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Some trends in the use of concrete : Indian scenario

Praveen Kumar and S.K. Kaushik

Concrete has undergone rapid and phenomenal development in the past few years in India. Revision of IS 456 : 2000 with emphasis on durability, appreciation of the quality assurance in general, setting up of a large number of RMC plants in metros, thrust on infrastructure development, etc have contributed to this growth and transformation. On the other hand, globalisation of the Indian economy paved the way for easy availability of micro-silica and latest superplasticisers in the country. M60 and higher grades of concrete are now becoming popular in the country with its proven utility in the construction of important structures. A brief account of the trends in the use of concrete and its production in the country is presented in the paper. Also presented is a glimpse of the current research and development scenario in the areas of self-compacting concrete, PQC and triple blend concretes in the country.

Concrete is the preferred construction material in India. The cement production has increased, thanks, mainly: to the renewed thrust on infrastructure development in the country. In the past five-six years mega construction projects involving the use of concrete have been executed in the country in a large number. Some of them include construction of a large number of flyovers, Delhi metro rail, atomic and thermal power plants, golden quadrangle road project, reconstruction of Gujarat after January 2001 earthquake, etc. The quality and type of concretes being employed have undergone a transformation with the use of state-of-the-art concrete technology.

Amongst the recent developments in the field of concrete such as high-performance concrete (HPC), compacted reinforced concrete (CRC) reactive powder concrete (RPC), self compacting concrete, etc, HPC could find applications in India in some of the prestigious projects. Of late, some interest is evinced in SCC too.

In addition, there is an increased thrust in the use of supplementary cementitious materials like fly ash, ground granulated blast-furnace slag (GGBS) silica fume, metakaolin, etc. With fly ash production in the country reaching 100 million tonnes, it is more important for India to develop technologies involving fly ash consumption in concrete. Triple blend concretes which have started coming up in the country makes up for deficiency in early age strength of high volume fly ash/GGBFS concretes and at the same time increase durability. The ternary mixes have found their applications in self-compacting concretes too.

Thrust on design mix concrete

A major part of concrete, which is being used in rural and semi-urban areas, still falls in M15 and M20 category with very little quality control. However, where big construction companies are involved, concreting is done mostly either through a batching plant commissioned at the site itself or RMC. With the adoption of IS 456: 2000[1], the construction agencies have now been left with no choice but to adopt design mix concretes. The adoption implied a better understanding of the role of aggregate shape, water content of fine aggregates, grading of aggregates and above all water-cement ratio for even M20-M40 grades of concretes by the average user[2]. This in turn improved the quality of the concrete in general. In general, the importance of proper curing of concrete is being realised and there is a marked improvement in the state of curing at construction sites, particularly those executed by PWDs. Overall lowering of the standard deviation values (though marginal only) by the IS 456: 2000 indicates the increase in confidence level. Even, the standard deviation value of 5.0 MPa,

Table 1: Expected growth of commercial RMC in India[9]

Year	Total concrete consumption, million m^3	Concrete consumption on sites without dedicated plants, 60 percent	RMC penetration percent of (3)	Total RMC usage, million m^3	Expected number of plants
(1)	(2)	(3)	(4)	(5)	(6)
2002	190	120	2	2.4	47
2007	280	168	3.75	6.3	98
2012	370	220	5.00	11.0	160
2017	470	282	7.50	21.00	260
2022	580	348	10.00	34.8	348

now specified for M30 to M50 grades of concrete is relatively high for seasoned producers of high strength concrete.

The major chunk of these grades of concrete is utilised in bridges, piles, high rise structures, power plants, etc, where good quality control is exercised[3-8]. In most of these places, ready mixed concrete (RMC) is now increasingly being used. The quantum of RMC being produced and used is increasing rapidly in the country, with setting up of RMC plants by major construction agencies like L&T and other private companies including ACC, Unitech, RMC Ready Mix (India) Ltd, Grasim Industries, India Cements, etc in various metros. Jain estimated the growth of commercial RMC in India as given in *Table* 1[9]. RMC not only offers uniform quality of the concrete mixes but also facilitates correct proportions of admixtures in the concrete.

For mix design of high strength concrete, recent work by Larrard[10] takes clue from one hundred-year old Feret's formula, which suggests that maximum strength is achieved when the ratio of voids per total matrix volume is minimal. Minimum cement paste content concept has been referred by Joshi, while discussing mix design principles in reference to Bandra-Worli sea link project[8]. It suggests that increase in cement content does not necessarily increase strength in concrete[8]. Addis and Alexander have discussed the cement saturation effect[11]. Authors too, recently experimented with very high cement contents (commensurate with those used in CRC matrix), with maximum sizes of aggregates varying between 4 to 20 mm, and observations confirmed that the rate of increase in compressive strength became low with higher cement contents with all aggregate sizes.

High cement contents produce higher heat of hydration and shrinkage. It is also realised that harmful effects of aggressive agents such as sulphates, chlorides, carbonates, etc are also due to cement[8]. Hence, lower the cement content, lower the harmful effects.

Mineral admixtures in concrete

IS 456: 2000 has a distinct difference than its earlier version of 1978 in that the revised code accepts and encourages the use of mineral admixtures in concrete. Clause 5.2 is specifically added to mention the use of fly ash, metakaolin, rice husk ash, GGBS and silica fume. Also, *Table* 5 of the standard[1], specifies that addition of these pozzolanas be considered while taking into consideration the specified minimum cement contents. Typical characteristic properties of three mineral admixtures being utilised in the country are given in *Table* 2. A difference is observed between the physical and chemical properties of these materials with difference in source. The values provided here show the properties of the three admixtures, which have been used by the authors in their research works recently.

An increased understanding of the adjustments in water and fine aggregate contents in fly ash concrete mix design has led to the use of fly ash in the production of RMC by one of the leading manufacturer[13].

Table 2: Typical physical and chemical properties of mineral admixtures used in India[*,12,15]

Sr No	Property	Fly ash[12]	Metakaolin[*,15]	Microsilica[*]
1.	Silicon dioxide (SiO_2) percent by mass	57.5	52.0	95.1
2.	SiO_2+Al_2O_3+Fe_2O_3 by mass	91.0	97.0	95.1
3.	Loss on ignition, percent by mass	0.57	0.68	2.79
4.	Fineness (specific surface) m^2/gm	0.372	14.0	22.0

Notes:
(i) *The characteristics reported above are as obtained from respective manufacturers.
(ii) Particle size distribution details of metakaolin: percent above 10 microns: 2.0; percent below 2 microns: 70.0; average particle size 1.5 micron.
(iii) Particles percent above 45 micron in microsilica was 0.70.

Increased availability of dry fly ash from ESPs

Out of a total of about 90 coal-based thermal power stations in the country producing fly ash, an increasing number (presently about 30) has already developed dry mode of collection of fly ash, resulting in the availability of better quality fly ash with better consistency of product than ever before in the country. Recent begining of a bagging facility for fly ash at Badarpur thermal power plant is a testimony of the ongoing development in thermal power plants to ensure better fly ash availability for concrete for RMC plants.

Commercial availability of metakaolin

Till three-four years ago, hardly anybody in India was aware of the use of metakaolin in concrete. During these four years, the developments that have taken place include increased awareness of the huge potential of production of metakaolin in the country (with huge mineral resource, that is, kaolin availability across the country), start of indigenous commercial production and many investigations on the development of concrete mixes containing metakaolin[14,15].

Increased use of micro- silica

The JJ flyover, Mumbai and primary containment dome structures of atomic power plant structures at RAPP 3 & 4 and Kaiga were some of the important structures built with silica fume concrete in the last few years[4,5,6,7,8,15]. Prestigious ongoing projects where microsilica is being used include the complete primary containment structure of Tarapur Atomic Power Project units (TAPP 3 & 4) and Tehri dam[15,16]. A major marketing firm of microsilica in the country has estimated its turnover in the current year be approximately seven to eight hundred million rupees.

Table 3: Typical concrete mixes used in India in recent years[7,12,17,18]

Quantity/ Strength	*Mumbai- Pune expressway[18]*		*Mumbai sewage disposal project[17]*			*J.J. Flyover,*	*Delhi Metro[12] Mumbai[7]*
	I[+]	*II[+]*	*M45*	*M35*	*M15*		
Cement	380.0	360.0	135	120	90	500	303.8
Water	152	138.8	153	160	180	148	165
Fly ash/GGBFS	——	——	315	280	210	——	130.2
Micro-silica	——	——	——	——	——	50	——
Sand	861[#]	915[#]	878	903	1022	682	724.7
Aggregates							
10mm	438	424	392	482	429	384	403.4
20mm	728	718	598	577	538	762	605
S.P	2.66	2.50	4.51	6.0	6.0	8.25	5.21
Other admixture	2.28[*]	0.7[**]	-	-	-	——	——
Slump, mm	5-15	5-15	-	-	-		145
28-day strength	66.09	60.60	60	50	25	86	52.15
Remarks	Specially hard. aggregates selected		Target strength values shown here			For C. A. sizes of I and II types need to be confirmed	slump retention: after 60 and 90 min. 130 and 90 mm respectively

Note:
(i) The units of quantities and 28 days compressive strength mentioned in the table above are kg/m^3 and MPa respectively.
(ii) +Pavement quality concrete (PQC): I type about 10, 500 m^3, II type about 20, 000 m^3.
(iii) Sand : crushed sand #.
(iv) Admixture: *a stabiliser, **air entraining agent.
(v) For Mumbai-sewage disposal project, GGBFS has been used, the reference quoted[17], speaks of "additives", it is presumed that this corresponds to SP, the quantities are included in the column of SP. However, a confirmation from the original author may be required.

Increased share of PPC

With increased availability of dry fly ash from the thermal power plants, the cement manufacturers can rely on economic production of PPC with better quality than before. This development has resulted in increased adoption of PPC by users too. This is indicated by a steep rise in share of PPC out of total cement production in the last few years (currently estimated to be about 55 percent).

Typical mixes used in recent years in the country

Table 3 shows that in prestigious project works in recent years, mineral admixtures in concrete have widely been used. The proper mix design has resulted in limiting cement content.

Enhancement of durability with mineral admixtures

Recent use of fly ash in Delhi Metro rail project has been mainly for attaining a design life of 120 years of the structure[12]. The comparative properties of hardened concrete of non-fly ash concrete and fly ash concrete reported for the project is shown in *Table* 4.

Krishnamoorthy has rightly pointed out that fly ash should be regarded more as a durability enhancer and void blocker than as a cement economiser (provided, it is a low calcium dry fly ash obtained from ESP hoppers and with a minimum fineness of 320 m^2/kg)[19]. The Delhi Metro project data shown in *Table* 4 amply illustrates the reduced permeability, water absorption and drying shrinkage in fly ash concrete[12].

The increase in flexural strength (of the order of about 25 percent), and tensile strength (of the order of about 10 percent) in fly ash concrete mix of the similar 28 days compressive strength as that of non-fly ash concrete is worth noting in *Table* 4. This advantage makes the fly ash concrete a worthwhile option for nuclear containment structures, which has not been tapped so far in the country. In nuclear power plants of RAPP 3 and 4 units and Kaiga, the split tensile strengths achieved were 4.08 MPa and 3.94 MPa, with even higher compressive strengths, that is, 73.5 MPa and 69.5 MPa respectively. With fly ash concretes of similar compressive strengths, higher tensile and flexural strengths can possibly be attained.

The primary reason for using ground granulated blast furnace slag (GGBFS) in large quantities, in the Mumbai Sewage disposal project, was again to make concrete dense, impervious and to have an ability to resist any deterioration on account of the hazardous elements in the sewage[17].

Micro-silica concrete of different grades has been used for durability aspects in various projects in the country, which includes:

(i) Deepak Fertilisers plant to achieve high chemical resistance in the concrete used for the storage silos[20].

(ii) Construction of piers and pier caps of the second bridge across river Narmada in Baruch, Gujarat (M60 grade)[20].

(iii) 5.6 km Bandra-Worli Sea Link project in Mumbai (2, 00, 000 m^3).

(iv) For abrasion resistant M50 grade concrete (20,000 m^3 in Baglihar hydro-electric project: Exterior 1.0 m thickness on upstream of spillways crest above elevation 805 m and down stream glacis of spillway except the portion covered by the steel lining, exterior 1.0 m thickness on upstream waterside faces of piers upto 11 m height from the spillway surface in the portion not covered by steel lining and top 1.0 m thickness in the plunge pool floor[21].

(v) The rapid chloride ion permeability test (RCPT) and initial surface absorption test (ISAT) values were less than 300 coulombs and of the order of 0.016 $ml/m^2/s$ respectively, implying a fairly impermeable concrete with the use of 10 percent micro-silica in J.J. Flyover, Mumbai[7] .

A laboratory study by Gupta *et al* shows that the decrease in the compressive strengths of fly ash and silica fume concretes show better performance in 1 and

Table 4: Comparison of properties of hardened concrete with and without fly ash[12]

S. N.	*Properties*	*Non fly ash concrete*	*Fly ash concrete*
1.	Compressive strength (28 d), MPa	52.09	52.15
2.	Flexural strength (28 d), MPa	5.98	7.45
3.	Indirect tensile strength, (28 d), MPa	4.20	4.60
4.	Drying shrinkage, percent	0.042	0.040
5.	Permeability (As per DIN- 1048), mm	11.65	6.19
6.	Water absorption, percent	1.43	1.0

Table 5: Advantage of using fourth generation super-plasticiser for SCC (authors)

Materials	*Mix 1*	*Mix 2*
Cement, kg	331	343
Fly ash, kg	236	244
Micro- Silica, kg.	16.5	17.2
Crusher dust , kg	827	858
Zero-size aggregate, kg*	662	686
Water, kg	237	213
Superplasticiser type	SNF-based	Polycarboxylate ether (PCE) based
Superplasticiser, kg	12.4	5.8
Superplasticiser solids weight, kg	4.84	1.4
Slump flow, mm	475	700
Compressive strength, MPa 7-day	18.0	32.4
28-day	33.8	55.7

Notes:
(i) The water content is total, for dry aggregates.
(ii) *Crusher dust and zero-sized aggregates (2-6 mm) used in the investigations have been sieved in different sizes and blended.
(iii) The materials used were 53 grade OPC and undensified (920 U grade) micro-silica with silica content of about 93.1 percent.

5 percent solutions of NaCl and Na_2SO_4 after 28 days in comparison to the concrete without fly ash and silica fume (the strength range was 70-90 MPa)[22] . The cement used was 53 grade OPC and aggregates employed were sandstone and granite with 12.5 mm maximum size, sands used were Badarpur sand and Yamuna sand[22] .

Current R&D scenario

Self compacting concrete

Several construction companies and research institutions have undertaken research and development works in self compacting concrete (SCC). Limited field trial studies on a segment of prestressed concrete girder of overall depth 1.4 m, deck depth 125 mm and top web width as 325 mm at Holenarsipura, Karnataka, has exhibited excellent finish with expected strength and prevention of rock pockets and other minor defects (observed without the use of SCC)[23,24]. Subramanian *et al* reports that with reasonable cement content, varying from 335 kg/m^3 to 371 kg/m^3, it was possible to get fairly high strength SCC of about 50-60 MPa at 28 days[23]. Recently, Vengala *et al* have reported to achieve about 66 MPa strength SCC (at 28 days) with water-powder ratio of about 1.25[25]. Vengala *et al* have reported in detail the test results for development of SCC mixes and provide insight into the role of VMA, role of paste volume ratio etc for producing SCC etc[25]. The paste volume in the range 0.43-0.45 is suggested. The test results once again underlined the advantage of using fly ash in SCC. Raghavan *et al* investigated creep, shrinkage, durability (through RCPT) and shear resistance properties of self-compacting concrete[26]. The test results indicate that although the initial elastic deformation is more in the case of SCC, final strain induced by creep is less than normal concrete. The drying shrinkage of SCC has been reported to be 25 percent lower than that of normal concrete. SCC for lower w/p ratio and greater compactness is reported to show more durability in terms of chloride permeation as compared to normal concrete[26]. The size of coarse aggregate in SCC is shown not to have a significant effect on shear resistance property.

The ongoing research work by authors indicate that marginal materials like stone dust and zero-size grit (aggregates 2-6 mm sieve size), can also be used to produce self compacting concrete. Fly ash based self-compacting concretes with 28-days compressive strengths in the range 60-70 MPa have also been produced by the authors.

Low clinker/green concrete

At laboratory scale, low clinker concrete (also known as green concrete) has been developed. It has been found to be more economical and durable than the conventional concrete[27]. The range of compressive strength generally is 10-15 MPa. In Denmark, growing of grass on such concrete is common (generally used at slopes).

Fourth generation superplasticisers

Recently, several companies have made polycarboxylate ether-based superplasticisers available in the country. The extra "steric repulsion" effect imparted by these admixtures is a boon for production of self-compacting concrete. *Table* 5 illustrates the advantage as observed by the authors. The products being marketed as "zero energy admixtures" facilitate early hydration in concrete in addition to the superplasticising action. Compatibility of various admixtures has to be checked when a VMA is to be used in association with either a fourth generation superplasticiser or zero energy admixture (for producing SCC specially).

Table 5 shows that while a SNF based superplasticiser content of 4.84 kg (solids), provided a slump flow of only 475 mm, a fourth generation polycarboxylete ether (PCE) based superplasticiser with approximately 30 percent of this quantity (1.4 kg), produced a slump flow of 700 mm. Also, the mix 2 exhibited a rise of 300 mm in a U- box test within 20 seconds. Simultaneously, the water content could also be reduced to 213 kg/m^3 instead of 237 kg/m^3. This resulted in a dramatic rise in the 7 day as well as 28-day strength of concrete.

It is now easier to produce concretes with low water/binder ratios with the fourth generation superplasticisers, provided compatibility between the various ingredients is established. It is, therefore, not surprising, that the authors struggled to find compatibility with three different brands of cement and one SNF based superplasticiser with metakaolin, even though compatibility was exhibited with microsilica and the cements/SNF based superplasticiser. However, one PCE based superplasticiser was found to be compatible with the same brand of cement and metakaolin.

The traditional mixing time of concrete mixes need to be increased in the case of silica-fume concrete applications in the country[7,16] (about 80-120 seconds mixing time reported). This was required to ensure proper dispersion of silica fume in the presence of relatively high quantities of plasticiser (SNF based). The importance of increased mixing time has also been observed by the authors in their ongoing research programme involving self-compacting concrete with multi-carboxylate ether based superplasticisers.

Triple blend concretes

With established knowledge of improvement in durability in concretes containing good amounts of fly ash or blast-furnace

Table 6: Portland slag cement with silica fume[27]

No	*Age, days*	*PSC*	*5 percent PSC replaced by silica fume*		*7.5 percent PSC replaced by silica fume*	
			SF1	*SF2*	*SF1*	*SF2*
1.	3	21.2	26.5	27.0	31.3	30.5
2.	7	37.5	40.0	38.0	42.3	38
3.	28	47.5	50.3	48.0	52.8	48.2
4.	60	50.0	54.0	533	52.6	526

Table 7: PQC with blended cements[32]

Sr No.	Material/property	M30		M40	
		PSC	PPC	PSC	PPC
1.	Cement, kg/m^3	400	400	400	400
2.	Water, kg	180	160	168	152
3.	Superplasticiser, *l*	0	2.0	0	4.0
4.	Slump, mm	85	35	30	50
5.	Compressive strength, MPa				
	1-day	10.2	10.4	14.3	14.0
	7-day	27.1	27.8	34.6	33.6
	28-day	40.3	41.8	50.3	48.2
6.	Flexure strength 28-day, MPa,	5.98	6.16	6.86	6.7
7.	Modulus of elasticity 28-day, GPa	37.6	36.85	45.3	43.89

slag, or PPC/PSC, one of the main reasons preventing their large-scale use has been the slower gain of compressive strengths at early age. One method for overcoming this slower strength gain is to add another more rapidly reacting supplementary cementitious material like micro-silica. Thus the potential long-term durability and strength improvements may be obtained with minimal impact on early age strength. This provides attractive option for specifiers looking to decrease the time before form-work may be removed, say particularly the time before bridge decks can be opened to traffic. Laboratory work on triple blend concretes (or ternary mixes as they are called), has already started. To allow the more widespread adoption of such mixes, it is necessary to build up a series of test data on its performance to allow designers and specifiers to make informed choices with regard to the selection of raw materials and their proportions. Limited test data are available so far, like those with combinations of lignite fly ash and micro- silica, slag and fly ash, slag and micro-silica, etc with cement. The test results of Tiwari and Illyas are reproduced in *Table* 6 to illustrate the increase in early age strength in such concretes[27].

Khalid *et al* reported physical and engineering properties of concretes made with multi-blend cements, referred as MBC (OPC clinker+fly ash+GGBS+low grade gypsum)[28]. A comparison of water cured compressive strengths upto one year of age, resistance in compressive strength of MBC concretes and OPC concretes in sea-water and 10 percent sulphate solution show better performance of MBC concretes. Typical percentage proportions of OPC clinker, GGBS and fly ash in four cements used in the tests were 50,35,15; 60,30,10; 60,25,15 and 100,0,0.

Most of the Indian fly ashes contain calcium oxide less than 5 percent. With the facility of RMC plants one can use large volumes of low calcium fly ashes with small percentage addition of micro-silica to produce high early strength and durable concretes. The test data are not available so far with Indian cements (which differ in Bogue's compound composition from that of ASTM Type I cements used in developed countries), our fly ashes and micro-silica. The use of fourth generation superplasticisers may provide high slump in such high strength concrete mixes. Such development with possible use of locally available aggregates in different parts of the country may be useful for the construction industry (and nation to consume a part of gigantic amounts of fly ash).

The authors have started research investigations in this area. The experimental test results have resulted in development of mix proportions for 180-250 mm slump concrete with 7 and 28-day strengths in the range of 50-60 MPa and 70-85 MPa, respectively.

Pavement quality concrete with fly ash/GGBFS

A roller compacted concrete wearing course of 100 mm thickness has been constructed with zero slump concrete in a demonstration project of rural road construction on Salarpur-Dadupur road in district Gautam Budh Nagar, Uttar Pradesh[29]. Nearly 220 kg of cement and an equal amount of fly ash per cubic metre of concrete were used in the construction. Other demonstration road projects include construction of concrete roads at Chandigarh on Morinda byepass Ludhiana by PWD Punjab, in Haryana by PWD Haryana with HUDA and NCCBM support, at Raichur by Karnataka PWD with support from fly ash mission and one in Mumbai with CANMET/CIDA support [30,31]. Satander *et al* and Malhotra have advocated the use of blended cements in general and high volume fly ash concrete respectively in road construction[30,31].

Tiwari and Bandopadhyay have reported a laboratory study on development of pavement quality concrete with blended cements[32]. A portland slag cement (PSC) with 48 percent slag absorption and a portland pozzolona cement (PPC) with about 23 percent fly ash absorption were used in development of PQC of grades M30 and M40. The cement contents and basic properties are reported here in *Table* 7.

Concluding remarks

From the above study, the following conclusions can be drawn

(i) Construction materials should be developed in a country keeping mainly in view its own resources and climatic conditions; cement concrete is no exception.

(ii) Use of supplementary cementitious materials particularly, fly ash, blast furnace slag and microsilica have been adopted in prestigious projects in the country, with an aim to achieve higher strengths and better durability.

(iii) The myth of dependence on an essential increase in the cement content, only to obtain higher performance in concretes, has been rightly broken and 50-60 MPa compressive strength concretes are being produced and used in the field with cement contents well below 400 kg/m^3 with addition of mineral admixtures.

(iv) Recent R&D activities have indicated compatibility of fourth generation superplasticisers with Indian cements to produce self-compacting concrete (SCC). Fly ash based SCC mixes with 28-day strength in the compressive strength range 50-70 MPa, have already been developed by the authors and are currently being tested comprehensively for their structural properties at Roorkee.

(v) The road sector in the country is likely to use cement concrete in a big way in coming years. Demonstration projects and laboratory studies have indicated good performance.

(vi) Triple blend concretes are the concretes of today and tomorrow, particularly in big projects having RMC plants.

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References

1. ______*Indian standard code of practice for plain and reinforced concrete*, IS 456 : 2000, Bureau of Indian Standards, New Delhi.

2. Naik, Suguna and Dordi, C.M. Checklists on materials, *The Master Builder*, June-August 2002, pp. 85-86.

3. Mittal, Amit Development of high performance concrete for containment dome of Kaiga atomic power project, *The Indian Concrete Journal*, April 1998, Vol 72, No 4, pp. 193-202.

4. Mittal, Amit, and Basu, Prabir, C. Development of HPC for P.C. dome of NPP, Kaiga, *The Indian Concrete Journal*, September, 1999, Vol 73, No 4, pp. 548-556.

5. Bapat, S.G. and Agarwal, Neeraj Experience in the development and production of HPC for RAPP 3&4, *The Indian Concrete Journal*, September, 1999, Vol 73, No 9, pp. 582-586.

6. Basu, Prabir C. NPP containment structures: Indian experience in silica fume based HPC, *The Indian Concrete Journal*, Vol 75, No 10, October 2001, pp. 656-666.

7. Saini, Sunil, Dhuri, S.S., Kanhere, D.K. and Momin, S.S. High performance concrete for an urban viaduct in Mumbai, *The Indian Concrete Journal*, October 2001, Vol 75, No 10, pp 634-640.

8. Joshi, N.G. Bandra-Worli sea-link: Evolution of HPC mixes containing silica fume, *The Indian Concrete Journal*, October 2001, Vol 75, No 10, pp. 627-633.

9. Jain, A.K. RMC - Growth prospects in India, *Concrete India*, Journal of the Indian Chapter of ACI, October-December 2002, Vol 17, No 4, pp. 5-8.

10. Larrard, F. De and Sedran, T. Optimization of ultra-high performance concrete by the use of a packing model, *Cement and Concrete Research*, Vol 24, No 6, pp. 997-1009.

11. Addis, B.J. and Alexander, M.G. Cement saturation and its effects on the compressive strength and stiffness of concrete, *Cement and Concrete Research*, 1994, Vol 24, No 5, pp. 975-986.

12. Agarwal, R., Gupta, A.K. and Garg, R. High performance fly ash mixed concrete in underground construction of Delhi Metro, *Proceedings of the third International conference on Fly ash utilisation and disposal*, February 19-21, 2003, CBIP, New Delhi, pp. IV-1- IV-15.

13. Bahadur, Sanjay and Pandey, Devendra Kumar First 2,00,000 m^3 of RMC using fly ash in India, *Proceedings of supplementary papers of the Seventh CANMET/ACI international conference on fly ash, silica fume, slag and natural pozzolans in concrete*, July 22-27, 2001, pp. 265-267.

14. Pal, S.C., Mukherjee, A. and Pathak, S.R. Development of high performance concrete composites using high volume cement replacement with supplementary pozzolanic and cementitious solid waste, *Proceeding, Recent Developments in Structural Engineering*, SEC 2001, October, 2001, IIT Roorkee, pp. 215-229.

15. Basu, Prabir C. High performance concrete, *Proceedings of the national seminar on engineered building materials and their performance*, INAE, January 17-18, 2003, IIT Bombay, pp. 426-450.

16. Lewis, Robert Using high performance silica fume concrete for dams in India, *Proceedings of the workshop on use of silica fume based high performance concrete in hydraulic structures*, February 13, 2003, ISCMS, CSMRS, New Delhi, pp.23-27.

17. Haridas, G.R. Mumbai sewage disposal project - A new experiment, *The Indian Concrete Journal*, June 1999, Vol 73, No 6, pp. 354- 362.

18. Erande, A.A. and Limaye, Shrikant Optimising mix design for concrete pavement in Section D, *The Indian Concrete Journal*, June 2000, Vol 74, No 6, pp. 353-365.

19. Krishnamoorthy, S. Some basic truths of concrete, *ICI Journal*, January-March 2002, p. 10.

20. Lewis, Robert and Hasbi, S.A. Use of silica fume concrete: selective case studies, *The Indian Concrete Journal*, October 2001, Vol 75, No 10, pp. 645-652.

21. Lazaric, Boris and Pandita, N.K. Silica fume based high performance concrete for hydraulic structures in Baglihar hydroelectric project, *Proceedings of the workshop on use of silica fume based high performance concrete in hydraulic structures,* ISCMS, CSMRS, New Delhi, pp. 4-8.

22. Gupta, S.M., Sehgal, V.K. and Kaushik, S.K. Durability of high strength concrete, *Proceedings of the structural engineering convention*, SEC 2001, IIT Roorkee, pp. 335-348.

23. Subramanian, S. and Chattopadhyay, D. Experiments for mix proportioning of self compacting concrete, *The Indian Concrete Journal*, January 2002, Vol 76, No 1, pp. 13-20.

24. Ramakrishna, A. Recent trends in construction of civil structures, *Proceedings of the workshop on NDE of concrete structures*, ISNT, Chennai, December 02-04, 2002, pp. 17-31.

25. Vengala, J. Sudarshan, M.S. and Rangnath, R.V. Experimental study for obtaining self-compacting concrete, *The Indian Concrete Journal*, August 2003, Vol 77, No 8, pp. 1261-1266.

26. Raghavan, K. P., Sarma, B. Sivarama and Chattopadhyay, D. Creep, shrinkage and chloride permeability properties of self-consolidating concrete, *Proceedings of the first North American conference on the design and use of self consolidating concrete*, Northwestern University, Evanston, pp.307-311.

27. Tiwari, A.K. and Illyas, Momin Improving early-age strength of PSC with indigenous silica fume, *The Indian Concrete Journal*, October 2000, Vol 74, No 10, pp. 595-598.

28. Khalid, M., Mehrotra, S.P., Verma, M.L., Ahmad, J. and Verma, C.L. Performance of multi blend cement concrete under aggressive environments, *The Indian Concrete Journal*, January 2002, Vol 76, No 1, pp. 22-30.

29. Vittal, Guru, U.K., Mathur, S., Sengupta, J.B. and Swami, R.K. A case study on rural road construction using fly ash, *Proceedings of the 3rd international conference - fly ash utilisation & disposal*, February 19-21, 2003, New Delhi, pp. VI- 47-51.

30. Kumar, Satander, Sikdar, P. K. and Sood, V. K. *Choice of blended cements and fly ash for cost-effective and durable concrete roads*, *Proceedings of the 3rd international conference on fly ash utilisation and disposal*, February19-21, 2003, New Delhi, pp. VI-103 - VI-111.

31. Malhotra, V.M. High performance HVFA concrete : A solution to the infrastructural needs of India, *The Indian Concrete Journal,* February 2002, pp. 103-107.

32. Tiwari, A. K. and Bandopadhyay, P. Pavement quality concrete using blended cements, *The Indian Concrete Journal*, February 2002, Vol 76, No 2, pp. 117-120.

Mr Praveen Kumar obtained his masters degree in structural engineering from Jodhpur University in 1989. He is lecturer (senior scale) in the department of civil engineering, Engineering College, Kota, Rajathan. He is presently pursuing his PhD programme in IIT Roorkee in the area of high strength self-compacting concrete. His research work also includes high slump high strength concrete using triple blend of fly ash and micro-silica.

Dr S.K. Kaushik is a professor in the civil engineering department of IIT, Roorkee, India. He was president of the Indian Concrete Institute during 1995-97, Indian Society of Construction Materials and Structures during 1996-98, International Centre for Fibre Reinforced Concrete Composites during 1998-2000 and vice-president of Indian Society of Earthquake Technology. His areas of research include reinforced and prestressed concrete, performance evaluation of new concrete and composite materials, ferrocement and fibre reinforced concrete technology development and applications, non-destructive evaluation and testing and repair/rehabilitation of structures.

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