High Performance Concrete

1.0 INTRODUCTION

Concrete is the most widely used construction material in India with annual consumption exceeding 100 million cubic metres. It is well known that conventional concrete designed on the basis of compressive strength does not meet many functional requirements such as impermeability, resistance to frost, thermal cracking adequately. Conventional Portland cement concrete is found deficient in respect of:

- Durability in severe environs (Shorter service life and require maintenance)
- Time of construction (longer release time of forms and slower gain of strength)
- Energy absorption capacity (for earthquake-resistant structures)
- Repair and retrofitting jobs

High performance concrete (HPC) successfully meets the above requirement.

HPC is an engineered concrete possessing the most desirable properties during fresh as well as hardened concrete stages. HPC is far superior to conventional cement concrete as the ingredients of HPC contribute most optimally and efficiently to the various properties.

High performance concrete (HPC) is a specialized series of concrete designed to provide several benefits in the construction of concrete structures that cannot always be achieved routinely using conventional ingredients, normal mixing and curing practices. In the other words a high performance concrete is a concrete in which certain characteristics are developed for a particular application and environment, so that it will give excellent performance in the structure in which it will be placed, in the environment to which it will be exposed, and with the loads to which it will be subjected during its design life.

It includes concrete that provides either substantially improved resistance to environmental influences (durability in service) or substantially increased structural capacity while maintaining adequate durability. It may also include concrete, which significantly reduces construction time without compromising long-term serviceability. While high strength concrete, aims at enhancing strength and consequent advantages owing to improved strength, the term high-performance concrete (HPC) is used to refer to concrete of required performance for the majority of construction applications.

The American Concrete Committee on HPC includes the following six criteria for material selections, mixing, placing, and curing procedures for concrete.

(1) Ease of placement
(2) Long term mechanical properties
(3) Early-age strength
(4) Toughness
(5) Life in severe environments
(6) Volumetric stability

The above-mentioned performance requirements can be grouped under the following three general categories.

(a) Attributes that benefit the construction process
(b) Attributes that lead to enhanced mechanical properties
(c) Attributes that enhance durability and long-term performance

2.0 Definition of HPC

The performance requirements of concrete cannot be the same for different applications. Hence the specific definition of HPC required for each industrial application is likely to vary. The Strategic Highway Research Programme (SHRP) has defined HPC for highway application on the following strength, durability, and w/c ratio criteria.

(a) It should satisfy one of the following strength criteria:

4 hour strength $\geq$17.5 Mpa

24 hour strength $\geq$35.0 Mpa

28 days strength $\geq$ 70.0 Mpa

(b) It should have a durability factor greater than 80% after 300 cycles of freezing and thawing.

(c) It should have a water-cement ratio of 0.35 or less.

In general, a “High performance Concrete” can be defined as that concrete which has the highest durability for any given strength class, and comparison between the concretes of different strength classes is not appropriate. This means that, with the available knowledge, one can always strive to achieve a better (most durable) concrete required for a particular application.

2.2 Paul Zia

HPC is a concrete, which meets special performance, and uniformity requirements that cannot be always achieved by using only the conventional materials and normal mixing, placing, and curing practices. The performance requirements may involve enhancement of placement and compaction without segregation and long term mechanical properties, early age strength, toughness, volume stability, service life.

2.3. R .N. Swamy

A High Performance concrete element is that which is designed to give optimized performance characteristics for a given set of load, usage and exposure conditions, consistent with requirement of cost, service life and durability.

High Performance concrete has,

(a) Very low porosity through a tight and refined pore structure of the cement paste.
(b) Very low permeability of the concrete
(c) High resistance to chemical attack.
(d) Low heat of hydration
(e) High early strength and continued strength development
(f) High workability and control of slump
(g) Low water binder ratio
(h) Low bleeding and plastic shrinkage

2.4 Civil Engineering Research Foundation (CERP)

High performance construction materials and systems: An essential program for American and infrastructure.

HPC is a concrete in which some or all of the following properties have been enhanced

(a) Ease of placement
(b) Long term mechanical properties
(c) Early age strength
(d) Toughness
(e) Volume stability
(f) Extended service life in severe environments

2.5. American Concrete Institute (ACI)

A more broad definition of HPC was adopted by the ACI. HPC was defined as concrete, which meets special performance and uniformity requirements that cannot be always be achieved routinely by using only conventional materials and normal mixing, placing and curing practices. The requirements may involve enhancement of placement and compaction without segregation, long term mechanical properties, early age strength, volume stability or service life in severe environments. Concretes possessing many of these characteristics often achieve higher strength. Therefore, HPC is often of high strength, but high strength concrete may not necessarily be of high performance.

3.0 Methods for achieving High Performance

In general, better durability performance has been achieved by using high-strength, low w/c ratio concrete. Though in this approach the design is based on strength and the result is better durability, it is desirable that the high performance, namely, the durability, is addressed directly by optimizing critical parameters such as the practical size of the required materials.

Two approaches to achieve durability through different techniques are as follows.

(1) Reducing the capillary pore system such that no fluid movement can occur is the first approach. This is very difficult to realize and all concrete will have some interconnected pores.

(2) Creating chemically active binding sites which prevent transport of aggressive ions such as chlorides is the second more effective method. There are two approaches are shown in Fig.1

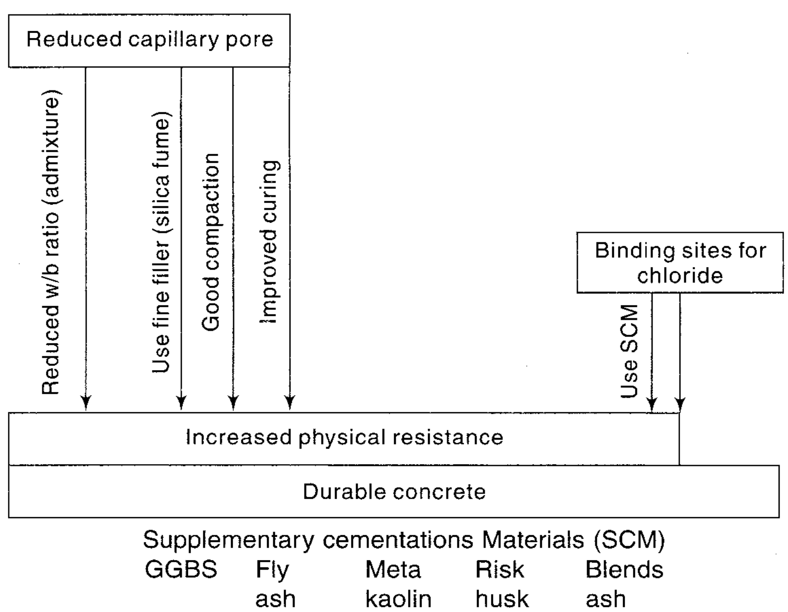

Fig: 1 Techniques of production of HPC.

4.0 Requirements for High-performance Characteristics

Permeation is a major factor that causes premature deterioration of concrete structures. The provision of high-performance concrete must centre on minimizing permeation through proportioning methods and suitable construction procedures (curing) to ensure that the exposure conditions do not cause ingress of moisture and other agents responsible for deterioration.

Permeation can be divided into three distinct but connected stages of transportation of moisture, vapour, air, gases, or dissolved ions. These stages are schematically shown in Fig 2.

Concrete takes in water by capillary suction. The rate at which water enters is called ***sorptivity.***

The ease with which fluid passes through concrete usually under a pressure differential is referred to as ***permeation.***

Vapor or gas ions are sucked through concrete under the action of ion concentration differential known as ***diffusion.***

Fig: 2 Three stages of transportation of fluids and gases.

It is important to identify the dominant transport phenomenon and design the mix proportion with the aim of reducing that transport mechanism which is dominant to a predefined acceptable performance limit based on permeability.

Like the requirement of permeation characteristics, there can be other performance characteristics which may become the specific need for which HPC is used. Table 1 gives a list of such desired characteristics for which HPC has been used.

Table: 1 salient high-performance requirements

1	Compressive strength > 70 MPa
2	Very early strength (4 h) > 17.5 MPa
3	Early strength (24 h) > 35 MPa
4	High degree of impermeability to prevent ingress of water/moisture/CO_2/SO_4/air/oxygen/chloride
5	High resistance to sulphate attack
6	Smooth fractured surface

7	Absence of micro-cracking
8	High level of corrosion resistance
9	High electrical resistivity
10	High chemical resistivity
11	High resistance to abrasion, erosion, and cavitation

The parameter to be controlled for achieving the required performance criteria could be any of the following.

(1) Water/ (cement + mineral admixture) ratio

(2) Strength

(3) Densification of cement paste

(4) Elimination of bleeding

(5) Homogeneity of the mix

(6) Particle size distribution

(7) Dispersion of cement in the fresh mix

(8) Stronger transition zone

(9) Low free lime content

(10) Very little free water in hardened concrete

5.0 <u>Material Selection</u>

The main ingredients of HPC are almost the same as that of conventional concrete. These are

1) Cement

2) Fine aggregate

3) Coarse aggregate

4) Water

5) Mineral admixtures (fine filler and/or pozzolonic supplementary cementitious materials)

6) Chemical admixtures (plasticizers, superplasticizers, retarders, air-entraining agents)

5.1. <u>Cement</u>

There are two important requirements for any cement: (a) strength development with time and (b) facilitating appropriate rheological characteristics when fresh. Studies made by Perenchio (1973) and Hanna et al. (1989) have led to the following observations.

1) High C_3A content in cement generally leads to a rapid loss of flow in fresh concrete. Therefore, high C_3A content should be avoided in cements used for HPC.

2) The total amount of soluble sulphate present in cement is a fundamental consideration for the suitability of cement for HPC.

3) The fineness of cement is the critical parameter. Increasing fineness increases early strength development, but may lead to rheological deficiency.

4) The superplasticizer used in HPC should have long molecular chain in which the sulphonate group occupies the beta position in the poly condensate of formaldehyde and melamine sulphonate or that of naphthalene sulphonate.

5) The compatibility of cement with retarders, if used, is an important requirement.

Ronneburg and Sandrik (1990) suggested tailor-made cements with characteristics suitable for HPC (Table 2). Note that SP30 is ordinary Portland cement. SP30-4A and SP30-4A (mod) are two varieties of tailor-made special cements. It is to be noted that the two special cements recommended to produce very high strength concrete have low C_3A content, sulphate level, and heat of hydration apart from phase composition.

Table: 2 Composition of special cement for HPC

Particulars	SP30	SP30-4A	SP30-4A(mod)
C_2S (%)	18	28	28
C_3S (%)	55	50	50
C_3A (%)	8	5.5	5.5
C_4AF (%)	9	9	9
Mgo (%)	3	1.5-2.0	1.5-2.0
SO_3 (%)	3.3	2-3	2-3
Na_2O equivalent (%)	1.1	0.6	0.6
Blain fineness (m^2/kg)	300	310	400
Heat of hydration (kcal/kg)	71	56	70
Setting time critical (min)	120	140	120
Final	180	200	170

5.2 Coarse aggregate

The important parameters of coarse aggregate that influence the performance of concrete are its shape, texture and the maximum size. Since the aggregate is generally stronger than the paste, its strength is not a major factor for normal strength concrete, or for HES and VES concretes. However, the aggregate strength becomes important in the case of high performance concrete. Surface texture and mineralogy affect the bond between the aggregates and the paste as well as the stress level at which micro cracking begins. The surface texture, therefore, may also affect the modulus of elasticity, the shape of the stress-strain curve and to a lesser degree, the compressive strength of concrete. Since bond strength increases at a slower rate than compressive strength, these effects will be more pronounced in HES and VES concretes. Tensile strengths may be very sensitive to differences in aggregate surface texture and surface area per unit volume.

5.2.1. Effect of Aggregate Type

The intrinsic strength of coarse aggregate is not an important factor if water-cement ratio falls within the range of 0.50 to 0.70, primarily due to the fact that the cement-aggregate bond or the hydrated cement paste fails long before aggregates do.

It is, however, not true for very high strength concretes with very low water-cement ratio of 0.20 to 0.30. For such concretes, aggregates can assume the weaker-link role and fail in the form of transgranular fractures on the failure surface. However, the aggregate minerals must be strong, unaltered, and fine grained in order to be suitable for very high strength concrete. Intra- and inter-granular fissures partially decomposed coarse-grained minerals, and the presence of cleavages and lamination planes tend to weaken the aggregate, and therefore the ultimate strength of the concrete.

The compressive strength and elastic modulus of concrete are significantly influenced by the mineralogical characteristics of the aggregates. Crushed aggregates from fine-grained diabase and limestone give the best results. Concretes made from smooth river gravel and from crushed granite containing inclusions of a soft mineral are relatively weaker in strength. There exists a good correlation between the compressive strength of coarse aggregate and its soundness expressed in terms of weight loss. There exists a close correlation between the mean compressive strengths of the aggregate and the compressive strength of the concrete, ranging from 35 to 75 MPa, at both 7 days and 28 days of age.

5.2.2. Effect of Aggregate Size

The use of larger maximum nominal size of aggregate affects the strength in several ways. First, since larger aggregates have less specific surface area and the aggregate-paste bond strength is less, the compressive strength of concrete is reduced. Secondly, for a given volume of concrete, using larger aggregate results in a smaller volume of paste thereby providing more restraint to volume changes of the paste. This may induce additional stresses in the paste, resulting in micro cracks prior to application of load, which may be a critical factor in very high strength (VHS) concretes. Therefore, it is the general consensus that smaller size aggregate should be used to produce high performance concrete.

It is generally suggested that 10 to 12 mm is the appropriate maximum size of aggregates for making high strength concrete. However, adequate performance and economy can also be achieved with 20 to 25 mm maximum size graded aggregates by proper proportioning with a mid-range or high-range water reducer, high volume blended cements, and coarse ground Portland cement. Change in emphasis from water-cementitious material ratio versus strength relation to water-content versus durability relation will provide the incentive for much closer control of aggregate grading than in the current practices. A substantial reduction in water requirement can be achieved by using a well-graded aggregate.

5.3 Mineral admixtures

Mineral admixtures form an essential part of the high-performance concrete mix. These are used for various purposes, depending upon their properties. More than the chemical composition, mineralogical and granulometric characteristics determine the influence of mineral admixture's role in enhancing properties of concrete. The fly ash (FA), the ground granulated blast furnace slag (GGBS) and the silica fume (SF) has been used widely as supplementary cementitious materials in high performance concrete. These mineral admixtures, typically fly ash and silica fume (also called condensed silica or micro silica), reduce the permeability of concrete to carbon dioxide (CO_2) and chloride-ion penetration without much change in the total porosity.

These pozzolanas react with OPC in two ways-by altering hydration process through alkali activated reaction kinetics of a pozzolanas called pozzolanic reaction and by micro filler effect. In pozzolanic reaction the pozzolanas react with calcium hydroxide, $Ca(OH)_2$, (free lime) liberated during hydration of cement, which comprises up to 25 per cent of the hydration product, and the water to fill voids with more calcium-silicate-hydrate (non-evaporable water) that binds the aggregate particles together.

The pozzolanas may also react with other alkalis such as sodium and potassium hydroxides present in the cement paste. These reactions reduce permeability, decrease the amounts of otherwise harmful free lime and other alkalis in the paste, decrease free water content, thus increase the strength and improve the durability.

Fly ash used as a partial replacement for cement in concrete, provides very good performance. Concrete is durable with continued increase in compressive strength beyond 28 days. There is little evidence of carbonation, it has low to average permeability and good resistance to chloride-ion penetration. Chloride-ion penetration rating of high volume fly ash (HVFA) concrete is less than 2000 coulombs, which indicate a very low permeability concrete. It continues to improve because many fly ash particles react very slowly, pushing the coulomb value lower and lower.

Silica fume not only provides an extremely rapid pozzolanic reaction, but its very fine size also provides a beneficial contribution to concrete. Silica fume tends to improve both mechanical properties and durability. Silica fume concretes continue to gain strength under a variety of curing conditions, including unfavorable ones. Thus the concretes with silica fume appear to be more robust to early drying than similar concretes that do not contain silica fume. Silica fume is normally used in combination with high-range water reducers and increases achievable strength levels dramatically.

Since no interaction between silica fume, ground granulated blast-furnace slag and fly ash occurs, and each component manifests its own cementitious properties as hydration proceeds, higher strength and better flowability can be achieved by adding a combination of SF, FA and GGBFS to OPC which provides, a system with wider particle-size distribution. HVFA concrete incorporating SF exceeds performance of concrete with only FA. The key to developing OPC-FA-SF and OPC-GBSF-SF concretes without reduction in strength is to incorporate within the mixture adequate amounts of OPC and water. Using both silica fume and fly ash, the strength at 12 hours has been found to improve suddenly over similar mixes with silica fume alone. This phenomenon has been attributed to the liberation of soluble alkalis from the surface of the fly ash.

The contribution of silica fume to any property of hardened concrete may be expressed in terms of cementing efficiency factor, K. For compressive strength of concrete, K is in the range of 2 to 5, which means that in a given concrete, 1 kg of silica fume may replace 2 to 5 kg of cement without impairing the compressive strength. This applies provided that the water content is kept constant and the silica fume dosage is less than about 20 per cent by weight of cement.

High-reactivity metakaolin (HRM) is a more recently developed supplementary cementitious material. It is a reactive alumino-silicate pozzolana manufactured by calcining purified kaolinite at a specific temperature range. It is classified as a natural pozzolana, with silica and alumina oxides content exceeding 95 per cent. The particle size is smaller than Portland cement but coarser than silica fume. Chemically, HRM combines with calcium hydroxide to form calcium-silicate and calcium-aluminate-hydrates. It has been reported that HRM in powder form is a quality-enhancing mineral additive that exhibits enhanced engineering properties comparable to silica fume slurry. At the present time, the supply of this material is limited and no practical cost data is available.

5.3.1. Chemical composition

The chemical compositions of mineral admixtures such as natural pozzolanas, fly ash, silica fume, rice husk ash, and metakaolin is presented in Table 3.

Table: 3 Typical oxide analysis of mineral admixtures.

Mineral admixtures	Main oxides present							
	SiO_2	Al_2O_3	FeO_3	C_2O	MgO	SO_3	Alkalis	LoI
Diatomaceous earth	86	2.3	1.8		0.6		0.4	5.2
Fly ash (coal)	55	2.5	9.2	4.4	1.0	1.0	1.0	2.0
Fly ash (lignite)	44	21	3.8	12.9	3.1	7.0	7.8	0.82
Blast furnace slag	38	8	2	40	11	0.1	0.8	2.0
Silica fume	90	1.0	0.03	0.1	0.2	2.2	0.1	3.6
Rice husk ash	92	0.41	0.21	0.41	0.45	0.1	2.9	2.8
Meta-kaolin	52	40	1.2	2.0	0.12	0.0	0.53	2.1

A look at this table reveals that silica and alumina content vary widely. However, these chemical differences do not significantly influence the properties of concrete. Fly ashes generally contain less silica and more alumina compared to natural pozzolanas. Both fly ash and blast furnace slag have high calcium and magnesium oxide content. Highly active admixtures such as silica fume and rice husk ash contain high content of silica. Metakaolin contains roughly equal proportions of silica and alumina.

The ground, granulated blast furnace slag and rice husk ash have to be ground to the required fineness to assist pozzolanic activity. Typically, particles less than 10 µm in size contribute to early strength; particles between 10 and 45 µm show strength gain up to 28 days; particles larger than 45 µm contribute little to the strength. The slag is generally ground to Blaine fineness of 450-550 m^2/kg. The typical BET surface area of silica fume is 12,000 m^2/kg. This is because the particle size of silica fume is in the range of 0.01-0.45 µm. However, the rice husk ash is ground only to a fineness of 6-10µm because of the porous structure. The metakaolin is ground to a fineness of about 1-2 µm.

The pozzolanic material with large surface area shows excellent reactivity. It imparts stability and cohesiveness to the mixture and prevents bleeding as well as segregation.

A summary of the characteristics of different mineral admixtures is given in Table 4.

Table: 4 Characteristics of mineral admixtures.

Type	**Classification**	**Chemical composition**	**Particle characteristics**
Ground granulated blast furnace slag (GGBS)	Cementitious and pozzolanic	Silicate glass containing calcium magnesium silicate	Unprocessed materials are grains like sand. These are ground to size < 45 µm (500 m^2/kg Blaine) particles and have a rough texture.
Calcium-rich fly ash	Cementitious and pozzulanic	Silicate glass containing mainly calcium, magnesium, aluminium alkides. Also contains C_3A, CaO, C_3S, C_4A_3S traces unburnt carbon 1-	Powder consists of particles < 45 µm. However, 10-15% are more than 45 µm. Particles are solid spheres of 20 µm. surface is generally smooth.

		2%	
Condensed silica fume	Highly active pozzolana	Pure silica of non-crystalline form	Extremely fine powder consisting of solid spheres of 0.1 µm average diameter, about 20 m^2/kg surface areas estimated by nitrogen absorption method.
Rice husk ash	Highly active pozzolana	Consists essentially of pure silica in non-crystalline form	Particles are <45 mm but have cellular and porous structure.
Low-calcium fly ash	Cementitious and pozzolanic	Mostly silicate glass containing aluminium and iron and alkides, small quantities of quartz, hematite, etc.	Powder having particles of 15-30% > 45 µm. most particles are solid sphere. Cenosph-eres and plerospheres may be present
Natural material	Natural pozzolana	Contains alumino silicate glass, natural pozzolanas containing quartz, feldspar, and mica	Particles are <45 µm and have rough texture. consists of crystalline silicate material
Slowly cooled blast furnace slag, bottom ash, field burnt rice husk ash	Weak pozzolana	Consists of crystalline silicate material	Pulverized to fine powder, and ground materials have rough texture.

5.4. <u>Superplasticizers or HRWR</u>

The superplasticizers are extensively used in HPCs with very low water-cementitious material ratios. In addition to deflocculation of cement grains and increase in the fluidity, the other phenomena that are likely to be present are the following.

(a) Induced electrostatic repulsion between particles.

(b) Dispersion of cement grains and consequent release of water trapped within cement flocks.

(c) Reduction of surface tension of water.

(d) Development of lubrication film between particles.

(e) Inhibition of the surface hydration reaction of the cement particles, leaving more water to fluidify the mix.

(f) Change in morphology of hydration products.

(g) Induced steric-hindrance preventing particle to particle contact.

The main objectives for using superplasticizers are the following.

(i) To produce highly dense concrete to ensure very low permeability with adequate resistance to freezing-hawing.

(ii) To minimize the effect of heat of hydration by lowering the cement content.

(**iii**) To produce concrete with low air content and high workability to ensure high bond strength.

(**iv**) To lower the water-cement ratio in order to keep the effect of creep and shrinkage to a minimum.

(**v**) To produce concrete of lowest possible porosity to protect it against external attacks.

(**vi**) To keep alkali content low enough for protection against alkali-aggregate reaction and to keep sulphate and chloride contents as low as possible for prevention of reinforcement corrosion.

(**vii**) To produce pumpable yet non-segregating type concrete.

(**viii**) To overcome the problems of reduced workability in fibre reinforce concrete and shotcrete.

(**ix**) To provide high degree of workability to the concretes having mineral additives with very low water-cementitious material ratios.

(**x**) To produce highly ductile and acid resistant polymer (acrylic latex) concrete with adequate workability and strength.

The following types of superplastisizers are used.

- Naphthalene-based
- Melamine-based
- Lignosulfonates-based
- Polycarboxylate-based
- Combinations of above

5.4.1. Superplastisizer Dosage

There is no a prior way of determining the required superplasticizer dosage; it must be determined by trial and error procedure. Basically, if strength is the primary criterion, then one should work with the lowest w/c ratio possible, and thus the highest superplasticizer dosage. However, if the rheological properties of the HPC are very important, then the highest w/c ratio possible consistent with the required strength should be used, with the superplasticizers dosage then adjusted to get the desired workability. In general, of course, some intermediate positions must be found, so that the combination of strength and rheological properties are optimized.

5.4.2. Retarders

Retarders are, generally, recommended for HSC to minimize the slump loss problem. However, it is difficult to maintain compatibility between the retarder and the superplasticizer. Therefore, the Retarders are recommended only as a last resort; the rheology is better controlled by the use of appropriate mineral admixture (supplementary cementing material) discussed before.

6.0. Mix Proportion

The main difference between mix designs of HPC and CC is the emphasis laid on performance aspect also (in fresh as well as hardened stages of concrete) besides strength, in case of HPC, whereas in design of CC mixes, strength of concrete is an important criterion. By imposing the limitations on maximum water–cement ratio, minimum cement content, workability (slum, flow table, compaction factor, Vee-Bee consistency), etc., it is sought to assure performance of CC; rarely any specific tests are conducted to measure the durability aspects of CC, during the mix design. In HPC, however, besides strength, durability considerations are given utmost importance. To achieve high durability of HPC, the mix design of HPC should be based on the following considerations:

i) The water-binder (w/b) ratio should be as less as possible, preferably 0.3 and below.

ii) The workability of concrete mix should be enough to obtain good compaction (use suitable chemical admixtures such as superplasticizer (SP)).

iii) The transition zone between aggregate and cement paste should be strengthened (add fine fillers such as silica fume (SF)).

iv) The microstructure of cement concrete should be made dense and impermeable (add pozzolanic materials such as fly ash (FA), ground granulated blast furnace slag powder (GGBFSP), SF, etc.)

v) Proper curing regime of concrete should be established (this is to overcome the problems associated with usual adoption of very low water content and high cement content in HPC mixes)

6.1. LIMITATIONS OF CONVENTIONAL MIX DESIGNS:

6.1.1. BIS method (IS: 10262 – 1982):

a). The Code lists the grade of concrete unto M60 only, while suggesting the values of standard deviation for each grade of concrete.

b). The graph of BIS Code suggesting the general relationship between water-cement (w/c) and 28-day compressive strength refers to a maximum compressive strength of 52 MPa only and another graph showing the same relationship depending upon (w/c) and 28-day strength of cement refer to a maximum compressive strength of 58Mpa only.

The HPCs usually have compressive strength often more than 70Mpa (100Mpa and more). Hence, the above provisions of BIS Code cannot be applied to HPC.

c). The extrapolations of standard deviations (SD) given in the Code to obtain SD for HPC, result in very high SD values. It is observed from the literature that the SD of HPCs would be quite lower owing to the maximum care taken in selection of ingredients, proportioning mixing and curing of HPCs. Use of unrealistic high values of SDs would push up un-necessarily the cost of HPCs as the HPC's have to be designated for much higher strength than required.

d). The BIS method gives a table for finding water content of the concrete for w/c ratio of 0.35 only. In this table, water contents of 200 and 180 kg/m^3 are suggested for maximum size of aggregates (MSAs) of 10 mm and 20m respectively. The HPCs usually have w/c=0.3 or less. Even assuming w/c of 0.3, the cement contents corresponding to the above water contents work out to 667 and 600 kg/m^3 respectively. These cements are too high and are never reported to be used for HPCs as seen from the published literature on HPC.

e). Maximum w/c ratio of 0.45 suggested or 'severe' exposure condition in IS: 10262 and IS: 456 is too high and the HPCs reported in the literature have very low w/c ratios (often 0.3 and below). Thus, the BIS suggestion of w/c=0.45, cannot be accepted for HPCs.

f). The suggestion of sand content at 28% (for MSA of 10mm) and 25% (for MSA of 25mm) in the BIS method leas to fine aggregates: coarse aggregate ratios of the order of 1:2 to 1:3 (by weight). From the published literature on HPCs these ratios seem to be quite high and hence, the cohesiveness of HPCs would be affected if these ratios are adopted. As the HPCs utilize SPs, it would be necessary to use more sand in order to avoid segregation of cement paste from aggregate due to the dispersing/flowing effect of SP on the cement paste.

g). The BIS code allows the use of Zone IV sand which may have particles passing through 300 micron sieve, to an extent of 50%. As the HPCs have usually very low water content, this large content of small particles (less than 300 microns) of sand would reduce the workability of the HPCs. More over, the fine particles of sand may not be required in HPCs as these concrete usually have high cement contents and also have often pozzlanic powdery materials such as FA, SF, etc.

6.1.2 <u>ACI Method</u>

This Code covers 28-day compressive strength upto about 60 MPa as seen from the curve of compressive strength-Vs-w/c ratio, suggested by this Code. The minimum water cement ratio covered is 0.3. As HPCs have often strengths more than 60 MPa and w/c ratio 0.3 and below, the ACI method can not give proportions for HPC.

6.1.3 <u>Road Note No.4</u>

This method covers up to a minimum w/c ratio of 0.35 which is more than the w/c ratio adopted usually in HPCs and hence, this method cannot be adopted for HPC.

6.1.4 <u>IRC-44 Method</u>

This method refers to a curve of compressive strength-Vs-w/c ratios in which minimum w /c ratio is 0.4 and maximum compressive strength is about 50 MPa. The HPCs usually have w/c ratio is 0.3 and less, which is quite less than 0.4 the value referred in this method. The HPCs usually have the strengths more than 50 MPa. Thus, it can be seen that the IRC-44 method cannot be used for the design of HPC mixes.

6.2 GENERAL COMMENTS ON CONVENTIONAL MIX DESIGN METHODS

It is observed from the study of conventional mix design methods (CMDs) that they are not generally applicable to HPC because of the following reasons:

i) The compressive strength levels covered by CMDs are far less than those usually obtained in case of HPCs.

ii) W/C or W/B ratio of CMD, are generally higher or quite close to the highest level of W/b ratio encountered in HPCs.

iii) The CMDs do not take in to account for changes in properties of fresh as well as hardened concrete due to incorporation of water reducing admixtures such as SP and also the permeability reducing mineral additives such as FA, SF, GGBS, SF, etc.

iv) The CMDs do not consider exclusively the durability aspects affecting properties of concrete such as porosity, impermeability, electric receptivity, etc.

v) Many a time the type and strength of aggregate limit the strength level of HPCs that can be achieved with the given aggregate. Such limitations are not usually encountered in case of CC designated by CMDs.

vi) The CMDs do not account for strength of transition zone. In HPCs, considerations with regard to the development of suitable transition zone need special attention.

vii) As the HPCs tend to have usually high cementitious content, use of cement replacement materials such as FA, SF, GGBS, SP, etc, is almost essential to reduce the ill effects of high cement content in a concrete.

viii) The strength developed in case of HPCs after conventional 28-days period is quantitatively considerable; hence, later age strength (say 90-day) is better criterion for design of HPC mixes.

ix) The standard deviations of HPCs could be less than those of CCs since the HPCs are produced under stricter quality control measures. This would help in making economical mix design of HPCs.

6.3 TYPICAL HPC MIX DESIGN METHODS IN PUBLISHED LITERATURE

The properties of HPCs not only depend upon the w/b ratio but also vary considerably with the richness of mix and the type and strengths of concrete of aggregates. Workability of HPCs depends upon the type of cement and its compatibility with chemical admixtures, shape of aggregate, method of mixing of ingredients of HPCs, etc. Thus, the properties of materials and mix preparation techniques have very high influence on the HPC mixes, suitable mix proportions cannot be suggested for HPCs. Therefore, any mix design procedure of HPCs can strictly be only a guideline and a separate development of HPC mix in the laboratory for the various ingredients, type of structure and concreting conditions etc., is very much essential. Hence, the HPC mix design can be only application-specific.

It should be noted that the strength increase as the w/c is reduced (provided the compatibility of concrete is maintained), and that for a given w/c, the strength is decreased as a mix is made richer (by adding more cement) beyond a limit. Therefore, the advantage of increase in strength due to lowering of the w/c, which also reduces consequently the workability. Hence, the HPCs require approaches other than the increase of cement content in order to achieve the high strength.

Though the strengths are not always true indicators of durability, the high strength associated with the HPCs generally tend to impart also high durability to them, due to reduced w/b and use of pozzolanic admixtures.

6.3.1 Canadian Portland Cement Association

It is explicitly suggested that the trial mix approach is the best for selecting proportions for high strength concrete.

6.3.2 LCPC Mix Design By Experimental Method

Various steps involved in this method are;

(i) Design a normal strength concrete (NSC) for a critical workability and the desired 28-day compressive strength.

(ii) Adjust the water content of NSC to obtain the workability with SP, to get control concrete (CC)

(iii) Measure lowing time (Marsh Cone) of binder paste of CC.

(iv) Arbitrary choose binder mixes such as 90% cement plus 10% FA or 75% cement plus 20% FA plus 5%SF, etc. Find SP content and w/b ratio to obtain flow time of binder paste of CC.

(v) Use Feret's law for trial casting. The HPC and CC would change in content of ingredients, if required.

(vi) Make HPC mix for trial casting. The HPC and CC could have same workability and same granular skeleton.

(vii) Depending upon the strength required, different binder paste has to be chosen.

6.3.3 Cement and Concrete Association of Australia

The technical report No.TR/F112 clearly states that the proportions of concrete mixes with 28-day compressive strength of 60Mpa and above have to be obtained only an investigating trial mixes using locally available materials.

6.3.4 Method proposed by Mehta and Aitcin

1. Choice of strength: Arbitrarily divided into five grades, namely 65, 75,95and 120 Mpa.
2. Estimation of Mixing water: from a given strength grade, Table is used to estimate the maximum content of mixing water.
3. Volume fraction of cement paste components: From the total volume of 0.35 m^3 of cement paste, the water content and entrapped air is subtracted to get cementitious material.
4. Estimation of aggregate content: From the total aggregate volume 0.65 m^3, assuming a 2:3 volumetric ratio between fine and coarse aggregate, individual volume fractions are calculated.
5. Calculation of batch weights: From the typical specific gravity values of ingredients the batch weights are determined.
6. Superplastizer dosage: If there is no prior experience with the superplasticizer, it is suggested to start with 1% and continue till the required workability is obtained.
7. Moisture correction: Depending on the moisture condition of batch aggregates, the appropriate moisture correction for fine and coarse aggregate must be made.
8. Trial batch adjustment: Several laboratory trials using the actual materials may be required before one arrives at the right combination of materials and mix proportions, which satisfy the given criteria of workability and strength.

6.3.5 ACI 211.4R Standard Practice

Data needed include- F.M. of sand, dry rodded unit weight of the C.A., Specific gravity of the aggregates.

1. Slump selection: Selected from the given table

The target strength $f_{cr} = (f_c + 9.65) / 0.9$

f_{cr} = Specified design compressive strength

f_c = Required average compressive strength

2. Selection of maximum size of aggregate (MSA): Based on the strength requirement, select the maximum size of aggregate.

3. Selection of optimum coarse aggregate content:

Weight of C.A. = (%xDRUW)x DRUW

4. Estimation of mixing water and air content: From the table get the estimate of mixing water and air content percentage.

Mixing Water adjustment, kg/m^3 + (V-35)x4.74

5. Selection of W / (C+P) Ratio: Table gives the recommended maximum W / (C+P) ratio as the function of the maximum size of aggregate to achieve different compressive strengths either at 28 days or 56 days for a mix made without HRWRA and a mix made using HRWRA.

6. Calculate cementatious Materials content: obtained by dividing the amount of mixing water by the W / (C+P) ratio.

7. Sand content: After determining the weights of C.A., cement and water and air content, the sand content can be calculated using absolute volume methods.

8. Proportion Companion mixture using FLY ash:

9. Trial mixtures

10. Adjustment of Trial mix proportions

7.0 Properties of High Performance Concrete

7.1 Properties of Fresh Concrete

High performance concrete is characterized by special performance both short- and long-term and uniformity in behavior. Such requirements cannot always be achieved by using only conventional materials or applying conventional practices.

It is wrong to believe that the mechanical properties of high performance concrete are simply those of a stronger concrete. It is also as wrong to consider that the mechanical properties of high-performance concrete can be deduced by extrapolating those of usual concretes as it would be wrong to consider that none of them are related. It is also wrong to apply blindly the relationships linking the mechanical properties of a usual concrete to its compressive strength that were developed through the years for usual concretes found in codes and text books.

7.1.1 Workability

The workability of HPC is normally good, even at low slumps, and HPC typically pumps very well, due to the ample volume of cementing material and the presence of chemical admixtures, particularly HRWR. Due to reduced water-cementing material ratio no bleeding occurs. In the flowing concrete bleeding is prevented by providing adequate fines in the concrete mix. The cohesiveness of superplastisized concrete is much better as a result of better dispersion of cement particles. Cohesion is a function of rheology of concrete mix, which is consequently improved. However, excessive dosages of superplastisizer can induce some segregation, but it has little effect on physical properties of hardened concrete.

7.1.2 Rheological Properties

Widening the particle-size distribution of a solid suspension while maintaining constant solid volume reduces the viscosity of the suspension, known as the Farris effect. Thus, the blended or composite cements with wider particle-size distributions can achieve better rheological properties. The OPC-FA-SF ternary-cement concrete requires less water and is less sticky than OPC-SF concrete; however, it requires more water and is stickier than OPC-FA or OPC-GGBFS based concrete. In ternary cements FA seems to compensate for the rheological problems associated with the use of high SF contents. In binary cements containing relatively coarser GGBFS for example, addition of fine pozzolanas, such as SF or rice husk ash, inhibits bleeding problems.

7.1.3 Curing

The compressive strength of HPC is less sensitive to temperature and relative humidity than the normal strength concrete. However, tensile strength of HSC has been found to be more sensitive. The concrete containing very large quantities of ground granulated blast-furnace slag requires longer moist curing times to develop adequate strength and is more sensitive to drying than plain Portland cement concretes.

The higher internal temperatures frequently found with high early strength HPC can lead to a rapid strength gain in concrete accompanied by a consequent gain in elastic modulus. The larger differential temperatures occurring within a stiffer concrete will create higher stresses and can cause more pronounced cracking than with normal concrete. These cracks will occur, regardless of the method of curing, due to stress caused by differential temperatures.

7.2. Properties of Hardened concrete

The behaviour of hardened concrete can be characterized in terms of its short-term (essential instantaneous) and long-term properties. Short-term properties include strength in compression, tension and bond, and modulus of elasticity. The long-term properties include creep, shrinkage, behaviour under fatigue, and durability characteristics such as porosity, permeability, freezing-thawing resistance, and abrasion resistance.

7.2.1 Stress-strain Behaviour

Axial stress versus strain curves for HPC is shown in fig. 3. The shape of the ascending part of the stress-strain curve is more linear and steeper for high-strength concrete, and the strain at the maximum stress is slightly higher for HPC. The slope of the descending part becomes steeper for high-performance concrete. To obtain the descending part of the stress-strain curve, it is generally necessary to avoid the specimen-testing system interaction.

High performance concrete exhibits less internal microcracking than lower-strength concrete for a given imposed axial strain. As a result, the relative increase in lateral stain is less for HPC. The lower relative lateral expansion during the inelastic range may mean that the effects of triaxial stresses will be proportionally different for HPC. For example the influence of hoop reinforcement is observed to be different for HPC.

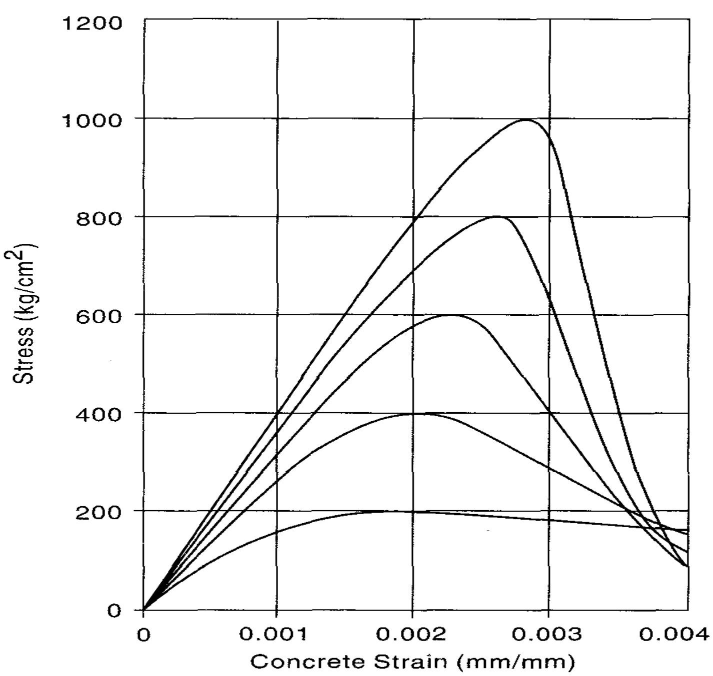

Fig: 3 Stress-strain relationship of HPC.

7.2.2 Strengths

Compressive, tensile and flexural strengths and modulus of elasticity of high performance concrete are much higher than those of the normal concrete of the same consistency. The enhancement in the mechanical properties is generally commensurate with reduction in water content when HRWR is used. In water reduced concrete the strength parameters can be generally increased by more than 20 percent. A strength of the order of normal concrete is achieved by superplastisized concrete with a reduced cement content.

The strength of the concrete depends on a number of factors including the properties and proportions of the constituent materials, degree of hydration, rate of loading, and method of testing and specimen geometry. The properties of the constituent materials which affect the strength are: the quality of fine and coarse aggregates, the cement paste and the paste-aggregate bond characteristics, i.e. properties of the interfacial transition zone. These, in turn, depend on the macro- and micro-scopic structural features including total porosity, pore size and shape, pore distribution and morphology of the hydration products, plus the bond between individual components.

7.2.3 Modulus of elasticity

It is generally agreed that the elastic modulus of concrete increases with its compressive strength. The modulus is greatly affected by the properties of the coarse aggregate; the larger the amount of coarse aggregate with a high elastic modulus, the higher would be the modulus of elasticity of concrete. The concrete in wet condition has about 15 percent higher elastic modulus than that in the dry condition. This is attributed to the effect of drying of transition zone between the aggregate and the paste. The modulus of elasticity increases with the strain rate. It also increases as the concrete is subjected to very low temperatures.

Addition of high volume of fly ash enhances elastic modulus significantly. The high elastic modulus of HVFA concrete is probably due to the fact that a considerable portion of the unreacted fly ash, consisting of glassy spherical particles, acts as a fine aggregate, and there is a strong interfacial bond between the paste and the aggregate.

7.2.4 Poisson’s Ratio

Experimental data on values of Poisson’s ratio for HPC are very limited. Pernchio and Klieger reported values for Poisson’s ratio with a compressive strength ranging from 55 to 80 MPa between 0.2 and 0.28. They concluded that Poisson’s ratio tends to decrease with increasing water-cement ratio. Kaplan found values for Poisson’s ratio of concrete determined using dynamic measurements to be from 0.23 to 0.32 regardless of compressive strength, coarse aggregate, and test age for concretes having compressive strengths ranging from 17 to 79 Mpa. Based on the available information, Poisson's ratio of HPC in the elastic range seems comparable to the expected range of values for lower strength concretes.

7.2.5 Modulus of Rupture

For usual concrete modulus of rupture and splitting tensile strength are quite low and don't vary much, because they are very much influenced by the tensile strength of the hydrated cement paste. However, this is no longer the case for high performance concrete, for which the water binder ratio and the compressive strength can vary over a wide range. The relationships that have been suggested between compressive strength and modulus of rupture for usual concrete lose some of their predictive value when going from usual concrete to high-performance concrete.

7.2.6 Splitting Tensile Strength

Dewar studied the relationship between the indirect tensile strength and the compressive strength of concretes having compressive strengths upto 83 MPa at 28 days. He concluded that at low strengths, the indirect tensile strengths may be as high as 10 percent of the compressive strength but at higher strengths it may reduce to 5 percent. He observed that the tensile splitting strength was about 8 percent higher for crushed rock aggregate concrete than for gravel aggregate concrete. He also found that the indirect tesile strength was about 70 percent of the flexural strength at 28 days.

7.2.7 Shrinkage

Little information is available on the shrinkage behaviour of High-Performance concrete. A relatively high initial rate of shrinkage has been reported, but after drying for 180 days there is little difference between the shrinkage of high-strength and lower strength concrete made with dolomite or limestone. Reducing the curing period from 28 to 7 days caused a slight increase in the shrinkage. Shrinkage was unaffected by w/c ratio but is approximately proportional to the percentage of water by volume in the concrete. Other laboratory and field studies have shown that shrinkage of high-performance concrete is similar to that of lower strength concrete. Nogataki and Yonekurus reported that the shrinkage of high performance concrete containing high-range water reducers was less than for lower-strength concrete.

7.2.8 Creep

Creep, the flow of the material under sustained load, is a very important factor in the long-term deformational performance of structures. It has been found that the specific creep and hence the creep coefficient value are less in high-performance concrete (HPC) than in normal-strength concrete (NSC).

The creep coefficient decreases while the strength increases, that is to say while the w/c ratio decreases. For ordinary concretes, the value of the creep coefficient ¢ is generally taken equal to 2.0 when loading is applied at 28 days. It seems that this coefficient may be as low as 1.0 for some C60 concretes and 0.50 for some C 100 concretes.

The creep of high-performance concrete made with high-range water reducers is reported to be decreased significantly. The maximum specific creep was less for high-strength concrete than for lower-strength concrete loaded at the same age.

7.2.9 Ductility

Compression tests show that the stronger the concrete the more brittle it is. This could be of concern since modern design methods take into account the plasticity of materials. Flexural tests run on the reinforced HPC beams show that their ductility is similar to that of beams with ordinary concrete.

Care should nevertheless be exercised concerning HPC elements such as columns submitted to axial loads. Experiments are being carried out in France in order to set the rules concerning minimum longitudinal and transverse reinforcements in such pieces.

7.2.10 Fatigue strength

As the static strength of concrete increases, it becomes increasingly more brittle and its ultimate strain capacity does not increase proportionately with the increase in strength. Therefore high performance concrete would be vulnerable to fatigue loading.

However in HPC the elastic modulus of the paste and that of aggregate are more similar, thereby reducing stress concentrations at the aggregate-paste interface is less susceptible to fatigue loading. Thus due to reduced microcracking in HPC, the fatigue life built-up damages are smaller when compared with those in normal strength concrete.

7.2.11 Alkali-Aggregate Reaction

Fly ash, blast furnace slag, and silica fume supplementary cementatious pozzolanic additions to the concrete mixture (SCM) have shown to be effective ingredients in resisting alkali-aggregate reaction. The effect of the addition pozzolanic fly ash (PFA), blast furnace slag (BFS), and condensed silica fume (CSF) are effective in reducing the expansion in concrete, provided that they are used correctly and of the appropriate quality and amount. Coating the aggregates with acrylic or epoxy might be a solution, but effectiveness and cost does not match the other solution.

7.2.12 Abrasion Resistance

Abrasion resistance of concrete is of major importance in highway pavements and concrete bridge decks. Work available on the abrasion resistance of high-performance concretes has shown that increase in strength results in substantially increased service life, as documented by Gjorv et. al. In this work, an increase in concrete strength from 50 MPa to 100 MPa can reduce the abrasion deterioration by almost 50%. While the type of aggregate and its abrasion resistance affects the performance of the concrete, its effect becomes less significant at the highest compressive strength to abrasion. Service life of pavements ranged from 7 years in 40 MPa to 31 years in153 MPa ultrhigh strength concrete.

7.2.13 Carbonation

Carbonation is the chemical reaction caused by the defusion of carbon dioxide (CO_2) in the air into the permeable concrete and its reaction with $Ca(OH)_2$ compound of the hydrated cement such that it carbonates to $CaCo_3$. This decomposition of the calcium compounds in the hydrated matrix combined with alternating wetting and drying in air containing CO_2 leads to an increase in the magnitude of irreversible shrinkage, contributing to crazing of the exposed surface and increase in the weight of the concretes, with progressive scaling of the concrete protective cover to the reinforcement.

Use of pozzolanic cementations replacements in concrete such as silica fume or fly ash does not seem to have any significant effect on the carbonation development or rate. However, if scaling is prevented because of the higher tensile strength of the high-performance concrete, its dense composition and extremely low pore volume and permeability inhibit the oxidation process that causes corrosion of the reinforcement.

7.2.14 Porosity and Permeability

The exceptional properties of HPCs proceed essentially from their reduced porosity and not from their high compressive strength which is only one of their many facets; it is their reduced porosity which makes them new material with multiple advantages. It is generally agreed that mixing water is indirectly responsible for permeability of the hydrated cement paste because its content determines at the first instance the total space and subsequently the unfilled space after the water is consumed by either cement hydration reactions or evaporation to the environment. In other words porosity of concrete resides principally in the cement paste.

8.0 Application of High Performance Concrete

Major applications of HPC have been in the areas of pavements, long-span bridges and high-rise buildings.

8.1 Pavements:

High Performance concrete is being increasingly used for highway pavements due to the potential economic benefits that can be derived from the early strength gain of high performance concrete, its reduced permeability, increased wear or abrasion resistance to steel studded tires and improved freeze-thaw durability. While the conventional normal strength concrete continue to be used in most cases of pavement construction, different types of high performance concretes are being considered for pavement repairs for early opening to traffic, bridge deck overlays, and special applications in rehabilitation of structures and other developments.

A durable concrete called fast track concrete designed to give high strength at a very early age without using special materials or techniques has been developed. The early strength is controlled by the water-cement ratio, cement content and its characteristics. Typically, a rich, low water content mix containing 1 to 2 per cent calcium chloride will produce adequate strength and abrasion resistance for opening the pavement to traffic in 4-5 hours at temperatures above 10^0C. Fast track concrete paving (FTCP) technology can be used for complete pavement reconstruction, partial replacement by an inlay of at least one lane, strengthening of existing bituminous or concrete pavements by a concrete overlay, rapid maintenance and reconstruction processes, and air-field pavements. The benefits of applying

FTCP technology in such applications are: a reduced construction period, early opening of the pavement to traffic, and minimizing the use of expensive concrete paving plant. Flowable HSC overlays over thick bridge decks can make the construction cost effective.

Polymer concrete overlays: The polymer overlays constructed with epoxy, methacrylate, and polyester styrene binders, and graded silica and basalt aggregates can provide skid resistance and protection against chloride intrusion. These are economical techniques for extending service life of reinforced concrete decks.

8.2 Bridges:

The use of high performance concrete would result in smaller loss pre-stress and consequently larger permissible stress and smaller cross-section being achieved, i.e. it would enable the standard pre-stressed concrete girders to span longer distances or to carry heavier loads. In addition, enhanced durability allow extended service life of the structure. In case of precast girders due to reduced weight the transportation and handling will be economical. Concrete structures are preferable for railway bridges to eliminate noise and vibration problems and minimize the maintenance cost.

In the construction of the concrete bridges and highway structures a general requirement of using a water-binder ratio of less than 0.40 combined with the use of silica fume so as to improve the chloride resistance against deicing agents and marine environment is recommended. This process improvement will provide the advantages of reduced weight, increased strength and enhanced durability. Based on an efficiency factor of 0.5 for fly ash and 2.0 for silica fume, typical examples of mix proportions designated types A and B are for the bridges exposed to sea water and precast girders on bridges, respectively.(Table 5)

Table: 5 Mix Proportions for the Bridges exposed to sea water.

Parameter	**Type-A**	**Type-B**
Water-cementitious material ratio	< 0.35	< 0.40
Fly ash content of cementitious material	>10 per cent	>10 per cent
Silica fume content of cementitious material	5-8 per cent	5-8 per cent
Fly ash plus silica fume content	< 25 per cent	< 25 per cent
Total water content	< 135 kg/m^3	< 140 kg/m^3

8.3 High-rise Buildings

The reasons for using the high strength concrete in the area of high-rise buildings are to reduce the dead load, the deflection, the vibration and the noise, and the maintenance cost.

8.4 Miscellaneous Applications

Fibre reinforced concrete has been used with and without conventional reinforcement in many field applications. These include bridge deck overlays, floor slabs, pavements and pavement overlays, refractories, hydraulic structures, thin shells, rock slope stabilization, mine tunnel linings and many precast products. The addition of steel fibres is known to improve most of the mechanical properties of concrete, namely, its static and dynamic tensile strengths, energy abrasion and toughness, and fatigue resistance. Hence proper utilization of steel fibre-reinforced concrete depends on the skill of the engineer.