Fly Ash Utilisation for Value Added Products
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Utilisation of flyash as cement replacement material to produce high performance concrete

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ABSTRACT

Disposal of fly ash, a waste product from thermal power plants, is a major problem in India. Many R&D and academic institutions are actively involved in the effective utilisation of flyash in Civil Engineering applications. The Structural Engineering Research Centre (SERC), Chennai has carried out extensive research on utilisation of fly ash in concrete as partial cement replacement material (CRM) since 1975 . Recently, SERC has carried out extensive R&D work on development of High Performance Concrete (HPC) mixes using flyash(FA), ground granulated blast furnace slag(GGBS) and silica fume(SF) as mineral admixtures, especially to improve the durability characteristics of cement concrete. This paper presents the mechanical and durability properties of different HPC mixes containing fly ash. HPCs using flyash as mineral admixture have been used to develop precast concrete products such as, non-pressure pipes and heavy duty paver blocks and these developments are reported in this paper.

Key words : *Fly ash utilisation, Cement substitute, Building materials*

1.0 INTRODUCTION

High performance concrete (HPC) is a cement based concrete possessing the most desirable properties during fresh as well as hardened concrete stages. The low porosity and the stronger transition zone of the HPCs results in their superior durability and strength characteristics[1]. However, HPCs require high cement paste volume which often leads to high shrinkage and greater heat evolution due to hydration, besides increased cost. In an attempt to solve these problems, mineral admixtures are often used as partial replacement for cement. In this investigation, flyash was used as a mineral admixture which not only improved the properties of concrete but also resulted in a reduction in the cost of concrete. Flyash in concrete makes efficient use of the products of hydration of cement, such as, calcium hydroxide (CH), which are otherwise a source of weakness in normal cement concretes and convert them into denser, stronger C-S-H compounds by pozzolanic reaction. The heat generated during hydration initiates the pozzolanic reaction of flyash[2]. When concrete containing flyash is properly cured, flyash reaction products fill in the spaces between hydrating cement particles, thus lowering the concrete permeability to water and aggressive chemicals[3]. Properly proportioned flyash concrete mixes impart properties to concrete that may not be achievable through the use of portland cement alone. These mixes are more durable, economical and strong, and also eco-friendly as it utilises an ecologically hazardous material.

During 1970s, the Structural Engineering Research Centre, Chennai has utilised flyash in concrete as partial replacement for cement, when only 33 grade cement was produced in the country. Based on the R & D work at the centre, a two storeyed building measuring 300 m^2 was constructed as early as in 1975 in SERC campus, using flyash as partial replacement of cement in precast reinforced and prestressed concrete structural elements and in cement mortar for plastering and masonry in the construction of the building. This experimental building was constructed to demonstrate the use of flyash in concrete construction with a view to effect savings in the use of cement and to study the long term performance of the building.The building is now giving excellent service for more than two decades after its construction. Recently, investigations have been carried out to develop high perfomance concrete mixes using flyash as cement replacement material and blending with 53 grade cement. Investigations have been carried out on the strength and durability characteristics of these mixes. Precast products such as heavy-duty paver blocks, non- pressure pipes, and electric poles are being developed using these mixes. This paper presents the results of the investigations on HPC mixes containing flyash and the properties of the precast products cast using these mixes.

Scope

A concrete mix to have a compressive strength at 28 days of 80 MPa was developed without using any mineral admixtures. The effect of cement replacement of 15,20,25 and 30% by flyash, by keeping the total cementitious content i.e. cement plus flyash, constant, on the various mechanical and durability properties of these mixes was then studied. The water binder (i.e. cement plus flyash) ratio was kept constant as 0.30 for the mixes in this investigations. The quantity of coarse aggregate was kept the same for all the mixes and the quantity of fine aggregate (sand) was suitably adjusted for the different cement replacement levels with flyash. The structural and durability properties of pipes and paver blocks cast using these mixes were also studied.

2.0 MATERIALS

The details of materials used in the present investigation are given below.

2.1 Cement

The properties of the cement used are given in Table 1.

2.2 Aggregates

Locally available river sand and crushed blue granite stone aggregates were used as fine and coarse aggregate respectively. The properties of these aggregates are given in Tables 2 & 3 respectively.

Table 1 : Properties of Cement

* Initial setting time = 101 minutes
* Final setting time = 224 minutes
* Standard consistency = 30%
* Compressive strength of cement mortar

  Cubes (size - 70.7 x 70.7 x 70.7 mm) as per IS:4031 (Cement : Sand = 1:3)

  3 days - 31.5 MPa

  7 days - 47.1 MPa

  14 days - 51.0 MPa

  28 days - 63.3 MPa
* Specific Gravity 3.15

Table 2 : Properties of Sand

Specific Gravity = 2.65, Bulk Density = 1650 kg/m^3

Sieve Size(mm)	Cumulative mass retained(%)	Cumulative mass passing (%)
2.36	0.0	100.0
1.18	7.2	92.8
0.600	57.8	42.2
0.300	85.3	14.7
0.150	98.7	1.3
0.075	99.2	0.8

Fineness Modules = 3.482

2.3 Flyash

A class 'F' flyash obtained from Ennore Thermal Power Plant (Tamil Nadu) was used and the properties are given in Table 4.

3.0. MIX DESIGN

The HPC mix for the present investigations was designed to have a minimum 28 days compressive strength of about 80 MPa. Since conventional mix design concepts and procedures cannot be directly applied to HPCs, the graphs and tables available for conventional mix design [4] were used for preliminary mix design and further trials were carried out to optimise all the ingredients. The aim was to achieve a minimum void content in the dry mixture of coarse aggregate, sand and cement. Further modifications in the proportions of ingredients were made by studying the cohesiveness/workability of fresh concrete mixes which required the utility of superplasticisers. The quantities of ingredients required for the concrete mix C1 are tabulated in Table 5.Mixes C2, C3, C4, C5 were obtained by replacing 15, 20, 25 & 30 of cement by flyash. The proportions of the mix are given in Table 5.

Table 3 : Properties of Coarse Aggregate

Specific Gravity = 2.71; Bulk Density = 1750 Kg/cm^2

Sieve Size(mm)	Cumulative mass retained (%)	Cumulative mass passing (%)
20.0	0.0	100.0
10.0	16.25	83.75
4.75	75.0	25.0
2.36	99.5	0.50
1.18	100.0	0.0
0.60	100.0	0.0
0.30	100.0	0.0
0.15	100.0	0.0

Fineness Modulus = 5.91

Table 4 : Chemical analysis of Fly ash

Sl. No.	Components	IS: 3812 (1981) Specifications, %	Fly ash used (Ennore), %
1.	$SiO_2 + Al_2O_3 + Fe_2O_3$	70 min.	99.0 - 99.1
2.	SiO_2 (alone)	35 min.	58.8 - 59.1
3.	MgO	5.0 max.	0.22 - 0.34
4.	Total sulphur as SO_3	2.75 max.	—
5.	Alkalies as Na_2O	1.5 max.	0.54
6.	LOI	12 max.	1.05 - 1.08
7.	CaO	—	0.86 - 1.02
8.	K_2O	—	0.05 - 0.71

Table 5 : Details of HPC Mixes

Mix designation	C1	C2	C3	C4	C5
CRM(%)	0	15	20	25	30
W/B	0.30	0.30	0.30	0.30	0.30
W/C	0.30	0.353	0.315	0.40	0.30
Cement content(kg/m^3)	534	454	428	401	374
Flyash Content(kg/m^3)	0	80	106	135	160
Aggregate Content(kg/m^3)	1848	1848	1848	1848	1848
Water ((l/m^3)	160	160	160	160	160
Superplasticizer(l/m^3)	13.3	13.2	13.3	13.4	13.17
Retarder(l/m^3)	0.4	0.4	0.4	0.4	0.4

Note : CRM-Cement Replacement Material (by mass of cement of control mix C1)

4.0 EXPERIMENTAL

4.1 Mechanical Properties

The ingredients for the various mixes were weighed and cast using a tilting drum type concrete mixer and proper uniform mixing was ensured. The specimens were cast in steel moulds and compacted on a table vibrator in three equal layers. Curing of specimens was started as soon as the top surface of the concrete in the mould attained certain hardness. The initial curing was carried out by spreading moist or wet gunny bags over the mould. 24 hours after casting, the specimens were de-moulded and placed immediately in water tanks for curing. The specimens were kept in water and were taken out just before testing. Compressive strengths were determined on 100 mm cubes after 7,28 and 90 days. In the present investigation, cylinders of 100 mm ϕ x 200 mm high were used to determine the split tensile strength and flexural tests were carried out on 100x100x500 mm beam specimens at 28 days.

4.2 Microstructure related Properties

Studies were carried out to evaluate the micro structure related properties such as saturated water absorption, porosity, coefficient of absorption, sorptivity and chloride diffusion.

4.2.1 Saturated water-absorption(SWA) : The SWA was determined on 100 mm cubes. The oven dried (at 1050°C to constant mass) concrete specimens were immersed in water until constant mass was obtained. The SWA of concrete is a measure of the pore volume in hardened concrete, which can be occupied by water in saturated condition and also the quantity of water which can be removed on drying. Higher SWA represents more pores and greater movement of water and hence higher degree of volume changes.

4.2.2 Effective Porosity[5] : This is found from the formula:

Effective porosity = Volume of voids / Gross volume of concrete specimen

The volume of voids is represented by volume of water lost on oven drying at 105°C to constant mass whereas the volume of the specimen is the difference in mass of the specimen in air and its mass under submerged condition.

4.2.3 Modified Sorptivity test[6] : Sorptivity measures the penetration of water into concrete by capillary suction. The quantity of water penetrated per unit surface area of exposure to water is plotted against the square root of time of exposure. The test data generally falls on a straight line passing through the origin. The slope of this straight line is considered as a measure of rate of movement of water through the capillary pores and is called sorptivity. Lower value of sorptivity is preferable. In the present study, the water penetration studies were made on 100 mm cubes by immersing them in water and measuring the gain in weight at different intervals.

4.2.4 Coefficient of absorption[7]

This is calculated from the formula

Coefficient of absorption $Ka = (Q/A)^2 \times (1/t)$

Where Q = Quantity of water absorbed by the oven dried specimen in time
t = 60 minutes.
A = Total surface area of concrete specimen through which water penetrates.

A lower value of Ka indicates a higher degree of imperviousness of concrete for water penetration.

4.2.5 Chloride diffusion : This is a modified version of chloride permeability test of AASHTO T-277[8] and ASTM C-1202[9]. Test specimens were of size 100x100x20 mm. The specimen was fixed in between two reservoirs/cells containing ionic solutions. One of the cells with saturated calcium hydroxide solution and the other cell was filled with saturated calcium hydroxide solution containing 2.4M, NaCl. Copper rods, inserted in each of the two cells, act as electrodes. 12V direct electric current was passed through the electrode to accelerate the migration of chloride ions from one cell to the other through the specimen. The intensity of current and the concentration of chloride in the two cells were periodically monitored. The diffusion coefficient was calculated, based on Nernst-Einstein equation[10].

5.0 RESULTS AND DISCUSSION

5.1 Effect of Cement Content

The compressive strength at 7,28 and 90 days of all the 5 series of mixes are tabulated in Table 6. It is observed that the compressive strength at 7 days for mixes containing 0, 15, 20, 25 and 30% cement replacements were 63.2, 56.5, 53.2, 49.2 and 48.9 MPa, respectively. The strengths at 28 days were 83.5, 89.5, 87.5, 85.2 and 75.2, respectively.

Table 6 : Compressive Strength of HPC Mixes

Mix	CRM(%)	Compressive Strength, σ_c, MPa		
		7 days	28 days	90 days
C1	0	63.2	83.5	93.7
C2	15	56.5	89.5	94
C3	20	53.2	87.4	95.0
C4	25	49.5	85.2	94.0
C5	30	48.9	75.2	86.0

The strengths at 90 days were 93.7, 94.0, 95.0, 94.0 and 86.0, respectively. Thus, it can be seen that by the addition of flyash, the strength at 7 days (Table 6) of the FA based HPCs has marginally decreased where as the strength at 28 days was observed to be slightly greater than that of the reference HPC mix. The decrease in strength at 7 days for the FA based HPCs varies from 10 to 23% for cement levels with FA of 15 to 30% when compared with the strength at 7 days of control mix having no CRM. However, the strengths at 90 days tend to be the same for replacement levels up to 25%. The reduction in the strength at 7 days may be attributed to reduction in the cement content, slower pozzolanic reaction at early ages and increase in the water-cement ratio. However, at the age of 28 days, the increase in pozzolanic activity was sufficient to contribute to the compressive strength. Thus, the efficiency of flyash to act as cementitious material has increased substantially at 28 days and the strength development continues beyond 28 days and stabilises towards 90 days.

Beyond 28 days, the FA- HPCs have marginally higher strength than HPC without flyash. This demonstrates that the replacement of cement by flyash even up to 30% for compressive strength of 80 MPa at 28 days is possible without loss of strength and resulting in saving in consumption of cement.

5.2 Rate of Compressive Strength Development

Based on the present investigation, the compressive strengths at 7 days and 90 days are compared with the compressive strength at 28 days in Table 6. The values of strength obtained with w/c ratio of 0.30 were 48.9 to 63.2 MPa at 7 days, 75.2 to 93.5 MPa at 28 days and 86 to 95 MPa at 90 days. In Table 7, these strengths at various ages are expressed relative to that at 28 days. The strength at 7 days varies for 58 to 76% of the strength at 28 days. The increase in strength at 90 days is 5 to 14% over the strength at 28 days.

5.3 Tensile and Flexural strength

The tensile and flexural strength of mixes C1, C2, C3, C4 and C5 are given in Table 8. The tensile strength at 28 days varies from 4.7 to 5.2 MPa and the flexural strength at 28 days varies from 6.3 to 7.5 MPa. It can be seen that the tensile and flexural strength of mixes (except mix C5) with flyash always recorded a higher tensile strength than the control mix without flyash.

Table 7 : Rate of compressive strength development

Mix designation	σ_{C7}/σ_{C28}	σ_{C7}/σ_{C90}	$\sigma_{C90}/\sigma_{C28}$
C1	75.7	67.5	112.2
C2	63.1	60.1	105.0
C3	60.9	56.0	108.7
C4	58.1	52.7	110.3
C5	65.0	56.9	114.4

σ_{C7}, σ_{C28}, σ_{C90} = Compressive strength of concrete at 7, 28, and 90 days, respectively

Table 8 : Tensile and Flexural Strength of HPCs

Mix designation	C1	C2	C3	C4	C5
CRM(%)	0	15	20	25	30
σ_{C28} (MPa)	83.5	89.5	87.4	85.2	75.2
σ_{t28} (MPa)	4.7	4.8	5.2	4.8	4.9
σ_{b28} (MPa)	6.9	7.4	7.3	7.5	6.3
$\sigma_{b28}/\sigma_{C28}$	0.08	0.08	0.08	0.08	0.084
$\sigma_{t28}/\sigma_{C28}$	0.056	0.05	0.05	0.05	0.065
$\sigma_{t28}/\sigma_{b28}$	0.68	0.65	0.71	0.64	0.78

$\sigma_{c28}/\sigma_{t28}$, σ_{b28} = Compressive, tensile and flexural strength of concrete at 28 days, respectively.

5.4 Durability related properties

After 90 days of water curing, the specimens were tested to determine the durability related properties such as saturated water absorption, porosity, sorptivity, coefficient of water absorption, and chloride diffusion as the results are given in Table 9. These results are discussed below. The mix C1 which had no flyash, is considered as control mix and the properties of mixes containing various levels of flyash are discussed with reference to control mix C1.

5.4.1 Water Absorption: The saturated water absorption of the mixes C1 to C5 was around 3%. However, flyash based mixes showed 30 to 50% reduction in coefficient of water absorption compared to control mix C1.

5.4.2 Effective Porosity and Sorptivity : The effective porosity for the mixes C1 to C5 ranged from 7.22 % to 8.06% The sorptivity value for the control mix C1 was high as 9.04 x 10^{-6} m/√s, whereas the mixes C2 to C5 (containing flyash) were less than that of mix C1 and the sorptivity values was in the range of 6.40 x 10^{-6} to 7.31x 10^{-6} m/√s. Thus mixes with flyash showed less sorptivity compared to control mix C1.

5.4.3 Chloride Diffusion : The results of chloride diffusion test are available only for mixes C1 and C4. It is seen that the diffusion coefficient is about 50% less for mix C4 compared to control mix C1.

Table 9 : Micro-structure related properties

Mix designation	C1	C2	C3	C4	C5
CRM(%)	0	15	20	25	30
Saturated Water Absorption, %	3.10	3.3	2.95	3.12	3.34
Porosity, ((%)	7.84	7.93	7.22	7.61	8.06
Coefficient of water absorption x 10^{-10} m²/s	1.36	0.89	0.73	0.60	0.70
Modified sorptivity x 10^{-10} m/√s	9.04	7.31	6.63	6.40	6.48
Chloride diffusivity (x10^{-12} m²/s) under 12V DC	0.204	–	–	0.102	–

6.0 PRECAST PRODUCTS

From the results of tests for durability related properties, especially chloride diffusion, coefficient of water absorption and sorptivity, it is noted that flyash based HPC is most suitable for producing the precast products which are exposed to aggressive environments, especially in coastal regions, with a view to have long term durability and minimise the expensive maintenance. For this purpose, SERC is developing two important products which have large scale consumption, viz., non-pressure pipes and heavy duty paver blocks using flyash based HPC mixes. The preliminary results of the developments are given below.

6.1 Non-Pressure Pipes

Un reinforced non-pressure pipes of 165 mm diameter and 25 mm thickness were cast and tested (Fig. 1) as per IS : 3597 - 1985[11]. Fig. 2. shows the failure pattern of pipe specimens tested under three-edge bearing test. The test results indicate that the pipes can be classified as Class NP3 (heavy duty for drainage and irrigation use, for culverts carrying heavy traffic, such as railway loading as per IS : 458 - 1988[12]). The addition of Fly Ash to HPC mix has not affected the properties of pipes even though this results in a net reduction in cement content.

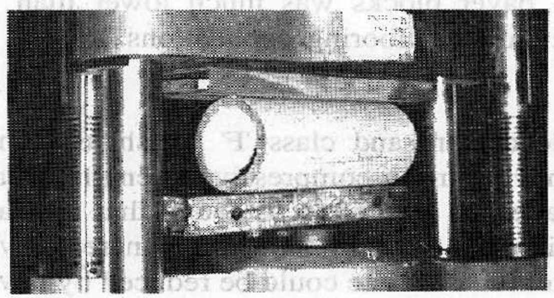

Fig. 1 : Three-Edge Bearing Capacity Test on Pipe Specimens

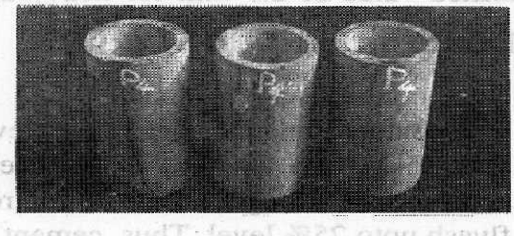

Fig. 2 Failure Pattern of Pipe Specimens under Three-Edge Bearing Test

6.2 Paver Blocks

Paver Blocks (PBs) of size 100 x 100 x 200 mm were cast using control Mix C1 and HPC mix C2 in steel moulds. Table vibrator was used for compaction of concrete. Demoulding of blocks was done 24 hours after the casting. The paver blocks were tested after curing with water for 28 days.

(a) Compression Test

Compressive strengths of paver blocks of mixes C1 and C2 at 28-days were found to be 70.2 and 80.0 MPa, respectively.

(b) Flexural Test

The paver blocks were tested under 3 point loading with a span of 160 mm. The average flexural strength of paver blocks produced using mixes C1 and C2 were found to be 12.3 and 13.9 MPa, respectively, at 28 days. These strengths are more than those obtained from beam specimens of size - 100 x 100 x 500 mm. This may be attributed to the use of simple bending theory for computation of flexural strength of paver blocks, where actually, deep beam effect needs to be considered.

(c) Water Absorption

Oven dried (at 105oC and for 72 hours) paver blocks were soaked in water for 24 hours and the water absorption was measured. It was found to be 0.99 and 0.81% for paver blocks of mixes C1 and C2, respectively.

(d) Abrasion Resistance

Specimens of size 68 x 68 x 30 mm cut from paver blocks were used to determine abrasion resistance using a tile abrasion testing machine as per IS : 1237[13]. The abrasion loss after 220 revolutions was found to be 1.41 and 0.87 mm for mixes C1 and C2, respectively. Thus, addition of FA was found to improve the abrasion resistance of paver blocks. The abrasion loss recorded for the paver blocks was much lower than the permitted value of 2.5 mm for heavy-duty industrial flooring applications.

7. 0 CONCLUDING REMARKS

1) HPC mixes using a blend of 53 grade cement and class 'F' flyash as cement replacement material upto 30% level, having mean compressive strength greater than 75 MPa at 28 days, have been made and studied. It is found that the same compressive strength as that of control mix at 28 days is obtained in concrete having flyash upto 25% level. Thus, cement content in concrete could be reduced by having flyash as CRM to produce concrete having mean target strength of 85 MPa at 28 days.

2) The 28 and 90 days compressive strengths of flyash based HPCs are found to be more than that of control mix for cement replacement levels up to 25%. Thus, flyash, for binder content considered in this study, acts as a highly efficient cementing material in concrete mix at ages beyond 7 days.

3) The 90 days compressive strength of HPCs with flyash upto 25% of replacement level tends to be in the same range.

4) Since concrete mixes having flyash as CRM have lesser cement content, adverse effects related to higher cement content, such as shrinkage, excessive rate of heat development etc., are minimized in the concrete.

5) Mixes having flyash as CRM are found to be more durable and corrosion resistant due to their refined pore size distribution, as seen from lower sorptivity and reduced chloride diffusion coefficient obtained in this study. Re-inforced concrete structures and precast products made with concrete having flyash as CRM would, therefore have long, maintenance-free service life.

6) In India, at present, in majority of reinforced or prestressed cement concrete construction, concrete having characteristic compressive strength upto 60 MPa at 28 days is being used. In this study, it is noted that for such low strength concretes, use of flyash as cement replacement material even beyond 30% level. Such concretes can have enhanced durability and hence long service life. Investigations are in progress at SERC to characterize such HPC mixes.

8.0 ACKNOWLEDGEMENT

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