ELSEVIER

Cement & Concrete Composites 23 (2001) 71–80

Cement & Concrete Composites

www.elsevier.com/locate/cemconcomp

Mix proportioning of high performance concrete

B.H. Bharatkumar [a], R. Narayanan [a,*], B.K. Raghuprasad [b], D.S. Ramachandramurthy [a]

[a] *Structural Engineering Research Centre, CSIR Campus, TTTI Taramani P.O., Chennai 600 113, India*

[b] *Civil Engineering Department, Indian Institute of Science, Bangalore 560 012, India*

Received 19 April 2000; accepted 9 November 2000

Abstract

High performance concrete (HPC) is that concrete which meets special performance and uniformity requirements that cannot always be achieved by conventional materials, normal mixing, placing and curing practices. Special performance requirements using conventional materials can be achieved only by adopting low *w*/*c*, which necessitates use of high cement content. But judicious choice of chemical and mineral admixtures can reduce the cement content and this results in economical HPC. However, the effect of a mineral admixture on the strength of concrete varies significantly with its properties and replacement levels. Mix proportioning methods of normal concrete cannot adequately account for the large variations in the properties of ingredients. This paper presents a modified mix design procedure, which utilises optimum water content and the efficiency factor of mineral admixture. Results of the experimental investigations on mixes using the modified mix design are presented. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: High performance concrete; Concrete mix proportion; Optimum water content; Minimum cement content; Effective water/binder ratio; Cement replacement material; Efficiency factor; Mineral admixtures; Superplasticiser; Mix design procedure; Experimental results

1. Introduction

High performance concrete (HPC) is that which is designed to give optimised performance characteristics for the given set of materials, usage and exposure conditions, consistent with requirements of cost, service life and durability [1]. Architects, engineers and constructors all over the world are finding that using HPC allows them to build more durable structures at comparable cost. HPC is being used for buildings in aggressive environments, marine structures, highway bridges and pavements, nuclear structures, tunnels, precast units, etc. [2,3].

The major difference between conventional concrete and HPC is essentially the use of chemical and mineral admixtures. Use of chemical admixtures reduces the water content, thereby reducing the porosity within the hydrated cement paste [4]. The reduction in water content to a very low value with high dosage of chemical admixtures is undesirable and the effectiveness of chemical admixtures such as superplasticiser (SP) principally depends on the ambient temperature, cement chemistry and fineness. Mineral admixtures, also called as cement replacement materials (CRM), act as pozzolanic materials as well as fine fillers, thereby the microstructure of hardened cement matrix becomes denser and stronger [5]. At ambient temperature their chemical reaction with calcium hydroxide is generally slow. However, the finer and more vitreous the pozzolana is, the faster will be this reaction. If durability is of primary interest, then the slow rate of setting and hardening associated with the incorporation of fly ash or slag in concrete is advantageous [6]. Also, the mineral admixtures are generally industrial by-products and their use can provide a major economic benefit. Thus, the combined use of SP and CRM can lead to economical high-performance concrete with enhanced durability [7]. It is also reported that the concrete containing CRM typically provides lower permeability, reduced heat of hydration, reduced alkali-aggregate reaction, higher strength at later ages and increased resistance to attack from sulfates [8]. However, the effect of a CRM on the strength of concrete varies markedly with their properties. Fly ashes are the most variable and least reactive of all CRMs and should be used with care and not on basis of any generalisation [9]. It is also not known at present what factor can maximise the fly ash contribution [10].

There have been several attempts to develop a method for the proportioning of mixes with CRM,

* Corresponding author. Fax: 91-44-2350508.
E-mail address: rn@sercm.csir.res.in (R. Narayanan).

0958-9465/01/$ - see front matter
PII: S0958-9465(00)00071-8

which could be classified as addition, replacement or rational methods. Existing methods of mix proportioning require large number of trial mixes to select the desired combination of materials. However, a good mix proportioning procedure has to minimise the number of trial mixes and achieve an economical and satisfactory mixture with desired properties. Therefore, a modified mix design procedure based on the ACI method for normal concrete mix design [11] has been proposed in this paper. Experimental investigations were carried out at the Structural Engineering Research Centre, Madras, to verify the proposed mix proportioning method. The mechanical and durability characteristics of a number of concrete mixes based on the proposed mix proportioning method are presented in this paper.

2. Review of literature

The general philosophy of different concrete mix proportioning methods proposed in the literature [11–18] is as follows:

- Select the w/c ratio for the required strength from chart.
- Arrive at the water content based on the required workability and the aggregate characteristics.
- If SP is used reduce the water content by 5–10%.
- Obtain cement content based on water content and w/c ratio.
- Arrive at the coarse aggregate content based on either fineness modulus of sand or aggregate grading.
- The optimum CRM content is assumed and the water/binder ratio is modified to obtain the required strength.
- Finally proportions are adjusted for unit volume to obtain the fine aggregate content.

However, the water content depends on the desired workability of fresh concrete and type, shape and grading of aggregates. With the use of SP, it is possible to reduce the water content and yet produce same workability without affecting the strength of concrete if the w/c ratio is kept constant [4,19]. But the effectiveness of the SP depends on the dosage used, ambient temperature, cement chemistry, fineness and other characteristics of the binder. When the water content decreases in a concrete mix of a given w/c ratio, the amount of cement correspondingly decreases, but at the same time, the amount of superplasticiser needed to achieve the desired workability is increased. Thus the saving in the cost of cement can compensate for the extra cost of the superplasticiser [18]. Hence, it is necessary to obtain required water content after establishing a relationship between water content and cost of superplasticiser plus cement for a given set of ingredients and for the same workability.

When CRM is used, its effect on the strength of concrete varies significantly depending on the properties of CRM and with the characteristics of concrete mixture. Smith [12] proposed a factor known as the cementing efficiency k such that a mass f of fly ash would be equivalent to a mass kf of cement in terms of strength development. He found that the strength and workability of the fly ash concrete with effective w/b ratio $[w/(c+kf)]$, is comparable to that of the conventional concrete without fly ash having same water content and w/b ratio. Based on his experimental results, the value of the cementing efficiency factor k was reported to be 0.25 upto 25% fly ash as CRM. The German standard [20] proposes a value of 0.3 for replacement of 10–25% fly ash. The British code recommends a value of 0.3 for fly ash replacement upto 50%. The CEB–FIP model code proposes an efficiency value as 0.4 for replacements between 15% and 40% fly ash. Munday et al. [15] observed that this method was insensitive to the type of cement, curing conditions etc., and hence not suitable for rich mixes. Schiessl and Hardtle [21] pointed out some variation in efficiency factor with percentage replacement and age. Ganesh Babu and Siva Nageswara Rao [22] reported that the contribution of the fly ash is not a constant determined solely by its physical and chemical characteristics but also varies depending on the type of cement, w/c ratio etc. Siva Nageswara Rao [23] proposed two efficiency factors, first, a general efficiency factor and the second factor, corresponding to the percentage replacement. If the efficiency factor is known, the strength of CRM mixes can be determined by modifying the Bolomey equation as [24]

$$S = A_1[c/w] + A_2 \quad \text{for no CRM mix,} \tag{1}$$

$$S = A_1[(c+kf)/w] + A_2 \quad \text{for CRM mix,} \tag{2}$$

where S is the compressive strength in MPa, c the cement content in kg/m^3, f the CRM content in kg/m^3, w the water content in kg/m^3, k the efficiency factor and A_1, A_2 are arbitrary constants. These arbitrary constants are reported to be influenced by type, size and grading of aggregate, type of cement, period of curing etc. [25–27]. Hence, it is necessary to obtain strength to effective w/b ratio relation for a given set of materials and for the same workability.

3. Proposed mix proportioning method

A modified mixture design procedure based on the ACI method of normal concrete mix design [11] has been proposed utilising the efficiency factor of the mineral admixture. This procedure also assumes that the strength is related to effective w/b ratio $[w/(c+kf)]$ and constant water content gives the constant workability of fresh concrete irrespective of w/b ratio. The steps to be followed for proportioning HPC, which is obtained by combined use of SP and CRM are:

1. *Obtain reference mix*: The reference mix proportion having w/b ratio of 0.50 and slump of 25–50 mm without any superplasticiser or CRM is arrived at using the ACI method [11]. ACI method is adopted in the present study since this method reported to yield the required workability for the specified coarse aggregates, fine aggregates and water content with the presently available cements in India [28,29]. If the workability obtained is not satisfactory, then coarse and fine aggregate contents may be modified, keeping the w/b and total aggregate/binder ratio same. This ensures that the sufficient water for workability is used in the concrete accounting for variability in the characteristics of the coarse and fine aggregates.
2. *Obtain operating water:* For the same w/b ratio and fine aggregate content, mix proportions without CRM for three or four different water contents less than that obtained in step 1 may be arrived (cement content will reduce and the coarse aggregate content will increase). The desired workability of these mixes can be obtained by adding superplasticiser. The dosage of superplasticiser for each mix is noted and the relationship between the total cost of superplasticiser and cement vs water content is established. Operating water content can be obtained from this relationship.
3. *Obtain the efficiency factor:* The mix proportions with and without CRM for two extreme w/c ratios (say 0.50 and 0.35) may be arrived at while keeping the operating water and the coarse aggregate contents constant. Specimens may be cast using these mixes and the strengths evaluated after the required curing period. From the strength results of concrete mix without CRM the constants A_1 and A_2 in Eq. (1) can be calculated adopting linear regression. Finally the efficiency factor of CRM is evaluated from the strength results of concrete mixes with CRM using Eq. (2). Thus the strength vs effective w/b ratio relationship is established for the set of ingredients used.
4. *Obtain the ingredient quantities of final mix*: Once the effective w/b ratio is known for the required strength from the above relationship, the proportion of cement, CRM and fine aggregates can be arrived, keeping the operating water and coarse aggregate contents constant.

4. Experimental investigations

4.1. Material used

Cement: The main characteristics of cement used (53 grade) are given in Table 1.

Table 1
Chemical composition of cementitious materials

Properties	Cement	Flyash	Slag
SiO_2 (%)	19.11	58.8–59.1	33.67
Al_2O_3 (%)	6.43	{39.9–40.3}	20.56
Fe_2O_3 (%)	5.22		1.01
MgO (%)	0.71	0.22–0.34	9.63
CaO (%)	63.78	0.86–1.02	32.45
SO_3 (%)	1.29	–	0.10
Na_2O, K_2O (%)	0.97	0.59–1.25	1.24
LOI (%)	1.34	1.05–1.08	–
Free lime (%)	0.20	–	0.27
Specific gravity	3.14	2.15	2.95

Coarse aggregate: Crushed granite aggregates (<12.5 mm) were used. The characteristics of coarse aggregates are:

Specific gravity = 2.71.
Dry rodded unit weight = 1550 kg/m^3.
Water absorption = 0.5% of the weight of the aggregates.

Fine aggregate: River sand passing 4.75 mm IS sieve is used. The specific gravity and the fineness modulus were 2.62 and 2.48, respectively.

Superplasticiser: A sulphonated napthalene formaldehyde type superplasticiser (CERAPLAST 300) was used.

Fly ash: Fly ash (Type F) from the thermal power plant near Chennai, India was used. Main characteristics of this fly ash are given in Table 1. Investigations were carried out with 15% and 25% of cement replacement by mass of fly ash.

Slag: Ground granulated blast furnace slag supplied by the Andhra Cements, Visakhapatnam, India was used. The main characteristics of slag are given in Table 1. Investigations were carried out with 15%, 30% and 50% of cement replacement by mass of slag.

4.2. Mix proportions

The ACI method [11] was adopted for obtaining reference concrete mix proportion having slump of 25–50 mm with $w/c = 0.5$. The water content for reference mix was found to be 196 kg/m^3. To obtain the operating water content, the mix proportions for various water contents (190–150 kg/m^3) were established by keeping the fine aggregate and w/c ratio same. Mix proportions for two extreme w/b ratios (0.50 and 0.35) with and without fly ash or slag as CRM were obtained (having the operating water and coarse aggregate content constant) and test specimens were cast. The fine aggregate (sand) content was adjusted to obtain the same total volume of concrete per unit mass by considering the low specific gravity of fly ash. No volume adjustment was made for use of slag as CRM, since the specific gravity of slag is close to that of cement.

A tilting drum type mixer machine was used for preparing the concrete. The following sequence of mixing was arrived at based on a few trials: First adding 50% of total quantity of water, then adding the aggregate, sand and cementitious material. The remaining water is added in steps with SP. Slump test and wet density measurements were carried out on fresh concrete to evaluate its workability. Slight variation in SP dosage was effected to account for changes in ambient temperature and humidity at the mixing and casting time. To validate the proposed method, specimens were also cast having $w/b = 0.42$ with and without CRM. Totally 16 different mixes were made. The concrete mix proportion and the fresh concrete properties are given in Table 2.

4.3. Preparation of test specimens

All the test specimens such as standard cubes, cylinders and prism were cast using steel moulds and care was taken to see that the moulds were filled with concrete in three layers and each layer was compacted well using a table vibrator. The specimens were demoulded after 24 h and cured in water.

4.4. Testing of specimens

The mechanical properties of hardened concrete, such as compressive strength, split tensile strength, flexural strength and elastic modulus were evaluated in accordance with IS:516 [30]. The water absorption test was performed according to the ASTM C-642 [31]. Coeffi-

Table 2
Experimental investigations – mix proportion and fresh concrete properties[a]

Mix designation ($w/b = 0.50$)	A	AF15	AF25	AS15	AS30	AS50
Binder						
Cement (kg/m^3)	340	289	255	289	238	170
Flyash (kg/m^3)	–	51	85	–	–	–
Slag (kg/m^3)	–	–	–	51	102	170
Fine aggregates (kg/m^3)	819	800	787	819	819	819
SP (Ceraplast 300), % by weight of binder	0.5	0.6	0.7	0.60	0.650	0.65
Slump (mm)	20	35	40	15	25	20
Wet density (kg/m^3)	2340	2338	2342	2338	2330	2333
Mix designation ($w/b = 0.42$)	B	BF15	BF25	BS15	BS30	BS50
Binder						
Cement (kg/m^3)	405	345	304	345	283	203
Flyash (kg/m^3)	–	60	101	–	–	–
Slag (kg/m^3)	–	–	–	60	122	202
Fine aggregates (kg/m^3)	765	742	726	765	765	765
SP (Ceraplast 300), % by weight of binder	0.5	0.65	0.85	0.60	0.750	0.85
Slump (mm)	15	25	35	15	25	20
Wet density (kg/m^3)	2365	2371	2376	2369	2360	2360
Mix designation ($w/b = 0.35$)	C	CF15	CF25	CS15	CS30	CS50
Binder						
Cement (kg/m^3)	486	413	365	413	340	243
Flyash (kg/m^3)	–	73	121	–	–	–
Slag (kg/m^3)	–	–	–	73	146	243
Fine aggregates (kg/m^3)	684	652	631	684	684	684
SP (Ceraplast 300), % by weight of binder	0.5	0.60	0.75	0.70	0.75	0.50
Slump (mm)	25	15	25	20	15	40
Wet density (kg/m^3)	2417	2393	2397	2411	2402	2415

[a] *Note*: Coarse aggregate content is 1054 kg/m^3 and water content is 170 kg/m^3 for all mixes.

cient of absorption and the sorptivity were also calculated based on the water absorption test.

5. Analysis of results

5.1. Operating water content

With the use of superplasticiser, the water content in a mix can be reduced which in turn reduces the cement content. The extent of reduction in water content depends on various factors as discussed earlier. Hence, it is necessary to study the effectiveness of the SP with the set of ingredients to be used. Trial mixes with w/c ratio of 0.5 were studied to estimate the amount of SP required to obtain the same workability when water content is reduced. The SP dosages were 0.2%, 0.4%, 0.6%, 1.25%, and 2.5% by weight of binder when water was reduced from 190 to 150 kg/m^3 in decrements of 10 kg/m^3, respectively. It was also noticed that the quantity of water required for a given consistency was the same regardless of w/c ratio, and thus same dosage can be used to evaluate the cost of SP+cement for different w/c ratios.

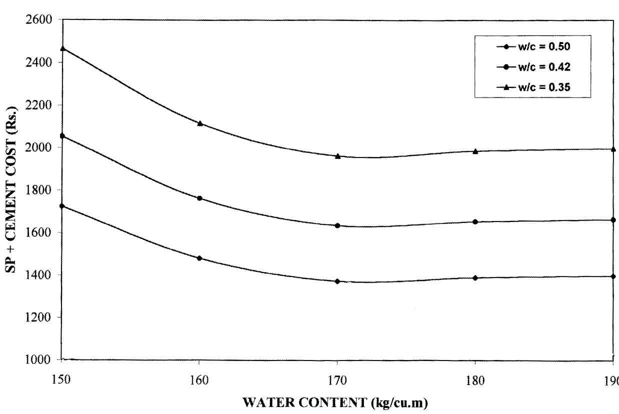

Fig. 1. Cost of SP + cement vs water content.

Fig. 1 shows how the cost of SP+cement varies with reduction in water content. For the set of ingredients used in present study, the operating water content was fixed as 170 kg/m^3 with SP dosage about 0.6% by weight of binder (without CRM).

5.2. Evaluation of efficiency factor of CRM

The results of the compressive strengths (100 mm cube) are given in Table 3. Based on the compressive strength results of mixes without any CRM having w/c ratio of 0.35 and 0.50, the constants in Bolomey equation (Eq. (1)) were evaluated by linear regression. It was seen that the constant A_1, which is slope of the compressive strength vs c/w plot (Eq. (1)) was almost the same at different ages ($\cong$40) in the range of c/w ratios considered. However, the constant A_2, which is the intercept appears to vary quite considerably with age ($-51.22, -41.69, -36.05$, and -34.07 at $7, 28, 56$ and 90 days, respectively). Therefore, a relationship between A_2 and the age in days (t) was obtained by linear regression as follows:

$$A_2 = B_1(t/28)^{B_2}, \tag{3}$$

where t is the age of curing in days, B_1 and B_2 are arbitrary constants, (for present study B_1 and B_2 are evaluated as -41.69 and -0.17, respectively). It is reasonable to assume that the constants A_1, B_1, and B_2 may depend on the type of aggregate, sand and cement used, although the same has not been verified.

These relationships were used to obtain the efficiency factor k for cement replacement materials as:

$$S = A_1(c + kf)/w + B_1(t/28)^{B_2}, \tag{4}$$

$$c + kf = w[S - B_1(t/28)^{B_2}]/A_1, \tag{5}$$

$$k = (1/f)\{-c + w[S - B_1(t/28)^{B_2}]/A_1\}. \tag{6}$$

Table 3
Compressive strength results for $w/b = 0.50$ and $w/b = 0.35$

Mix designation	A	AF15	AF25	AS15	AS30	AS50
Compressive strength (MPa) at						
3 days	23.86	17.33	16.11	23.24	17.31	14.41
7 days	29.20	26.34	24.71	30.05	27.41	23.30
28 days	40.93	35.28	33.53	35.61	38.28	40.03
56 days	44.84	43.52	44.18	44.35	46.17	46.44
90 days	45.52	45.97	45.46	46.09	47.57	48.85
	C	CF15	CF25	CS15	CS30	CS50
3 days	57.10	48.87	45.24	45.57	43.58	39.60
7 days	63.67	59.95	51.56	60.54	59.60	53.95
28 days	75.07	72.06	65.58	70.08	72.93	75.46
56 days	79.51	76.96	73.00	74.78	77.72	79.36
90 days	79.64	79.01	76.57	80.71	79.91	81.28

Table 4
Efficiency factor k at various age for CRM (present investigations)

Age	Efficiency factor k for CRM				
	Flyash		Slag		
	15%	25%	15%	30%	50%
7 days	0.90	0.76	0.98	0.97	0.88
28 days	0.86	0.78	0.81	1.00	1.04
56 days	0.98	0.94	0.97	1.05	1.06
90 days	0.98	0.95	1.05	1.04	1.05

Value of k was obtained from the strength results for 0.35 and 0.50 w/b ratio of fly ash and slag. It was seen that the curing period and the percentage replacement influences the efficiency factor. The variation in the value of k is assumed constant for the range of w/b investigated (0.35–0.50). The average values of efficiency factor obtained from the strength values for 0.35 and 0.5 w/b ratios, are given in Table 4.

The efficiency factor for CRM shows increasing trend as the curing period is increased indicating slower pozzolanic reaction at early age. Thus, it is essential that the concrete containing CRM requires prolonged curing. Fly ash mixes showed decreasing trend as the replacement level is increased, whereas, slag mixes showed increasing trend as the replacement level is increased (except at higher replacement level) with age for the replacement levels investigated. However, if the effective w/b ratio is kept constant, the higher replacement is economical and will also have advantage of having lower w/b.

The compressive strengths predicted using Eq. (4) for w/b of 0.42 were found to be within ±10% of experimental values (Table 5). Thus, the constants A_1, B_1, B_2 and efficiency factors (for each replacement level) can be obtained from the compressive strength values for the two extreme w/b ratios. These values can be used for arriving at mix proportion for any strength in between, with slight adjustment in fine aggregate and binder content without changing coarse aggregate and operating water content.

The validation of the proposed procedure was checked with some of the data available in literature. Using data of Siva Nageswara Rao [23], the values of constants evaluated using the strength results of two extreme w/b were found to be $A_1 = 28.3$, $B_1 = -9.12$ and $B_2 = -0.62$ and the efficiency factors for fly ash were obtained at different ages. The predicted strengths were within ±5.0% as seen from Fig. 2(a). Similarly for the data of Malhotra [32], the values of $A_1 = 23.5$, $B_1 = -13.3$, $B_2 = -0.32$, and efficiency factors for slag were obtained at different ages. The predicted strengths were within ±10% as seen from Fig. 2(b). However, it is to be noted that the water content reported in the above investigations was not constant as adopted in the present investigations.

5.3. Effective w/b ratio

Based on the efficiency factor of the CRM, one can estimate the effective w/b ratio ($w/[c + kf]$). For various levels of CRM, the relationship between strength and the effective w/b ratio remains the same, however, the total binder content will be different depending on the CRM level and its efficiency. For a constant water content of 170 kg/m^3 the binder and cement contents per unit strength were calculated for various effective w/b ratios and for various replacement levels using Eq. (4). The variation of cement content per unit compressive strength vs effective w/b ratio for various percentages of CRM is shown in Fig. 3. It is seen that as the effective w/b ratio reduces or CRM content increases, there is a reduction in cement required per unit compressive strength of the concrete. Thus, it is possible to effectively utilise the cement by adopting lower effective w/b ratio with higher CRM content.

Table 5
Experimental and predicted compressive strength results for $w/b = 0.42$[a]

Mix designation	B	BF15	BF25	BS15	BS30	BS50
Compressive strength (MPa) at						
7 days	46.00	43.67	38.77	45.14	43.32	33.23
	(42.72)	(41.30)	(37.00)	(42.43)	(41.85)	(37.00)
28 days	53.47	54.80	53.39	54.10	52.84	52.62
	(53.79)	(51.81)	(48.56)	(51.11)	(53.79)	(55.70)
56 days	60.33	61.15	61.42	62.95	63.37	64.97
	(58.43)	(58.15)	(57.00)	(58.00)	(59.87)	(61.29)
90 days	64.17	66.90	65.87	65.90	68.82	68.89
	(61.30)	(61.02)	(60.11)	(62.01)	(62.45)	(63.68)

[a] *Note*: Values given in parenthesis are predicted based on Eq. (4).

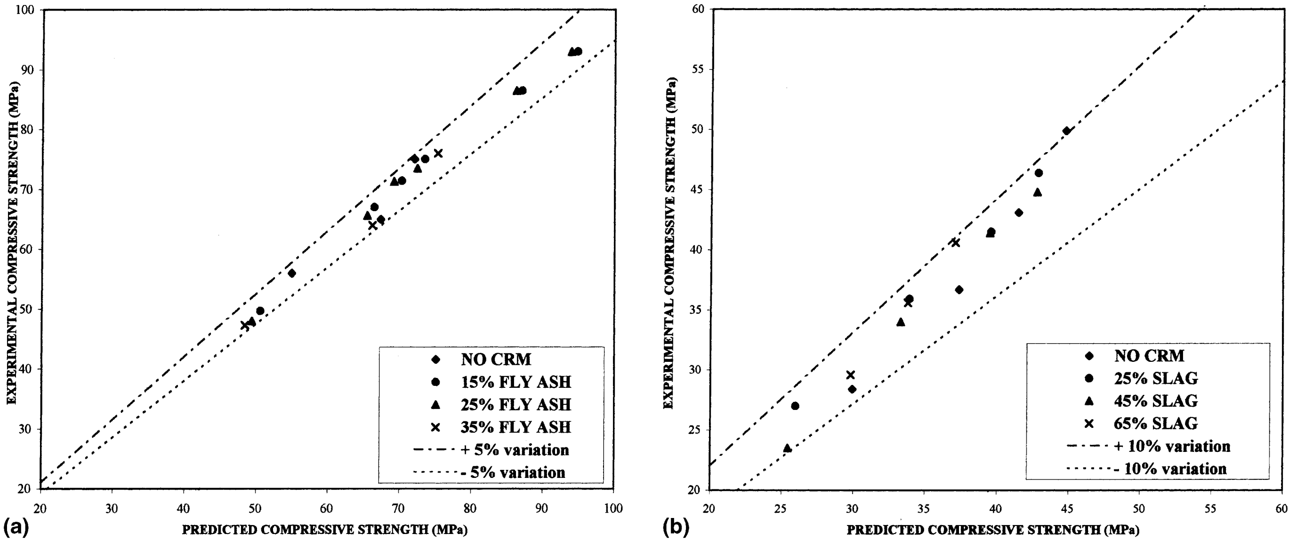

Fig. 2. (a) Predicted and experimental compressive strength [23]. (b) Predicted and experimental compressive strength [32].

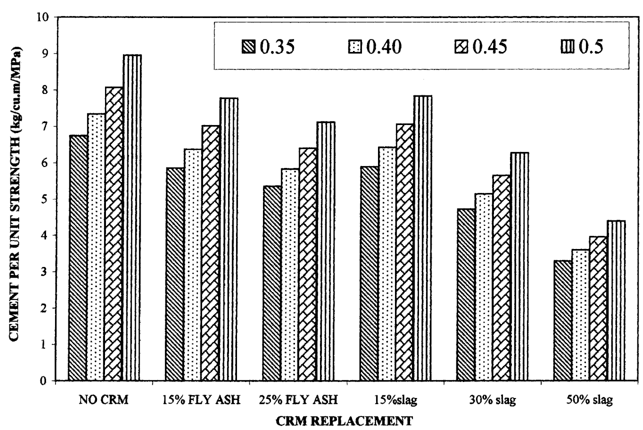

Fig. 3. Cement content per unit compressive strength for various effective w/b ratio $[w/(c+kf)]$.

5.4. Mechanical properties

5.4.1. Compressive strength

The compressive strength for various mixes are presented in Tables 3 and 5. The 28 day strengths obtained vary from 33 to 75 MPa depending upon the w/b ratio and the CRM content. It is seen that the compressive strength of the CRM mixes were less than the companion mixes at early stages but as the age increases it is equal to the companion mixes, with proper curing. Thus curing is an important factor for achieving HPC with higher level of CRM.

5.4.2. Tensile strength

The most commonly used tests for estimating the indirect tensile strength of concrete are the split tensile strength and flexural strength or modulus of rupture.

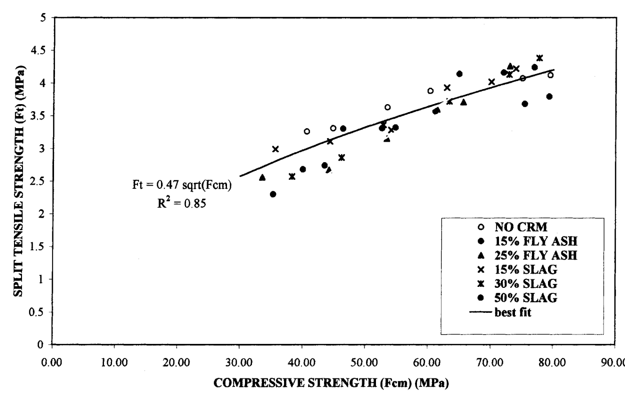

Fig. 4. Split tensile strength vs compressive strength.

The variation in the split tensile strength (using cylindrical specimens of size 100 mm diameter and 200 mm height) and flexural strength (using 100 × 100 × 500 mm prism) with the cube compressive strength of a 100 mm cube is shown in Figs. 4 and 5. It is seen that the use of fly ash and slag did not alter the split and flexural tensile strengths significantly. It is also seen that the relationship of 100 mm cube compressive mean strength (f_{cm}) with the split tensile strength (f_t) or flexural strength (f_r) compares well with the relationships given in various codes of practices.

5.4.3. Modulus of elasticity

The modulus of elasticity for various mixes (using cylindrical specimens of size 150 mm diameter and 300 mm height) is shown in Fig. 6. It is varying between 35 and 45 GPa depending on the w/b ratio and the CRM, which shows that addition of CRM did not alter the modulus of elasticity significantly.

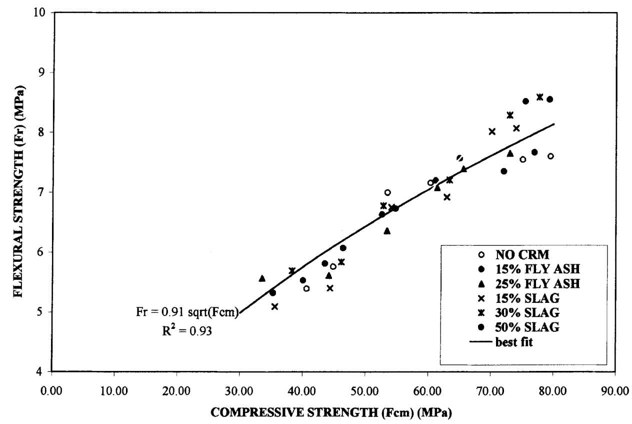

Fig. 5. Flexural strength vs compressive strength.

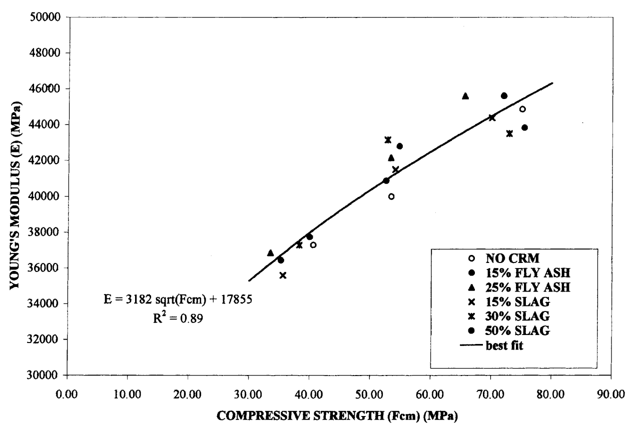

Fig. 6. Young's modulus vs compressive strength.

5.5. Durability characteristics

5.5.1. Water absorption

The results of the durability studies using 100 mm cube specimens are given in Table 6. The water absorption for the mixes investigated after 28 days curing is found to be in the range of 2.90–4.78%. Results show that the water absorption reduces as the w/b ratio reduces and also with the addition of CRM. Siva Nageswara Rao [23] obtained water absorption of the order of 2.46–6.80% for concrete mixes containing fly ash, which compares well with the present results. It is also noticed that replacement level of 50% slag is more efficient than that of 25% fly ash in reducing the water absorption.

5.5.2. Coefficient of absorption

Powers [33] suggested the use of coefficient of absorption as a measure of the permeability to water for a hardened concrete. This is measured by the rate of uptake (capillary absorption) of water by dry concrete in a period of 60 min. The values of the coefficient of absorption obtained are given in Table 6. It is in the range of 0.63×10^{-10} to 3.01×10^{-10} m²/s. It is seen that there is reduction in the value of coefficient of absorption as the w/b ratio decreases and further improved with the addition of CRM. Slag showed better performance than fly ash.

5.5.3. Sorptivity

Sorptivity measures the rate of penetration of water into the pores of concrete by capillary suction. When the

Table 6
Durability test results

Mix designation	Water absorption(%)		Bulk specific gravity (gm/cm³)		% Void	Coefficient of absorption K_a (m²/s)	Sorptivity (m/√s)
	Wet	Boil	Dry	Wet			
A	4.91	5.10	2.35	2.46	11.98	3.01×10^{-10}	1.14×10^{-5}
AF15	4.70	4.78	2.29	2.40	10.95	2.82×10^{-10}	1.47×10^{-5}
AF25	4.60	4.70	2.27	2.38	10.68	2.69×10^{-10}	1.38×10^{-5}
AS15	4.65	4.74	2.31	2.42	10.95	2.46×10^{-10}	1.04×10^{-5}
AS30	4.52	4.71	2.35	2.46	11.07	2.42×10^{-10}	1.09×10^{-5}
AS50	4.39	4.54	2.25	2.35	10.20	2.38×10^{-10}	0.99×10^{-5}
B	3.64	3.79	2.37	2.46	8.99	1.36×10^{-10}	1.00×10^{-5}
BF15	3.57	3.68	2.37	2.45	8.70	1.31×10^{-10}	0.76×10^{-5}
BF25	3.49	3.59	2.40	2.48	8.62	1.27×10^{-10}	0.71×10^{-5}
BS15	3.51	3.72	2.36	2.44	8.77	0.90×10^{-10}	1.01×10^{-5}
BS30	3.62	3.75	2.36	2.43	8.54	1.00×10^{-10}	0.99×10^{-5}
BS50	2.90	3.09	2.38	2.45	7.33	0.72×10^{-10}	0.71×10^{-5}
C	3.64	3.74	2.39	2.48	8.95	1.20×10^{-10}	0.95×10^{-5}
CF15	3.55	3.65	2.37	2.45	8.65	0.95×10^{-10}	0.85×10^{-5}
CF25	3.51	3.60	2.35	2.44	8.47	0.89×10^{-10}	0.81×10^{-5}
CS15	3.68	3.75	2.29	2.37	8.60	0.74×10^{-10}	0.85×10^{-5}
CS30	3.49	3.57	2.38	2.46	8.50	0.74×10^{-10}	0.71×10^{-5}
CS50	3.49	3.53	2.32	2.40	8.40	0.63×10^{-10}	0.62×10^{-5}

cumulative volume of water penetrated per unit surface area of exposure is plotted against the square root of time of exposure, the resulting graph could be approximated by a straight line passing through the origin [34]. 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. The sorptivity values for various mixes are given in Table 6 and are in the range of 0.62×10^{-5} to 1.47×10^{-5} m/$\sqrt{}$s. Slag mixes gave lower sorptivity values than the fly ash mixes. It is also seen that the sorptivity values for CRM mix were less than that of mix without CRM except for mixes with fly ash with $w/b = 0.50$. Charles Allen [35] reported that sorptivity value is 2.1×10^{-5} m/$\sqrt{}$s and 1.92×10^{-5} m/$\sqrt{}$s, respectively for fly ash concrete ($w/b = 0.50$) with 30% and 40% replacement, at 28 days as compared to 1.5×10^{-5} m/$\sqrt{}$s for concrete without CRM. He concluded that although the sorptivity is slightly higher for fly ash concrete at 28 days, it could be expected to improve with age. Slag mixes gave lower sorptivity values than fly ash mixes.

6. Conclusions

1. Proposed mix proportioning method combines the use of superplasticiser and cement replacing material in obtaining economical HPC mix.
2. The early age strength of CRM mixes shows lower value for the same w/b because of slower pozzolanic reaction. However, the same early strength can be achieved by increasing the binder content keeping the effective w/b ratio ($w/[c + kf]$) and the water content constant (i.e. increase in binder based on the efficiency of the CRM)
3. The efficiency factor for CRM, evaluated from the results of two extreme w/b ratios, shows increasing trend with the curing period. Therefore, it is essential that the concrete containing CRM may require prolonged curing.
4. The efficiency factor for fly ash mixes showed decreasing trend as the replacement level is increased, whereas, slag mixes showed increasing trend (except for high replacement level). However, the higher CRM replacement is economical and will also have advantage of having lower w/b if the effective w/b ratio is kept constant.
5. There is an increase in total binder content as the effective w/b ratio decreases. However, as the CRM content increases, the cement required per unit strength reduces. Thus, it is possible to effectively utilise the cement by adopting the lower effective w/b ratio with higher CRM content.
6. Predicted values of the compressive strength for intermediate w/b compares well with the experimental results (±5–10%) obtained in the present investigation and for data from some of the published literature.
7. The limited durability properties investigated (after 28 days curing) are found to improve by reduction of w/b ratio and further improved by addition of CRM. However, there is a need to investigate all other durability properties to arrive at specific conclusions.
8. Slag mixes upto 50% replacement level showed better performance in terms of mechanical properties and durability characteristics when compared with fly ash mixes.

Acknowledgements

This paper is being published with the kind permission of the Director, Structural Engineering Research Centre, Madras, India. The authors also express their sincere thanks to their collegues for their co-operation and assistance during the investigation.

References

[1] Swamy RN. High performance and durability through design. ACI SP-159 1996:209–30.
[2] Shah SP, Ahmad SH. High performance concrete: properties and applications. McGraw Hill 1994.
[3] Mittal A, Basu DC. Development of HPC for PC Dome of NPP, Kaiga. Indian Conc J 1999;73(3):571–9.
[4] Hover KC. Concrete mixture proportioning with water reducing admixtures to enhance durability: a quantitative model. Cem Concr Compos 1998;20:113–9.
[5] CEB-FIP. Application of high performance concrete. Report of CEB-FIP working group on HS/HPC, 1994, 69 pp.
[6] Mehta PK. Role of pozzolanic and cementitious material in sustainable development of the concrete industry. ACI SP-178 1998:1–20.
[7] Malhotra VM. Making concrete greener with fly ash. Concrete International, May 1999, pp. 61–6.
[8] Swamy RN. Design for durability and strength through the use of fly ash and slag in concrete. ACI SP-171 1997:1–72.
[9] Aitcin PC. High-performance concrete. E&FN SPON, New York, 1998.
[10] Popovics S. What do we know about the contribution of fly ash to the strength of concrete. ACI SP-91 1986:313–31.
[11] ACI Committee 211.1-91. Standard practice for selecting proportions for normal, heavy weight and mass concrete. ACI manual of concrete practice, 1996, part 1, pp. 211.1-1 to 211.1-38.
[12] Smith IA. The design of fly ash concretes. Proc Inst Civil Eng, London 1967;36:769–90.
[13] Brandt AM. Optimisation methods for material design of cement-based composites. E&FN SPON, London, 1998.
[14] Cannon RW. Proportioning fly ash concrete mixes for strength and economy. ACI J 1968;65(11):969–79.
[15] Munday JGL, Ong LT, Dhir RK. Mix proportioning of concrete with PFA: critical review. ACI SP-79 1983:267–88.
[16] ACI Committee 211.1.4R-93. Guide for selecting proportions for high-strength concrete with Portland cement and fly ash. ACI manual of concrete practice, 1996, Part 1, pp. 211.4R-1 to 211.4R-13.

[17] Mehta PK, Aitcin PC. Principles underlying production of high-performance concrete. Cem Concr Aggreg 1990;12(2):70–8.
[18] Rougeron P, Aitcin PC. Optimisation of the composition of a high performance concrete. Cem Concr Aggreg 1994;16(2):115–24.
[19] Collepardi M. Admixtures used to enhance placing characteristics of concrete. Cem Concr Compos 1998;20:103–12.
[20] DIN 1045. Beton und Stahlbeton. Beton, GMBH, Koln.
[21] Schiessl, Hardtle. Efficiency of fly ash in concrete-evaluation of ibac test results. Technical Report of Institute fur Bauforsching, RWTH, Aachen, pp. 1–31.
[22] Ganesh Babu K, Siva Nageswara Rao G. Efficiency of fly ash in concrete. Cem Concr Compos 1993;15:223–9.
[23] Siva Nageswara Rao G. Effective utilisation of fly ash in concrete for aggressive environment. Ph.D. Thesis, IIT, Madras, 1996.
[24] Bolomey J. Durecissenment des Mortiers ets benton. Tech Suisse Romande Nos 1927;16:22/24.
[25] Walker S, Bloem DL. Effect of curing and moisture distribution on measured concrete strength. Highw Res Rec, Highw Res Board 1957;36:334–46.
[26] Gilkey HJ. Water–cement ratio vs strength-another look. ACI J Proc 1961;57(10):1287–312.
[27] Cordon WA, Gillespie HA. Variables in concrete aggregates and Portland cement paste, which influence the strength of concrete. ACI J Proc 1963;60(8):1029–50.
[28] Raju PVSN. Corrosion behaviour of steel in concrete. Ph.D. Thesis, IIT, Madras, 1990.
[29] Venkateswara Rao K. Deterioration of concrete in marine environment. Ph.D. Thesis, IIT, Madras, 1992.
[30] IS:516–1959. Methods of tests for strength of concrete. Bureau of Indian Standards, New Delhi, India.
[31] American Society for Testing and Materials. Standard test method for specific gravity, water absorption and voids in hardened concrete. ASTM Stand Concr Aggreg 04.02,C642; 1990:318–9.
[32] Malhotra VM. Strength and durability characteristics of concrete incorporating a pelletized blast furnace slag. ACI SP-79 1986;2: 891–921.
[33] Powers TC. Properties of fresh-concrete. New York: Wiley; 1968.
[34] Atzeni A, Massidda L, Sanna U. Capillary absorption of water in hardened cement paste treated with silicic ester or alkylal koxysiloxane. Mag Concr Res 1993;45(162):11–5.
[35] Charles A, Ian B, Frank P. High performance wet-shotcrete – a practicle review. In: TCDC International Workshop on Advances in High Performance Concrete Technology and its Applications, 16–18 April 1997, SERC, Madras, pp. III-1 to III-20.