Use of HSC/HPC for road bridges in India

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The paper presents an exhaustive review of the use of highstrength concrete (HSC)/high-performance concrete (HPC) for road bridges in India. Major historical landmarks right from the 1940s till date in the bridge engineering field in India are discussed. The paper also presents a broad overview about various specifications/properties of different ingredients of concrete as had been used in the construction of Indian road bridges. Recent development in the use of HPC for some of the outstanding bridges in the world are highlighted. The paper concludes with remarks on the future scenario.

The use of high-strength concrete for road bridges in India is not of recent origin. Outstanding examples of such use include the Coronation bridge in West Bengal and the Napier bridge in Chennai city, both built in the early forties and both in excellent condition today. However, the widespread use of HSC was confined to the development of prestressed concrete as a bridge construction material.

The first prestressed concrete bridge in India was built in 1948 for the Indian Railways (Assam rail link) and the first prestressed concrete road bridge was built in the early fifties (Palar bridge near Chennai). Since then, concrete of characteristic strength in the range of 40 to 55 N/mm^2 has been in use for a large number of prestressed concrete road bridges in India. Due to peculiarities of the codes and specifications prevalent in India and consequent requirements of high margins, concrete which will easily pass characteristic strength 60 to 75 N /mm^2 has been produced for a number of road bridges in India.

Some of this concrete had many features of what is today known as high performance concrete (HPC). The paper highlights the Indian developments in this regard and concludes with an analysis of the prospects for the future.

Definition of high performance concrete

Traditionally, HSC/HPC has always been defined by its high compressive strength. However, the meaning of "high strength" has changed during the past decades. Concrete with a compressive strength of 35 N/ mm^2 was considered HSC in the 50's while 40 N /mm^2 or above was regarded high strength in the 60s.

Today,. high strength probably means a strength of 50 N/mm^2 and above.

There have been a number of alternative definitions proposed by various authorities. However, the following definition appears most appropriate[1] :

High performance concrete may be defined as concrete with :

1. a maximum water cement ratio of 0.35

2. a minimum durability factor of 80 percent as determined by ASTM C-666, Method A , and

3. a minimum strength criteria of either

   21 N /mm^2 at 4 hours (VES),

   34 N/mm^2 at 24 hours (HES),

   or N/mm^2 at 28 days (VHS).

Very early strength (VES) concrete would most likely be used for repairs to various components of bridges and for precast members to facilitate early removal of formwork. High early strength (HES) concrete has potential applications in prestressed concrete members of bridges to facilitate very early prestressing of first stage tendons at 24 to 48 hours after concreting. Very high strength (VHS) concrete having a strength of 69 N/mm^2 or more at 28 days will have primary applications in all types of bridge construction where structural efficiency is at a premium.

In addition to the above referred definition, durability criteria is another important factor.

Historical landmarks

Period : 1941 to 1950

A number of reinforced concrete and some prestressed concrete bridges were built in the country during this period. The design and construction of these bridges were based on the materials and construction equipment then available in the country. Outstanding examples of bridges constructed during this period include :

1. Coronation bridge in West Bengal - 82 - m main span, reinforced concrete open-spandrel arch bridge, Figure 1.

2. Napier bridge in Chennai city - Reinforced concrete multiple-span, bowstring girder bridge exposed to sea water.

3. Three railway bridges in prestressed concrete near Siliguri for The Assam Rail Link[2].

Each one of these examples have specific characteristics. The Coronation bridge near Siliguri is one of the outstanding examples of long-span, cast-in-situ construction spanning a deep gorge.

The Napier bridge is an outstanding example of durable reinforced concrete structure exposed to severe environmental condition. Though more than 55-years old, the bridge is still in excellent condition, inspite of being directly exposed to the marine environment.

The three prestressed concrete railway bridges built in 1948 consist of 'I'sections of modest spans of 13 to 18m. The web thickness varies between 125 to 150 mm[3]. The cables, each consisting of 12 x 5 mm wires, were painted with bitumen and wrapped with waterproof paper, an ingenious alternative to provision of ducts. Zero slump concrete of grade equivalent to M-40 was placed manually and compacted by rodding in the absence of mechanical vibration. Prototype test girders were manufactured and tested at Kalyan near Mumbai. Although designed for metre gauge railway loading, the test beams were placed under broad gauge railway track, using one of the heaviest broad gauge engines. The engines were made to skid on the final test, a loaded open wagon was derailed and made to skid on the beams, but only surface marks were left on the beams without any cracks or serious damage. The test beam was subsequently used on the Western Railway.

Considering the level of concrete and construction technology prevalent in India nearly five decades ago, the quality of concrete in all the three bridges had been quite high which is reflected in their almost trouble-free performance till date.

** This is illustrated in the photo-feature on pages 666 and 667.*

Period : 1951 to 1960

The first road bridge in prestressed concrete in the country is the Palar bridge on the National Highway near Chennai city. The bridge has 23 spans of 28.35 m. Each span consists of four 'U' beams stressed by a number of tendons, each consisting of 32 x 5 mm wires. Magnel - Blaton system of prestressing was employed.

Nominal 1 : 1.5 : 3 concrete mix has been used for the beams. The maximum compressive stress on the concrete under working load has been limited to about 10 N/mm^2. After the concrete attained a cube strength of at least 31 N/mm^2, tendons were threaded through the pre-formed holes and prestressed. Once the prestressing was over, 150-mm thick reinforced concrete deck slab was cast on top of the 'U' shaped girder. The web thickness was only 120 mm.

Figure 2 shows the cross section of the bridge deck[4]. This also used a zero-slump manually-placed concrete of relatively high strength at the time of transfer of prestress.

After the successful completion of Palar bridge, a number of prestressed concrete bridges were planned and constructed in the fifties, all over the country. Outstanding among these is the Coleroon bridge in Tamil nadu having 14 spans of about 46-m each.

Period : 1961 to 1970

During this period, there was a virtual explosion of the use of high-strength concrete for road bridges. An outstanding example relates to the construction of the 3,062m long Sone bridge at Dehri-on-Sone --- the longest road bridge in Asia at that time, Figure 3. The superstructure of the bridge consisted of 93 spans of 33m and concrete grade was 42 N/mm^2. The construction of the bridge also witnessed the introduction of the industrialised construction techniques in the country. All the 465 girders were mass produced by precasting in a yard 6-km away from the bridge site. Each beam was transported on a specially-built truck trailer and erected in position using a pair of mechanised gantries travelling on river bed.

During the construction of the bridge, statistical concrete quality control techniques were introduced for the first time in the country, even before their induction in IS:456. Here again, zero slump concrete was used and the web thickness was only

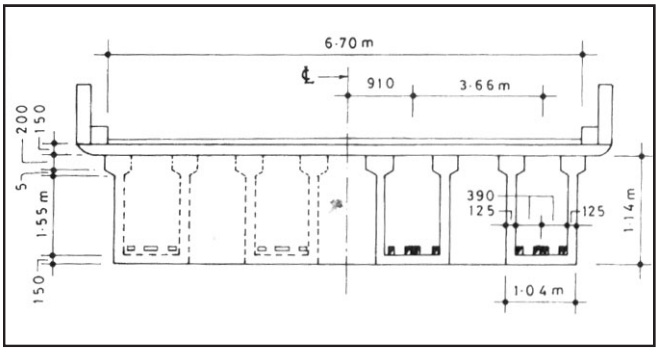


Figure 2. Cross section of the deck of Paler bridge near Chennai.

125 mm against the current codal requirements of minimum 200 mm plus the duct diameter.

Kosi bridge at Kursela in Bihar is another outstanding structure involving the use of high strength concrete for the piers and the superstructures.

During the early sixties, three prestressed concrete bridges were built across Sutlej river and its tributory [3]. The specified concrete grade was of strength 42 N/mm^2. Refined mix design methods using natural river gravel as coarse aggregates had resulted in average works cube strength of about 70 N/mm^2. Such high strength was aimed at in the field to facilitate very early prestressing.

India witnessed the commencement of construction of long-span balanced cantilevered bridges during this period[6]. Barak bridge in Silchar[7], Figure 4, built in the sixties has a clear central span of 122 m. As the cantilevers were progressively built in 3 m segments, the uniformity of concrete strength was a critical factor for evaluation of precamber to be provided at the time of construction. The specified characteristic strength was 39 N/mm^2. Aggregate cement ratio of 4 and water-cement ratio of 0.4 was used.

This was followed by the Lubha bridge, Figure 5, also in Assam with a main span of 130 m and the Bassein Creek bridge near Mumbai, Figure 6 with a continuous deck of 361.6m. For Bassein Creek bridge, concrete strength of 46 N/mm^2 was adopted in order to restrict the depth of girders.

Thana Creek bridge near Mumbai, Figure 7, was constructed in precast reinforced and prestressed concrete. Even though the bridge subsequently suffered damage due to corrosion, recent investigations revealed that the quality of the concrete is excellent and that other factors were responsible for the distress.

Gurumukteshwar bridge in U.P., spanning the holy Ganges river, has a length of more than 700 m. The decking consists of simply supported prestressed beams over reinforced concrete cellular piers. The entire insitu decking was completed in 16 working months. The web thickness is 125 mm and zero slump concrete was used.

Bhagirathi bridge in West Bengal constructed during the same period is a balanced cantilever bridge with suspended spans. The balanced cantilever section is made up of twin cell box girders. In view of the structural arrangements, the sequence of concreting was extremely important in this case.

Barak bridge at Badarpur was constructed with 42N/mm^2 concrete. The bridge has a total length of 359 m and is of cantilever configuration with suspended spans.

Period : 1971 to 1980

During this period, one of the longest river bridges was built across the Ganges at Patna. This 5575 m long bridge consists of

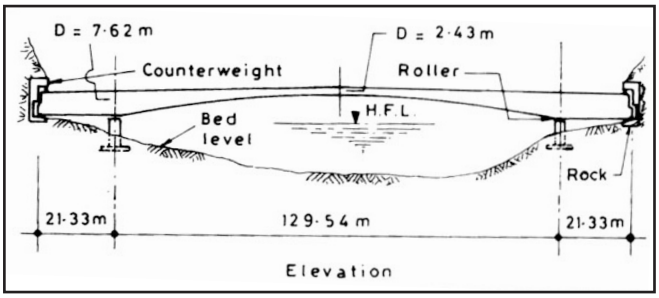


Figure 5. Elevation of the Lubha bridge In Assam

46 spans of about 121m each, Figure 8. High strength concrete was used in this bridge, both for piers and superstructure. The cellular piers were built with 35 N/mm^2 concrete and superstructure with 45 N/mm^2 concrete[8]. However, the concrete mix was designed for high early strength of 20 N/mm^2 at 8 hours and 35 N/mm^2 at 48 hours. These were required both for early removal of formwork in the case of piers and for early prestressing of the deck cables. The pier formwork was removed about 6 hours after concreting. The deck cables were prestressed between 48 to 72 hours after concreting. With such high early strength requirements, the actual 28-day strength achieved exceeded 60 to 65 N/mm^2. Precast epoxy glued segmental construction was adopted on a large scale for the first time in India and about 60 tonnes of epoxy consumed for the joints.

Other examples of precast segmental construction during the same period include the **Ganga bridge at Buxar, Narmada bridge at Zadeshwar** and a submersible **bridge across Krishna river at Deodurg** in Kamataka.

Krishna bridge at Deodurg is also significant in terms of method of construction. This 540m long bridge consisted of 18 spans of 30m each with expansion joints at approximately 180m spacing. The superstructure consists of three cell trapezoidal box section supported on teflon bearing over solid elliptical pier, Figure 9. The precast box units were match-castvertically for ease of concreting, then rotated and launched in position and jointed with epoxy mortar, while being supported on staging. The prestressing was carried out

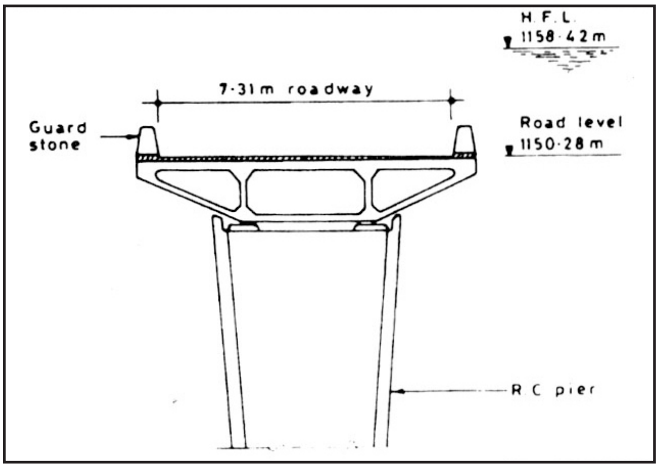


Figure 9. Cross section of deck of Krishna bridge at Deodurg

** This is illustrated in the photo-feature on pages 660 and 667.*

thereafter.

The construction of Morhar bridge in Bihar on the Grand Trunk road between Delhi and Calcutta heralded the use of precast steam -cured prestressed beams for road bridge construction.

High early strength of 35N/ mm^2 was realised in 12 hours after concreting with the help of suitably-designed steam curing cycle. In order to ensure that the entire bridge superstructure consisting of 14 spans of over 30m each was completed in one working season of six months, decking was designed with 8 beams for a two-lane road bridge.

Period : 1981 to 1990

This period marked the awareness of durability requirements for bridges and re-appraisal of standards and codes of practice. The collapse of some spans of Mandovi bridge[9] and corrosion-induced damages to Thana Creek bridge and a number of other bridges in the coastal areas necessitated a serious review of design and construction practices. The Indian Roads Congress (IRC) special publication SP-33[10] which was brought out during this period contained a number of specific requirements to satisfy durability. For example, the minimum grade of concrete for reinforced and prestressed concrete components of any prestressed concrete bridge for severe exposure condition was specified to be not less than M-40. A number of road bridges have since been constructed according to the revised norms.

The 2.5-km long **Pamban bridge** across Palk Strait, Figure 10, located at the southern tip of India is an outstanding example of use of high strength concrete, keeping in view the durability requirements". The minimum grade of concrete for plain and reinforced concrete is 35 N/mm^2 and for prestressed concrete, 45 N/mm^2. A majority of beams for the superstructure were precast, steam cured and prestressed before being transported and launched. The steam curing facility made it possible to achieve a compressive strength of 30 to 35 N/mm^2 at 12 hours[12]. This has resulted in fast track construction and turn around in the precasting yard. The second stage prestressing as well as grouting was completed within seven days after casting and the beam transported for launching immediately thereafter.

The **Akkar bridge** in Sikkim, Figure 11, was the first all concrete cable - stayed bridge in India. The bridge consists of two symmetrical spans of 79m supported from the central pylon, 50m high. The superstructure deck consists of 180 mm thick reinforced concrete slab integral with transverse beams spaced at 3m centres. The slab-cum-beam system is monolithic with main longitudinal girders having a depth of 800 mm. The pylon legs are hollow in section with 250 mm thick walls.

The construction of the second Hooghly bridge, Figure 12, with cable-stay span of 457m which at the time of commencement of construction was the longest in the world, necessitated high grade concrete, both for the piers and the deck slab. In particular, tolerances specified for the deck slab were quite stringent. The permitted tolerance was + 5mm, with no negative tolerance permitted in a deck width of 32m. This had necessitated design of special high strength concrete mix equivalent to 50 N/mm^2 grade. Specially imported screed vibrators were used for vibrating and finishing the deck surface. The actual strength obtained was 60 N/mm^2 at 56 days.

Hethauda Narayangarh bridges in Nepal : On this Asian Development Bank (ADI3) - aided bridge project, four major bridges were constructed utilising HSC. The reinforced concrete piers were of solid circular configuration with heights upto 20 m. These were required to be concreted in one pour as construction joints were not permitted. Specially-designed high strength concrete mix was adopted for this activity. The deck for all the bridges consisted of precast prestressed concrete girders with reinforced concrete slabs on top. The 30m span girders were precasting using M - 45 grade concrete and launched in position.

Period : 1991 to 1996

Arising out of the provisions of IRC SP:33 of Indian Roads Congress and large scale mechanisation of bridge construction, the concrete mixes began to be designed with high workability. For the reconstruction of Mandovi bridge in Goa, even the piles were of M -40 grade concrete. As the concreting was carried out underwater, a minimum slump of 200 mm was aimed at in the mix design stage, even for reinforced concrete elements. This has been made possible with the use of super - plasticisers. For the Mandovi bridge, the minimum strength of concrete for both reinforced and prestressed concrete elements was 40 N/mm^2. The overall actual strength realised was in the range of 55 to 65 N/mm^2.

For the construction of a flyover, Figure 12, for the Railways near Kings Circle in Mumbai, for some elements of the structure the specified strength was 45 N/mm^2. The construction sequence for the box girders necessitated concreting in layers without forming cold joints and retardation of upto 6 hours was realised with the use of retarding plasticisers. Concrete of high slump in the range of 80 - 120 inm was used for box girders.

High strength concrete was used extensively for the construction of elevated box girders for the metro railways transport system (MRTS)in Chennai, Tamil Nadu. The concrete mix of M- 45 grade was designed for prestressed concrete box girders for 3-day strength of 35 N/mm^2 and 7-day strength of 40 N/ mm^2 [14].

The third Godavari bridge[15] for the Railways is another outstanding bridge under construction. The bridge consists of 28 spans of 92.55m, of bowstring arch configuration in prestressed concrete. Each span comprises of prestressed concrete deck of box section hung from twin arches by means of hangars. The arches are of reinforced concrete having concrete of grade M-45. They are braced in the lateral directions by means of precast reinforced concrete struts. The arch is constructed using the cantilever system. Apart from the

** This is illustrated in the photo-feature on pages 666 and 667.*

high grade of concrete, it was necessary to reduce imbalance of concreting on either side. This necessitated specifying stringent tolerances for concrete density with permissible variations of 5 percent only.

The pier caps are cast with 42 N /mm^2 strength concrete. The construction of arch involves precise control of alignment of twin arches and proper levels. The permitted tolerance is 1 mm. Such stringent requirements have resulted in the use of concrete which can be termed as high performance concrete. In consequence, even though the specified characteristic strength was 45 N/ mm^2, the average cube strength has been reported as 57 N/mm^2 and the maximum cube strength of 70 N /mm^2. A very high grade of quality assurance has been ensured with standard deviations of 3.6 N/mm^2.

Underwater high-strength concrete

During the construction of the C;anga bridge at Patna one of the 12-m diameter wells sunk to a depth of about 55 m had developed distress cracks and after detailed study and investigations, it was decided to construct a fresh well of smaller diameter inside the cracked well. The steining for the smaller diameter well is heavily reinforced and of grade M-40. This was required to be concreted underwater, with a water depth of 55m. This perhaps represents possibly the deepest underwater structural concrete carried out for a bridge structure anywhere in the world. In this case, high performance requirements relate to its ability to be placed underwater with the help of a tremie maintaining the required structural integrity with a concrete strength of 40 N /mm^2 [(16)].

In the case of the second Hooghly bridge, the main foundations consisted of cellular reinforced concrete caissons with diameters upto 23 m. The internal diaphragms divided the caissons into 9 cells The design envisaged that during the service life of the bridge, the caissons should be kept empty in order to minimise the dead loads. This was achieved by providing concrete of liquid retaining structure grade for the well steining, including provision of water bars at construction joints. On the caisson being sunk to the designed founding level, the bottom plugging was carried out utilising special grades of colcrete/concrete [17].

In the case of colcreting, the mix was suitably designed to ensure water-tight bottom plug. The effectiveness has been demonstrated by pumping the inside of the well dry after bottom plugging. In some cases, underwater concreting placed by tremie was used for bottom plugging.

High strength/high performance concrete

From the above review and from Table 1, it may be noted that in India it has been possible to achieve high early strength as required and also specified characteristic strengths of upto 50 to 55N/ mm^2. In reality, the actual strengths achieved have been much higher, upto 70 N/mm^2. This situation has arisen out of outdated acceptance criteria and mix design practice being used in the country.

Materials

After the revision of cement specification in 1987, the ordinary Portland cement is today available in three distinct grades, namely 33, 43 and 53, the number indicating the compressive strength of cement-sand mortar in N/ mm^2 at 28 days. Even before this revision, the cement industry in India had supplied the required quality of cement for various bridge projects. Recent experience shows that the 53 grade cement available in the country is adequate for realising strength upto 70 N/mm^2 with water-cement ratio of about 0.35. With the possible reduction of water-cement ratio to about 0.3 or even 0.25, it should be possible to achieve strength of upto 100 N / mm^2 with the use of suitable superplasticisers and silica fume.

Aggregates

Unlike low and medium strength concretes, the quality of aggregates is critical in realising high strength concrete. Fortunately, good quality aggregates are available in plenty all over the country. Thus availability of quality aggregates is not a problem in realising high strength concrete. Already for some multistoried structures in Mumbai, M-60 grade concrete is being realised. This means a target mean strength of around 75 to 80 N/ mm^2.

Table 1. Concrete grades for typical bridges surveyed

Sr. No.	Name of the bridge	Grade of concrete N/mm^2	Year of Construction
1.	Barak Bridge, Badarpur, Assam	42	1968
2.	Sone Bridge at Dehri-on-Sone	42	1963
3.	Kandroor, Salapur, Gambhirkhad, H.P.	42	1962
4.	Bassein Creek Bridge near Mumbai	48	1969
5.	Gangoli Bridges, Karnataka	42	1964
6.	Morhar Bridges, Bihar	41	1971
7.	Narmada Bridge at Zadeshwar, Gujarat	38	1972
8.	Gangs Bridge at Patna, Bihar	45	1972
9.	Krishna Bridge at Deodurg, Karnataka	42	1972
10.	Ganga Bridge at Buxar, Bihar	45	1970
11.	Khalidiyah Bridge, Iraq	48	1984
12.	Pamban Bridge, Tamilnadu	45	1985
13.	Sringeri Foot Bridge, Karnataka	40	1989
14.	Second Hooghly Bridge, Calcutta	45	1992
15.	Raoli Flyover Bridge, Mumbai	45	1991
16.	Mamring Bridge, Sikkim	40	1994
17.	Tapi Bridge at Idgaon, Maharashtra	43	1994
18.	Teesta Bridge, Sikkim	40	1995

Trends in the construction of road bridges in India

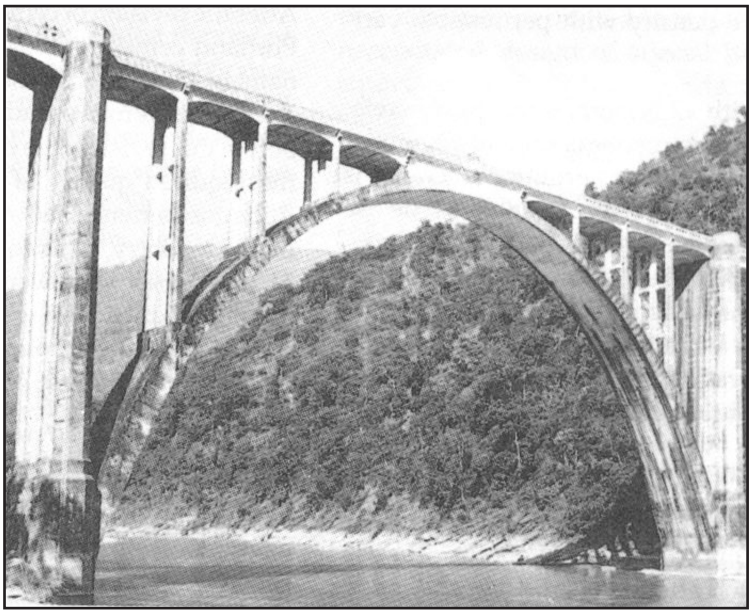


Figure 1. Coronation bridge over Teesta river in West Bengal -- an elegantly looking reinforced concrete open spandrel arch bridge.

Figure 3. Sone bridge at Dehri-on-Sone: when completed, it was one of the longest road bridges in Asia.

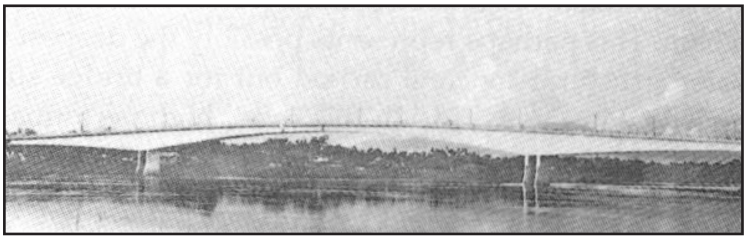


Figure 4. Barak bridge in Silchar, a long-span balanced cantilevered bridge with a clear central span of 122m.

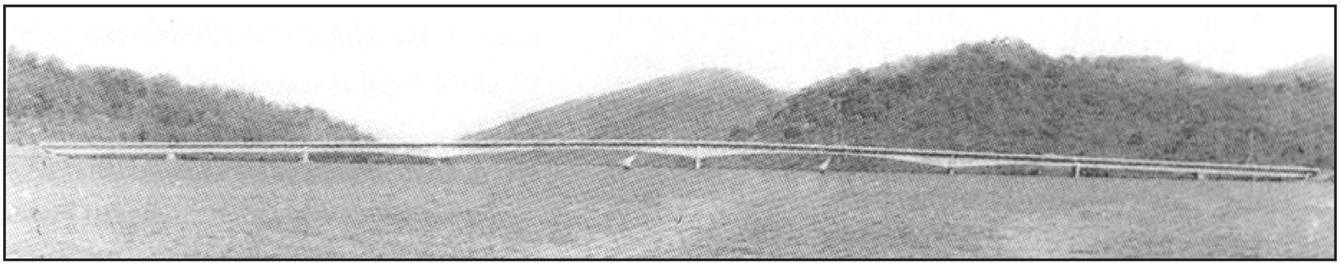


Figure 6. Bassein Creek Bridge near Mumbai with a continous deck of 361.6 m

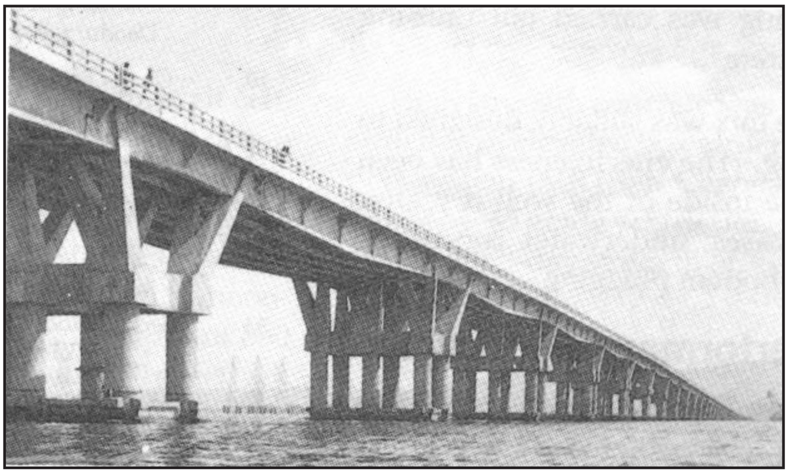


Figure 7.
Thane creek bridge constructed in precast prestressed concrete superstructure.

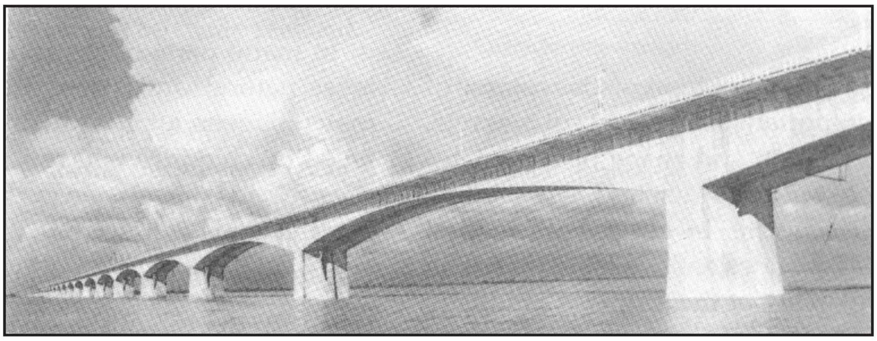


Figure 8. Ganga bridge at Patna — 5575-m long, one of the longest river bridges in the world.

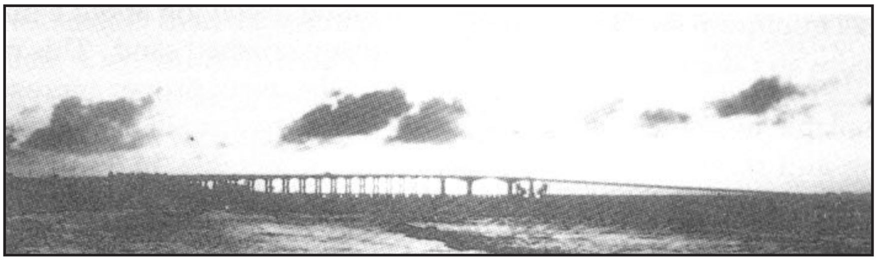


Figure 10. Pamban bridge across the Palk Strait, which is 2.5 km long.

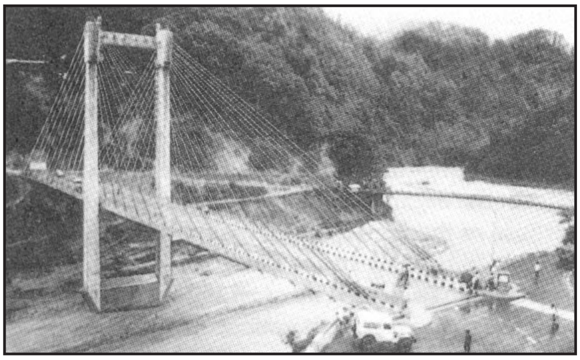


Figure 11. Akkar bridge in Sikkim -- the first all-concrete, cable -stayed bridge in India.

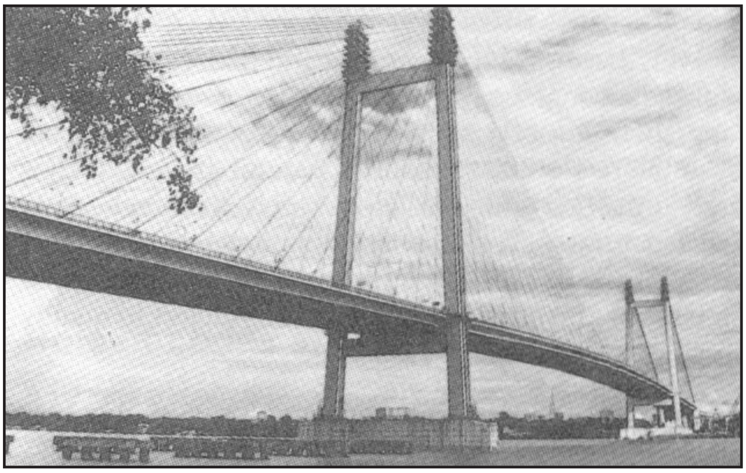


Figure 12. Vidyasagar Setu (second Hooghly bridge) in Calcutta : a cablestayed bridge with a central span of 457 m.

Figure 13. Raoli flyover near King's Circle in Mumbai

Aggregates, constituting 70 to 80 percent of the volume of a typical concrete mix, are important components of concrete. Properties such as size, gradation and shape of aggregates have an important influence on water demand, workability, strength and durability of concrete. In India, both natural gravel and crushed stone aggregates are available for use in concrete, although the availability of the former is gradually dwindling especially in urban areas in view of the dredging restrictions. Wherever easily available, the preference should be for natural gravel which has minimum surface to volume ratio and consequently reduced water demand.

Natural gravel is easily available in graded form. It can also be regraded by screening and recombining in the required proportions. By the very process of formation of gravel, all softer materials are converted into sand and it is a case of survival of the fittest as gravel. Fortunately, many parts of India are endowed with large volume of natural gravel. Wherever available, natural gravel should be preferred.

However, there are apprehensions and reservations in the minds of Indian engineers towards the use of natural gravel. Such apprehensions and reservations are totally unfounded. In fact, in the rest of the world, it is natural gravel which is preferred as the first option for preparation of concrete. Only when such natural gravel is not available, crushed aggregates are resorted to. IS:383 concerning aggregates permits the use of both natural gravel and crushed stones, subject to quality conformation.

In view of the reduced water demand for natural gravel, there is a corresponding reduction in cement content also. With the use of natural gravel it is possible to achieve a reduction in the water-cement ratio, for the same workability resulting in higher strength. This has been demonstrated on a number of bridges, both in India and elsewhere. The author has been using natural gravel successfully for all prestressed concrete bridges in various regions of India where natural gravel are available in abundance.

For a bridge in Norway which was recently completed, the following mix was successfully used to achieve the concrete grade corresponding to M-75, Table 2.

The aggregate-cement ratio works out to 3.6. Such a ratio would not have been possible without the use of natural gravel.

Fine aggregates

Normal sand or crushed fine aggregates conforrming to IS:383 are adequate for use in HSC/HPC. In the case of fine aggregates, Indian prejudice is the opposite to that of coarse aggregates. While in the coarse aggregates, the preference (though not justified) is for crushed stone, for fine aggregates, crushed stone materials are not generally preferred (without justification). So long as the properties conform to standard specification (IS:383), there is no objection to the use of crushed fine aggregates.

In many parts of the country, particularly in the coastal areas, natural sand is dredged from the creek or sea bed. Such material, even after normal washing, is invariably contaminated by chlorides which is not acceptable for reinforced or prestressed concrete. In such situations, crushed fine aggregates should be preferred.

A classic example of preferred usage of crushed aggregates relates to the recently-completed channel tunnel connecting the U.K. with France. The entire concrete used for the tunnel lining involving about 6 million m^3 of concrete was prepared using crushed sand. This requirement was specifically based on the use of proper aggregates to ensure durability. The only alternative available was sea dredged aggregates, which was not acceptable. In India also, concrete for a large number of dams is being produced with crushed fine aggregates.

The strength of aggregates is not a limiting factor in HPC, barring exceptions in a few cases with relatively low strength rock. Aggregates - paste bond strength is the limiting factor with most high strength concrete.

Admixtures

All over the world, chemical admixtures are widely used for a vast majority of the concrete placed today. In the Indian context, admixtures have found wide usage only recently, at least in the organised sector of construction. This is perhaps because of the non-availability of uniform quality of admixtures indigenously in the past. The situation has since improved with the setting up of a number of manufacturing units with international collaboration.

For ambient conditions prevailing in India, the use of retarders, plasticisers and superplasticisers is more relevant. Use of some of these admixtures becomes obligatory in order to avoid cold joints and also to ensure increased work ability during placing of concrete.

Superplasticisers

Superplasticisers are relatively a new class of admixtures, currently in use. Most of the commercially-availiable superplasticisers belong to the family of either melamine, nephatline or lignosulphonate. Unfortunately, there is no Indian standard or code of practice as yet for superplasticisers.

However a reference may be made to ASTM C-494 or BS code of practice. The main purpose of using superplasticisers is to producing flowing concrete with high slump in the range of

Table 2. Concrete mix for a bridge in Norway

1.	Cement	475 kg.
2.	Admixtures	6.5 kg.
3.	Condensed silica fume	40 kg.
4.	Sand 0- 8 mm	1080 kg.
5.	Natural gravel 8 - 16 mm	720 kg.
6.	Water	180 litres
7.	Slump achieved	240 to 260 mm

150 to 200 mm to be used in the heavily reinforced bridges and in areas where adequate vibration cannot be easily realised.

Condensed silica fume (CSF)

Silica fume is a by-product generated during the production of silicon and ferro silicon alloys. In the initial years, nearly all the silica fumes were discharged into the atmosphere. After environmental concerns necessitated the collection of silica fume, it is necessary to find out avenues for economically justified use of silica fume.

Silica fume consists of very fine vitreous particles with particle size approximately 100 times smaller than the average cement particle. In view of its extreme fineness and high silica content, silica fume is a highly effective pozzolanic material and as such is used in concrete to improve its various properties including compressive strength. It also reduces permeability and thus helps in protecting the reinforcement from corrosion. The silica fume, after collection, is usually condensed in order to facilitate handling. Hence the name condensed silica fume.

The use of CSF by itself increases water demand due to increased surface area generated by fine particles. This problem is easily overcome by the use of superplasticisers. The use of CSF and superplasticisers is obligatory for realising HPC, especially beyond strengths of 70-80 N/mm^2.

CSF is now being extensively used for concrete bridge construction. Apart from the case of the bridge in Norway cited earlier and a large number of other bridges, CSF is being used extensively for bridge deck overlays in the developed countries with an accent on durability. Among the case histories of bridges presented in the recent FIP Congress in Washington (1994), more than 50 percent have reported to have used CSF for bridge girders. In India, CSF is not yet used in the construction of bridges, mainly because of its indegenous inunavailability.

Role of supervision

This is crucial for realising high strength and high performance concrete. Some reputed construction companies have qualified and trained personnel for realising concrete upto 100 N/mm^2, if other parameters are satisfied. However, there is a tremendous amount of misinformation and mis-understanding regarding the concrete mix design. This needs to be corrected before we proceed for utilising higher grades of concrete.

In this context, the example of concrete mix design to attain the specified strength for the Ganga bridge at Patna may be cited. A full-fledged field testing laboratory was established at the project site before commencement of the activities. Junior and middle level engineers were sent for refresher programmes and trained in all aspects of concrete mix design, quality assurance, production, placing, supervision and inspection.

In consequence, an excellent degree of control was exercised on site, and it was possible to achieve the most economical design, resulting in about 25 percent saving in cement and overall costs compared with conventional practice elsewhere in the country. The concrete mixes successfully adopted are indicated in Table 3.

Table 3. Concrete mixes for Ganga bridge, Patna

Parameter	Reinforced Concrete	Prestressed Concrete
Characteristic strength	35 N/mm^2	45 N/mm^2
Maximum size of aggregates	40 mm	20 mm
Water-cement ratio	0.42	0.36
Aggregate-cement ratio	5.6	4.0
Cement consumption per m^3	340 kg	450 kg

The excellent control realised at site is reflected by relatively low standard deviations in the range of 3 to 5 N/mm^2. The bridge was built in the seventies and the only equipment used for concrete production was the ordinary 10 x 7 mixers. Ordinary Portland cement grade 33 conforming to IS:269, but from selected factories, was used in the construction. It may be recalled that during the time of construction, cement grades 43 and 53 were not in vogue. The mix components were designed by weight and converted into volume during actual execution. This was found necessary in the context of indifferent quality of swing bucket weigh batchers available in the country at that time. Such economic mix was possible, as the mix design was based on the author's own innovations.

Role of codes and specifications

A review of concrete construction practices for bridges in the last 50 years reflected in the above examples reveals that the highest characteristic strength of concrete adopted for bridge construction remains more or less static in the range of 40 to 50 N/mm^2, Table 1, despite tremendous improvements in the availability of superior quality materials and the equipment and practices elsewhere in the world. A number of adverse factors have contributed to the state of affairs.

Cement of very good quality was available in the forties and fifties. However, the introduction of controls on pricing, production and distribution, adversely affected the cement industry in the sixties and seventies and this was at times getting reflected in the quality of the product. After the decontrol situation has improved dramatically. Quality of Indian cement now available in the market is comparable to that of developed countries. However, the reservations introduced in the sixties and seventies regarding mix design on account of cement quality still continues.

Admixtures of good quality are now being produced and marketed in the country. Unfortunately, the codes are rather restrictive and at best only grudgingly admit the use of admixtures. Thus, use of super-plasticisers and retarders is not effectively made.

The introduction of IS:10262 [18], detailing a particular method of mix design has, in the opinion of the author, done enormous damage to development of higher grades of concrete. While the intention might have been to provide guidelines to the uninitiated, most of the owners' representatives take the guidelines as the Bible and insist on designing the mix only as per the document. The publication's stumbling block for experienced technocrats comes in the form of the higher current margins based on standard deviations specified in this document. In fact, the standard deviations specified, at time act as a license for poor quality of concrete.

So long as concrete is based on performance specifications, it should be left to the producer to decide on the mix and satisfy the owners regarding the quality of the mix and this is the internationally accepted practice. In fact, no developed country in the world has brought out a national standard or guidelines for concrete mix design. This is normally left to professional bodies such as ACI, BRE etc.

In the case of the Ganga bridge at Patna, the contractors were able to optimise the concrete mix with cement consumption as detailed above, primarily because of the absence of IS guidelines at the time of commencement of work in the early seventies.

The current Indian Roads Congress codes[19, 20] are more conservative when it comes to use of high strength concrete. The maximum grade of concrete envisaged by IRC :18 is only 55 N/mm^2. Even for this grade, the target mean strength is specified as 69 N/mm^2, an abnormally high value.

The acceptance criteria given in IS:456[21] and I RC:18 are both not capable of being implemented in practice and also inhibits use of higher grades of concrete. As per the current IRC codes, the maximum permissible stresses in reinforced concrete are limited to 8.5 N/mm^2 in compression and 11.5 N/mm^2 in flexure corresponding to the characteristic strength of 40 N/mm^2. For prestressed concrete, the maximum permitted compressive stress is limited to 20 N/mm^2. In view of these constraints, the maximum characteristic strength used in the designs so far in the country is limited to 55 N/mm^2. If the codal constraints are removed, it is possible to use concrete upto characteristic strength of 70 to 80 N/ mm^2 in the country with all of the attendant advantages.

Until recently, prestressed concrete bridges have been constructed with 28-day compressive strength of 40 to 50 N/mm^2 with 80 percent strength required at the time of prestressing. For various reasons, it is necessary to take up prestressing at the earliest, after concreting. Typically, precast girders and cantilever segments are required to be prestressed after 48 to 72 hours of concreting from various considerations. In such a situation, the requirement of high early strength becomes a critical factor. The mix is required to be designed to achieve a strength of 35 N/ mm^2 at 48 hours.

In the formative days of prestressed concrete bridge construction in India, the common practice was to use very low slump concrete. However, with the advent of mechanised construction involving the use of batching plant, tower cranes and concrete pumps, it has become common to use concrete of high workability. Many components of the bridge structure are heavily reinforced, resulting in congestion of reinforcement. In order to ensure that the concrete can easily be worked through congested reinforcement, it is necessary to have highly workable concrete. A slump requirement of between 100 to 150 mm in such cases is not uncommon.

Table 4. Examples of Some bridges using HPC

Sr. No.	Name and location	Year	concrete strength N/mm^2	Other data
1.	Three railway bridge in Japan	1973	60-80	W/C 0.30
2.	Deutzer bridge in Germany	1979	69	-
3.	Laval, Canada	1992	70	0.30
4.	Mirabel, Canada	1993	80	-
5.	Helgeland, Norway	1991	73	0.38
6.	Perluiset, France	1988	80	-
7.	Joigny, France	1983	78	Without silica fume
8.	Roize, France	1990	89	Ccement Content= 495 kg/m^3
9.	Normandie, France	1994	60	World's longest spam
10.	Elorn, France	1994	97	-
11.	Great Belt, Denmark	1990-1997	70	One milion m^3 of concrete
12.	CNT, Japan	1993	122	W/C = 0.2

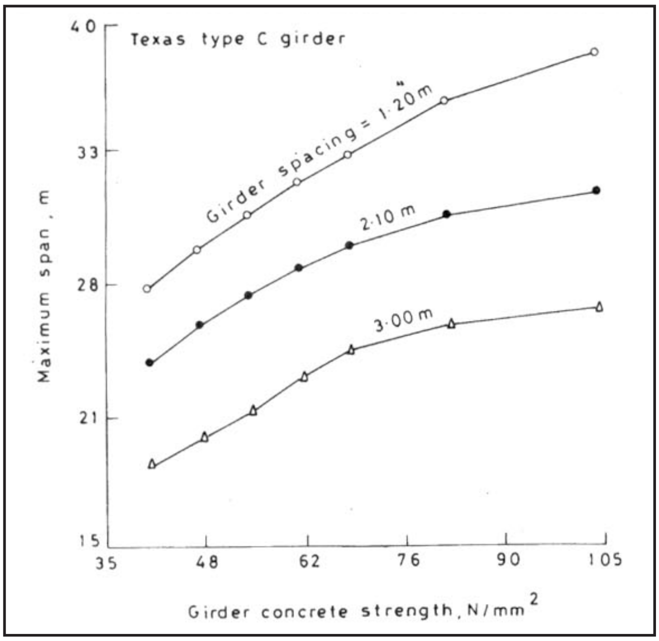
HPC- International scenario

HPC has been advantageously used in the construction of a large number of bridges all over the world. Reasons for using HPC in bridges include :

1. economy
2. smaller cross section
3. slender members
4. extended service life
5. reduction in weight
6. launching due to reduced weight
7. reduced beam height
8. low creep, shrinkage

Some cases of actual bridge construction using HPC in the recent years are given in Table 4.

HPC is also used for bridge substructures and pylons of cable-stay bridge extensively. For the new bridge over the Elorn river in France, the main central span is 400m. A cablestay configuration is used. The two vertical pylons are 117-m high



(83 m above the deck level) to support single rows of cable-stays. The pylons are made of high strength concrete (80 N/mm2). This is a relatively high strength application for a reinforced concrete bridge member proposed for the first time in the world. The pylon was cast in 4.17-ni lifts using a selfclimbing formwork. The progress achieved is one lift per week. Other options available for fast track construction include the use of slipform pier. A number of viaducts recently constructed for Konkan Railway Corporation in the west coast of India involved the use of tall piers upto 80m in height, constructed with the help of slipforms.

Impact on design

The subject was recently studied by the University of Texas, U.S.A. The impact of concrete design strength varying from 40 N/mm^2 to 100 N/mm^2 was examined to determine the effect on the maximum span length and girder design spacing for 12 different girder cross sections. Some of the conclusions are given below.

1. The increase in concrete strength allows an increase of 10 to 40 percent in maximum span for a given section depending on the girder spacing.

2. An increase in concrete strength also allows consequent increase in girder spacing for a given span, thus requiring less number of girders (Figures 14 and 15).

3. Figure 15 indicates the variations in allowable girder spacing with increased strength for three different span lengths. For a span length of 37 in, an increase of concrete strength from 40 to 70 N/mm^2 results in more than doubling the girder spacing from 1.2 m to 2.7m. However, for effective usage of higher concrete strength above 70 N/mm^2, higher capacity strands are required to be used, Figure 16.

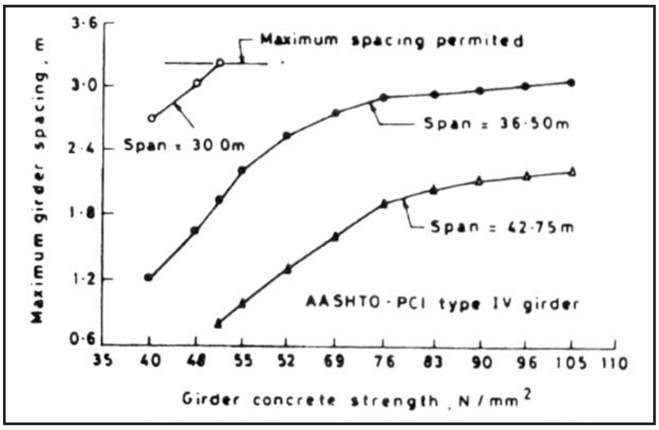


Figure 15. Maximum girder spacing versus concrete strength

4. The resultant design for 35m span are shown in Figure 17. The upper portion of the figure gives the girder spacing with 40 N/mm^2 concrete, whereas the lower portion relates to 70 N/mm^2 concrete. In the latter case, only four girders are involved as against 9 girders with 40 N/mm^2 concrete. Due to the increase in girder spacing, there is a slight increase in the deck thickness by 25 mm.

Economics of HPC

The main reason for using HSC/HPC is not only to obtain improvement in concrete properties but also to reduce overall costs. The cost saving comes from several areas. The basic concrete cost per m' of HSC/HPC is obviously higher, but this is offset by the reduced quantity of concrete required. The cost of prestressing strands remains relatively unchanged. The real cost saving comes from the reduction in non-material costs associated with the girders. These include reduction in cost of labour per girders, transportation and erection costs and overheads due to reduced number of girders.

The comparison of cost for sample design shown in Figure 4

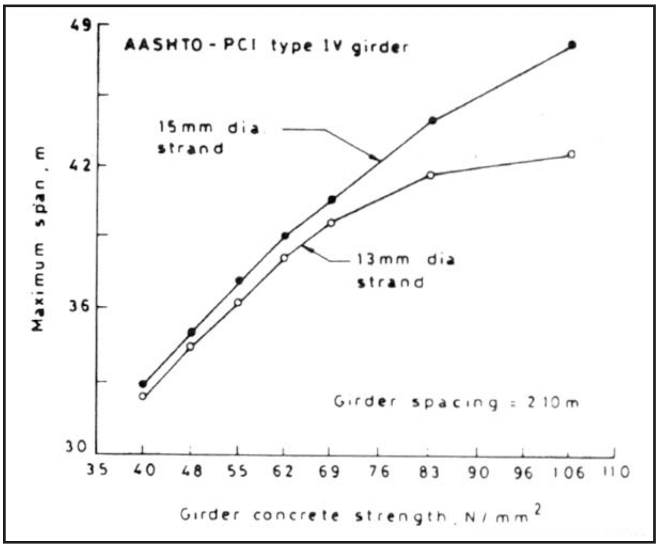


Figure 16. Maximum span versus concrete strength

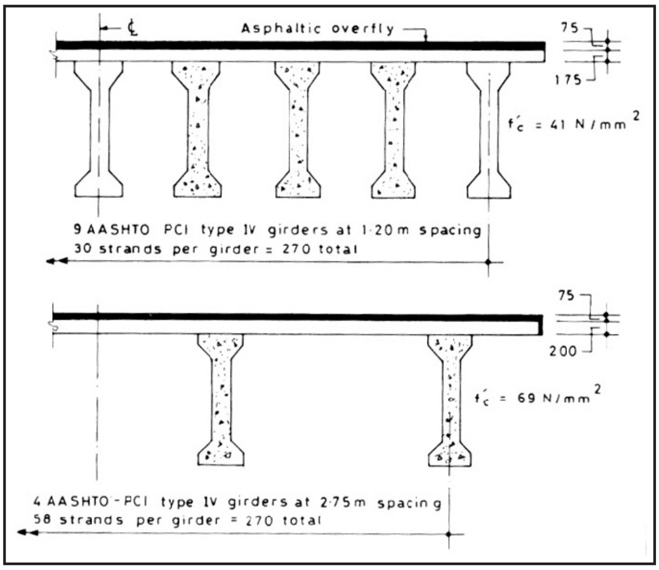


Figure 17. Superstructure design comparison - 41 14/mm ^{2} versus 69 N/mm^2

has also been reported. The total cost per m^2 has been given as under :

With 40 N/mm^2 - US $ 8,000

With 70 N/mm^2 - US $ 6,000

Even though the cost data will not be applicable to Indian conditions, the figures are a pointer towards the overall economy.

Codes and regulations

Most national standards are applicable to concrete strengths upto about 60 N/mm^2. However, some documents have specifications for HPC, Table 5.

Table 5. Some national standards including HPC

Country	Specifications	Maximum strength N/mm^2	Method
CEB/FIP	MC-90	80 N/mm^2	Cylinder - 150 mm
Norway	NS-3473 : 1992	105 N/mm^2	Cube -100 mm
Finland	MK B4 - 1984	100 N/mm^2	Cube - 150 mm
Japan	HSC Spec	80 Nimm^2	Cylinder - 200 mm
Germany	DIN 1045 Supplement	115	Cube - 200 inm
Sweden	BBK 79	80 N/mm^2	
Netherlands	NEN 6720 Supplement	105 N/mm^2	Cube - 150 mm

Impact on construction methods

Construction with high performance concrete requires a precise and greater degree of control in all facets of construction. The use of automated batching plants with electronic controls for batching and mixing concrete will be advantageous. Matching mechanised equipment for placement of concrete will be essential.

As superplasticisers are invariably used for HSC/HPC, the time elapsed between mixing and placement of concrete should be kept to the minimum. Concrete with superplasticisers have a tendency to lose its workability relatively fast.

Condensed silica fume has a tendency to fly off and disperse at the time of feeding into the batching plant. Necessary provisions are required to be incorporated to prevent loss of CSF during such operations.

Control on water-cement ratio is extremely crucial for high performance concrete and as such, a sensitive water metering device with variations not exceeding one percent is required.

High frequency vibrators, both internal and external, will assist in proper compaction of concrete. As the water- cement ratio is extremely low, adequate preventive measures are necessary to protect the fresh concrete from the effects of the wind and sun. For the same reason, a very rigid system of controlled round-the-clock curing, for a minimum of seven days is necessary.

All the measuring and testing equipments shall be calibrated initially and at periodic intervals during the operation of the equipment. The cube moulds shall be of the dimensions and tolerances specified in the codes (This is rarely observed in most of the normal concreting operations).

Future prospects

From the above review, it is evident that the technology and materials for high-strength/high-performance concrete exists in the country. However, there is at present no incentive to go in for high-performance concrete in particular because of the various restrictions of Indian codes and specifications. There is an urgent need to remove the restrictive clauses and incorporate the provisions relating to high-performance concrete in the existing codes. There is no need for a separate code for the purpose.

Cement manufacturers have supplied cement of required quality in the past for the manufacture of HSC. It is hoped that they will be in a position to supply good quality cement for HPC too. Infact, cement manufacturers are now ready to manufacture 63 grade cement.

Condensed silica fume of the requisite purity which is not indigenously available today is also required. Possibly the ferro alloy industries could take a lead in this regard. Till then, it is better to import the material and commence production of high performance concrete. There are already some agencies in India offering imported CSF.

Adequate training programmes should be initiated, both by the owners as well as construction agencies for the dissemination of the latest technological advances in

HSC/HPC.

With the above refinements there is no reason to hesitate and it should be possible to gradually increase the characteristic strength of concrete produced in India to 80 N/mm^2 in the first instance and to 100 N/mm^2 before the end of the millennium.

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