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EFFECT OF FLY ASH ON WATER PERMEABILITY AND STRENGTH OF CONCRETE

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Abstract- Durability is one of the major design aspects for concrete structures exposed to aggressive environments. This paper discusses the effects of cement replacement with supplementary cementitious material fly ash on the water permeability and compressive strength development of concrete up to the curing period of 90 days. Two different grades of concrete M20 and M35, each with seven different fly ash replacement level, 10, 20, 30, 40, 50, 60 and 70% were used for the experimental program. Compressive strength and permeability coefficient was determined upto 90 days. Test results show that coefficient of permeability of concrete decreases with the increase of fly ash level up to an optimum value and then start to increase. Among all the concretes studied, the optimum amount of cement replacement is reported to be 40%, which provides around 18% lower permeability and also around 25% higher compressive strength as compared to ordinary Portland cement concrete.

Keywords: Cement, Compressive strength, Durability, Fly ash, Water permeability.

1. INTRODUCTION

Concrete is the most widely used man-made material in the world. Almost three tonnes of concrete per person are produced in the world, twice as much as the rest of all other materials together, including wood, steel, plastics and aluminium. Concrete is the second most consumed substance on Earth after water and is an essential product in the building sector. Portland cement is one of the ingredients in concrete. Cement is a fine grey powder and constitutes 7 to 15% by weight of concrete's total mass. The net cement production in the world is increased from about 1.4 billion tonnes in 1995 to almost 3 billion tonnes in the year 2010, expected to be around 5 billion tonnes in the year of 2040 [Energy efficiency]. CO_2 emission is in the range of 0.72–0.98 tonne CO_2 per tonne of cement [1] from which 50–70% comes from calcinations [2], 40–30% from fuel combustion and around 10% from transportation and other ancillaries [3]. After electricity generation company, the cement industry is a significant contributor to global CO_2 emissions. According to IPCC [4] and IEA [1] 5 to 7% of worldwide CO_2 emissions are caused by the cement industry. Its considerable energy consumption, 4–5 GJ per tonne of cement [1], is mainly due to fuel combustion. The cement industry represents around 20% of industrial carbon emissions [5], with growing production that has gained importance in the last few years [6].

Permeability is defined as the coefficient representing "the rate at which water is transmitted through a saturated specimen of concrete under an externally maintained hydraulic gradient" [7]. Permeability is inversely linked to durability in that the lower the permeability, the higher the durability of concrete. Fly ash increases the cementitious compounds, minimizes water demand and reduces bleed channels – all of which increase concrete density. These factors yield concrete of low permeability with low internal voids and hence durability is increased with regard to freeze-thaw damage and disintegration from attack by acids, salts, chlorides or sulfates.

Portland cement substitution by supplementary cementitious materials also called mineral admixtures or mineral additives such as natural pozzolana, slag, coal fly ash, silica fume, rice husk ash and wood fly ash is one of viable alternatives to reduce the amount of cement requirement [8]. It is generally agreed that with the proper selection of admixtures, mixture proportioning and curing, supplementary cementitious materials can noticeably improve the durability of concrete [9]. Recently these has been a growing trend for the use of supplementary cementitious materials, whether natural waste or by products, in the production of composite cement because of ecological, economical and diversified product quality reason. Mineral admixtures should be studied in research level in order to understand their ability to enhance the properties of concrete.

Fly ash is one of the most common pozzolan and is being used quite extensively. Nowadays the utilization of fly ash in concrete as partial replacement of cement has increased rapidly. Fly ash contains high amount siliceous and aluminous compounds and has high potential to be used as pozzolanic material to partially replace cement in concrete [10]**.** Through pozzolanic activity, fly ash chemically combines with water and calcium hydroxide, forming additional cementitious compounds which result in denser, higher strength concrete. The calcium hydroxide chemically combined with fly ash is not subject to leaching, thereby helping to maintain high density. The conversion of soluble calcium hydroxide to cementitious compounds decreases bleed channels, capillary channels and void spaces and thereby reduces permeability. Depending on the location of each power plant, the unused fly ash is disposed at the ponds, lagoons or landfills. When unused fly ash and bottom ash disposed from coal combustion power plants, it makes major negative environment effects such as air pollution and groundwater quality problem due to leaching of metals from the ashes, specially unused fly ash which has very small particle size [11]. The cement content in concrete mixture can be reduced by using fly ash as a replacement of cement, inconsequence, decreasing both energy and CO_2 from the production of cement. This CO_2 is a major contributor to the greenhouse effect as well as responsible for global warming of the planet [12]. The fineness or particle size of fly ash is an important factor in developing the strength of concrete. According to the ASTM 618, the fly ash is suitable for use in concrete when no more than 34 percent of the particle is retained on the No. 325 (45µm) sieve. Fineness of ground disposed fly ash plays very important role on compressive strength of concrete. However, the ground disposed fly ashes which have particle sizes retained on sieve No. 325 less than 5% by weight can be used as good pozzolanic material [13].

Compressive strength is the most important design parameter for any types of concrete structures. This critical parameter drives the design process and can influence the cost of a structure as well as a project. Through the use of certain mineral admixtures, the cost of concrete can be reduced. These admixtures also enhance the properties of mortar or concrete. The ACI Committee, 232 reported that the properties of freshly mixed, unhardened concrete and the strength of hardened concrete are influenced by the shape, fineness, particle size distribution and density of fly ash particle. With help of these pozzolan, less permeability and a denser calcium silicate hydrate (C–S–H) concrete can be obtained as compared with Portland cement [14]. Fly ash replacement in concrete would be remarkable cement saving as well as cost minimizing steps for the construction of concrete structures without sacrificing the strength of concrete.

The pozzolanic reaction in fly ash converts the calcium hydroxide into more of the CSH, thus leading to reduce permeability and increase strength. With the use of fly ash, the ingress of moisture, oxygen, chlorides, and aggressive chemicals are slowed significantly, thus improving durability and serviceability. The major aim of this investigation is to evaluate and explore the compatibility of the use of fly ash in structural concrete and its efficiency in enhancing concrete durability performance as well as strength characteristics through improvement of the concrete microstructure.

2. RESEARCH SIGNIFICANCE

It is now well recognized that durability of concrete is to a great extent governed by its permeability. A decrease in permeability reduces deterioration of concrete caused by various factors such as chloride attack, sulfate attack, freezing and thawing, alkali-aggregate reaction, carbonation, etc. In general, use of fly ash or other mineral admixtures causes pore as well as grain refinement which leads to reduced permeability. Optimum use of fly ash must be ensured to achieve the desired strength as well as durability requirement of the structural concrete. Use of fly ash as partial replacement of cement also ensures the proper utilization of fly ash, by-product of coal combustion in power plants, in an effective way which otherwise been dumped making environmental hazard. Limited studies are reported to carry out to investigate the permeability/transport properties of fly ash concrete as obtained by partial replacement of cement. This experimental program was carried out with a view to study the effects of inclusion of different quantities of ASTM Class F fly ash on concrete permeability as well as strength.

3. EXPERIMENTAL PROGRAM

The experimental program was planed to study the effect of replacement of cement with supplementary cementing material fly ash on the water permeability and strength of hardened cement concrete. Cement replacement at various percentage levels were used in this investigation to observe the effects of different fly ash levels on concrete in developing water permeability resistance and strength at different curing ages.

3.1 Materials Used

Concrete test specimens were cast using ASTM type-I Ordinary Portland cement (OPC), ASTM Class F Fly ash, crushed gravel as coarse aggregate and natural river sand as fine aggregate. **Table-1** provides the physical properties and chemical compositions of the OPC and fly ash.

Table 1 : Physical properties and chemical composition of ordinary portland cement and fly ash

Types	ASTM Type-I Cement	ASTM Class F Fly ash
Physical properties		
Fineness		
Passing #200 Sieve, %	95%	99%
Blains, m^2/kg	340	400
Specific gravity	3.15	--
Chemical analysis, %		
Calcium oxide, CaO	65.18	8.6
Silicon dioxide, SiO_2	20.80	59.3
Aluminum oxide, Al_2O_3	5.22	23.4
Ferric oxide, Fe_2O_3	3.15	4.8
Magnesium oxide, MgO	1.16	0.6
Sulfur trioxide, SO_3	2.19	0.1
Sodium Oxide, Na_2O	--	3.2
Loss on ignition	1.70	--
Insoluble residue	0.6	--

-- = not measured items.

12.5 mm down graded crushed stone, with fineness modulus 6.58 and specific gravity 2.70, was used as coarse aggregate. The fine aggregate was river sand with fineness modulus 2.58 and specific gravity 2.61. The gradations of coarse and fine aggregates are presented in **Table-2.**

Table 2 : Grading of aggregates

Coarse aggregate		Fine aggregate	
Sieve size, mm	Cumulative percentage retained	Sieve size, mm	Cumulative percentage retained
19	0	4.75	0
12.5	0	2.36	4
9.5	58	1.18	21.5
4.75	100	0.6	46.5
–	–	0.3	88
–	–	0.15	98
–	–	Pan	100

3.2 Mix Design and Sample Preparation

Two different grades of concrete namely M20 and M35 were used in the program. Seven different mix proportions of cement fly ash (90:10, 80:20, 70:30, 60:40, 50:50, 40:60, 30:70) were used as cmentitious material. Cement fly ash mix ratio of 100:0 i.e. plain concrete specimens were also cast as reference concrete for comparing the properties of fly ash concrete. Thus the fly ash concrete means the concrete made by using cement and fly ash as cementitious material with sand, stone chips and water. Relevant information of different concrete mixes is given in **Table-3** and **Table-4.**

3.3 Experimental Procedures

Strength

The concrete specimens were tested for compressive strength at the ages of 7, 14, 28 and 90 days in accordance with the BS EN 12390-3:2009. At each case, the reported strength is taken as the average of three tests results.

Water permeability test

Water permeability test was performed in accordance with the EN 12390-8 at the age of 28 and 90 days. The average of three test results was taken for each type of concrete specimen.

4. RESULT AND DISCUSSIONS

4.1 Compressive Strength

The compressive strength of OPC and fly ash concrete of two different grades M20 and M35 has been graphically presented in **Fig.1** and **Fig.2**. Also for the ease of comparison, the relative compressive strengths are plotted in **Fig.3** and **Fig.4**. At early ages of curing, OPC concretes achieve relatively higher compressive strength as compared to fly ash concrete.

Test result shows that 7 days compressive strength for OPC concrete is around 13%, 20%, 40%, 48%, 55%, 75% and 80% higher than M20FA10, M20FA20, M20FA30, M20FA40, M20FA50, M20FA60 and M20FA70 concrete respectively. At initial age of curing, compressive strength is seen to decrease with the increase of fly ash content as a replacement of cement when compared with no fly ash concrete. For relatively longer period of curing, compressive strength of the fly ash concrete specimens up to 40% replacement level are higher than that of OPC concrete.

Table 3 : Mix proportions and properties of fresh concrete M20 grade

Mixture constituent & properties (kg/m^3)	Mix Type*							
	M20 FA0	M20 FA10	M20 FA20	M20 FA30	M20 FA40	M20 FA50	M20 FA60	M20 FA70
Cement	435	391.5	348	304.5	261	217.5	174	130.5
Fly Ash	0	43.5	87	130.5	174	217.5	261	304.5
Water	200	200	200	200	200	200	200	200
Sand	545	545	545	545	545	545	545	545
Stone Chips	1150	1150	1150	1150	1150	1150	1150	1150
w/(c+fa)	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
Slump (mm)	68	72	71	75	77	79	82	83
Air content %	1.3	1.3	1.6	1.7	1.7	1.8	1.9	1.9

*** M – Grade of Concrete, FA – Fly Ash, M20FA10 means Grade of concrete 20 and Cement : Fly Ash = 90:10**

Around 100 no's of cylindrical specimen of size 150 mm diameter and 175 mm high and other 200 no's of cubical specimens of 100 mm size from eight different types of fly ash concretes were prepared according to the mix proportion as described. The small size of specimen i.e. 100 mm cube was taken in order to accommodate large number of specimens in the limited sized curing tanks. The specimens were demoulded after 24 hours of casting and cured in plain water at 27±2°C.

28 days compressive strength of OPC concrete of M20 grade is higher by around by 7%, 28% and 35% respectively for M20FA50, M20FA60 and M20FA70 concrete, whereas the same value is reported to be lower by 6%, 8%, 12% and 9% for M20FA10, M20FA20, M20FA30 and M20FA40 concrete respectively. Cement normally gains its maximum percentage of its strength within 28 days. During that period, lime produced form cement hydration remains within the hydration product.

Generally, this lime reacts with fly ash and imparts more strength. For this reason, concrete made with fly ash will have slightly lower strength than cement concrete at early ages of curing and higher strength at the later ages of curing. Conversely in cement concrete, this lime would remain intact and with time it would be susceptible to the effects of weathering, loss of strength and durability. Also fly ash retards the hydration of C_3S in the early stages but accelerates it at later stages. 90 days compressive strength data shows almost similar trend. 90 days compressive strength for M35FA10, M35FA20, M35FA30, C60FA40 and C50FA50 concrete are respectively 11%, 15%, 24%, 27% and 5% higher than no fly ash concrete; whereas the same value for M35FA60 and M35FA70 concrete are lower by 23% and 28% than OPC concrete.

Rate of strength gaining for different types of concrete is observed to vary with the grade of concrete. Gain in strength is higher for the higher grade of concrete. Among all the concrete studied, 90 days compressive strength is increased by about 11%, 21%, 25%, 33%, 36%, 12%, 8.3% and 7.9% for concrete M20FA0, M20FA10, M20FA20, M20FA30, M20FA40, M20FA50, M20FA60 and M20FA70 respectively as compared to 28 days strength of OPC concrete of M20 grade; whereas the same value is increased by around 11%, 23%, 27%, 37%, 40%, 16%, 8.5% and 8% for concrete M35FA0, M35FA10, M35FA20, M35FA30, M35FA40, M35FA50, M35FA60 and M35FA70 respectively compared to 28 days strength of no fly ash M35 grade concrete. At the end of 90 days curing period, the overall strength gaining for M35 grade concrete is around 4% higher as compared to M20 grade concrete. So it can be concluded that strength gaining is relatively faster for higher grade concrete as compared to lower grade concrete.

4.2 Water Permeability

Permeability characteristics of M20 and M35 grade of concrete exposed to plain water for 90 days of curing are graphically presented in **Fig.5** and **Fig.6.** Lower values of coefficient of permeability are found to associate with relatively higher grade of concrete. After 90 days of curing, the reduction of coefficient of permeability for M20 and M35 grade concrete associated with no fly ash are found 15% and 17% respectively as compared to 28 days concrete of same grade.

Table 4 : Mix proportions and properties of fresh concrete M35 grade

Mixture constituent & properties (kg/m^3)	Mix Type*							
	M35 FA0	M35 FA10	M35 FA20	M35 FA30	M35 FA40	M35 FA50	M35 FA60	M35 FA70
Cement	500	450	400	350	300	250	200	150
Fly Ash	0	50	100	150	200	250	300	350
Water	200	200	200	200	200	200	200	200
Sand	520	520	520	520	520	520	520	520
Stone Chips	1120	1120	1120	1120	1120	1120	1120	1120
w/(c+fa)	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Slump (mm)	63	66	67	69	72	73	78	79
Air content %	1.2	1.3	1.4	1.4	1.5	1.6	1.6	1.7

*** M – Grade of Concrete, FA – Fly Ash, M35FA60 means Grade of concrete 35 and Cement : Fly Ash = 40:60**

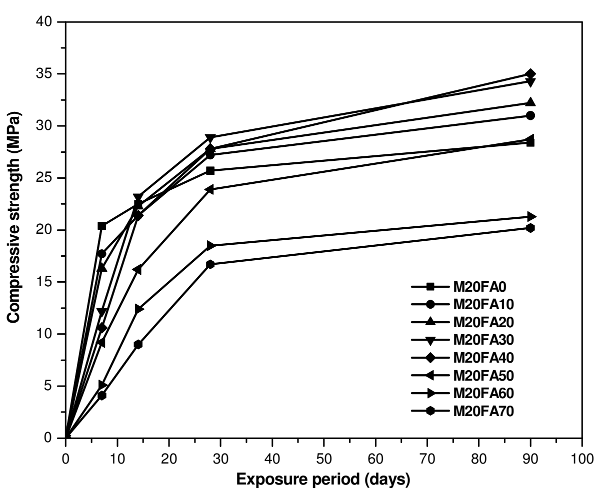

Fig.1: Compressive strength - Exposure time relation for M20 fly ash concretes

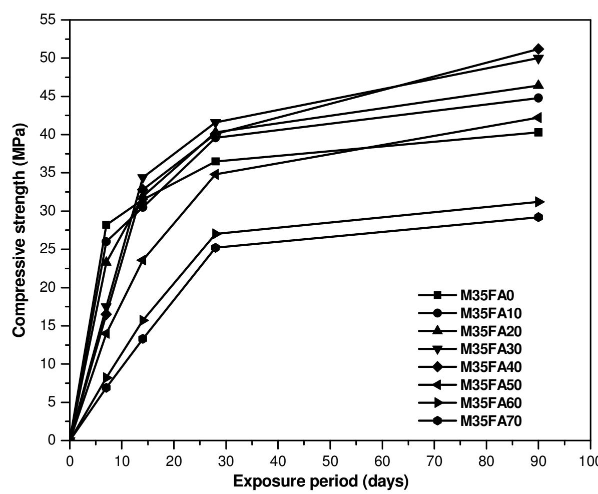

Fig.2: Compressive strength - Exposure time relationfor M35 fly ash concretes

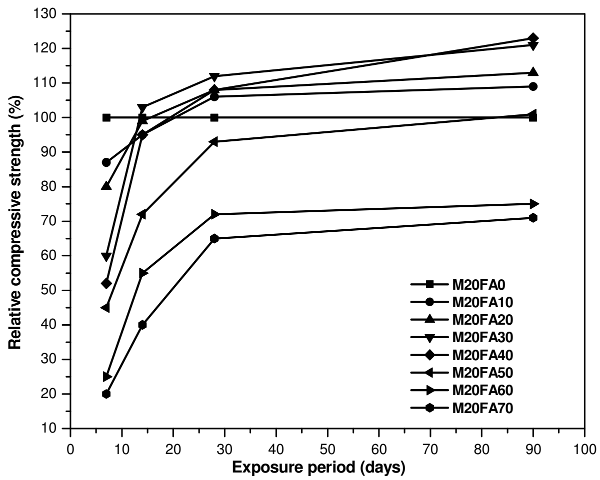

Fig.3: Relative compressive strength - Exposure time relation for M20 fly ash concretes

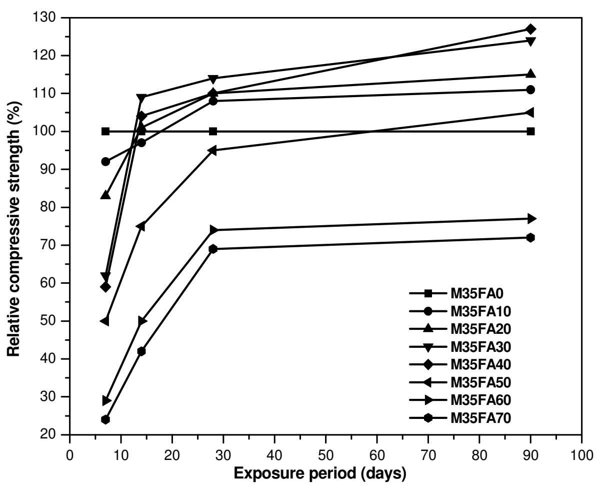

Fig.4: Relative compressive strength - Exposure time relation for M35 fly ash concretes

The permeability of all grades of concrete rapidly decreases with the increase of curing age. Coefficient of permeability values are $3.67 x 10^{-12}$ and $2.99 x 10^{-12}$ m/sec for M20FA20 concrete and $3.18 x 10^{-12}$ and $2.52 x 10^{-12}$ m/sec for M35FA20 concrete for 28 and 90 days exposure period respectively. Thus the permeability decreases very rapidly at the initial ages of curing and the rate depends on grade of concrete. The progressive decrease in permeability may be connected to the micro voids dispersed in the mortar matrix of the concrete. As the hydration of cement progresses, crystallization of compounds take place as a result of which the concrete micro voids keep on getting subdivided into capillary micro pores of increasingly smaller sizes. Many of the micro pores lose their connectivity with the passage of time. The reduction in pore sizes coupled with the loss of pore connectivity result in a substantial progressive decrease in the permeability.

Test result showed that fly ash concrete has higher resistance against water permeability as compared to OPC concrete. After 90 days curing period, coefficient of permeability values are 7%, 10%, 15%, 20%, 23%, 26% and 24% lower for M35FA10, M35FA20, M35FA30, M35FA40, M35FA50, M35FA60 and M35FA70 concretes respectively as compared to OPC concrete of M35 grade. Also for relatively longer curing period coefficient of permeability reduced faster for fly ash concrete compared to OPC concrete.

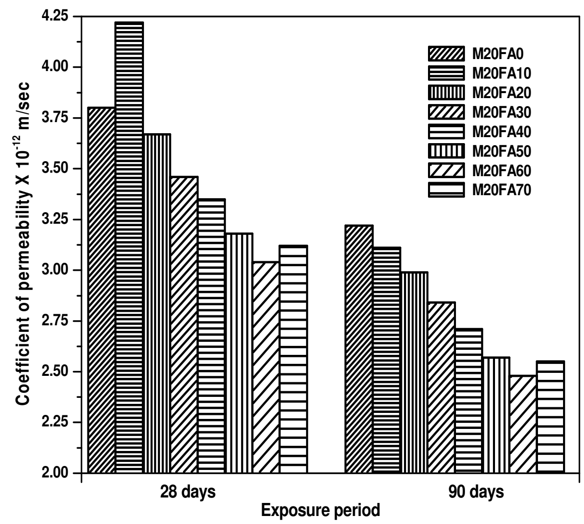

Fig.5: Permeability - Exposure time relation for M20 fly ash concretes

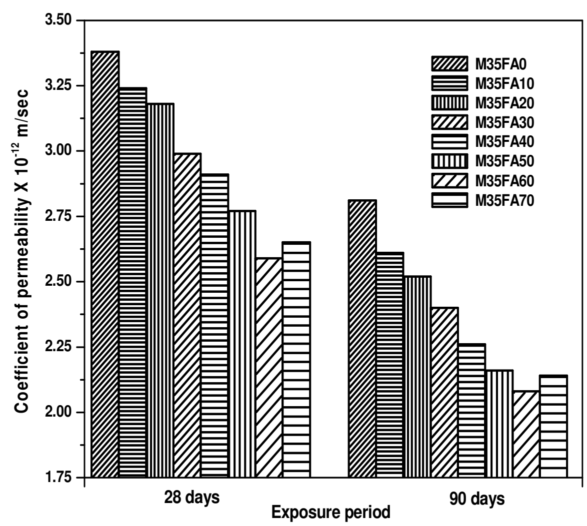

Fig.6: Permeability - Exposure time relation for M35 fly ash concretes

Overall observation showed that for 90 days curing period, coefficient of permeability value decrease around 16% for OPC concrete; whereas the same value decreases around 20%, 23%, 27%, 31%, 34%, 37% and 35% for 10%, 20%, 30%, 40%, 50%, 60% and 70% fly ash replaced concrete respectively compared to 28 days OPC concrete. As the amount of fly ash in concrete increases, water flow though the concrete specimen decreases. Fly ash has high fineness and can react with the products liberated during hydration. It forms secondary C-S-H gel that fills all the pores inside concrete specimen that makes the concrete dense and compact, as a result coefficient of permeability decreases. Among all the fly ash concretes studied upto 90 days curing period, 30%, 40%, 50% and 60% fly ash replaced concrete shows better result from water permeability test point of view. For 90 days curing period coefficient of permeability value is reduced by 15%, 20%, 23% and 26% for M35FA30, M35FA40, M35FA50 and M35FA60 as compared to OPC concrete of same curing period.

4.3 Effect of Fly Ash on Strength and Coefficient of Water Permeability

Overall observation shows that after 90 days curing, compressive strength values obtained for 10%, 20%, 30%, 40% and 50% fly ash concrete were 9%, 13%, 21%, 23% and 1% higher for M20 grade concrete as well as 11%, 15%, 24%, 27% and 5% higher for M35 grade concrete than OPC concrete. Coefficient of water permeability obtained for 30%, 40%, 50%, 60% and 70% fly ash concrete were 12%, 16%, 20%, 23% and 21% lower for M20 grade concrete and 15%, 20%, 23%, 26% and 24% lower for M35 grade concrete as compared to OPC concrete. From both strength and water permeability point of view, these fly ash concretes are comparable. Compressive strength is the most important property of concrete, durability property comes next. Among all the fly ash concrete stated, 20%, 30% and 40% fly ash concretes are better from compressive strength consideration. From these three concrete mix 40% fly ash concrete has better resistance against water permeability. 60% fly ash concrete shows best result against water permeability. Coefficient of permeability for this concrete is 25% lower as compared to OPC concrete but strength is around 25% lower as compared to OPC concrete. So this concrete is not good form strength point of view. After analyzing all the experimental result, it may be concluded that 40% fly ash concrete is best from strength as well as durability point of view.

5. CONCLUSIONS

Based on the results of the investigation conducted on different grades of concretes made with various replacement level of cement by fly ash and cured for varying curing period up to 90 days, the following conclusions are drawn:

(1) The rate of gain in compressive strength of fly ash concrete specimens is slower than OPC concrete at early ages of curing.

(2) The resistance to water permeability of concrete is significantly increased with the incorporation of fly ash. Coefficient of permeability value for fly ash concrete is observed to be rapidly decreased with curing ages as compared to OPC concrete.

(3) Fly ash concrete mix having various cement replacement level up to 50% exhibited satisfactory results for compressive strength.

(4) From both strength and water permeability consideration, the optimum fly ash content is observed to be 40% of cement. After 90 days curing, fly ash concretes with 40% cement replacement shows around 25% higher compressive strength as well as 18% lower coefficient of permeability as compared to OPC concrete.

(5) Higher grade concrete M35 showed around 3% higher strength gaining as well as 4% lower coefficient of permeability value as compared to lower grades of concrete M20.

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