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Laboratory Investigations on Mechanical Properties of High Volume Fly Ash Concrete and Composite Sections

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***Abstract*—**Use of fly ash as a supplementary cementing material in large volumes can bring both technological and economic benefits for concrete industry. In this investigation mix proportions for high volume fly ash concrete were determined at cement replacement levels of 50%, 55%, 60% and 65% with low calcium fly ash. Flexural and compressive strengths of different mixes were measured at ages of 7, 28 and 90 days. Flexural strength of composite section prepared from pavement quality and lean high volume fly ash concrete was determined at the age of 28 days. High volume fly ash concrete mixes exhibited higher rate of strength gain and age factors than corresponding reference concrete mixes. The optimum cement replacement level for pavement quality concrete was found to be 60%. The consideration of bond between pavement quality and lean of high volume fly ash concrete will be beneficial in design of rigid pavements.

***Keywords*—**Composite section, Compressive strength, Flexural strength, Fly ash.

I. Introduction

SUSTAINABLE development of the cement and construction industries can be achieved by maximizing the use of supplementary cementitious materials. Supplementary cementitious materials may be classified as natural and artificial materials. Fly ash is a pozolanic material which in presence of moisture reacts with $Ca(OH)_2$ to form strong CSH gel during the hydration process of cement. This results in more refined pore structure of concrete increasing the performance characteristics. Fly ash is classified into two categories [1]. The first category is referred to as class C fly ash, which contains between 15 to 35 percent of CaO. This ash is generally obtained from the combustion of lignite and bituminous coals. The second category is low-calcium fly ash referred as class F, which usually contains less than 5 percent of CaO. Because of the difference in calcium content, the reactivity between the two types of fly ash is different. Low-calcium or Class F fly ash is less reactive and needs about 2 weeks to hydrate.

The high volume fly ash concrete is one specific type of fly ash concrete with higher fly ash contents, lower water to cementitious materials ratio (w/cm), and lower cement contents. This is to take full advantages of the increased workability and durability, provided by fly ash and the low w/cm, and to produce a more environmentally friendly concrete by reducing its cement content. As per the definition given by Mehta [2], a concrete having minimum cement replacement level of 50% by fly ash is termed as high volume fly ash concrete (HFC).

The compressive strength of concrete containing fly ash is generally lower than that of regular concrete, especially in its early ages [3]-[5]. Despite the lower early-age compressive strength of fly ash concrete, the long-term compressive strength of HFC is comparable with regular concrete after 90 days; this is because of the late (usually after 2 weeks) hydration of fly ash. Malohtra et al. [6] have reported that usage of supplementary cementitious materials results in reduction of green house effect. They emphasized on the necessity of adequate percentage of superplasticizer and air content for optimum performance of high volume fly ash concrete. It was concluded that the dosage of superplasicizer is dependent on characteristics of cement and fly ash mainly. Naik et al. [7] investigated the long-term performance of concrete pavements made with high volumes of Class F and Class C fly ash. Test results revealed that both Class C and Class F fly ash contributed to higher long-term compressive strength. Binodkumar et al. [8] reported that HVFA concrete mixtures containing 50-60% fly ash could be designed to fulfill the requirement of strength and workability suitable for cement concrete pavement construction.

A dry lean concrete (DLC) sub base is generally recommended for modern concrete pavements, particularly in case of high intensity traffic. DLC layer helps in distribution of wheel load stresses much effectively and in turn reducing the thickness of pavement quality concrete. The bond between pavement quality concrete and lean concrete helps in reducing the stresses generated due to increased flexural stiffness. The lower cement content in DLC makes it an economically viable option. But there are concerns expressed over propagation of crack generated in DLC into pavement quality concrete. Hence current Indian codal provisions [9] suggest a separation layer between DLC and overlaying concrete. Behavior of fully bonded pavement quality concrete and DLC layers is still on an experimental stage.

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II. Research Significance and Scope

The current work is aimed at determining the mix proportions of HFC and optimum cement replacement level mainly for pavement applications. Also investigations were conducted to establish the long term strength behavior and relations between different strength properties.

Also it is aimed to study the static flexural strength of composite sections made up of pavement quality and lean high volume fly ash concrete, a property which will be helpful in design of rigid pavements. A total of 66 cube specimens were tested under compression to study the behavior of HFC and establish mixture proportion for lean high volume fly ash concrete (LHFC). A similar number of beam specimens were tested under pure flexure. For determining static flexural strength of composite sections 6 number of beam specimens have been used.

III. Laboratory Investigations

A. Materials

Ordinary Portland cement from single batch has been used in the present investigation. The specific gravity and 28 day compressive strength of cement were respectively 3.14 and 55MPa. The coarse fraction consisted of equal fractions of crushed stones of maximum size 20mm and 12mm confirming to gradation specified by codal provisions [10]. Low calcium fly ash satisfying the criteria of fineness, lime reactivity and compressive strength requirements [11] has been used in the investigation. Properties of fly ash are listed in Table I. Fine aggregate used was natural river sand with maximum particle size of 4.75mm confirming to zone-II gradation [10]. Polycarboxylic based superplasticizer has been used as high range water reducing admixture (HRWA) to get the desired workability. The optimum dosage of superplasticizer was fixed by carrying out compaction factor test. Since the mixes with high levels of cement replacement levels were sticky target compaction factor was kept in the range of 0.90 to 0.91.

TABLE I
Physical Properties of Fly Ash

Characteristics	Laboratory value	Requirements as per IS 3812
Particles retained on 45μ IS sieve (wet sieving) in percent	29	Max 34
Lime reactivity in N/mm^2	4.9	Min 4.5
Compressive strength at 28 days	88% of the strength of corresponding plain cement mortar cubes	Minimum of 80% of the strength of corresponding plain cement mortar cubes
Specific gravity	2.01	--------

B. Mixture Proportions

A minimum grade of M30 which results in a minimum static flexural strength of 3.9N/mm^2 has been specified for pavement quality concrete [12]. Water to cementitious ratios (w/cm) of 0.35 and 0.3 has been used in the investigation. Trial mixes were developed for HFC mixes with cement replacement levels of 50%, 55%, 60% and 65% at each w/cm ratio. Lower limit of w/cm utilized in the investigation i.e., 0.3 was the lowest value that could be used from the limitation of reduction in water content that can be achieved using HRWA and usage of conventional means of mixing and compaction. Corresponding concrete with 0% replacement has been used as reference concrete (PCC).

HFC mix proportions were obtained using the criteria of density of concrete and air entrainment of 2%. The quantity of fine aggregate was adjusted for HFC mixes for the difference in specific gravity value of cement and fly ash. Trial mix proportion for LHFC was developed from trial mix proportion specified for lean PCC mix in the literature [13]. Mix proportions for all the types of concretes are presented in Tables II to IV. In Tables II and III high volume fly ash concrete mixes with cement replacement levels of 50%, 55%, 60%, 65% are denoted by HFC50, HFC55, HFC60 and HFC65 respectively. P1 and P2 represent PCC mixes with w/cm ratio of o.3 and 0.35 respectively.

TABLE II
MIXTURE Proportions of Concrete with w/cm = 0.30

Mix Designation/Mixture Components	P1	HFC50	HFC55	HFC60	HFC65
Cement (OPC 53 grade) in kg/m^3	440	220	198	176	154
Class F fly ash in kg/m^3	0	220	242	264	286
Water in kg/m^3	132	132	132	132	132
Superplasticizer in liter/m^3	15.4	3.5	3.5	3.5	3.5
Saturated surface dry sand in kg/m^3	937.6	871	865.9	858.2	853.1
Saturated surface dry coarse aggregate in kg/m^3	1059	1059	1059	1059	1059

TABLE III
MIXTURE PROPORTIONS OF CONCRETE WITH W/CM = 0.35

Mix Designation/Mixture Components	P2	HFC50	HFC55	HFC60	HFC65
Cement (OPC 53 grade) in kg/m^3	440	220	198	176	155
Class F fly ash in kg/m^3	0	220	242	264	285
Water in kg/m^3	154	154	154	154	154
Superplasticizer in liter/m^3	9.9	1.76	1.76	1.76	1.76
Saturated surface dry sand in kg/m^3	871.0	807.0	799.3	791.6	789.0
Saturated surface dry coarse aggregate in kg/m^3	1059	1059	1059	1059	1059

TABLE IV
MIXTURE PROPORTIONS OF LEAN HIGH VOLUME FLY ASH CONCRETE

Mix Designation/Mixture Components	LHFC
Cement (OPC 53 grade) in kg/m^3	88
Class F fly ash in kg/m^3	132
Water in kg/m^3	132
Superplasticizer in liter/m^3	0
Saturated surface dry sand in kg/m^3	660
Saturated surface dry coarse aggregate in kg/m^3	1100

C. Test Specimens and Test Procedure

Cube specimens of size 150mm×150mm×150mm were used for determining compressive strength. Beam specimens of size 75mm×100mm×500mm confirming ASTM C 78 [14] have been used for determining static flexural strength of HFC mixes. For flexural testing of composite sections beam specimens of size 75mm×200mm×500mm have been used. In case of composite sections top 100mm depth was of HFC60 and bottom 100mm depth consisted of LHFC. Bond between HFC60 and LHFC was achieved by using unfinished top surface of LHFC and casting the HFC60 above that after initial setting time of LHFC and no additional treatments were used. Static test in flexure was conducted using third point loading. Typical beam specimens used for HFC and composite section are shown in Figs. 1 and 2 respectively.

The compressive and flexural strength tests were conducted as per [15]. Wet curing was done for first 24 hours. After that specimens were immersed in potable water until testing. Compressive and flexural strengths were determined at three ages i.e., after 7 days, 28 days and 90 days for HFC and PCC specimens. At each age six specimens of each mixture were tested for strength properties and the mean of these values is reported. For composite specimens, 28 day flexural strength has been reported as average result of six specimens.

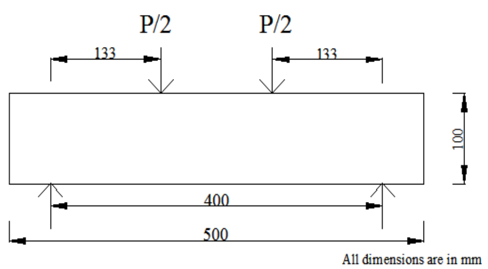

Fig. 1 Beam specimen for flexural testing of HFC and PCC

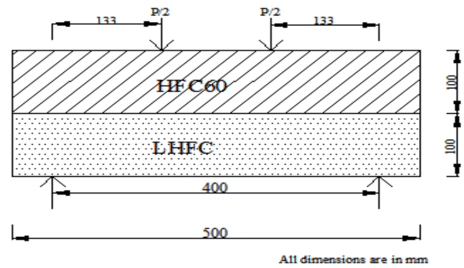

Fig. 2 Beam specimen for flexural testing of composite sections

IV. RESULTS AND DISCUSSION

A. Compressive Strength of HFC

The experimental results are presented in Figs. 3 and 4. Ratios of 7 day strength (f_{c7}) to 28 day strength (f_{c28}) and 90 day strength (f_{c90}) to 28 day strength (age factor) are presented in Table V. From figures and tables it is evident that rate of strength gain is significantly higher for HFC mixes when compared with reference mixes at both w/cm ratios. Strength gain was insignificant after 28 days for PCC mixes. But for HFC mixes there was considerable strength gain even up to age of 90 days. Rate of strength gain was highest for HFC mix with 50% cement replacement level. Strength gain mechanism is mainly due to pozolanic activity. Since age factor for HFC mixes is varying from 1.14 to 1.22 due consideration has to be given for strength gain mechanism in the design of structures using HFC.

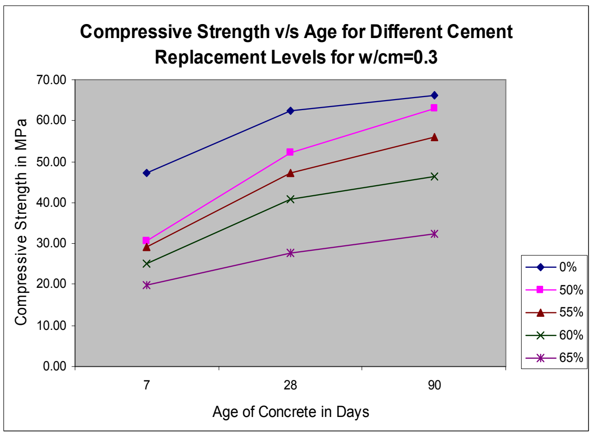

Fig. 3 Compressive strength development in concrete (w/cm = 0.30)

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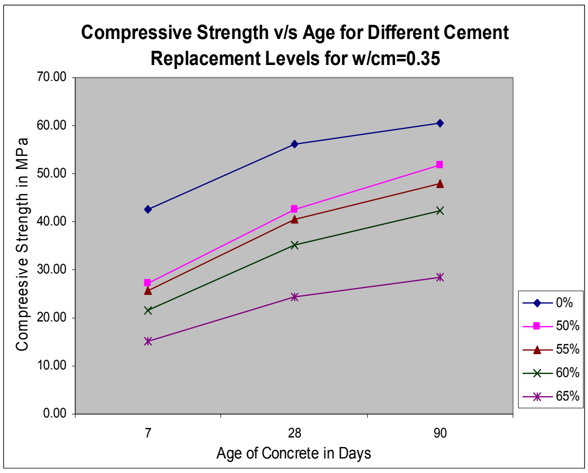

Fig. 4 Compressive strength development in concrete (w/cm = 0.35)

TABLE V
RATIOS OF 7 DAY COMPRESSIVE STRENGTH TO 28 DAY COMPRESSIVE STRENGTH AND AGE FACTORS IN COMPRESSION FOR DIFFERENT CONCRETE MIXES

Property/Mix Designation	w/cm of the mix	f_{c7}/f_{c28}	Age Factor
P1	0.3	75.96	1.06
P2	0.35	75.65	1.08
HFC50	0.3	58.72	1.21
	0.35	64.21	1.22
HFC55	0.3	61.44	1.18
	0.35	63.15	1.18
HFC60	0.3	61.39	1.14
	0.35	61.57	1.19
HFC65	0.3	71.39	1.17
	0.35	61.90	1.17

B. Flexural Strength of HFC

Variation of flexural strength with age is shown in Figs. 5 and 6. Age factors with reference to flexural strength gain (f_{b90}/f_{b28}) and ratios of 7 day flexural strength (f_{b7}) to 28 day flexural strength (f_{b28}) are listed in Table VI. Similar trend to that of compressive strength gain was shown in case of flexural strength also. Age factors in flexure were higher for HFC mixes than that for PCC mixes. But age factor in flexure for HFC mixes were lower than the corresponding values in compression. 7 day and 28 day strengths of HFC were lower than the corresponding values of PCC. In case of HFC50 flexural strength value at 90 days (f_{b90}) is nearly equal to that of reference PCC at both w/cm ratios. HFC mix with 60% cement replacement level and with w/cm of 0.3 has satisfied the flexural strength criteria of pavement quality concrete. A relation between 28 day flexural strength (f_{b28}) and compressive strength (f_{c28}) was developed for HFC mix by conducting regression analysis. The relation obtained is given by (1).

$$f_{b28} = 0.1214 f_{c28} - 0.0811 \quad (1)$$

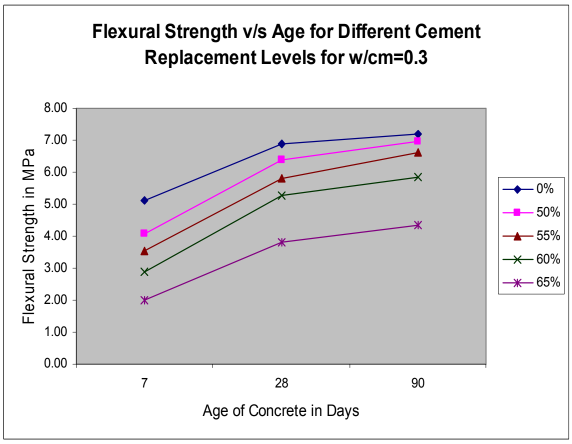

Fig. 5 Flexural strength development in concrete (w/cm = 0.30)

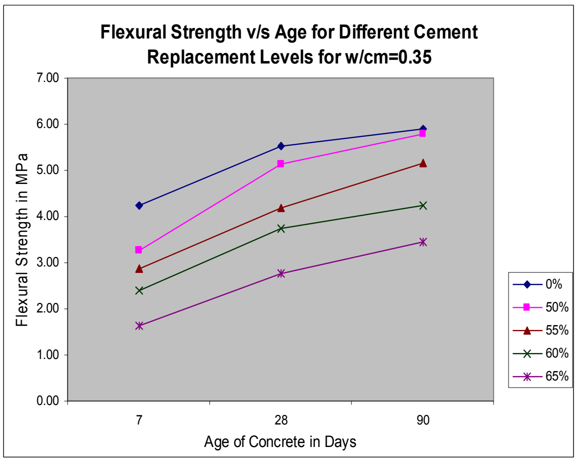

Fig. 6 Flexural strength development in concrete (w/cm = 0.35)

TABLE VI
RATIOS OF 7 DAY FLEXURAL STRENGTH TO 28 DAY FLEXURAL STRENGTH AND AGE FACTORS IN FLEXURE FOR DIFFERENT CONCRETE MIXES

Property/Mix Designation	w/cm of the mix	f_{b7}/f_{b28}	Age Factor
P1	0.3	74.27	1.05
P2	0.35	76.39	1.06
HFC50	0.3	64.04	1.10
	0.35	63.83	1.13
HFC55	0.3	61.05	1.13
	0.35	68.23	1.16
HFC60	0.3	54.77	1.12
	0.35	64.29	1.14
HFC65	0.3	52.50	1.14
	0.35	59.06	1.15

C. Flexural Strength of Composite Sections

Flexural strength of composite section was determined after a curing period of 28days. Static compressive strength and flexural strength values for HFC60 with w/cm of 0.3 and LHFC are shown in Table VII. Ultimate static flexural load for HFC60, LHFC and composite sections are also shown in Table VII. The advantage of a composite system with pavement quality concrete and lean concrete can be seen in the increase in the ultimate flexural load value. The increase in

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ultimate flexural load value for composite section was 53.5% when compared with that of HFC section. The failure plain for all the specimens was lying in the flexural zone. Hence deep beam effect was not seen in any of the specimens. The bonding between HFC60 and LHFC was perfect as indicated by static test. The progress of crack did not stop at interface of pavement quality and lean concrete, instead whole beam cracked by the extension of single crack through the depth. The interface between the two concretes allowed stresses and strains to pass through it thus indicating possibility of stress concentration at the interface. Even though the phenomenon of failure of composite section by a single vertical crack raises apprehensions about usage of bonding between the two layers, the bond will be beneficial from the consideration of higher load carrying capacity and stiffer construction.

TABLE VII
MECHANICAL PROPERTIES OF CONCRETE

Property of concrete/ Type of concrete	28 day characteristic cube compressive strength* in MPa	28 day Ultimate Flexural Load (P) in Static Test in kN*	28 day characteristic static flexural strength* in MPa
HFC60	40.8	9.9	5.3
LHFC	14.5	4.2	2.2
Composite Section	-----	15.2	-----

* Average value of six specimens

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V. CONCLUSIONS

Based on experimental investigations following conclusions were made.

- Even though early strength of HFC mixes is less than PCC mixes, the rate of strength gain is higher in case of HFC mixes at all ages.
- Strength gain mechanism for HFC mixes is mainly due to pozolanic action exhibited by fly ash.
- Optimum percentage of cement replacement for pavement quality concrete is 60%.
- Age factor for HFC mixes in compression varies from 1.14 to 1.22 while in case of PCC mixes it varies from 1.06 to 1.08.
- Age factor for HFC mixes in flexure varies from 1.10 to 1.16 while in case of PCC mixes it varies from 1.05 to 1.06.
- Relation between 28 day flexural strength and compressive strength for HFC is given by:

$$f_{b28} = 0.1214 f_{c28} - 0.0811$$

- In case of composite sections perfect bonding was exhibited between HFC60 and LHFC as indicated by static flexural test. The bond can be obtained without any additional treatments
- From the criteria of higher load carrying capacity and much stiffer construction the bond between pavement quality HFC and lean HFC will be beneficial in design of rigid pavements.

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