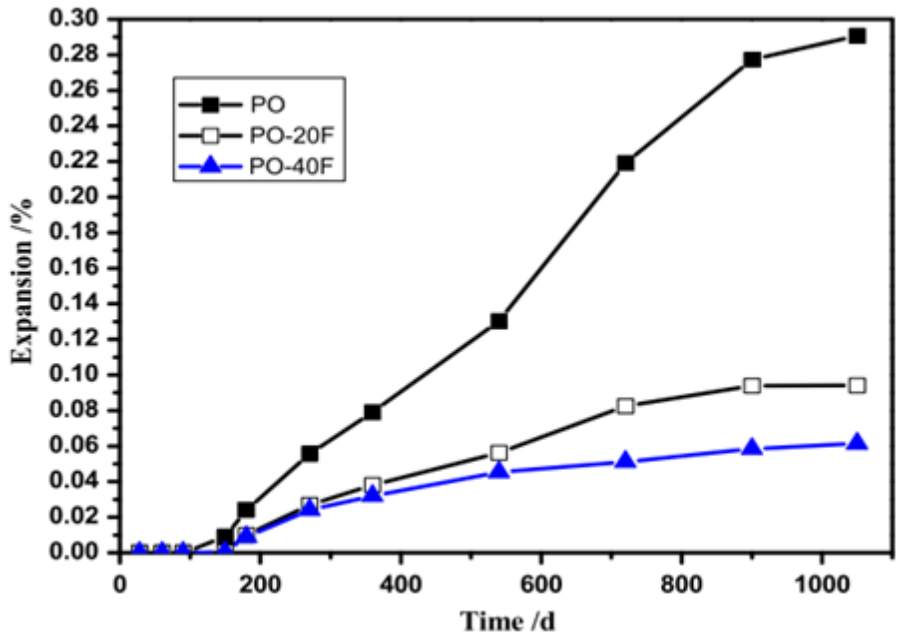


Fig. 10: Change in length of the samples stored in a Na2SO4 solution (Liu et al. 2018)

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Alkali resistance

The durability properties like alkali-silica reaction (ASR) of high volume fly ash concrete were experimented by Nokken et al. (2014). Two forms of fly ash (class CI and class F) 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.

From the experiment, it was observed (Fig. 11) that the expansion of concrete due to ASR decreased with increasing cement. Although the ASR expansion of silica fume concrete was less than the control concrete at 14 days, it exceeded the Canadian code limit. This indicated that silica fume alone was not sufficient to reduce ASR expansion of concrete. The ASR expansion of concrete decreased with increasing the fly ash content in concrete. For class F fly ash, better result in terms of expansion was observed at 40% content. A dramatic reduction in expansion due to ASR was noticed for the specimen containing low-alkali cement and class F fly ash.

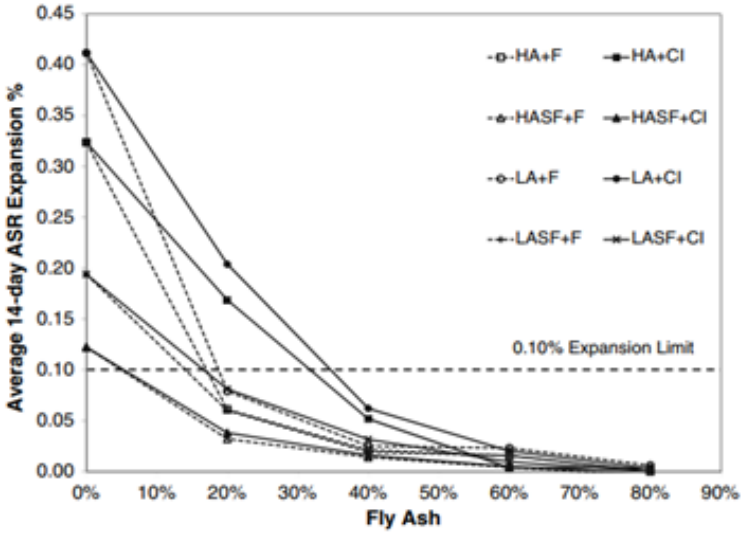


Fig. 11: Effect of fly ash on ASR expansion of concrete at 14 days (Nokken et al. 2014)

Note: F = class F fly ash; CI = class CI fly ash; LA = low-alkali cement; HA = high-alkali cement; LASF = low-alkali silica fume cement and HASF = high -alkali silica fume cement.

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Moreover both types of fly ash (class CI and class F) showed excellent performance against ASR expansion of concrete specimens. Suppression of alkali-silica reaction in concrete due to use of fly ash also noticed by Thomas and Matthews (1993).

CONCLUSIONS

From the review, it is observed that fly ash contributes some advantages to concrete by increasing workability and durability of it. In case of chloride ion penetration, it is found that cement-replaced fly ash concrete samples perform better than that of concrete samples without fly ash (Bouzoubaa et al. 2002) because fly ash reduces the permeability of chloride ion into concrete. Thus, it is also suggested 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. Fly ash also 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.

From the review, it is also seen that fly ash shows better resistance against freezing and thawing, water permeability, carbonation of concrete. Moreover, an excellent performance against expansion of concrete due to acid-silica reaction (ASR) is noticed for concrete containing fly ash from the review (Thomas and Matthews 1993).

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.

Moreover, fly ash is cheaper than OPC and using fly ash in mortar/concrete reduces the heat of hydration in mortar/concrete mix. Thus, it might be concluded that fly ash could be adopted in concrete due to its cost-effectiveness, fast processing, and environmentally friendly nature (Sahoo et al. 2016).

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