HIGH PERFORMANCE CONCRETE-PRESENT SCENARIO AND FUTURE PROSPECTS IN INDIAN CONTEXT

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ABSTRACT

Construction activities account for a major component of the budget in developing countries including India. Portland cement concrete is the most extensively used material for the construction of large infrastructural facilities worldwide. Significant distress or deterioration is being observed in reinforced concrete structures, such as bridges, multi-storeyed buildings, hyperboloid cooling towers and chimneys, particularly in coastal regions even well within their expected life span. Ensuring durability of concrete is one of the important issues to be addressed in evolving strategies to bring about sustainable development. This paper presents the typical results of investigations carried out at Structural Engineering Research Centre, Chennai, India on the development of High Performance Concrete (HPC), including Self Compacting Concrete (SCC) and the present scenario and future prospects on application of HPCs in the construction industry in India.

INTRODUCTION

High performance concrete (HPC) is a concrete in which enhancement of some or all of the properties of concrete, such as placement, compaction, no segregation, long-term mechanical properties, early age strength, toughness, volume stability and durability related properties resulting in extended service life in severe environment, is ensured/achieved[1,2]. Research carried out worldwide has well established that suitable addition of pozzolanic materials in concrete mixtures can lead to improvements in the durability of concrete [3,4]. Such concrete mixtures come under the category of HPC. Pozzolanic materials, such as fly ash (FA), ground granulated blast furnace slag (GGBS), and silica fume (SF), when used in concrete mixtures, due to their reaction with calcium hydroxide (a product of cement hydration) results in calcium syndicate hydrate compounds which, in turn, render the transition zone between the matrix and aggregates in the concrete mixture, denser and stronger and result in refinement of pore structure, thereby high degree of impermeability to ingress of water, air, chlorides, sulphates and CO_2. Pozzolanic materials are also known as mineral admixtures, supplementary cementitious materials (SCMs) and cement replacement materials (CRMs).

Experimental investigations were carried out at the Structural Engineering Research Centre (SERC), Chennai, on the use of SCMs, viz., FA, GGBS and SF, in developing HPC mixtures[5,6,7]. These studies were further extended to develop self-compacting concrete (SCC) mixtures using fly ash as SCM. Typical result of these studies are presented in this paper. The presentation is preceded by a review of Indian scenario on use of SCMs in construction industry during 1990s and during the present decade. It is seen that the performance of concrete mixtures, both in terms of strength and durability is enhanced with the use of SCMs. Details of typical construction in India using HPC and future prospects of HPC in the construction industry are also presented.

INDIAN SCENARIO TILL 1990s

Use of mineral admixture to make blended cements, i.e., Ordinary Portland Cement (OPC, termed as 'cement' in this paper) blended with pozzolanic materials to produce concrete mixtures is not new in India and can be traced back to the 1960s. Use of blended cements, viz., Portland slag cement[8] and Portland pozzolana cement[9] has been permitted by Bureau of Indian Standards (BIS). However, use of the blended cements in concrete construction in the country has been much limited till recent years.

The lack of large scale effort in India in exploiting the durability related improvements that fly ash imparts to concrete mixtures can be attributed to the rather poor quality of fly ash which was being generated in the country till 1980s. However, during the past decade (i.e., 1990s), there has been considerable improvement in the quality of fly ash collected through the mechanism of electrostatic precipitators in the various thermal power plants as reflected in the characteristics of fly ash with reduced loss on ignition (<5%) and increase in its fineness.

The importance of ensuring long term durability of concrete structures using SCMs has been incorporated in the revised Indian Standard IS 456-2000[10], wherein the earlier clause on durability aspects has been revised, permitting use of combinations of OPC with SCMs in the manufacture of concrete.

INDIAN SCENARIO DURING THE PRESENT DECADE

With the provisions made in the IS 456-2000 on the use of SCMs to manufacture structural grade concretes up to M80 grade, use of SCMs, especially fly ash and GGBS, in concrete mixtures, either as an additive/admixture while mixing the concrete or in the form of blended cements is on ever increasing trend in the construction industry. It is pertinent to point out that codes issued by the Indian Road Congress (IRC), which govern the construction of bridges/ flyovers in the country, are yet to be revised to permit use of SCMs in the concrete mixtures. However, efforts have been made to issue guidelines for use of HPC in the construction of bridges by the Ministry of Surface Transport / IRC in India and is in the draft stage. Central Public Works Department (CPWD) in India has recently issued circular permitting the use of fly ash based concrete mixture for constructions in the country only in a restricted manner. Ready Mixed Concrete Plants in India have also been contributing much on the use of SCMs in concrete mixtures. These efforts would lead towards attaining the much-needed sustainability on the use of cements in the construction industry in India.

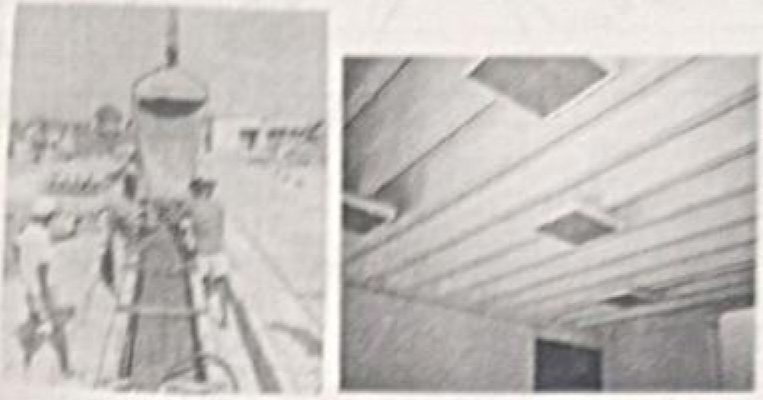
R&D AT SERC, CHENNAI ON CONCRETE MIXTURES CONTAINING SCMs

Demonstration on use of fly ash in concrete during 1970s

During 1970s, when only 33 grade cement was available in India, SERC, Chennai, was one of the few institutions in the country to demonstrate use of fly ash in concrete mixtures. To demonstrate the use of fly ash in Reinforced Concrete (RC) and Prestressed Concrete (PSC), during 1973-1977, a two-storeyed experimental building in SERC Campus was constructed [11,12,13]. The floor and the roof of this building were built by using RC / PSC precast channel units. The RC channel units were used for spans up to 5m and PSC channel units were used for longer spans. Fly ash from the Basin Bridge Thermal Power Station (North Chennai) was used in cement mortar and concrete. Three different grades of concrete mixtures, M15, M20, and M40 by replacing 20% cement with fly ash were developed and used in producing the channel units. About 20% savings in total cement consumption and about 4% savings in total cost of the building were achieved at that time with the use of fly ash. This building, which is known as the fly ash building, now houses the Experimental

Mechanics Laboratory and is in good condition even after more than two decades of its construction (Figs. 1 and 2). This building serves as a successful model construction using fly ash to achieve cost-effective and durable construction.

Fig. 1 A two storied building constructed using fly ash based concrete in 1973 at SERC, Chennai



(a) (b)

Fig. 2
a) PSC Channel units being cast in the prestressing bed
b) A view of the under deck of the floor constructed using PSC Channel units

Investigations on the Use of SCMs in Concrete Mixtures

Three grades of concrete mixtures having target mean strength (compressive strength on 100 mm cubes) at 28 days of 40MPa, 60MPa and 70MPa, were investigated as follows:

(i) Fly ash (at 30% CRM level) based concrete mixtures and designated as AF30, BF30 and CF30 corresponding to the three target mean strengths respectively,

(ii) GGBS based concrete mixtures, designated as AS40, BS40 and CS40 (for 40% CRM level) and AS70, BS70 and CS70 (for 70% CRM level) corresponding to the three target mean strengths respectively and

(iii) OPC based concrete mixtures (without SCMs and meant as control mixtures for purposes of comparison of results with those of SCM based concrete mixtures) and designated as AO, BO, CO corresponding to the three target mean strengths respectively.

Mechanical properties: The mixture proportions and mechanical properties, viz., compressive and flexural strengths at 28 days for the above concrete mixtures are given in Table I. The standard deviations arrived at from the results of testing 30 cubes for compressive strength, for all the concrete mixtures are in the range of 3.0 to 4.0 MPa.

Table I Mixture proportions and properties of OPC based, fly ash based and GGBS based concrete mixtures

Concrete Series	OPC 53 gr.	SCM	Sand	Aggre-gate	Water l/cu.m	SP % of binder (OPC+SCM)	Compres-sive Strength	Flexural Strength
	Kg/cu.m						at 28 days (MPa)	
OPC Based (Control) concrete mixtures								
AO	300	--	804	1129	165	0.4	41	4.8
BO	375	--	715	1195	150	1.2	62	5.3
CO	450	--	635	1195	150	1.4	71	6.9
Fly ash* based (30% CRM Level) concrete mixtures								
AF30	232	101	782	1085	160	0.6	39	4.1
BF30	286	122	672	1135	155	1.2	58	5.2
CF30	375	161	609	1195	150	1.6	69	5.8
GGBS based (40% CRM level) concrete mixtures								
AS40	198	132	779	1129	165	0.5	43	4.53
BS40	247	166	683	1195	150	1.4	62	5.59
CS40	310	206	595	1195	150	1.45	69	6.20
GGBS based (70% CRM level) concrete mixtures								
AS70	103	241	787	1135	155	0.6	40	4.40
BS70	131	300	714	1135	155	1.2	59	5.20
CS70	161	375	638	1135	150	2.5	67	6.30

* Properties of FA: % retained on 45 micron sieve: 33; LOI: 1.08 %; CaO:1.02%; SiO_2: 59.1%, Specific gravity: 2.15

AO: A Series with OPC as binder; AF30: A Series with FA at 30% CRM level; AS40: A Series with GGBS at 40% CRM level; AS70: A series with GGBS at 70% CRM level

From Table I, it is observed that by a judicious choice of binder (OPC + SCM) and water-binder ratio, it is possible to produce SCM based concrete mixtures of desired strength levels at 28 days. The flexural strength of SCM based concrete mixtures is also in par with that of OPC based concrete mixture at 28 days.

Stress Strain Characteristics: Typical plot of stress-strain curves at the age of 28 days by testing cylindrical specimens for control concrete mixtures, AO, BO and CO and for control concrete mixture, AO, together with that for SCM based concrete mixtures viz., AF30 and AS70, are given in Figs.3 and 4 respectively. From Fig.3, it is observed that for higher strength concrete mixtures (BO and CO), the failure strain of concrete is less than the value of 0.0035, which is the ultimate strain considered/assumed in the designs. From Fig. 4, it is seen that for 40MPa concrete, stress-strain behaviour of SCM based concrete mixtures is similar to that of control concrete mixture.

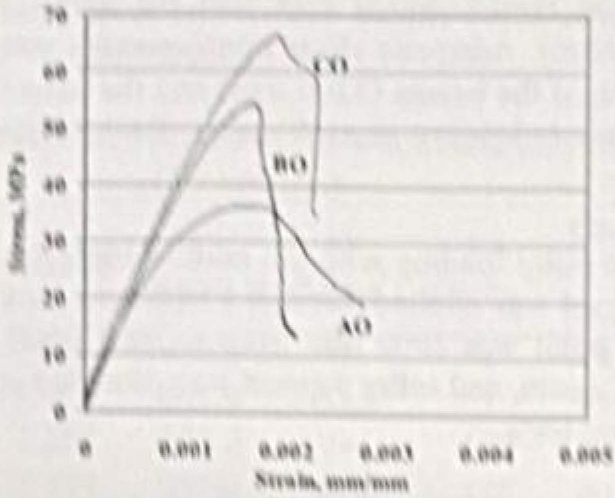


Fig. 3 Stress-strain plot for 40, 60, and 70 MPa control concrete (at 28 days)

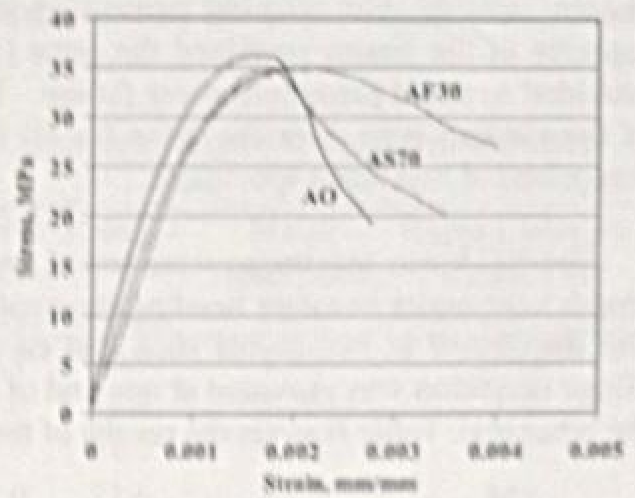


Fig. 4 Stress-strain plot for 40 MPa concrete (OPC and SCM based at 28 days)

Study of pore size distribution using Mercury Intrusion porosimetry (MIP): Pore structure of the concrete matrix greatly influences the strength and durability properties of concrete. Pore structure of cement paste and concrete has been studied by various researchers[14,15,16]. Hence, tests were carried out at SERC using MIP to evaluate the pore size distribution of OPC based and SCM based concrete mixtures. Typical results of test carried out on samples of concrete for control concrete mixtures and for slag based (40% CRM level) concrete mixtures, using MIP are presented in Figs.5 and 6. From Fig. 5, it is seen that as w/b decreased (i.e., with increase in strength from A series to C series), incremental intrusion plot shifts towards lower range of pore size and the peak intrusion (critical pore diameter) decreases. From Fig. 6, it is also seen that as w/b decreased, cumulative intrusion descends towards the x-axis indicating reduced porosity level. From Figs. 5 and 6, it is seen that in the case of slag based concrete mixtures, the above pore structure characteristics are further improved than those of OPC based concrete mixtures, which reflect in their improved durability properties. These trends are more pronounced as the age of concrete increases.

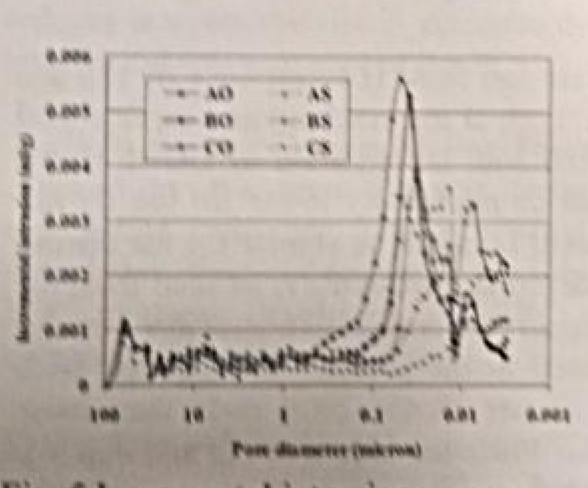


Fig. 5 Incremental intrusion vs pore diameter (at 28 days)

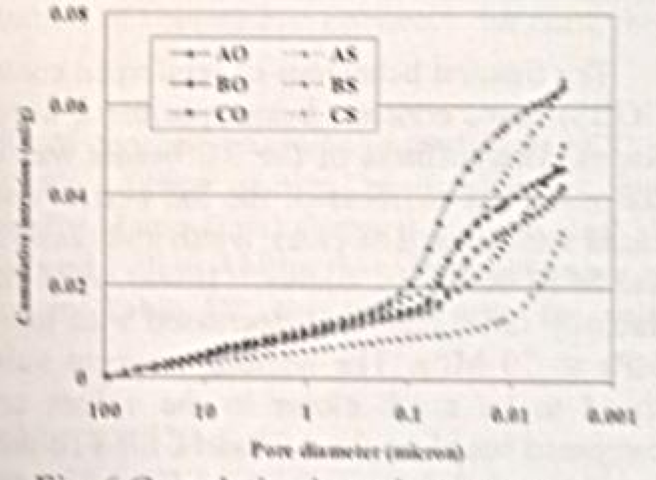


Fig. 6 Cumulative intrusion vs pore diameter (at 28 days)

Flexural Behaviour of Reinforced SCM based Concrete Beams: Flexural behaviour was investigated on a series of rectangular reinforced concrete (RC) beams cast using both OPC based concrete mixtures, fly ash based concrete mixtures and GGBS concrete mixtures as per mixture proportions given in Table 1. All the RC beams were designed, as balanced section as per IS 456:2000. The cross section of the beams for all the concrete test series were chosen suitably with varying percentage of tension reinforcement such that the moment capacity of the beams remained the same (≈ 90 kN-m). Adequate shear reinforcement was provided to avoid premature shear failure. The span of the beams (3200 mm) and the nature of the loading were kept the same for all the beams belonging to each series. Each series comprised of two beam specimens.

The RC beam specimens were tested under two-point loading with the middle 1000 mm length kept under constant bending moment. The load was applied through a hydraulic jack and distributed at two points such that each load point was 1000 mm from support point. Hinge condition was provided at one end of the RC beam, and roller support was provided at the other end. Table II gives the results of the flexural tests.

Table II Results of the flexural test on the RC beams (balanced capacity)

Beam Id.	Cross section (mm)	P_{cr} (kN)	P_u (kN)	P_{sl1} (kN)	P_{sl2} (kN)	Crack Spacing (mm)	Crack Width at P_{sl1} (mm)	Ductility Ratio
AO		30	192	140	128	76.9	0.14	2.02
AF30		30	187	130	125	83.3	0.16	1.74
AS40	150x300	35	187	130	125	71.4	0.18	1.68
AS70		30	187	140	125	83.3	0.16	-
BO		20	198	116	133	69.7	0.20	1.62
BF30		20	175	108	116	66.6	0.24	1.79
BS40	150x250	20	193	118	129	77.4	0.20	1.60
BS70		25	187	110	125	83.3	0.24	-
CO		20	168	87	109	91	0.19	1.60
CF30		20	170	85	114	100	0.16	1.63
CS40	150x225	20	170	82	113	87.1	0.20	-
CS70		20	170	90	113	83.3	0.16	1.55

P_{sl1} - Service load corresponding to deflection = span/250 (12mm); Span : 3200 mm
P_{sl2} - Service load computed as (P_u/1.5); P_{cr} : Load at first cracking; P_u : Load at failure

The flexural behaviour of reinforced control concrete and SCM (i.e., for both fly ash and GGBS) based concrete beam specimens were similar, both at the cracking and service load stages. The stiffness of the RC beams was not affected with the addition of GGBS in the concrete. The stiffness of the RC beams was found to be marginally lower for the fly ash based RC beam. The crack width and crack spacing were found to be similar for the control and SCM based RC beams. It was noted that the deformation ductility, as seen from the ductility ratio, relatively decreased with increase in concrete compressive strength from 40 MPa to 70 MPa. The bending moment values obtained in the present investigation were found to be much closer to the values computed as per IS:456-2000 code than those computed based on the ACI and CEB-FIB model codes. From the values of P_{sl1} and P_{sl2}, it is noted that defining service load **from** deflection criteria is more conservative, especially for higher strength concrete (i.e., for B and C series).

Concrete Mixtures having Ternary Blends: To offset the effect of retardation on strength development at early ages of concrete due to the incorporation of SCMs, such as fly ash, studies were carried out at SERC on triple blended concrete mixtures, i.e., concrete mixtures containing FA and SF as SCMs. Table III gives the mixture proportions and properties of control concrete, silica fume based concrete at 8% CRM level, fly ash based concrete at 25%

CRM level and ternary blends based concrete mixtures (i.e., SF at 8% together with FA at 25% CRM levels).

Table III Mixture proportions and properties of Concrete without SCMs and with SCMs (SF and FA)

Mix Id.	C (kg/m^3)	SF (kg/m^3)	FA (kg/m^3)	Compressive Strength MPa			Water Absorption (%)	Rapid Chloride Permeability (Coulombs)
				3days	7 days	28days		
C2	480.0	-	-	40.1	56.1	70.7	4.85	1672
C2D1	441.6	38.4	-	45.0	57.0	72.4	2.76	576
C2F1	360.0	-	120	33.0	44.6	61.0	4.46	515
C2T1	321.6	38.4	120	40.0	62.0	73.6	3.12	348

The parameters which were kept constant for all the concrete mixtures given in Table IV are w/b = 0.4 ; sand = 672 kg/m^3 ; coarse aggregate = 1105 kg/m^3; water = 192 l/m^3.

From the properties given in Table III, it is seen that drastic reduction in percentage water absorption and chloride permeability values are obtained in concrete mixtures having ternary blends. For the concrete mixtures containing only SF as SCM and both SF with FA as SCMs, the compressive strengths are in par or marginally improved when compared with that of control concrete.

Self Compacting Concrete (SCC): As an extension to the studies on developing HPC using SCMs, a study was performed at SERC, Chennai to develop SCC mixtures using locally available materials, especially fly ash as SCM. SCC requires a very high slump, which could be achieved using superplasticiser. However, to ensure that such concretes remain cohesive during handling operations, special attention needs to be given while proportioning the mix to avoid instability. Viscosity Modifying Agent (VMA) prevents segregation on addition of superplasticiser. Incorporating large quantities of fines, especially SCMs, such as fly ash, as partial cement replacement material, improves cohesiveness, reduces temperature rise in concrete during hydration of cement and enhances the durability besides reduction in cost of the SCC.

Tests for Self Compactibility: The workability of concrete mixtures to qualify as SCC is checked by the tests for self compactibility, viz., filling ability, passing ability and segregation resistance. This is verified by testing for slump flow, slump flow time, and V-funnel flow time and testing in the L-box, U–box, and Filling Ability Box. With reference to SCC mixtures developed at SERC and given in Table IV, the test results for self-compactability are as follows:

Slump flow →Mix S1:700mm; Mix S2:700 mm; Mix S5: 720 mm
Slump flow time → Mix S1: 4Sec.; Mix S2: 3 Sec.; Mix S5: 3 Sec.
V-funnel flow time→ Mix S1 =8 Sec.; Mix S2 = 6 Sec., ; Mix S5= 6 Sec.

The above values, obtained from the tests for self-compactibility for the concrete mixtures, are within the ranges specified by EFNARC-2004[17] for SCCs. Visual observations on the different SCC mixtures indicated that they were cohesive and possessed high stability. Proportions and properties of typical SCC mixtures, developed at SERC, are given in Table IV.

Table IV Mixture proportions and properties of SCC mixtures

Mix Id.	Cement kg/m^3	FA kg/m^3	VMA % of binder	SP % of binder	Sand kg/m^3	CA kg/m^3	Water l/m^3	Comp. Strength at 28days MPa	Chloride permeability-Coulombs	Resistivity kilo ohms-cm
S1	650	-	-	0.4	790	700	220	72	2552	8.0
S2	490	160	-	0.4	790	700	220	68	864	23.6
S5	390	260	0.05	0.5	880	730	202	58	324	62.8

From Table IV, it is observed that a significant reduction in the total charges passed through the concrete matrix was observed during the accelerated chloride permeation test (under 60V DC) for the concrete mixtures with SCMs, especially for the mixture with ternary blend, which could be attributed to the combined effect of particle packing, pozzolanic reaction and reduction in the conductivity of the pore fluid.

For both the SCC mixtures, S2 and S5, which have resistivity values greater than 20 kilo ohms-cm, the likelihood of corrosion risk is low as per guidelines given by J.H. Bungey[18].

Reinforced SCC Beams: RC beams were cast using SCC mixture and tested under flexure (Fig.7). From the test results, it was seen that even though the SCC mixture had higher binder content, lower values for maximum size and quantity of coarse aggregate (CA), the flexural behaviour of RC beam cast using SCC was similar to that of conventional concrete.

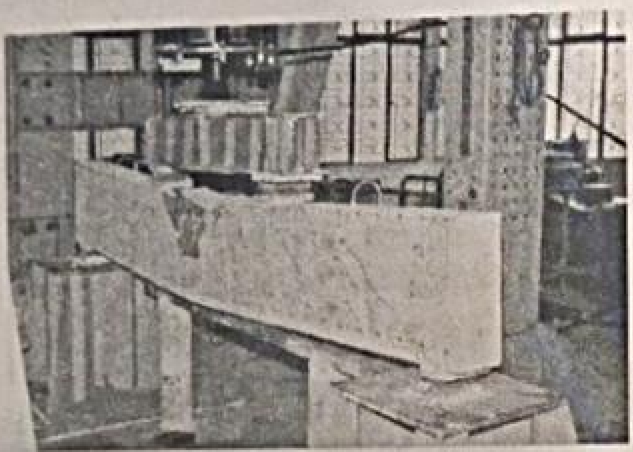


Fig. 7 View of a tested SCC beam

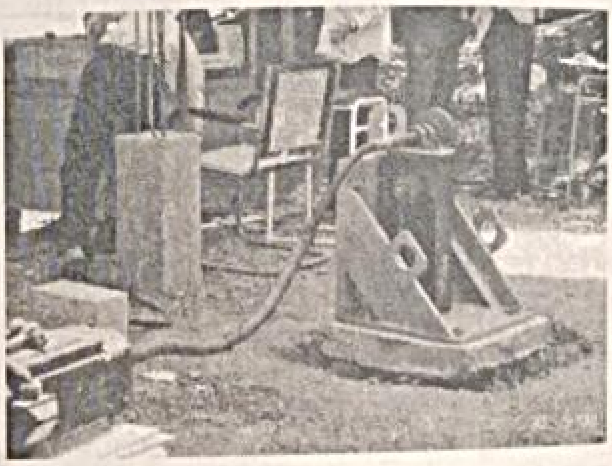


Fig. 8 Under reamed SCC pile ready for dynamic test

Under-reamed piles: The dynamic behaviour of cast-in-situ under-reamed piles (one with SCC and one with conventional concrete having similar strengths), 25 cm diameter and 4m long with two bulbs, was studied by exciting the pile in both horizontal and vertical directions using a Lazon type mechanical exciter (Fig. 8). It was observed that the dynamic characteristics, such as natural frequency, percentage damping, resonant, acceleration response and the normalised resonant displacement response for the SCC pile were almost the same as that of the conventional concrete pile.

Application of HPC Technology in Typical Construction in the Country

Details of typical construction in the country, which have been constructed using HPC technology based on the technical, advise of SERC, are given below.

Construction of Superstructure of the Flyover Bridge Across the Dumper Lines in Vizagapatnam Port Trust: As part of consultancy services, M45 grade GGBS based HPC (with 40% CRM level) for the construction of the prestressed concrete beams for the superstructure of the flyover bridge was designed and demonstrated by SERC. As per the requirements of the construction, the mix was designed for target strength of 57 MPa, which was to be achieved in 14 days. The compressive strength at 28 days was 64 MPa. The mix had a slump of 130 mm with water-binder ratio of 0.35. Naphthalene based superplasticizer at the rate of 0.85% by weight of the binder was added to get the required workability. Fig. 9 shows a view of the prestressed concrete bridge girder cast using M45 grade GGBS based HPC.

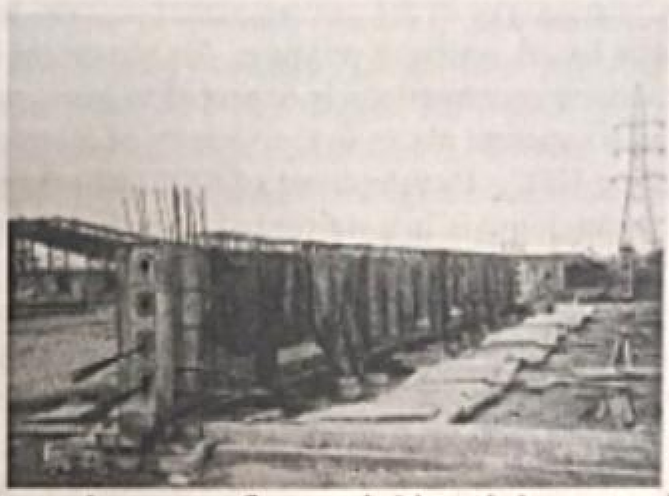


Fig. 9 A view of prestressed concrete fly over bridge girder cast using GGBS based HPC.

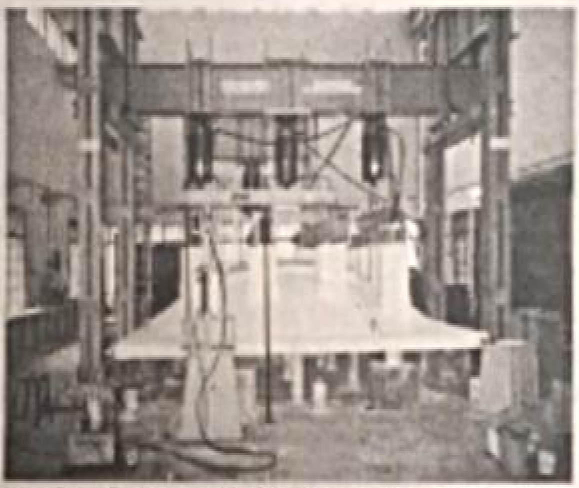


Fig. 10 Shows the dome unit being tested for strength at SERC

Construction of Bubble Type Dome Units for the Roof structure of the Parliamentary Library Building, New Delhi.: Central Public Works Department, New Delhi, sponsored a project to SERC on development of bubble type dome units for the roof structure of the Parliamentary Library Building, New Delhi. After detailed technical considerations, steel fibre reinforced HPC, M50 grade was selected and designed. The assessment of characteristics of the HPC including the casting and testing the structural capacity of the bubble type dome units were carried out at SERC, as part of the project. The concrete mixture was designed as a ternary blend with total CRM level of 40%, comprising 35% GGBS and 5% Silica Fume and with Dramix steel fibres at 0.75 % by volume of concrete. Naphthalene based superplasticizer was used to obtain the required workability. The water-binder ratio adopted was 0.35. The maximum size of coarse aggregate was limited to 10mm. Steel fibres were added with a view to improve the shrinkage resistance of fresh concrete and the tensile strength of hardened concrete so that the possibility of microcracking of concrete was minimised besides enhancing the toughness i.e., energy of absorption capacity. Fig. 10 shows a view of the dome being tested for strength at SERC.

FUTURE PROSPECTS AND R&D NEEDS

The awareness amongst civil engineering professionals in the country on the benefits of using SCMs in concrete mixtures to ensure long-term durability of RC/PSC structures is growing. This aspect, coupled with the enabling provisions, permitting use of SCMs in concrete mixtures, incorporated in the IS 456-2000 Code has paved the way for use of HPC in the concrete constructions in the country. Already, HPC has been used in some of the important infrastructural constructions in the country. Governmental agencies, such as Ministry of Surface Transport (MOST) and Central Public Works Department (CPWD), who construct most of the infrastructures in the governmental sectors, are taking steps to lift the ban on the use of fly ash based concrete mixtures for structural grade concrete. On the whole, use of HPC in concrete constructions is expected to grow rapidly in India during the coming decade. Ready mix concrete plants in the vicinity of metropolitan cities in India, are well poised towards making HPC. Development of SCC, which is a recent development in the country in the HPC technology, is in a nascent state and holds much potential for use in the construction industry in the near future.

For the application of HPC, especially high-strength HPCs in the RC/PSC constructions, salient R&D requirements are listed below. R&D is in progress at SERC on some of these aspects.

- Verification and extension of the design recommendations of IS 456-2000, which are essentially applicable for concretes up to medium strengths ($\leq$40MPa), to the present day needs of higher strengths (up to 80 MPa).
- Evaluation of ductility aspects of structural elements constructed using high strength concretes and imparting ductility to such concretes to ensure lower damage levels during accidental over loading or during natural disasters.
- Evaluation of performance of reinforced high strength HPC structural elements under cyclic loading.

CONCLUDING REMARKS

In this paper, it is demonstrated through laboratory investigations that SCMs (available in India) could be used to produce HPCs. Through judicious choice of water-binder ratio and use of SCMs conforming to standards, it is possible to produce durable concretes having desired rate of strength development.

Use of HPC, besides ensuring long-term durability of concrete structures would also bring in economy and sustainability in concrete constructions in the country. Further, significant savings on use of cement (OPC), which consumes considerable energy in its production, could be realised by adopting SCMs in concrete mixtures.

ACKNOWLEDGEMENT

This paper is published with the kind permission of the Director, Structural Engineering Research Centre, Chennai.

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