# CHAPTER-2: REVIEW OF LITERATURE

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CHAPTER-2

REVIEW OF LITERATURE

2.1 General:

The main objective of this extensive literature survey is to bring out the state of art Techniques available in the production of polymer based concretes and also to summarize the information available on the effect of rubber latex on the properties of concrete. Thus the gaps in the literature can be identified and the present research can be effectively planned to address these gaps paving the way for better utilization of Natural Rubber Latex in the production of fibre reinforced High-Performance-Concrete. In India reinforced concrete has been used extensively for the construction of houses, multi-storied buildings, roads, bridges and Dams. The advantage of concrete is well known to Engineers and Architects. However, in recent days the use of conventional concretes designed on the basis of compressive strength do not meet many functional requirements such as impermeability, resistance to frost, thermal cracking adequately and also in the present construction activities like industrial projects and the projects where the completion time of the project is the criteria these conventional concretes which possess the compressive strength not more than 40 MPa are not suggestible. In such a case the usage of High Performance Concrete (HPC) has become more prominent.

The Specific definition of HPC required for each industrial application is likely to vary. The HPC will vary based on the strength, durability and w/c ratio criteria. Plain HPC possesses less strength and higher permeability when compared to High Performance Concrete containing admixtures and fibres. Hence, the present investigation is carried out on high performance concrete with the addition of mineral admixture, fibres and polymers. The mineral admixture used is Metakaolin, fibres
used are crimped steel fibres and polymer used is Natural rubber latex. There is need to conduct an extensive literature research and review about the mechanical properties of high performance concrete for better understanding.

The aim of the present work is to develop the polymer modified concrete with the addition of dispersed polymer (Natural Rubber Latex) in to the concrete. This has not only concern on the strength of concrete, but also enhances the durability. To achieve this objective, natural rubber latex and steel fibres are added to the plain HPC using low water-cement ratios. An attempt is made in this section to review the literature on polymer based concretes, mineral admixtures and fibres. Steel fibres of crimped in nature and natural rubber latex are proposed to use in production of latex modified HPC. The raw materials used in production, the workability aspects, properties of hardened concrete such as detailed compressive strength, split tensile strength and flexural strength characteristics and durability aspects are presented in the following manner

1. Introductory Remarks
2. Properties of Fresh Concrete
3. Properties of Hardened Concrete.

The basic properties related to Fibre reinforced High Performance Concrete and raw materials used in this research work are described. A detailed review on Compressive Strength, Spit Tensile Strength and Flexural Strength characteristics of HPC are presented. The characteristics of Mineral admixtures, steel fibres and polymers have been reviewed and presented here with a special emphasis on Natural Rubber Latex (NRL).
2.2 Introductory Remarks:

2.2.1 Conventional Concrete:

During the last decade, developments in admixtures and mixing and placing methods have made it possible to produce concretes with much higher strengths (70-100 MPa). Conventional Concrete is the one which has compressive strengths of less than 50 MPa. Concrete having compressive strength greater than 200 MPa is classified as ultra-high-strength concrete. The Table 2.1 shows the classifications of various concretes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conventional</th>
<th>High Strength</th>
<th>Very high Strength</th>
<th>Ultrahigh Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Strength(MPa)</td>
<td>&lt;50</td>
<td>50-100</td>
<td>100-200</td>
<td>&gt;200</td>
</tr>
<tr>
<td>Water-binder Ratio(typical)</td>
<td>0.45-0.55</td>
<td>0.30-0.45</td>
<td>0.24-0.30</td>
<td>&lt;0.24</td>
</tr>
<tr>
<td>Chemical Admixture</td>
<td>Not necessary</td>
<td>WRA*/HRWRA</td>
<td>HRWRA** essential</td>
<td>HRWRA Essential</td>
</tr>
<tr>
<td>Mineral binder Addition</td>
<td>Not necessary</td>
<td>Fly ash/slag/</td>
<td>Silica fume</td>
<td>Silica fume</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Metakaolin/rice</td>
<td></td>
<td>And fly ash</td>
</tr>
<tr>
<td>Aggregate type</td>
<td>Gravel/crushed Stone/light weight aggregate</td>
<td>Crushed stone</td>
<td>Crushed stone/ Artificial aggregate</td>
<td>Artificial Aggregate</td>
</tr>
<tr>
<td>Maximum size of Aggregate(mm)</td>
<td>Any size</td>
<td>15</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Fibres</td>
<td>Optional</td>
<td>Beneficial</td>
<td>Beneficial</td>
<td>Essential</td>
</tr>
<tr>
<td>Air entertainment</td>
<td>Necessary</td>
<td>Necessary</td>
<td>Necessary</td>
<td>Not Necessary</td>
</tr>
<tr>
<td>Processing</td>
<td>Conventional</td>
<td>Conventional</td>
<td>Conventional</td>
<td>Heat and pressure required</td>
</tr>
<tr>
<td>Permeability Coefficient(cm²/s)</td>
<td>10⁻¹⁰</td>
<td>10⁻¹¹</td>
<td>10⁻¹²</td>
<td>10⁻¹⁴</td>
</tr>
<tr>
<td>Chloride Diffusivity(cm²/s)</td>
<td>10⁻¹⁰</td>
<td>10⁹</td>
<td>10⁸</td>
<td>10⁷</td>
</tr>
</tbody>
</table>
The ingredients of high-Strength concrete are the same as those used in conventional concrete with the addition of one or two admixtures, both chemical and mineral.

However, there are two crucial aspects to be considered while deciding upon the ingredients to be used. The first relates to the use of an extremely low water-cement ratio and the second to the use of a proper mix in order to produce concrete with minimum or no voids. A proper mix can be obtained using a proper particle packing method.

### 2.2.2 High strength concrete:

The developments in the last decade, in admixtures, mixing and placing methods have made it possible to produce concretes with much higher strengths (70-100MPa). High strength concretes have compressive strength up to 100MPa as against conventional concrete which has compressive strengths of less than 50MPa. The concrete having compressive strength greater than 200 MPa is classified as ultra-high strength concrete. The High strength concrete essentially has a low water-binder ratio. A value of 0.3 is suggested as the boundary between normal and high strength concrete. For ultra high-strength concretes this value is further reduced by the use of high-range water-reducing admixtures [1].

**2.2.2.1 Microstructure of High-Strength Concrete**

A number of microstructure studies have revealed dense distributions of particles in high-strength concrete as shown in the fig 2.1 compared to conventional concrete (Fig 2.2).
The following conclusions have been made:

a. The material is more homogeneous on a millimeter scale

b. No pronounced transition zone between the sand and the paste is seen

c. Low porosity (1-3%)

d. Proportionately lower percentage of capillary porosity (10% of total porosity)

The features lead to low water absorption, gas permeability, and chloride diffusivity.

Fig 2.2 Weak Micro Structure of conventional concrete
2.2.2.2 Composition of High/Ultrahigh-strength concrete:

The composition of high-strength concrete aims at using all the constituents of concrete fully. In ordinary concrete, not all the cement that is added gets hydrated. Hence, some form of mineral admixture is added in high-strength concrete. This acts as a cementitious material and hence reduces the water binder ratio. The examples of the composition of 200-MPa concrete, have been studied by Suzette et al. [1] and Aitcin and Richard [2].

The key ingredients of this type of concrete are the following.

a. Low water-binder ratio.

b. Large quantity of silica fume and/or fine material powder.

c. Aggregates containing fine sand with good particle packing characteristics

d. High dosage of super plasticizers.

2.2.3 High-Performance-Concrete (HPC):

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. While the discussion made on High-Strength concrete aims at enhancing strength and consequent advantages owing to improved strength, the 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 ACI [3] 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. Volume 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.

The performance requirements of concretes 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 Program (SHRP) has defined HPC for highway application on the following Strength, durability and w/c ratio criteria.

It should satisfy one of the following strength criteria

a. 4 hrs. Strength > 17.5 MPa (2500 psi)
b. 24 hrs. strength > 35.0 MPa (5000 Psi)
c. 28 days strength > 70.0 MPa (10,000 Psi)

It should have a durability factor greater than 80% after 300 cycles of freezing and thawing it should have a water-cement ratio of 0.35 or less.
Forster [4] defined HPC as "a concrete made with appropriate materials combined according to a selected mix design and properly mixed, transported, placed, consolidated, and cured so that the resulting concrete will give excellent performance in the structure in which it will be exposed, and with the loads to which it will be subjected for its design life."

In discussing the meaning of HPC, Aitcin and Neville [5] stated that "in practical application of this type of concrete, the emphasis has in many cases gradually shifted from the compressive strength to other properties of the material, such as a high modulus of elasticity, high density, low permeability, and resistance to some forms of attack."

The performance of concrete structure is influenced by its microstructure and its composition. The performance of the concrete means either its good workability, low heat of hydration in case of mass concretes or quick setting and hardening in case of spray concrete which is used for road repair works, low impervious in case of storage vessels. However, structural point of view high strength, high ductility and high durability which are most important feature of high performance concrete.

2.2.3.1 Methods for Achieving High Performance Concrete:

In recent days, high durability performance has been achieved by using High Performance Concrete. The mix design is to be based not only on the strength but also on durability. It is desirable that the high performance, namely durability is addressed directly by optimizing critical parameters such as particle size of the material. The approaches to achieve the durability are reducing the capillary pore system such that no fluid movement can take place. The second one is creating chemically active binding sites which prevent the transportation of aggressive ions like chlorides.
2.2.3.2 Parameters required for High performance characteristics:

The major factor that causes premature deterioration of concrete structures is permeation. The provision of High performance concrete must center on minimizing permeation through proportioning methods and suitable construction procedures to ensure that the exposure conditions do not cause ingress of moisture and other agents responsible for deterioration.

The parameter to be controlled for achieving the required performance criteria could be any of w/c ratio, strength, densification of cement paste, elimination of bleeding homogeneity of the mix, particle size distribution, dispersion of cement in the fresh mix, stronger transition zone, low free lime content and very little free water in hardened concrete.

2.2.4 Comparison between the microstructure of high performance concrete (HPC) and nominal strength concrete (NSC) or conventional concrete:

The microstructure of concrete can be described in three aspects, namely

- Composition of hydrated cement paste,

- Pore structure

- Interfacial transition zone.

The hydrated cement paste is nothing but the hydration products which are formed when cement reacts with water. The pore structure refers to the gel pores, capillary pores and voids, as well as their connections within the hardened concrete. The interfacial transition zone refers to the boundaries between the cement paste and aggregates or particles of admixtures. The composition of NSC is relatively simple,
which consists of cement, aggregate and water. Fig 2.3 shows the microstructure of NSC.

![Microstructure of NSC](image)

**Fig.2.3 Microstructure of NSC**

The product for hydration of cement and water is (C-S-H) gel. The C-S-H gel dominates the hydrated cement paste of Normal Strength Concrete (NSC). The gel pores, capillary pores and voids increases the porosity in concrete. Hence, C-S-H is having a limiting strength and lower density phase but it is space filling. The concrete which is having a compressive strength below 50MPa. The increase of strength in concrete is mainly achieved by way of reducing the capillary porosity. In order to generate the strength in concrete above 50MPa, gel porosity should also be reduced in addition to the capillary porosity. The substantial reduction in the total porosity of concrete can be achieved by reducing the gel porosity and capillary porosity. The gel porosity further reduced by way of chemical reaction. There chemistry is to convert C-S-H to more crystalline phases, which leads to the production of High Performance Concrete [6]. The total porosity of the cement paste matrix has a great effect on strength of concrete. The pore structure and its connectivity have a significant impact on permeability. A high permeability concretes obviously have low durability. The concrete which has high permeability leads to chemical attack by surrounding
chemicals. However, the concrete which has high permeability gets high early strength using suitable curing process because of continuous hydration process carried out with the permissible flow of water within the pore network. The porosity and the pore connectivity of Normal Strength Concrete (NSC) are usually higher than that of High Performance Concrete (HPC) due to the absence of fine particles (see Figure 2.4).

The zone of cement paste in concrete which is adjacent to the surface of embedded components, like aggregates and steel fibres, has a modified structure when compared to C-S-H gel. This is known as interfacial transition zone. This interfacial zone is about 2-3mm wide on average. This zone is characterized by a higher porosity than the bulk paste matrix because of poor packing of cement particles adjacent to the embedment surface. The interfacial transition zone of higher porosity is subjected to accumulation of water leading to a locally higher water-cement ratio in these regions. Therefore, the interfacial transition zone in Normal Strength Concrete may be weaker than other regions in the concrete system. The permeability of the bulk material adversely affect the various interfacial transition zones with prolonged moisture curing, the interfacial transition zone may gradually be filled up with hydration products. The bonding between the paste and the embedded materials may be
improved with this process. However, the strength of the interfacial transition zone is still the lowest after moisture curing. As a result, the interfacial transition zone in normal strength concrete leads to bond cracking along the boundaries of aggregates under external loading.

In order to improve the performance in concrete, the following three aspects are considered:

- The hydrated cement paste should be strengthened,
- The porosity in concrete should be reduced,
- The interfacial transition zone should be made toughen.

The above three aspects are evaluated as follows.

Firstly, in order to strength the hydrated cement paste, the gel porosity inside the paste is to be reduced. As explained previously, the crystalline of C-S-H gel has a lower gel porosity when compare to amorphous C-S-H gel. A crystalline C-S-H gel can be achieved with addition of suitable admixture.

Secondly, the reduction of porosity in concrete can be achieved by adding suitable fine admixture which can fill up the empty space inside concrete. In High Performance Concrete, the fine admixture, such as Metakaolin or silica fume, is added to reduce the empty space inside concrete significantly. Meanwhile, the pore connectivity is lowered because the capillary network is filled by very fine particles as shown in Figure 2.4.

Thirdly, the interfacial transition zone can be toughened by reducing the water-cement ratio and by improving the particle packing in this zone. In order to achieve very low water cement ratio, the super plasticizer is added into the concrete.
Fine admixtures, like Metakaolin is added as well to improve the particle packing in the interfacial transition zone. It is observed that in order to improve the performance of concrete, admixture is a necessary component to be added into the design mix to achieve the HPC. Hence, the microstructure of HPC is quite different from that of NSC. The microstructure of HPC is shown in Figure 2.5. The most important admixtures are mentioned here. They are super plasticizer, Metakaolin and silica fume.

![Microstructure of HPC](image)

**Fig. 2.5 Microstructure of HPC Young [6]**

### 2.2.5 Factors influencing High Performance Concrete:

High Performance Concrete should give better performance when compared to normal strength concrete. The following are the three important features of High Performance Concrete (HPC).

- Strength,
- Ductility
- Durability.

#### 2.2.5.1 Strength:

The compressive strength plays a major role out of the various strengths of concrete. The concrete of compressive strength less than 50MPa is regarded as Normal Strength Concrete (NSC), while concrete possessing the compressive strength
about 50 MPa regarded as high strength concrete (HSC). Recently, concrete with the compressive strength of more than 200MPa has been achieved [1,2]. The concretes which give a compressive strength more than 200MPa is defined as ultra-high strength concrete. As the compressive strength of concrete has been steadily increasing with ample experimental validation, the commercial potential of high strength concrete became evident for columns of tall buildings in 1970s in the U.S. [8]. In general, the addition of admixture does not improve the concrete strength only. Usually, other aspects of performance, like ductility and durability, are also enhanced. Hence, the characteristics of HSC are very similar to those of HPC.

HSC is considerably more brittle than NSC. Meanwhile, HSC has a larger Young’s modulus than NSC and the post-peak softening branch is steeper. HSC behaves linearly up to a stress level which is about 90% of the peak stress, whereas lower strength concrete shows nearly no linear part at all. When the peak stress has been reached, the stress decays rapidly in high strength concrete. A qualitative comparison of uniaxial compressive stress-strain curve of HSC with that of NSC is given in Figure 2.6.

![Comparison of uniaxial compressive stress-strain curve of HSC with that of NSC](image)

**Fig. 2.6.** Comparison of uniaxial compressive stress-strain curve of HSC with that of NSC Van Geel, [141]
In reality, concrete is usually in a biaxial or triaxial stress state rather than under uniaxial compressive stress. In the following, the structural behavior of HSC under biaxial and triaxial stress states is discussed. Biaxial testing with brush loading platen has been reported by Hussein and Marzouk [7]. Three concrete grades have been tested with all the combinations of compression and tension in the two major axes. There are two important aspects that can be noticed in pure tensile or combined tension-compression loading. The tensile strength decreases with respect to the compressive strength with higher concrete grade and decay of compressive strength due to a simultaneous lateral tensile stress is large for high strength concrete. In the compression-compression regime, with a stress ratio of 1.0, NSC shows an increase of 20%, while the HSC only shows a 10% increase. This means again that a confining stress is less effective in HSC.

2.2.5.2 Ductility:

The high performance concrete is more brittle compared to normal strength concrete. The ductility can be improved by applying a confining pressure on high performance concrete. The ductility of HPC can also be improved by altering its composition through the addition of fibres in the design mix. The Concrete which has fibres inside is regarded as fibre reinforced concrete (FRC). The mechanical behavior of Fibre Reinforced Concrete can be divided into two categories by their tensile response. They are High performance FRC and conventional FRC. The conventional FRC which is made by the addition of fibres in Normal Strength Concrete only exhibits an increase in ductility compared with the plain matrix, but in case of High Performance FRC made by adding fibres in HPC exhibits adequate strain hardening type of response, with this there will be a large improvement in both strength and toughness when compared with the plain matrix. (see Fig. 2.7). Because of this
increase in ductility, high performance FRC is referred as an ultra-ductile concrete. In order to examine the scope of high performance FRC, it is required to identify two parameters which relate to performance a) elastic limit, and b) strain hardening response. The first one (i.e. elastic limit) refers to the point of first cracking and the second one (i.e. strain hardening response) refers to the plastic region.

![Fig.2.7. Comparison of plain matrix with FRC in Mechanical Behavior](image)

[Shao and Shah, 1997]

### 2.2.5.2.1 Elastic limit:

It was assumed that the elastic limit of Fibre Reinforced Concrete is influenced by the tensile strength of the plain matrix itself and then the fibres primarily control deformation after cracking. Recently, it was reported that the elastic limit can be enhanced with the addition of fibres provided that the addition of fibres should effectively bridge the micro cracks of the matrix. [8]. The effectiveness of the fibre-bridging action will depend on volume fraction, length, diameter, and distribution of fibres, as well as the properties of the fibre and matrix. It was found that the inherent tensile strength and strain capacity of the matrix itself was enhanced when small fibres were used [1]. When 4% (by volume) of carbon fibres were added, the first cracking, indicating the elastic limit, was observed at about 30% of the maximum tensile load [9].
2.2.5.2.2 Strain hardening:

Strain hardening occurs during the process of multiple cracking which occurs after the start of the first crack. In the post-peak region, the number of cracks remains constant while crack widths increase. Failure is obtained by way of fibre pullout and rupture of fibre. Uniform distribution of the fibres affects the stress distribution in the matrix and hence, higher stress is required to propagate the crack [10]. After the first crack starts, distributed multiple matrix cracking follows. The width of the cracks is usually between 1-3mm [9]. The multiple cracking process exhibits a ductile behavior which causes strain hardening phenomenon of the high performance FRC. To increase the elastic limit of high performance FRC and achieve strain hardening response, the volume content of the fibres should be increased as well. Meanwhile, the fibres should be closely spaced and well distributed [11,12,13]. However, it is difficult to mix such a high content of fibres in the matrix with conventional mixing methods. In practice, there are two commonly adopted processes to produce high performance FRC, namely, cast and extrusion processes. In the extrusion process a stiff mixture is forced through a die with desired shape. The effect of processing, cast and extrusion, has been studied using two different types of fibres by Shah [14]. It was reported that the Fibre Reinforced Concrete which was obtained from extrusion exhibits substantial strain hardening response, higher toughness, higher flexure and tensile strengths when compared to the concrete which was obtained by way of cast processing. Under the scanned electron microscope (SEM), it is found that extruded composite has longer fibres and the rougher fibre surfaces when compared with the cast composite. This shows that there is a stronger fibre matrix bond in the extruded composite. Meanwhile, it is known that the size of pores and amount of pores are significantly higher for the cast fibre reinforced concrete. It is concluded that the FRC gives the
better mechanical performance because of its strong fibre-matrix bond and the low porosity of the extruded. Dhir, et al [15] have studied the effect of fibre length on tension and flexural behavior of cast and extruded FRC and found that the decreasing fibre length significantly enhances the tension and flexure response of the extruded FRC. In general, short fibres are preferable during cast process because they are easy to handle during mixing and result in less broken fibres and better dispersion in the FRC. It was also found that the distribution of the smaller fibres in the extruded FRC cross-section was more homogeneous than that of larger fibre. In case of fibre reinforced high performance concretes also similar trends but of lesser extent was observed.

2.2.5.3 Durability:

One of the major factors for the deterioration of concrete is the attack from environmental factors such as sulphates and acids [16,17,18,19,20]. Meanwhile, failure of hydraulic cement concrete to perform effectively in aggressive environments during the anticipated service life has been attributed to the particulate orientations of the concrete, particularly the cement-sand matrix. Indeed, According to Navy [21], deterioration, long-term poor performance and inadequate resistance to hostile environment, coupled with greater demands for more sophisticated architectural form, led to accelerated research into the microstructure of cement matrix resulting into more elaborate codes and standards. Concrete matrix consists of pores and voids interconnected by channels or existing micro cracks, which are the main contribution to moisture permeability. In fact, one of the most impressive characteristics of polymer modification is its ability to resist the entry of water and aggressive agents, thereby improving its impermeability and consequently saving the concrete from undue attack. It is believed that the polymer film lining the capillary
pores and micro cracks does an excellent job in subsidizing the fluid flow in polymeric products [22].

Generally the durability of fibre reinforced composite depends on fibre type, mix design and conditions of service. A comparative study was carried out by Kosa et al. [23] on fibre reinforced mortar using accelerated test, in which specimens were in continuous exposure or intermittent drying and wetting in simulated sea water maintained at 20\(^0\) C and 80\(^0\) C from 2 to 10 months. Flexural tests showed that the fibre reinforced concretes have better overall durability. It may be concluded that the durability of FRC is better than that of conventional concrete. Numerous Studies have demonstrated that Polymer modified concretes or mortars perform well in terms of durability [23].

2.2.6 Strength Development: The Transformation of concrete from fresh state to hardened state takes place in the following three stages.

2.2.6.1. Fresh Stage: In this stage the concrete possesses plastic behavior. It is workable and capable of being moulded.

2.2.6.2. Transition Stage: In this stage, the workability of concrete reduces and the process of setting begins. The excess water evaporates along with heat evolution and its strength slowly develops.

2.2.6.3. Hardened Stage: This is the final stage of concrete in which it becomes stiff and gains enough strength to support a load. Therefore, it has sufficient load-carrying capacity as per design. In this process the 28 days strength is taken as the reference strength for hardened concrete.

The 28 day strength is chosen because this gives the 4 weeks time for assessing the strength of concrete. Most of the strength of normal concrete made with
standard ordinary Portland cement is developed. The strength development of concrete depends on its age, water cement (w/c) ratio, air content, cement type, aggregate type, paste aggregate bond, curing and environmental conditions in which it was made [22].

2.2.7 Admixtures:

IS: 1343–1980 allows using admixtures that conform to IS: 9103 - 1999, “Concrete Admixtures Specification”. The admixtures can be categorized into two.

(a) Chemical admixtures

(b) Mineral admixtures.

The common chemical admixtures are as follows.

1) Air-entraining admixtures

2) Water reducing admixtures

3) Set retarding admixtures

4) Set accelerating admixtures

5) Water reducing and set retarding admixtures

6) Water reducing and set accelerating admixtures.

The common mineral admixtures are as follows.

1) Fly ash

2) Ground granulated blast-furnace slag

3) Silica fumes

4) Rice husk ash

5) Metakaolin
2.2.8. Mineral admixtures:

With the advancement of technology and increase in fields of application of concrete and mortar, the strength, workability, durability and other characters of the matrix need modifications to make it more suitable for any situation. Added to this is necessity to combat the increasing cost and scarcity. Under these circumstances the use of mineral admixture is found to be an important alternative solution.

Admixture is defined as a material other than water, aggregate and cement that is added as an ingredient of concrete or mortar either immediately before or during the process of mixing to modify certain desired properties of the normal fresh or hardened concrete or mortar or the grout. The most common reasons for adding admixtures are to alter the workability, improve the rate of gain of strength, increase the strength itself, and improve the impermeability and durability and also to improve the appearance. Sometimes many admixtures affect more than one property of concrete.

Sometimes they affect the desirable properties adversely. An admixture should be employed only after and appropriate evaluation of its effects on the particular concrete under the conditions in which the concrete is intended to be used. Therefore one must be cautious in the selection of admixture and in prediction of the admixture effect in concrete.

Admixtures are classified mainly into 15 groups as follow according to the type of material constituting the admixture or characteristic effect of the use.

- Air entraining agents
- Accelerators
- Retarders
- Pozzolans
- Gas forming agents
- Air -detraining agents
- Alkali aggregate expansion inhibitors
- Damp proofing and permeability reducing agents
- Working agents
- Grouting agents
- Corrosion inhibiting agents
- Bonding agents
- Coloring agents
- Fungicidal, germicidal and insect cal agents
- Miscellaneous agents

Extensive research work both at national and international level has been carried out on the use of various admixtures in mortars and concretes with common goal as:

“To modify the properties of traditional concrete to the desired level this is suitable to the specific circumstances”.

2.2.8.1 Metakaolin:

Metakaolin is obtained by calcinations of pure or refined kaolinitic clay at a temperature between 650$^\circ$C, and 850$^\circ$C, followed by grinding to achieve a fineness of 700 to 900m$^2$/kg. The resulting material has high pozzolanic properties.
Metakaolin is manufactured from pure raw material to strict quality standards. It is not a by-product. Other pozzolanic materials are currently available, but many are by-products, which are available in chemical composition. They may also contain active components (such as sulphur compound, alkalis, carbon, reactive silica) which can undergo delayed reactions within the concrete and cause problems over long time periods.

When Metakaolin is blended with Portland cement it improves the durability of concrete and mortar. Metakaolin removes chemically reactive calcium hydroxide from the hardened cement paste. Metakaolin reduces the porosity of hardened concrete. Metakaolin densifies and reduces the thickness of the interfacial zone, thus improving the adhesion between the hardened cement paste and particles of sand or aggregate. High Reactivity Metakaolin (HRM) enhances the strength and durability of concrete to make concrete even more suitable for sustainable construction.

In General Calcium hydroxide produced by cement hydration decreases the durability of the concrete placed in an aggressive solutions and fibre reinforced cement composites. To overcome this drawback, Metakaolin will be added to cement. Oriol and Pera [24] studied about the pozzolonic properties of Metakaolin. The effect of microwave curing on lime composition in Metakaolin blended cements was investigated. Microwave curing has been applied successfully to fibre reinforced cement composites. They concluded that the pozzolonic reaction of metakaolin can be promoted by microwave heating. In the experimentation 30-40% replacement of cement by Metakaolin is adopted. But due to microwave heating the heat is generated quickly inside the cementitious materials, thermal acceleration of reaction is more efficient allowing reduction of Metakaolin to 15% instead of 30-40%.
Zhang and Malhotra [25] studied about the characteristics of thermally activated alumina silicate pozzolanic material (Metakaolin) and its use in concrete. In the case of Metakaolin, the change that is taking place is dehydroxylization, brought on by the application of heat over a defined period of time. Beyond the temperature of dehydroxylization, kaolinite retains two dimensional orders in the crystal structure and the product is termed “Metakaolin”. The key in producing metakaolin for use as a supplementary cementing material or pozzolan is to achieve as near to complete dehydroxylization as possible without overheating. Successful processing result in a disordered amorphous state, which is highly pozzolanic. Metakaolin confirms to class N pozzolana as per ASTM C 618. Class N refers to the raw or claimed natural pozzolans. Bureau of Indian standards have recommended the use of metakaolin in mortar and concrete as mineral admixture in IS: 456-2000.

Metakaolin is processed to remove non-reactive impurities, producing an almost 100 percent reactive pozzolana. Its particle size is significantly smaller than cement particles. The study shows that reactivity of Metakaolin with Portland cement is highest among all supplementary cementitious materials [25].

Khatib and wild [26] studied about the porosity and pore size distribution of OPC with Metakaolin paste. Experiments were conducted on pastes containing 0,5,10 and 15% Metakaolin at a constant water/binder ratio of 0.55. It was observed that the incorporation of Metakaolin in cement paste leads to refinement of the pore structure. The threshold value for the paste decreases as the Metakaolin content in the paste increases. The proportion of pores with radii smaller than 20mm is increased as the replacement level of cement by metakaolin increases. Total instructed pore volumes increases between the ages of 14 and 28 days for metakaolin paste.
Khatib and Wild [26] studied about the role of Metakaolin in enhancing the strength of concrete. Experiments were conducted on Metakaolin concretes [0-30%] with curing periods of 1 to 90 days. They observed that the three elementary factors, which influence the Metakaolin concrete, are filler effect, the acceleration of OPC hydration and the pozzolanic reaction of Metakaolin. The optimum replacement level of OPC by Metakaolin to give maximum long-term strength enhancement is reported as 20%.

2.2.8.1.1. Applications of Metakaolin:

Metakaolin has found application in

- High performance, High strength and light weight concretes.
- Precast concrete for architectural, Civil, Industrial and structural works
- Fibre cement and Ferro cement products, glass fibre reinforcement concrete
- Mortars, stuccos, repair material, pool plasters
- Shot Crete applications.
- Manufactured repetitive concrete products.

Metakaolin can be used in mortars and concrete for:

- Increased compressive & flexural strength
- Reduced permeability & efflorescence
- Increased resistance to chemical attack
- Reduced shrinkage, improved finishability, color and appearance
2.2.8.1.2 Metakaolin for specific concrete:

In a recent application in coastal belt, where soil has high sulphate and chloride contents, concrete of ternary blend has been proposed. The combination of Normal Portland cement is Ground Granular Blast Slag (GGBS) and Metakaolin has been used to impart both chloride and sulphate resistance to concrete. The use of Metakaolin allowed GGBS concrete to achieve enough initial strength. The ternary blend not only resulted in savings but also gave better durability to structures in the coastal area [27].

2.2.9. Raw materials and proportions:

Extensive research work both at national and international level has been carried out on the use of various admixtures in mortars and concretes with common goal as:

- To modify the properties of traditional concrete to the desired level suitable to the specific circumstances.
- To conserve the natural resources used in the production of construction materials.
- To bring down the increasing cost economics of cement, building blocks and high strength concretes.
- Of late, to rehabilitate the existing structures which are deteriorated over period of time.

2.2.10. Fibres:

Plain concrete has a low tensile strength, limited ductility and little resistance to cracking. Internal micro cracks are inherently present in the concrete and its poor
Tensile strength is due to the propagation of micro cracks which leads to brittle fracture of the concrete. Fibre a small piece of reinforcing material which has certain characteristic properties. It can be either circular or flat. Advanced cement based materials and advanced concrete construction techniques provide necessity to design the structures to resist severe loads resulting from earthquakes, impact, and fatigue and blast environments. The cracking nature is more in conventional concretes. When the concrete is reinforced with randomly dispersed fibres, favorable properties are obtained. Fibres prevent micro cracks from widening. The addition of fibres in the concrete makes the component ductile and tough. Previous researches concluded that the addition of fibres improves the static flexural strength, fatigue, ductility and fracture toughness of the material. Recent investigations have also given rise to highly reinforced SFRC containing up to 20% volume of steel fibres. The recent developments are due to the incorporation of additives such as super plasticizers and micro silica’s which allow the use of high volume of steel fibres.

The durability of the concrete when reinforced with conventional rebar is a major concern in aggressive environments. Many efforts are made in the recent investigations to develop alternatives to conventional rebar. Fibre reinforced plastics and fibre reinforced concrete with different types of fibres have shown better results because of their inherent ability to stop and delay crack propagation. Reinforcing fibres stretch more than concrete under loading. The following are the types of fibre reinforcing materials used in the concretes.

2.2.10.1 Types of fibres:

There are several fibre types in the market to address various design requirements and constraints. In this section each of the most commonly used fibre
types is discussed, giving information on the manufacture of the fibre, its properties, fibre content in applications and effects of the fibre type on concretes and mortar.

A. Glass

B. Steel

C. Synthetic fibres
   
   a. Acrylic
   
   b. Aramid
   
   c. Carbon
   
   d. Nylon
   
   e. Polyester
   
   f. Polyethylene
   
   g. Polypropylene

D. Fabric and composite fibre reinforcement

E. Natural fibres
   
   a. Unprocessed natural fibres
   
   b. Processed natural fibres
2.2.10.2 Steel fibres:

The percentage of fibres in concrete mix is based on volume and is expressed as a percentage of volume of mix. The percentages of fibres commonly used vary from 1% to 2%. The main properties of fibre Reinforced Concrete in tension, compression, and shear are influenced by the type of fibre, volume fraction of fibres, aspect ratio and the orientation of fibre in the concrete matrix. The properties of steel fibres with random orientation are the commonly used fibres in the civil engineering applications. Although every type of fibres are suitable in cement and concrete not all of them can be effectively and economically used. Each type of fibre has its own characteristic properties and limitations.

Steel fibres have been used in concrete since the early 1900s. The early fibres were round and smooth and the wire was cut or chopped to the required lengths. The use of straight, smooth fibres has largely disappeared and modern fibres have either rough surfaces, hooked ends or are crimped or undulated through their length. The
crimped type of steel fibres are shown in Fig. 2.8. Modern commercially available steel fibres are manufactured from drawn steel wire, from slit sheet steel or by the melt-extraction process which produces fibres that have a crescent-shaped cross section. Typically steel fibres have equivalent diameters (based on cross sectional area) of from 0.15 mm to 2 mm and lengths from 7 to 75 mm. Aspect ratios generally range from 20 to 100. Some fibres are collated into bundles using water-soluble glue to facilitate handling and mixing. Steel fibres have high tensile strength (0.5 – 2GPa) and modulus of elasticity (200GPa), a ductile plastic stress-strain characteristic and low creep. The study carried out by Oh [28] indicates that ductility and ultimate resistance of flexural members are remarkably enhanced due to the addition of steel fibres. Also it was emphasized that the neglect of fibre contribution may considerably underestimate the flexural capacity of fibre reinforced concrete beams.

2.2.10.3 Aspect Ratio:

Aspect ratio is defined as the ratio between fibre length and its equivalent diameter, which is the diameter of a circle with an area equal to the cross-sectional area of the fibre. Normally the aspect ratios range from 30 to 150. Steel fibre is the most commonly used fibre in the concrete and generally round fibres are used in the concretes and its diameter varies from 0.25mm to 0.75 mm. Mixing of fibre reinforced concrete needs careful conditions to avoid balling of fibres and segregation.

2.2.10.4 Different type of steel fibres:

1. Round steel fibres are produced by cutting or chopping wires

2. Flat steel fibres are produced by shearing sheets or flattering wire.

3. Crimped and deformed steel fibres have also been produced.
2.2.10.5 Basic properties of fibre reinforced concrete:

The behavior of concrete in tension and compression with the fibres has better results in comparison with the normal concrete. The most significant effect of incorporating the fibres is to delay and control the tensile cracking of this composite material. Fibres provide a ductile member in a brittle matrix which results the composites behave ductile in nature. The fibre and matrix share the tensile load until the matrix cracks and then almost the full force gets transferred to the fibre. This is a predominant feature of fibre reinforced concrete (FRC). Several studies on the tensile strength of fibrous composite have been reported in Mangat [29]. The effect of fibres in a cementitious material is principally to cause relief of tensile stress at the crack tip and prevent unstable crack propagation. Kelly [30] investigated the mechanism of fibre pull-out.

In case of compression, the increase in the compressive strength of fibre-reinforced concrete is marginal and ranges from 0% to 20%. The post cracking compressive stress-strain response changes substantially. This change is generally characterized by a noticeable increase in strain at peak load and a significant increase in ductility beyond ultimate load, resulting in substantially higher toughness. The improvements in ductility and energy absorption capacity resulting from the increase in fibre volume fraction are comparable to those improvements due to the effect of confining steel of conventional concrete. The characteristic model of fibre reinforced concrete consists of ascending and descending branches similar to confined concrete.

2.2.11 Steel fibre Reinforced High Performance Concrete (SFRHPC):

Concrete is the most widely used construction material in the world. The cracks in the concrete occurs for the various reasons. The reason of suffering concrete
from cracking may be attributed to structural, environmental or economic factors, but majority of the cases of cracking due to the inherent weakness of the material to resist tensile forces. Concrete again crack when it shrinks. In order to overcome the problem of cracking and shrinking in concrete, a well established steel fibre reinforcement offer a solution by making concrete tougher and more ductile. An extensive research and field trials carried out over the past three decades has proved. Th addition of steel fibres in to conventional plain or reinforced and pre stressed concrete members at the time of mixing production, imparts improvements to several properties of concrete, particularly concretes related to strength, performance and durability.

The concrete when it reinforced with steel fibres, the weak matrix in concrete get distributed uniformly across its entire mass, thereby the concrete strengthens enormously, which leads to rendering the matrix to behave as a composite material with properties significantly different from conventional concrete.

The orientation of fibres also imparts reducing the cracking nature of concrete. The randomly-oriented steel fibres control the propagation of micro-cracks present in the matrix in two ways. Firstly by improving the overall cracking resistance of matrix itself, secondly by bridging across even smaller cracks formed after the application of load on the member, which preventing their widening into major cracks. The Fig 2.9 shows the failure mechanism of cracks in concrete.
The idea that concrete can be strengthened with fibre inclusion was first put forward by Porter in 1910, but little progress was made in its development till 1963, when Roumaldi and Batson carried out extensive laboratory investigations and published their classical paper on the subject. Since then, there has been a great increase in applications of SFRHPC in many parts of the world. While steel fibres improve the compressive strength of concrete only marginally by about 10 to 30%, significant improvement is achieved in several other properties of concrete. Some Popular shapes of fibres are presented in Fig 2.10, 2.11 & 2.12.
Figure 2.11 (a) Dramix steel fibres.

Figure 2.11 (b) Trinity Steel Fibres.

Figure 2.11 (c) Hooked steel fibres.
In general, Steel Fibre Reinforced High Performance Concrete (SFRHPC) is very ductile and particularly well suited for structures which are required to exhibit the following properties.

(a) Resistance to impact, blast and shock loads and high fatigue

(b) Shrinkage control of concrete (fissuration)

(c) Very high flexural, shear and tensile strength

(d) Resistance to splitting/spilling, erosion and abrasion
(e) High thermal/temperature resistance

(f) Resistance to seismic hazards.

The degree of improvement gained in any specific property exhibited by Steel Fibre Reinforced Concrete is dependent on a number of factors which includes,

- Concrete mix and its age
- Steel fibre content
- Fibre shape, its aspect ratio and bond characteristics.

The efficiency of steel fibres depends on fibre content, fibre strength, aspect ratio and bonding efficiency of the fibres in the concrete matrix. The efficiency of concrete further improved by deforming the fibres and by way of advanced production techniques also. Any improvement in the mechanical bond ensures that the failure of a SFRC specimen is due mainly to fibres reaching their ultimate strength, and not due to their pull-out [31].

2.2.12 Mix Design for SFRC:

Various types of fibres possess different characteristics. The concrete made with steel fibres will also have different properties. While developing a Steel Fibre Reinforced Concrete (SFRC) mix design, two aspects must be considered. They are fibre type and the application of the concrete. The quantity of mortar fraction in the concrete should be sufficient in order to adhere to the fibres and allow them to flow without tangling together. This phenomenon called ‘balling of fibres’. In case of Steel Fibre Reinforced Concretes, the Cement content is usually higher than conventional mixes. Aggregate shape and content is critical. In SFRC mixes coarse aggregates of sizes ranging from 10 mm to 20 mm are commonly used. As the size of aggregate increases the volume of fibre reduces per cubic meter. Steel fibre reinforced concrete
with 10 mm maximum size aggregates typically uses 50 to 75 kg of fibres per cubic meter; where as the use of aggregate with 20 mm size requires 40 to 60 kg. It has been demonstrated that the workability and material properties have significant effect on shape of coarse aggregate also. Crushed coarse aggregates result in higher strength and tensile strain capacity. Fine aggregates in SFRC mixes typically constitute about 45 to 55 percent of the total aggregate content.

Typical mix proportions adopted in SFRC mix will be 325 to 560 kg of Cement, w/c ratio of 0.4-0.6; ratio of fine aggregate to total aggregate 0.5-1.0; maximum aggregate size 10mm; air content 6-9%; fibre content 0.5-2.5% by volume of concrete. An appropriate admixture may be used to replace a portion of the Ordinary Portland cement to improve workability further, and reduce heat of hydration and production cost, [32, 33, 34, 35, 36].

The slump can generally be reduced about 50 mm by using the steel fibres in concrete when slump reduces, the workability reduces. To overcome this and to improve workability, it is strictly recommended to include super plasticizer in the mix. This is especially true for SFRC used for high performance applications. Generally, the ACI Committee Report [34] Guide for Specifying, Mixing, Placing and Finishing Steel fibre Reinforced Concrete’ is followed for the design of SFRC mixes appropriate to specific applications.

**2.2.13 Factors Controlling SFRC:**

- Aspect ratio, l/d
- Volume fraction, VF
- Fibre reinforcing index, RI=l/d x VF
- Critical length, l min
• Balling of fibres

• Good mix design: more matrix, small aggregate, workable

• Type of fibres-size, shape, strength, modulus

2.2.14 Polymers in concrete:

Polymers or epoxies are used for imparting certain special properties to concrete. These polymers have been used for the reasons of improving the strength and durability of hardened concrete, to improve chemical resistance and impermeability of hardened concrete, to modify the flow characteristics of fresh concrete and to improve the bond characteristics between old and new concrete for repair work. The cost of polymers varies considerably, but for approximate calculations it can be assumed that the polymers cost 20 times to that of the ordinary cement. Some of the popular polymers are Urethanes, Acrylics, Styrene butadiene resin (SBR), Vinyl and Epoxies. The urethanes polymer and co polymers produced by the reaction of isocyanides with polios. Polymers can be used in the concretes as polymer impregnated concrete, polymer concrete, polymer-modified concrete mortar, polymer protective coating, and polymer as bonding agent. These are the artificial polymers and the rubber latex which is drawn from the natural rubber tree can also be used as a polymer in the concrete.

2.2.15 Latex:

The latex modified concrete is defined as Portland cement and aggregate combined at the time of mixing with organic polymers that are dispersed in water. This dispersion is called Latex.
The organic polymer is a substance composed of thousands of simple molecules known as monomars. The reaction that combines the monomars is called polymerization.

2.2.15.1 Principles of Latex Modification:

When latex is used in mixes with portland cement, aggregates, and water, fresh concrete is produced with consistency and workability characteristics only slightly different from conventional concrete.

After curing, the latex-modified concrete (LMC) consists of hydrated cement and aggregate, all interconnected by a continuous film of latex. This continuous film imparts the superior physical and chemical properties to latex-modified concrete [37]. Some indication of how latex systems function to modify the internal structure of cement paste and concrete has been provided by Ohama [38]. Ohama divided the internal responses into three distinct stages, as follows.

In the first stage, on mixing the concrete, the small spherical polymer latex particles (ca. 0.2 um in size) are uniformly mixed into the fresh cement paste. The small polymer particles are considered to partially coat the surfaces of the cement grains and perhaps the early hydration products as well.

In the second stage recognized by Ohama, [38] the progress of cement hydration reduces the remaining water content; in consequence the still Deposited polymer particles flocculate to form close packed layers on available surfaces.

In the third stage, with further depletion of water by continued cement hydration, the close-packed layers of polymer particles condense to form continuous films or membranes. These seem not to be confined to surfaces, but interpenetrate
throughout the cement hydration products. Thus the fine cement paste matrix of ordinary concrete is transformed to a cement-polymer film matrix.

The details of these processes, and the length of time required for the various stages to occur remain speculative. No mention is made by Ohama of the effect of the latex on the important "transition zone" surrounding the aggregates in concrete or mortar.

2.2.15.2 Important Properties of Latexes:

The following polymeric properties are usually tested to ensure quality control.

1. Total solids or non-volatile content:

   This is the polymer content of latex along with any ingredient of latex which is non-volatile at test temperature. This is simple to determine by weighing a representative sample of latex, drying it under specific condition at $70^0 \text{C}$ for 16 hours or $125^0 \text{C}$ for 0.5 hours and weighing the residue and expressing as a percentage of original weight (Total solid content)

2. pH value:

   The value indicates whether material is acidic (pH=1-6) or alkaline (8-14). This is a logarithmic scale and an increment of 1 indicates 10 fold increase in acidic or alkaline content.

3. Coagulum

   This is quality of polymers retained on ASTM series 100,200 or 325. The test is a measure of quantity of polymer that has particles larger than intended.
4. Viscosity

This is internal resistance to flow exhibited by a fluid. There are several methods for its determinations however a viscometer made by Brookfield (ASTM 1417) is generally used.

2.2.16 Natural Rubber Latex:

Concrete is one of the mostly used materials in construction field all over the world. However, in cement production process, release of CO₂ contributes to air pollution. So, concrete industry has considered using recycle industrial by-products as concrete additives in order to reduce demand for cement and use more sustainable construction material. One of the additives that have been tried in recent years is polymer. The idea of using polymers in cement-based materials dates back to early 1920s when the first patents on using natural rubber polymer-modified cementitious systems were issued [38]. The first patent on the use of synthetic rubber latexes in such application was issued in 1932 [38]. Since then many products, patents, and applications have been developed. In North America, latex-modified concrete (LMC) was used as a bridge overlay in Michigan as early as 1958. In Ontario, the first major application of LMC was a 1980 overlay on collector lanes of Highway 401 in North York. Polymer-modified mortar and concrete are prepared by mixing either a polymer or monomer in a dispersed, powdery, or liquid form with fresh cement mortar and concrete mixtures, and subsequently curing, and if necessary, the monomer contained in the mortar or concrete is polymerized in situ. Besides that, the optimum quantity of the polymer additive that should be added into the concrete mix would also be determined.
Natural rubber, also known as India rubber is a mixture of organic compound Polyisoprene and small amounts of other organic compounds as well as water. This polymer is the main component. This material is classified as an elastomer (an elastic polymer). It is derived from latex, a milky colloid produced by some plants. The plants are ‘tapped’, that is, an incision made into the bark of the tree and the sticky, milk colored latex sap collected and refined into a usable rubber. Polyisoprene can also be produced synthetically. Natural rubber is used extensively in many applications and products, as is synthetic rubber. It is normally very stretchy and flexible and extremely waterproof.

The commercial source of natural rubber latex is the Para rubber tree (Heveabrasiliensis), a member of the spurge family, Euphorbiaceous. This species is widely used because it responds to wounding by producing more latex. In order to make the concrete durable the Latexes are used. South America remained the main source of limited amounts of rubber latex which is used in the 19th century in 1879. In India Commercial cultivation of natural rubber latex has been introduced by...
British planters. The first Commercial Hevea plantations in India were established at Thattekadu in Kerala in 1902. But the commercial scale of growing rubber in India was first started at Botanical Gardens in Calcutta.

The two important solvents for rubber are turpentine and naphtha (petroleum). The turpentine is being used since 1764 when Francis Fresno made the discovery. Because rubber does not dissolve easily, this material is divided by shredding before immersion. The Natural rubber which is drawn from the tapping of tree in the rubber cultivation sites gets coagulated. In order to avoid the coagulation of raw latex when it is transported from its cultivation sites to the required work site an ammonia solution of minimum quantity can be used.

Walters [39,40] reported that latex modified cement mortars and concretes are attractive because the latex addition substantially increases the flexural strength and the compressive strength. On the other hand Hahne [41] said that fibre-reinforced mortars and concretes are attractive because the fibre addition substantially increases the flexural toughness and in some cases it increases the flexural strength as well it is therefore appropriate to combine these two methods.

In concretes a little attention was given to natural rubber latex, though it has numerous outstanding qualities when compared with its counterpart. For example according to John Kendo and Bradley [42], Natural Rubber Latex has superior qualities over other elastomeric latexes especially in the areas of high performance applications that require excellent mechanical characteristics such as high tensile strength and resilience as well as abrasion resistance. Introduction of latex system in mortar and concrete, the use of the latex hydraulic cement system was introduced in the beginning of the 20th century [43]
Since the late 1940s, latex-modified mortars and concretes have been used in various applications, such as bridge pavings, floorings, anti-corrosive adhesives and deck coverings for ships. Sevens [44,45] conducted feasibility studies on the applications of natural rubber modified systems. Their work succeeded in generating a strong interest on the use of synthetic-latexes in the latex-modified systems.

Ohama [46,47] has studied extensively the properties and proportioning of polymer modified mortars. Polymer dispersions are added to mortars and concrete to improve certain desired properties of the final product including improved bond strength to concrete substrates, increased flexibility (ductility) impact resistance, improved resistance to penetration by water, dissolved salts and improved resistance to frost action was reported by Amdur [48]. Although latex as a protectant has a long history of usage dating back to the 1800s, due to its complex mechanical and chemical properties, latex is considered to have the best broad range of desirable properties. Despite significant development of synthetic rubber latex (SRL), natural rubber latex (NRL) consumption reached 1.08 million tons in 2004 and continues to increase [49]. The market share for dipped products in this consumption is 65%. The primary considerations for this preference are economical and technical.

The price of oil (main raw material for SRL) has increased significantly. Furthermore, the properties of NRL are superior when compared to SRL (for example, stability against environment. The microstructure of mortar and concrete is of considerable importance since it governs their mechanical properties, cement hydration and durability [49,50]. In addition, chloride permeability is recognized as a critical intrinsic property affecting the durability of reinforced concrete [51].

The use of polymer as a modifier in new structures seems to be a promising strategy in improving microstructure and enhancing the durability of cement mortar
and concrete. As one of the popular polymers suitable for admixing into fresh mortar and concrete [52,53] styrene–butadiene rubber (SBR) latex has been widely used for a long time [52,53,54]. The molecular structure of SBR comprises the flexible and the rigid styrene chains, offering characteristics such as good mechanical properties, water tightness and abrasion resistance [48,55]. The incorporation of SBR improved the chloride penetration resistance along with the general ionic permeability of the mortar, while increasing its ionic transport resistance and decreasing its electric capacitance. These data suggest that admixing SBR led to denser and more refined microstructure of the cured cement mortar. Field-emission scanning electron microscopy images confirmed such improvements in the pore structure and the formation of an interpenetrating network structure of SBR and cement hydrate phases at relatively higher P/C ratios. Besides slightly reducing Portlandite content and mitigating carbonation with the increasing P/C ratio in mortar, SBR was also found to promote the formation of calcium aluminatethiosulfate hydrate phases and facilitated chloride binding. Polymer latexes are being increasingly used in civil engineering applications as modifiers, especially for the purpose of improving workability, drying shrinkage, strengths characteristics and durability properties of cement products [49,50]. Natural Rubber Latex as a dispersion of poly-isoprene is naturally polymerized by Hevea brasiliensis tree [51].

Most of its properties are therefore determined during the process of natural polymerization rather than controlled as normally is the case with emulsion polymerization. In its fresh state, NRL comprises of 30–40% rubber particles suspended in a serum together with non-rubber substances such as proteins, volatile fatty acids, sludge and some inorganic material [56]. However, the non-rubber components are in minor quantities amounting to about 6% only [52]. Water is
present as a medium of dispersion and this forms the major component. Even though, the first patent with the present concept of polymer latex-modified systems published by Lefebvre in 1924, and subsequent patents throughout 1920s and 1930s used NRL as the modifier, its continuous application was overshadowed by the advent of synthetic latexes [57]. Compositional instability especially coagulation and presence of non-rubber substances are the major factors believed to be responsible for reluctance in its continuous utilization [53]. Non-rubber substances are still found in NR latexes. It is feared that strength developments in concrete could be affected by the presence of these non-hydrocarbon substances. Honeycutt [53] reported strength depreciations associated with concrete modified with NRL.

2.2.16.1 Chemical composition of Rubber Latex:

The molecular weight of Natural Rubber latex is 1,00,000 to 10,00,000. In Natural rubber we found a small quantity of (up to 5% of dry mass) proteins, resins, acids and inorganic materials. Natural rubber is an elastomer and a thermoplastic. However once the rubber is vulcanized, it turns into a thermo set. Most of the rubber which is being used in regular practice shares properties of both elastomer and thermo plaster if it is heated and cooled. It is degraded but not destroyed. The elastic behavior is caused by bond distortions when force is applied.

2.2.16.2 Cultivation of Rubber:

Rubber is cultivated in large plantations in the state of Kerala in India. Rubber latex is extracted from rubber trees. The economic life period of rubber trees in plantations is around 32 years out of which the immature period is 7 years and productive period is 25 years. The soil requirement for the plantation of rubber is well drained weathered soil consisting of laterite. The climatic condition for optimum
growth of rubber trees consist of rain fall of around 250 cm evenly distributed without any marked dry season and with at least 100 rainy days per year. The temperature ranges from 20 degrees to 34 degrees centigrade with a monthly mean of 25 degrees centigrade to 28 degrees centigrade. There should not be strong winds because of more height of rubber trees, due to strong winds there is ever possibility of collapse of trees.

2.2.16.3 Collection of Rubber Latex:

Figure 2.14 (a): Latex being collected from a tapped rubber tree

Fig 2.14 (b): Process of harvesting rubber by tapping the Rubber Tree.

When Rubber is harvesting a tree is tapped and the milky fluid rubber collected by using coconut shell in the state of Kerala in India where coconuts are in abundance
The half shell of coconut is used as the collection container for the latex. But in places of cultivation other than in Kerala glazed pottery or aluminum or plastic cups are more commonly used material for collection of rubber. The cups are supported by a wire that is tied to the tree. This wire incorporates a spring so that it can stretch as the tree grows. Tapping normally takes place early in the morning, when there is a high internal pressure of trees. The trees tapped usually alternative days or third daily. The latex collected from the trees will drip for about four hours, stopping as latex coagulates naturally on the tapping cut, thus blocking of the latex tubes in the bark. A little quantity of ammonia is added to avoid coagulation. The range of different constituents present in Natural Rubber are presented in Table 2.2

**Table 2.2 Constituents of Natural Rubber**

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>55-70</td>
</tr>
<tr>
<td>Rubber</td>
<td>30-40</td>
</tr>
<tr>
<td>Resins</td>
<td>1.5-2.0</td>
</tr>
<tr>
<td>Protein</td>
<td>1.5-3.0</td>
</tr>
<tr>
<td>Ash</td>
<td>0.5-1.0</td>
</tr>
<tr>
<td>Sugar</td>
<td>1.0-2.0</td>
</tr>
</tbody>
</table>

2.3 Behavior of HPC in Fresh state:

2.3.1 Introduction:

The behavior of High Performance Concrete in fresh state is not substantially different from conventional concrete. While many High Performance Concretes exhibit rapid stiffening and early gaining of strength. Where as others may have long set times and low early strength. Since setting time and slump loss are not necessarily
related, the specifics of each mix must be analyzed individually. The Workability of High performance concrete is normally better than conventional concrete which is produced from the same raw materials of same proportions. Super workable concretes can be used in case of works having difficulty in placements of concrete due to problem in internal vibration. Curing of High performance concretes are same as conventional concretes. Many HPC’s with good early strength characteristics may be less sensitive to curing.

However, the high performance concrete of high volume of cementitious material and low bleeding characteristics, particularly when combined with rapid slump loss, contribute to various characteristics which must be anticipated. In some cases it is very difficult to attain hard troweled surfaces. Plastic shrinkage problems may be exacerbated. The pumping of High performance concretes are typically easy. But in case of breakdowns in pump operations may cause more inconvenience and problematic. In order to overcome this kind of problems, an adequate planning is required at the time of pumping operations.

2.3.2 Workability:

The workability of High Performance Concrete is normally good, even at low slumps High Performance Concretes pumps very well, due to the presence of more quantile of cementitious material and particularly due to the addition of chemical admixtures. High Range Water Reducers (HRWR) reviewed pumping operations and concrete mixtures used to successfully pump concrete on the 79 storied structures of South Wacker Tower in Chicago. The proper planning is required in pumping of any concrete, including many of the High Strength Concretes. Multiple pumps should be arranged during the time of pumping operations so that if one pump breaks down, concreting can be done with the alternative pumps without any interruption Many
High Strength Concretes are good for pumping. But it is difficult to restart pumping, once the movement of the concrete and vibration of the pump have stopped due to the thixotropic behavior of these mixes. Contingency plans should therefore also address the issues of line clean-out and disposal of waste concrete. Again, detailed pre-construction and pre-pour meetings are very important.

The influence of internal vibration on air contents was investigated by Simon et al [58]. They concluded that at the point of insertion, the air content was dramatically changed but that away from the vibrator. Where as in case of High Performance Concretes this property of concrete has not been investigated in any depth. However, due to the increase in consistency this concrete should behave as well or better. Cursory examination of cores from C-205 HPC field placement in North Carolina using a bridge deck type of slip form paver with significant internal vibration showed no dramatic difference between cores and standard cylinders.

High strength concretes have a tendency of rapid slump loss and extended set times, with which it is difficult to attain hard, smooth, hand troweled finishes. It is very difficult to judge the time required to begin troweling operations. As moisture evaporates from the surface without being replaced, the surface will stiffen and appear ready for troweling. The troweling on such concrete which are not achieved true strength may produce irregularities on the surface in addition to trowel marks. In addition, the slab must be adequately protected against plastic shrinkage during this time, otherwise the development of severe plastic shrinkage cracks occurred. This is, of course, not a problem for most formed members.

High Performance Concretes have the ability to fill heavily reinforced sections without internal or external vibration, without segregation and without developing large sized voids. These mixtures are intended to be self-leveling. The rate of flow in
High performance Concretes is an important factor in determining the rate of production and placement schedule. It is also a useful tool in assessing the quality of the mixture. The workability is normally not difficult to attain in case of flowing concretes.

2.3.2.1 Workability of fibre reinforced concrete:

The ASTM C 125-93 has defined workability as the property determining the effort required to manipulate a freshly mixed quantity of concrete with minimum loss of homogeneity. In essence workability is defined as the ease of placement with resistance to segregation. The definition of workability given in ACI 116R-90 is “The property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated and finished”.

Therefore the workability of concrete is associated with terms such as flowability, mobility, stability, resistance in segregation and pumpability. Each of these terms has a specific meaning but all of them are related to workability. Workability is necessary to compact to the maximum possibly density. We can express the strength of partially compacted concrete compared to that of fully compacted concrete in terms of the strength ratio “R strength”.

$$R_{strength} = \frac{F_{ck\text{ of partially compacted concrete}}}{F_{ck\text{ of fully compacted concrete}}}$$

Similarly it can be expressed as the density of partially compacted concrete compared to the density of fully compacted concrete, in the terms of density ratio.

The properties of NRLMFRHPC are different from that of the conventional concrete. Many HPCs exhibits rapid stiffening and early strength gain, whereas other concretes may have long setting time and low early strength. The workability of the High performance concrete is better than the conventional concrete although the
ingredients used are same. Zain et al. [59,60,61] presented a study on the properties of freshly mixed high performance concrete. The workability of high performance concrete is observed in terms of V-funnel flow than slump flow. Chang and Peng [62] presented the influence of mixing techniques on the properties of high performance concrete.

2.3.3 Setting Time:

The Setting time of High Performance Concrete depends on the application and the presence of set modifying admixtures and paste composed of Portland cement. Concretes produced for applications of early strength requirements such as road works etc., and concretes containing retarders such as High Range Water Reducers (HRWR) can lead to mixtures with rapid slump loss and reduced working time. This is particularly true in warmer construction periods and when the concrete temperature has been kept high to promote rapid strength gain.

Field trials using HPC intended for early strength applications in bridge decks or other transportation structures were conducted by SHRP C-205 and C-206. The concrete was easy to place, as long as the ready-mixed concrete trucks had adequate mixing capacity. The concrete was also easy to finish with bull float or highway straightedge, even though it was somewhat sticky. The early strength development of these mixes was enhanced by keeping the temperature near the maximum permitted by most specifications and then insulating the slabs after placement, this clearly also reduced setting times.

The use of large quantities of High Range Water Reducers (HRWR) or other water reducing admixtures can significantly delays setting times and therefore reduce very early strengths even though strengths at more than 24 hours may be relatively
high. Dosage has to be monitored closely with mixtures containing substantial quantities of mineral admixtures so as not to overdose the portland cement if adding the chemical admixture on the basis of total cementitious material. The use of non-chloride accelerating admixtures was employed in mixtures tested by SHRP C-205 investigators to offset the retarding effects of the minimal dosages of melamine HRWR used [63,64,65]. Extended set times are of value when using HPC which does not require very early strength, especially when transit and discharge times exceed about 30 minutes. This is easily attained through the use of retarding admixtures.

2.3.4 Curing:

Since the last State-of-the-Art Report on HPC, A significant additional work has been carried out on early age characteristics and on curing requirements or sensitivity of low water-cement ratio concretes by using various admixtures. Samurai et al [66], examined the effect of temperature, relative humidity and curing in hot climates on High Strength Concrete (HSC) properties. They report that the compressive strength of HSC in the aspect of sensitive to temperature and relative humidity is less when compared to conventional strength concrete. However, tensile strength of High Strength Concrete was found to be more sensitive. Swami and Bouikni [67] report that concrete require long moist curing time when it contains very large quantities of ground granulated blast furnace slag (GGBFS) to develop adequate strength and also it is more sensitive to drying than plain portland cement concretes.

Mak and Lu [68] investigated High Performance Concrete which contained Ground Granular Blast Furnace Slag (GGBFS) under low standard curing conditions, including the effects of temperature rise due to heat of hydration. They found that the compressive strength of concrete significantly reduced due to lack of moist curing. In such cases as much as 50% or more of the Portland cement had been replaced by
GGBFS. But if the replacement of the cement is 30% by GGBS, they did not have a significant effect. However, they also observed that the heat of hydration in such high GGBFS mixes reduced, with the associated reduction in micro cracking, appeared to offset the extra sensitivity of the mixes to moist curing so that the results were comparable up to 91 days.

The higher initial curing temperatures associated with HPC with high cement contents require that slabs and pavements be sawed earlier than usual to prevent cracking. Cracks which form in the first 24 hours after placement have occasionally been mislabeled as shrinkage cracks. At these ages the concrete is too young to have undergone any significant drying shrinkage.

The internal temperatures observed high in case of high early strength HPC. As the concrete gets cool these concretes create a relatively large temperature change. The concrete which is to be placed during the day and intended to early release of traffic conditions, the temperature drop associated with a drop in the rate of reaction can coincide with cooling temperatures as evening approaches. As the concrete tries to contract, restraint by the base course creates tensile stresses.

A rapid strength gain in concrete is accompanied by a consequent gain in elastic modulus, although typically at a slightly slower rate. Higher stresses in concrete developed due to the large temperature change occurring with a stiffer concrete and it can cause more pronounced cracking than with conventional concrete pavements unless relieved by sawing. These cracks will develop irrespective of the method of curing, due to stress caused by temperature gradients. But these cracks can be controlled with the proper insulation of pavement on the surface until sawed.
The addition of large dosages of retarding admixture into concrete, the problem of cracing can be controlled. Although retarders, including extended set high range water reducers, delay setting and, typically, the onset of strength gain, increase in the temperature rise compared to non-retarded mixtures is common.

In case of concrete slabs having 200 mm thickness, the increase in early strength associated with higher temperatures was not found any problem by the SHRP C-205 research team using concretes with high cement factors [69,70]. Burg and Ost [71,72] provide additional information on the effects of temperature rise on mechanical properties of HSC in large sections. They concluded that the temperature rise is not a significant problem for members where High Strength Concrete is appropriate. Sanvik and Gjorv [73] also the concluded the same for lightweight HSC. Detwiler et al and Dhir et al [74,75] found that the use of admixture like Metakaolin, fly ash in the concrete mixture also improved the resistance to chloride ion penetration of concrete at elevated temperatures. Metakaolin and Silica fume were also reported to improve the resistance. Marzouk and Hussein [76] reported on HPC properties at low temperatures. As expected, the temperature influences the gain of strength as temperature drops, the strength gain also. In this aspect the High Performance Concrete did not differ from conventional concrete.

Early strength gain for transportation applications under field conditions has been reported by Schemmel et al.; Leming et al; and Whiting et al. [77,70,78]. The results of these field trials indicate that it is possible to reliably produce concretes which attain compressive strengths of 14 MPa at 4 hours up to 35 MPa at 24 hours, depending on mix composition, under summer and fall placing conditions.
2.3.5 Testing:

There are no specific established tests available to measure the workability, resistance to segregation, self-leveling capability and filling capacity of super-workable concretes. However, substantial research has been conducted in this area. Super-workable concrete mixtures are self-leveling, making the slump test inappropriate. In case of slump cone test the reduction in height of the settled concrete is measured. Whereas the test methods used by Kuroiwa et al. [79] to determine the workability of super-workable concrete include the conventional slump cone test and apart from slump cone test, the increase in the diameter of the concrete base, or "slump flow" is measured rather than the reduction in height of the settled concrete, for comparison. A measure of the rheological characteristics based on the rate of increase in diameter during the slump test, termed "flow speed". This flow speed is also used for comparison. This is determined as the time, in seconds, required for the base diameter to exceed 50 cm Kuroiwa et al. [79]. Workability may also be gauged by time of flow through a funnel, similar to standard grout flow cone tests, adapted for use with concrete.

The test conducted to determine the resistance to segregation and resistance to self-compaction simultaneously, termed "filling capacity", involved allowing concrete to flow down through one branch of a U-shaped tube, under a very slight pressure, and back up the other branch, past a mat of reinforcing bars. The filling capacity of the mixture is measured with the height to which the concrete rose. Other tests include the use of mock-ups. Investigation may include examination of cores for indications of segregation. The high workable concretes give Poor filling capacity due to segregation of the paste and aggregate. Filling capacity was found to be reasonably well correlated with the behavior of the concrete in the funnel test, in that concretes
which segregated blocked the outlet of the funnel with aggregate, resulting in a longer flow-out time. This phenomenon is, of course, familiar to anyone who has tried to pump concrete which was too "wet" through several elbows.

Considerable research was reported in the previous State-of-the-Art Report on the effects of different testing parameters of High Strength Concretes. An additional research in this area has been provided by Carino [80], who concluded that cylinder size, cylinder end preparation, load rate, and testing machine capacity all had significant effects and all had significant interactions. Lessard et al. [81] also report on the effects of testing methodologies for HSC. While the magnitude of the effects varies from researcher to researcher, the primary conclusions have not. The small cylinder have greater average measured strength compare to large cylinders., stiffer machines typically provide higher measured strength and grinding ends is strongly recommended for HSC above at least 90 to 100 MPa.

The in-situ properties of High Performance Concrete, particularly strength and permeability, have been reported. Haque et al. [82], discussed the estimation of in situ strength of low, medium and high strength concretes compared to standard cylinders. They found that in situ strengths were 80% to 85% of cylinder strengths.

The Air permeability test developed is to provide a relatively quick measure of the permeability of concrete, particularly in-situ, have increased in popularity. However, the sensitivity of the test to the moisture content of the concrete has limited its utilization due to concerns over interpretation of data. Concrete absorption tests, such as the Initial Surface Absorption Test, or ISAT, have also been used to characterize concrete permeability with some success. The low absorption of mature, low W/C ratio concretes has reduced the use of this test on HPC. However, it appears well suited to lab studies, especially of deteriorated concrete.
The main application of this existing testing methodology was to the determination of early strength of High Performance Concrete. Accurate determination of in-situ strength is essential to ensure that the pavement can be safely opened for release of traffic. Testing of concrete is purely based on maturity concepts or using match cure systems to estimate the in-situ strength of concrete was conducted in several early-to-open HPC pavements.

Both SHRP C-205 and SHRP C-206 successfully used conventional maturity methods to determine the strength of concrete in-situ on several pavements constructed with HPC. SHRP C-206 used a match cure system. This system keeps the cylinders at the same temperature as the concrete in the pavement so that the compressive strength of the cylinder could be used to estimate the in-situ strength. SHRP C-205 used a simpler, more cost effective system of keeping the test cylinders insulated until testing. This method was found to keep the cylinders at approximately the same temperature as the pavement so that the measured strength of the insulated cylinders provided a reasonable estimate of the in-situ strength.

SHRP C-206 also investigated the use of pulse velocity in estimating the in-situ strength of the pavements. Small access holes were left in the pavement to permit the use of conventional test apparatus. Another SHRP C-206 development was determination of the water content of concrete by microwave. However, this procedure proved highly variable.

The nuclear density gauges to the pavement construction industry for decades has been developed by Troxler, Inc.. Another water cement ratio gauge has been recently developed by Troxler, Inc., This apparatus quite suitable for assessing both the water and cement content of mixes accurately as batched. This product is still undergoing modifications and adjustments, but a substantial testing program was
recently completed by the Highway Innovative Technology Evaluation Center (HITEC). This HITEC was established by the Federal Highway Administration and the American Association of State Highway and Transportation Officials. Preliminary evidence [HITEC 1996] suggests that the Troxler Model 4430 water-cement gauge can effectively estimate water and cement contents, when properly calibrated, within about 3.56 kg/m³ for water and 11.87 kg/m³ for cement, in approximately 10 minutes. Although at this time a separate and extensive calibration is required for each different concrete mix to be tested, additional work in this area is continuing. This device appears to provide a significant improvement in quality testing of concrete as delivered.

2.3.6 Latex-Modified Concrete:

The dispersion of organic polymer particles in water is termed as Latex. Most lattices are milky fluids that are generally white to off-white in color. The following are the lattices used with hydraulic Cements.

1. Polyvinyl acetate;

2. Acrylic copolymers;

3. Styrene acrylic copolymers;

4. Vinyl acetate acrylic copolymers;

5. Vinyl acetate ethylene copolymers;

6. Vinlyidene chloride and vinyl chloride copolymers;

7. Styrene butadiene copolymers;

8. Epoxy resin latex.
Among all the above latexes, styrene butadiene copolymer latexes are used in far greater amounts than any other types of above latexes. Ohama [39] listed four typical formulations. All contain about 53% water by weight. About 44% of the total weight is in the form of the latex particles.

2.3.7 Properties of Fresh Latex-Modified Concrete (LMC):

The addition of latex generally improves the properties of fresh concrete. The very small (about 0.2 mm in diameter) spherical polymer particles that make up the latex may act much as entrained air bubbles to improve the workability and decrease the bleeding of paste. The surface active agents included in most formulations also tend to disperse the paste. Usually they also entrain considerable amounts of air. Latex-modified concretes used on bridge deck overlays are almost universally mixed and placed using "concrete mobile" traveling mixers. The overall effect of the addition of latex allows a significant reduction in the water: cement (w: c) ratio of the concrete [83]. A workable slump (4 to 6 inches) can be achieved at a w: c ratio of 0.40 or less, including the water in the latex [84]. There is very little published experimental data on the effects of latex on the physical properties of fresh concrete. Nevertheless, there also are no reports known to the author of this thesis that mention workability of latex modified concrete as a problem.

The results of a study on setting time of latex-modified concrete indicate that latex-modified concrete did not set any faster than concrete without latex [85]. However it does form a "crust" or relatively dry layer on the surface if exposed to dry air for prolonged period, even though the concrete underneath is still quite plastic, where the concrete is mixed only briefly as it passes through an auger arrangement and deposited rapidly on the overlay site. Wallace [86] indicated that in such field
applications there is only about 10 minutes to finish latex-modified concrete after depositing it on the deck.

It has been found that LMC responds badly to extend curing under wet conditions. In consequence, in the usual procedures for laboratory studies of LMC, the concrete is de moulded after 1 day, but instead of further wet or fog-room curing, it is subsequently "air-cured"; that is, the concrete is merely exposed to the less-than-100% relative humidity of the laboratory air.

2.4 Behavior of Hardened Concrete:

The behavior of hardened concrete can be categorized in to short-term (essentially instantaneous) and long-term properties.

1. Short-term properties (essentially instantaneous): It includes strength in compression, Tension, Bond, and Modulus of Elasticity.

2. Long-Term Properties: these properties include Creep, Shrinkage, and Behavior under fatigue, and durability characteristics such as porosity, permeability, freeze-thaw resistance, and abrasion resistance.

2.4.1 Strength of concrete:

The determination of compressive strength has received a large amount of attention because the concrete is primarily meant to withstand the compressive stresses. Cubes, cylinders and prisms are the three types of specimens used to determine the compressive strength of the concrete. Testing conditions such as age, rate of loading, method of testing and specimen geometry are significantly influence the measured strength. The strength of saturated specimens can be 15 to 20 percent lower than that of dry specimens. In this research work cubes of 150mmx150mmx150mm and cylinders of 150mm Diameter and 300mm Height are
The Specimens are cast, cured and tested as per standards prescribed for such tests. The properties of constituent materials which affect the strength are the quality of fine and coarse aggregate, the cement paste and the paste–aggregate bond characteristics.

The information on the behavior of very early strength (VES) concrete and high early strength (HES) concrete is limited, whereas sufficient information on the behavior of high strength concrete exists and additional information is being developed rapidly. Since high performance concretes will have low water-cement ratios and high paste contents, their characteristics will in many cases be similar to those of high strength concrete.

A specific difference in behavior of early strength and the high strength concretes is with the relationship of compressive strength to other mechanical properties. Typically, strength gain in compression shall be faster than the strength gain in aggregate-paste bond, which leads to relative differences in elastic modulus and tensile strength of early strength concretes and high strength concretes, expressed as a function of compressive strength. The relation of 28-days’ compressive strength and mechanical properties of High strength concrete cannot be expected necessarily to apply to Very Early Strength (VES) and High Strength Concrete (HES) concretes.

The strength of concrete depends on the 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 of concrete are the quality of fine and coarse aggregate, the cement paste and the paste-aggregate bond characteristics (properties of the interfacial, or transition, zone). The
strength in turn, depends on the macro- and microscopic structural features including total porosity, pore size and shape, pore distribution and morphology of the hydration products and the bond between individual solid components.

2.4.1.1 Constituent Materials and Mix Proportions:

Concrete composition limits the ultimate strength that can be obtained and significantly affects the levels of strength attained at early ages. Two dominant constituent materials that are considered to control maximum concrete strength are coarse aggregate and paste characteristics.

2.4.1.1.1 Coarse Aggregate:

The shape, texture and the maximum size are the important parameters of coarse aggregate since the aggregate is generally stronger than the paste, its strength is not a major factor for normal strength concrete, or for High Early Strength and Very Early Strength concretes. In case of higher-strength concrete or lightweight aggregate concrete the aggregate strength plays an important role. The 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 may also affect the modulus of elasticity; 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.

A. Influence of Aggregate Type: The Influence of different types of coarse aggregate on concrete strength has been explained in various articles. Sarkar and Aitcin [87] conducted detailed petro logical, petro graphical and mineralogical
characterization of twelve different coarse aggregates that have performed with variable success in very high strength concrete in Canada and the United States. They pointed out that the intrinsic strength of coarse aggregate is not an important factor if water-cement ratio (W/C) 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 W/C of 0.20 to 0.30. For such concretes, aggregates can assume the weaker role and fail in the form of trans granular fractures on the failure surface. It was concluded that the minerals must be strong, unaltered, and fine grained in order to be suitable for very high strength concrete. Intra- and intergranular 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.

B. Influence of maximum size of aggregates: The use of larger maximum size of aggregate leads to higher strength this was due to the fact that the larger the aggregate the lower is the total surface area and therefore, the lower is the requirement of water for the given workability. Because of this reason a lower water/cement ratio can be used which will result in higher strength, 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. However later it was found that the use of large size aggregate did not contribute to higher strength as expected from the theoretical considerations due to the reasons that the larger maximum size aggregate gives lower surface area for developments of gel bonds which is responsible for the lower strength of the concrete. Secondly bigger aggregate size causes a more heterogeneity in the concrete which will prevent the uniform distribution of load when stressed. Therefore,
it is the general consensus that smaller size aggregates should be used to produce higher strength concrete.

The influence of size of coarse aggregate on concrete strength was investigated by Cook [88] who used limestone of two different sizes: 10 mm and 25 mm super plasticizer was used in all the mixes. In general, the smallest size of the coarse aggregate produced the highest strength for a given water cement ratio. However the compressive strengths in excess of 69 MPa is possible by using a 25 mm maximum size aggregate when the mixture was properly proportioned with a high-range water-reducing admixture.

In a similar study by Larrard and Belloc [89] using crushed limestone aggregates, portland cement, silica fume, and superplasticizer for eight different concrete mixtures, it was shown that better performances and economy could be achieved with 20 to 25 mm maximum size aggregates even though previous researchers had suggested that 10 to 12 mm is the maximum size of aggregates preferable for making high-strength concrete.

2.4.1.1.2 Paste Characteristics:

It is generally accepted that the most important parameter affecting concrete strength is the water cement ratio, sometimes called as the W/B (binder) ratio. Even though the strength of concrete is dependent largely on the capillary porosity or gel/space ratio, these are not easy quantities to measure or predict. The capillary porosity of a properly compacted concrete is determined by the w/c ratio and degree of hydration. The w/c ratios used to produce most high performance concrete are 0.40 or less. The practical use of very low w/c ratio concretes has been made possible by
use of both conventional and high-range water reducers. These water reducers permit production of workable concrete with very low water contents [90,91,92].

**A. Influence of Mineral Admixture:** Metakaolin, Fly ash, slag and silica fume have been used widely as supplementary cementitious materials in high performance concrete. Metakaolin is a factory made product, whereas Fly ash, slag and silica fume are the waste products produced in the factories like thermal plants etc.

High-reactivity Metakaolin (HRM) is a more recently developed supplementary cementitious material. It is high reactive pozzolanic material formed by claiming purified kaolinite at a specific temperature change. Metakaolin improves most mechanical and durability properties of concrete. Chemically, HRM combines with calcium hydroxide to form calcium silicate and calcium aluminate hydrates. Properties of concrete incorporating Metakaolin are comparable and sometimes better than Steel Fibre concretes. It has been shown that HRM in powder form is a quality-enhancing mineral admixture that exhibits enhanced engineering properties comparable to silica fume slurry [93]. Hence it is proposed to use Metakaolin as a mineral admixture in this investigation.

**B. Influence of Chemical Admixtures:** The performance of chemical admixtures is influenced by the particular cement and other cementitious materials. Combinations which have been shown to be effective in many cases may not work in all situations, due to adverse cement and admixture interaction. Substantial testing should be conducted with any new combination of cements, and mineral or chemical admixtures prior to large scale use for compatibility.

Baalbaki and Aitcin [94] conducted a research program to study the compatibility between three air-entraining agents, four water reducers, and one
polynaphthalene sulphonated super plasticizer. Tests conducted on twelve different combinations of admixtures cement showed that the addition of super plasticizer nearly always increased the air content without changing the bubble spacing. The only exception was when the air content of the concrete was lower than 4.5 % after 70 minutes of batching. In that case, the total air content decreased after the introduction of the super plasticizer and the spacing factor increased significantly. The tests were duplicated with another type of cement and the results were not significantly different from the first set of test results.

2.4.1.2 Strength Development and Curing Temperature:

The strength development with time is a function of the constituent materials and curing techniques. An adequate amount of moisture is necessary to ensure that hydration is sufficient to reduce the porosity to a level necessary to attain the desired strength. Although cement paste in practice will never completely hydrate, the aim of curing is to ensure sufficient hydration. In pastes with lower w/c ratios, self-desiccation can occur during hydration and thus prevent further hydration unless water is supplied externally [91].

2.4.1.3 Compressive Strength:

Compression test is the most common test conducted on hardened concrete because it is an easy test to perform. The most of the desirable characteristic properties of concrete are quantitatively related to its compressive strength. The properties of Concrete like Tensile strength, Flexural Strength, Shear strength, Elastic modulus, stress-strain relationship and Bond strength are usually expressed in terms of uniaxial compressive strength of 150 x 300 mm cylinders, moist cured to 28 days. Compressive strength is the common basis for design for most of the structures, other
than pavements, and even then is the common method of routine quality testing. The terms "strength" and "compressive strength" are used virtually interchangeably. Maximum, practically achievable, compressive strengths have increased steadily over the years.

The variables for testing have considerable effect on the measured compressive strength. Mould type, specimen size, end conditions, and rate of loading are the major testing variables. The sensitivity of measured compressive strength to testing variables varies compressive strength.

Since the compressive strength of Very Early Strength; and High Early Strength are at conventional levels, conventional testing procedures can be used for the most part, although curing during the first several hours can affect test results dramatically. Testing of Very High Strength (VHS) concretes is much more demanding. However, in all concretes, competent testing is critical especially for high performance concrete.

2.4.1.3.1 Influence of Testing Variables:

An extensive study is carried out to investigate the influence of testing variables on the measured strength of HSC cylinders by Carino et al. [95]. The variables included cylinder size (100 versus 150 mm diameter), type of testing machine (1.33-MN capacity versus 4.45-MN capacity), end preparation (sulfur capping versus grinding) and nominal stress rate. For each run two levels of strength (45 and 90 MPa) and three replicates were tested. Specific gravities were measured to check on the consistency of cylinder fabrication. The ends of all cylindrical test specimens that are not plane within 0.05mm are capped. Statistical analyses indicated that all the factors had significant effects on the measured compressive strength. On
average, the 100 mm cylinders resulted in about 1.3% greater strength, the faster stress rate produced about 2.6% greater strength, the ground cylinders were 2.1% stronger, and the 1.33-MN testing machine produced about 2.3% greater strength. There were significant interactions among the factors, so that the effects were greater than the average values for particular factor setting. For example, the effect of end preparation depended on the strength level. For 45-MPa concrete, there was no strength difference due to the method of end preparation, but for the 90-MPa concrete, grinding resulted in as much as 6% greater strength in certain cases. Analysis of dispersion indicated that the 100-mm cylinders had higher within-tests variability, but the differences were not statistically significant. Based on the results, recommendations were made for modifications to testing standards with respect to the loading rate, the capping method, the test cylinder size, and the required time for removal of molds.

2.4.1.3.2 Influence of Mold Type:

The influence of mold type on strength was reported by Carrasquillo et al., [96]. The use of 150 x 300 mm plastic molds gave lower strengths than steel molds and use of 100 x 200 mm plastic molds gave negligible difference with steel molds. In the report of French and Mokhtarzadeh [97] also indicated that the compressive strength of heavy gauge cylinders cast in 150 x 300 mm. Reusable steel molds were 2.5% higher than that of cylinders cast in flexible single-use plastic molds. The height of the mould and the distance between the opposite faces are of the specified size +_0.2mm. The angle between the adjacent internal faces top and bottom planes of the moulds is required to be 90 degrees+_0.5 degrees. The interior faces of the mould are plane surfaces with a permissible variation of 0.03mm. It appeared that as long as the manual rodding method was used to consolidate the concrete, the effect of mold type
on the compressive strength of concrete was insignificant. Carrasquillo et al. [98] recommended that steel molds should be used for concrete with compressive strengths up to 103 MPa. For higher strength concrete, it seems logical that steel molds should only be used.

2.4.1.3.3 Influence of Specimen Size:

The size of the specimen also influences the compressive strength. Many studies have been conducted to investigate the influence of specimen size on the compressive strength [69,95,97,99,100,101]. Comparisons were usually made between the compressive strength of 100 x 200 mm cylinders and that of 150 x 300 mm cylinders. Generally, the cylinder of size 100 x 200 mm cylinders exhibit higher strengths when compared to the cylinders of size 150 x 300 mm. The difference may vary from 2 to 10% but in case of higher strength concretes this difference is lower. Burg and Ost [71] reported that, the strength of 100 x 200 mm cylinders was within 1% of the strength of 150 x 300 mm cylinders. Whereas the report given by Carrasquillo et al. [98] is contradiction to the earlier report which showed that the compressive strength of 100 x 200 mm cylinders was approximately 7% lower than 150 x 300 mm cylinders.

2.4.1.3.4 Strength of Concrete Core:

A study by Cook [88] for concrete with strength of 69 MPa showed the relationship between the compressive strength of 150 x 300 mm cylinders and cores from a column. It was concluded that the 85% criterion specified in the ACI Building Code (ACI 318-89) [102] would be applicable to high strength concrete. The study also confirmed that job cured specimens did not provide accurate measurements of the in-place strength. The reason for lower core strength in the middle portion of the
columns was attributed to temperature rise, i.e., 38°C for high strength mixtures. The relationship between 150 x 300 mm cylinders, 100 x 200 mm cylinders and drilled cores has been evaluated by Miller [103]. The results indicated that the strengths obtained from drilled cores influenced greatly by three factors, their tested orientation relative to that in the structure; the elevation of the core in the structure; and the type of pre-test conditioning. A comparison of the core and cylinder compressive strengths indicated that the acceptance criteria of the ACI Building Code may have limited applicability at the higher strength levels. It was suggested that prior to core testing high strength concrete, the testing conditioning and acceptance criteria should be agreed upon in advance and be rigorously followed. Aitcin et al. [87] also tested the strength of 100 mm cores taken from a mock column at two and four years after casting and found that it was nearly identical to that of cube specimens cured for 28 days in lime–saturated water at room temperature. The strength of the concrete tested was 85 MPa.

In an evaluation of engineering properties of six commercially available high-strength concrete mixes in the range of 69 to 138 MPa. Burg and Ost [71] reported that the core strength tested at 91 days and 14 months was slightly lower than the strength of corresponding insulated cylinders and all but one concrete mix exceeded 85% of the specified design strength of the concrete. They further reported that no significant strength difference was found between cores taken from near the surface and the center of large-sized cubes. This is in contrast to the findings of Cook [88].

An extensive study on compressive strength of concrete cores was made by by examining and statistically analyzing hundreds of core test data. They found that the core strengths were greatly influenced by the variations of four critical factors: (1) the core sizes (50 or 100 mm diameter); (2) the length-to-diameter ratio of the core (l/d);
(3) the moisture condition (moisture content and moisture gradient) of the core; and
(4) the damage sustained during drilling of the core.

2.4.1.3.5 Influence of End Condition:

The preparation of the end conditions (cappings) of the concrete is applicable to cylindrical specimen. The ends of all cylindrical test specimens that are not plane within 0.05 mm are capped. The capped surfaces are not departed from a plane by more than 0.05 mm and shall be neatly at right angles to the axis of the specimens. The planeness of the cap is required to be checked by means of straight edge and feeler gauge, making a minimum of three measurements on different diameters. Caps are made by thin as practicable and care should be taken so that flaw or fracture does not take place. When the specimen is tested capping can be done on completion of casting or a few hours prior to testing of specimen. Cylinder capping can significantly affect the measured compressive strength. Generally speaking, the standard sulfur mortar capping is suitable for concrete strength up to about 52 MPa. There are different procedures adopted for higher strength concrete to prepare the end conditions of cylinders for compressive testing. One procedure is the parallel grinding of the ends of the cylinder, in which the need of end cap is eliminated while grinding is regarded as the best procedure, it entails expensive equipment and longer preparation time so that it is not practical for field applications. Another procedure is the use of a unbounded cap consisting of a restraining cap and an elastomeric pad as insert. The unbounded cap system is far more cost-effective and can be easily equipped by any laboratory and used in the field. A previous study showed that for concrete strengths between 28 and 69 MPa, the use of polyurethane inserts with aluminum restraining caps produced average test results within 5% of those obtained using sulfur mortar caps [104]. For concrete strengths below 76 MPa, the use of
neoprene inserts with steel restraining caps yielded average test results within 3% of those obtained using sulfur mortar caps.

2.4.1.3.6 Influence of Loading Rate:

It is known that the measured compressive strength of concrete increases with increasing rate of loading. Many studies have been conducted over the past seven decades, covering a wide range of strength of concrete (17.4 to 60.4 MPa), strain rate (10^-6/s to 10/s), size of specimen and shape of specimen (cylinder, cube, and prism), curing and testing conditions (wet and dry), and loading mechanism (electro hydraulic servo system, pressure-activated piston system, ballistic pendulum and drop hammer apparatus).

An excellent review of the literature has been prepared by Fu et al., [105] and the following conclusions have been made.

1. Both compressive strength and stiffness increase with increasing strain rates.

2. Increasing the rate of strain has not resulted in consistent increase or decrease in ultimate strain and strain at maximum stress. The degree of change depends on the constitutive model used as much as on the strain rate itself.

3. Higher strain rates appear to have a more profound effect on low to moderate strength concrete than on high-strength concrete.

4. Wet concrete is relatively more sensitive to a change in loading rate than dry concrete.

5. The failure of concrete at very high strain rates can be explosive.

6. Slope of the descending branch in the stress–strain diagram increases with increasing rate of straining.
Review by Fu et al., [105] also presented four different dynamic constitutive models to represent a complete stress–strain curve for plain and reinforced concrete under compression. It should be noted that the proposed models have been based on axial compression and the effect of strain gradient has not been accounted for [106] had pointed out that strain gradient due to eccentric compression may lead to an increase in the strain at failure and a decrease in strength. Virtually no information is available on the effect of loading rate for concrete with strengths in excess of 69 MPa.

2.4.1.3.7 Influence of Temperature:

In case of normal temperatures the strength properties of concrete are not affected. However the behavior of concrete may be substantially different under the extreme temperature conditions. Castillo and Durrani [107] reported a study on the influence of transient high temperature on the strength and load-deformation behavior of high-strength concrete. The concrete strength ranged from 31.1 to 89 MPa and the temperature exposure was in the range of 23 to 800°C. Before exposure to elevated temperature, the test specimens were preloaded to simulate the presence of loads in real structures. It was observed that the compressive strength of high-strength concrete decreased by 15 to 20% when exposed to temperatures in the range of 100 to 300°C with temperatures in the range of 300°C to 800°C, the compressive strength of concrete decreased to about 30% of its strength at room temperature.

The influence of exposure to low temperature on the mechanical properties of high-strength concrete containing silica fume and fly ash was reported by Marzouk and Hussein [108]. Test cylinders were exposed to cold ocean water with temperature varying from -10 to 20°C after the cylinders being cured for only 24 hours. The low rate of maturity was attributed to slow hydration process due to low temperature,
which caused the rate of evolution of calcium hydroxide to decrease and the secondary pozzolanic reaction to stop.

Lee et al. [109] also conducted studies on the basic mechanical properties of concrete under low temperature in the range of -70 to 20°C. Their results indicated that the compressive strength increased as the temperature decreased and the rate of increase for high-strength concrete at different low temperatures was generally lower than that for normal strength concrete.

2.4.1.4 Tensile Strength:

It governs the cracking behavior and influences other properties such as stiffness, damping action, bond to embedded steel, and durability of concrete. It is also of importance with regard to the behavior of concrete under shear loads. There are two tests conducted to determine the tensile strength. They are direct tensile strength and indirect tensile strength such as flexural or split cylinder tests.

2.4.1.4.1 Direct Tensile Strength:

The direct tensile strength is difficult to obtain. Due to the difficulty in testing, only limited and often conflicting data is available. The direct tensile strength of concrete is assumed about 10% of its compressive strength.

From the several previous studies using different specimen sizes and geometries, examining the effects of curing, loading rate, sustained and cyclic loadings as well as impact, has been given by Zia et al. [91]. It was concluded that the uniaxial tensile strength of concrete can be estimated by the expression $6.5f'_c$ and that data were not available for higher strength concrete with $f'_c$ greater than 55 MPa, where $f'_c$ is characteristic compressive strength of concrete.
In case of Tensile Strength of high strength concrete, very few involved direct
tensile testing. One such study was reported by Marzouk and Jiang [110] regarding
the effects of freezing and thawing on the tension properties of high-strength concrete.
Flat direct tension specimens of 20 x 75 x 300 mm, with sawed notches (11 mm in
depth and 3 mm in width) on both edges, were attached to a pair of special wedge-
type frictional grips and subjected to direct tension test in a closed-loop servo-
hydraulic universal test machine. An electromechanical extensometer (gage length of
25 mm) was used to control the loading. The direct tensile strength was found to be
4.2 and 3.4 percent of the compressive strength before freezing-thawing cycling and
after 700 cycles, respectively. The average value of cracking stain was found to be
115 mm before cycling and 65 after 700 cycles of freezing and thawing.

2.4.1.4.2 Indirect Tensile Strength:

The splitting Tensile strength (ASTM C 496) and the third-point flexural
loading test (ASTM C 78) are the most commonly used tests for estimating the
indirect tensile strength of concrete. Both the splitting tensile strength \( f_{ct} \) and the
flexural strength or modulus of rupture \( f_r \) are related to the compressive strength by
the following general expression:

\[
f_{ct,orfr} = k \sqrt{f'_c}
\]

Eqn 2.1

ACI Committee [111] has recommended that the coefficient should be taken
for concrete strength up to 83 MPa is 7.4 for and as 11.7 for. Other investigators
proposed the values which are differing slightly with these values. More details can be
found in [91].

The studies of SHRP [112-116] indicated that the recommendation of ACI
Committee 318 is equally acceptable as that of ACI Committee [117] for splitting
tensile strength. However, the recommendation of ACI [102] is a better representation than that of ACI Committee [117] for the flexural strength (modulus of rupture).

The investigation carried out by Burg and Ost [71] showed that the average values of modulus of rupture and splitting tensile strength when compared to compressive strength were similar to the recommendation of ACI Committee [117]. The moist cured specimens consistently produced higher strength than air cured specimens.

2.4.1.5 Bond:

The strength of the concrete is also influenced by shape and surface texture of aggregate, especially so for high strength concretes, flexural strength is more affected than compressive strength. A rougher texture gives more adhesion or bond between the particles and the cement matrix. Similarly the angular aggregates having larger surface area provides a greater bond. Bond strength is of two types one is bond strength of concrete to concrete and the other one is bond strength of concrete to reinforcing steel.

2.4.1.5.1 Bond Strength of Concrete to Concrete:

In many cases a new concrete has to be placed against existing concrete. The bond of concrete with the concrete occurs in many situations in the field of construction. The development of stress at the bonding surface will vary considerably depending on the type and the use of the structure. In case of Bridge deck overlay the bond may be subject to shear stress in conjunction with tensile or compressive stresses induced by shrinkage or thermal effects, in addition to compression and shear from service loads.
In addition to the binding material, bonding agents are often used to produce the bond that is as strong as the components being joined. In practice a wide variety of bonding agents used are, Epoxy resin, acrylic latex, styrene butadiene rubber (SBR) latex, copolymer polyvinyl acetate (PVA), and Portland cement mortar.

Several investigations made by describing the test methods and evaluating bonding materials were summarized by Zia et al. [91]. But no single method of test can replicate all in-service state of stresses in bond. Generally, there are three different methods to measure the interfacial bond strength between two concrete surfaces being joined [118]. They are slant shear test, direct shear test and direct tensile test. In case of slant shear test, the bonding plane is inclined at 30 degrees from the longitudinal or loading axis and it is subjected to normal compression and in-plane shear. The specimen used in this test either in the form of cylinder or rectangular prism, if failure occurs by shearing of the bonding plane. The bond strength is then obtained by the following relation.

\[
\text{Bond Strength} = \frac{\text{Maximum Load}}{\text{Area the shearing plane}}.
\]

For the direct shear test, there are three alternatives push-off test using a specimen of two L-shaped parts [119]. In all these three cases, the bond strength is determined by dividing the maximum shear load by the area of the shear plane.

The third one is the direct tensile test. In this test, the bond strength of the joint is actually measured by the tensile strength of the test specimen. The direct tensile test has been adapted to field application where a partially cored specimen is pulled in-place through a steel plate epoxied to the top of the core [118,120].
2.4.1.5.2 Bond strength between Steel and Concrete:

The ACI Building Code [102] has recommended for estimating the development length and anchorage of tensile steel are based on bond tests generally using concrete with compressive strength not greater than about 28 MPa. It is uncertain that these empirical equations for estimating the steel–concrete bond are applicable for higher strength concrete.

The bond strength between steel and concrete is obtained by using pull-out test. However, this test does not represent the stress conditions which exist in the concrete around the reinforcement in a flexural member. In order to overcome this drawback a flexural test is often used in which both the steel and the concrete are in tension.

Several researches indicated that higher rate of loading would cause more rapid deterioration of anchorage bond and that the bond characteristics of deformed bars were affected significantly by the age of concrete [91]. The research also concluded that the use of super plasticizer did not seem to affect the bond strength. Especially in the high compressive strength concretes, it "densifies" the interfacial zone between the steel and the concrete surrounded by steel [121].

Since 1990, several researches have been made to investigate specifically the bond strength of reinforcement in high strength concrete. De Larrard et al. [122] evaluated the bond strength between high strength concrete and reinforcing bars using the RILEM beam test. A high strength concrete with 28-day compressive strength of 95 MPa was used along with a normal strength concrete of 42 MPa as control. Three different sizes of deformed bars of diameters 10 mm, 16 mm, 25 mm and one smooth bar of diameter 25 mm were used. Based on the recommendations of several RILEM
tests, the bond (anchorage) length of 10 times bar diameter had to be reduced to 3
times to 2.5 times the bar diameter for high strength concrete to ensure bond failure
rather than yielding of reinforcement. The average bond strength along the bond
length was calculated corresponding to the free end slip of the bar at 10 and 100 mm.
It was concluded that the bond strength was more affected by the size of bar used. In
case of high strength concrete (as compared to normal strength concrete) the increase
in bond strength was approximately 80% for 10 mm deformed bars and 30% for 25
mm deformed bars. The improvement of bond is attributed to the increase in concrete
tensile strength and confinement due to both concrete shrinkage and transverse
reinforcement.

2.4.2 Deformation:

The deformation of concrete depends on short-term properties such as the
static and dynamic modulus, as well as strain capacity. It is also affected by time
dependent properties such as shrinkage and creep.

2.4.2.1 Static and Dynamic Elastic Modulus:

The modulus of elasticity is generally related to the compressive strength of
concrete. This relationship depends on the aggregate type, the mix proportions, curing
conditions, rate of loading and method of measurement. The measurement of static
modulus can be performed easily when compare to dynamic modulus because of more
information available on the static modulus than on the dynamic modulus. Since the
measurement of elastic modulus can be routinely performed whereas the measurement
of dynamic modulus is relatively more complex.
2.4.2.1.1 Static Modulus:

It is known that the elastic modulus of concrete increases with its compressive strength. The modulus is greatly affected by the properties of the coarse aggregate; the modulus of elasticity of concrete would be higher when the larger the amount of coarse aggregate with a high elastic modulus is used. The modulus also increases with concrete age. Regardless of the mix proportions or curing age, concrete specimens tested in wet conditions show about 15% higher elastic modulus than tested in dry conditions. This is attributed to the effect of drying of transition zone between the aggregate and the paste. As strain rate is increased, the measured modulus of elasticity increases.

The reports of previous researches presented in the past few years confirm the above fundamental understandings. The effect of aggregate type was considered by Baalbaki et al. and Giaccio et al. [123,124], the effect of curing conditions by Asselanis et al. and Cabrera and Claisse [126,127], and the size effect of test specimens by Baalbaki et al., [123]. The effect of cold temperature on the elastic modulus was investigated by Lee et al. [113] and their results indicated that the elastic modulus increased as the concrete is subjected to very low temperatures.

2.4.2.1.2 Dynamic Modulus:

As per the previous statements, much less information is available on the dynamic modulus than on the static modulus of High Performance Concrete (HPC). In the past few years, very little has been published in the literature. What has been summarized in the previous state-of-the-art report [91] still represent the current knowledge of the subject.
Generally speaking, the measurement of dynamic modulus corresponds to a very small instantaneous strain. For low, medium, and high strength concretes, the dynamic modulus is generally 40%, 30% and 20% respectively higher than the static modulus of elasticity [128]. Recently, Nilsen and Aitcin [129] used pulse velocity test to predict the static modulus of elasticity of high-strength concrete.

2.4.2.2 Strain Capacity:

The strain capacity of concrete can be measured either in compression or in tension. In case of compression it can be measured in two ways. Those are eccentric mode and concentric; mode of compression testing. In the tensile mode, the strain capacity can be either for direct tension or indirect tension.

2.4.2.2.1 Stress-Strain Behavior in Compression:

The stress-strain behavior is dependent on many parameters which include material variables such as aggregate type and testing variables such as age at testing, loading rate, strain gradient and others. Higher strength and corresponding strain are achieved for crushed aggregate from fine-grained dia base and limestone as compared to concretes made from smooth river gravel and from crushed granite that contained inclusions of a soft mineral.

Several studies have been made to obtain the complete stress-strain curves in compression with compressive strengths up to the range of 140 MPa. In case of High Strength Concrete (HSC) the shape of the curve ascending becomes more linear and steeper, the strain at maximum stress is slightly higher, and the slope of the descending part becomes steeper. This is true whether the aggregate is normal weight or lightweight.
In order to obtain the descending part of the stress-strain curve, the specimen-testing machine interaction must be avoided. One approach is to use a closed-loop testing system with a constant rate of axial strain as a feedback signal for closed-loop operation. Where as in case of very high strength concretes, the use of lateral strains as a feedback signal is necessary rather than the axial strains. Another method of testing the high strength concrete cylinders in parallel with two or more instrumented auxiliary high strength steel tubes as reported by Banthia and Sicard [130].

2.4.2.2.2 Stress-Strain characteristics of concrete in Tension:

It is difficult to test the concrete in direct tension, because of this; the direct tensile stress-strain curve is difficult to obtain due to the availability of limited and conflicting data. There is no developments found in the recent literature other than the studies made in the report [91].

2.4.2.2.3: Flexural Tension:

While the information on the stress-strain behavior in tension is severely limited, virtually no data is available regarding the strain capacity in flexural tension. In the SHRP C-205 studies, Zia et al., [114,115,116] developed a special mounting device which was utilized to measure the flexural strain capacity of HPC under flexural tension tests. As expected, there was a wide range of scatter of the test data, roughly varying from 120m to 200m with 150m being a reasonable average value. This remains an area for which research is sorely needed to provide a basis for design where flexural cracking is an important consideration.

2.4.2.3 Poisson’s Ratio:

It is determined under uniaxial loading conditions as the ratio of lateral to longitudinal strain in compression test and may vary from 0.11 and 0.21. This value is
slightly higher and is about 0.24 when the dynamic tests are performed in the inelastic range, due to volume dilation resulting from internal micro cracking, the apparent Poisson's ratio is not constant but is an increasing function of the axial strain.

In general, Poisson's ratio for normal weight and light weight concretes lies in the range of 0.15 to 0.2 when determined from strain measurements taken in the static modulus of elasticity tests (ASTM C496-87a and BS 1881: part 121:1983). In case of higher strength concrete in the elastic range appears comparable to the expected range of values (0.15 to 0.20) for lower-strength concrete. Slightly higher values (0.22) are given by ultrasonic tests. In the inelastic range, the relative increase in lateral strains is less for higher-strength concrete than for concrete of lower strength. That is, higher-strength concrete exhibits less volume dilation than lower-strength concrete. This implies less internal microcracking for concrete of higher strength.

2.4.2.4 Shrinkage and Creep:

Shrinkage and creep are time-dependent deformations that, along with cracking, provide the greatest concern for designers because of the degree of uncertainty associated with their prediction. Concrete exhibits elastic deformations only under loads of short duration, and due to additional deformation with time, the effective behavior is that of an inelastic and time-dependent material.

2.4.2.4.1 Shrinkage:

The decrease in the volume of concrete with time is known as Shrinkage. This decrease is due to changes in the moisture content of the concrete. Swelling is the increase of concrete volume with time. Shrinkage and swelling are usually expressed as a dimensionless strain (in. /in. or mm/mm) under given conditions of relative
humidity and temperature. The Concrete immersed in water does not shrink but it may swell.

Shrinkage of HPC may be expected to differ from conventional concrete in three broad areas: plastic shrinkage, drying shrinkage, and autogenous shrinkage. Plastic shrinkage occurs during the first few hours after fresh concrete is placed. During this period, moisture may evaporate faster from the concrete surface than it is replaced by bleed water from lower layers of the concrete mass. Paste-rich mixes, such as high performance concretes, will be more susceptible to plastic shrinkage than conventional concretes. Drying shrinkage occurs after the concrete has already attained its final set and a good portion of the chemical hydration process in the cement gel has been accomplished. Drying shrinkage of high strength concretes, although perhaps potentially larger due to higher paste volumes, does not, in fact, appear to be appreciably larger than conventional concretes. This is probably due to the increase in stiffness of the stronger mixes. Data for VES and HES mixes is limited. Autogenous shrinkage due to self-desiccation is perhaps more likely in concretes with very low W/CM ratio, although there is little data outside indirect evidence with certain high strength concrete research [7]. Shrinkage should not be confused with thermal contraction which occurs as concrete loses the heat of hydration.

2.4.2.4.2 Creep:

Strictly speaking in concretes, the relation between stress and strain is a function of time. Creep is defined as the increase in strain under a sustained constant stress after taking into account other time-dependent deformations not associated with stress. It is usually determined by subtracting, from the total measured strain in a loaded specimen, the sum of the initial instantaneous strain (usually considered
elastic) due to sustained stress, the shrinkage, and any thermal strain in an identical load-free specimen, subjected to the same history of relative humidity and temperature conditions.

Creep is closely related to shrinkage and both phenomena are related to the hydrated cement paste. As a rule, a concrete that is resistant to shrinkage also has a low creep potential. The principal parameter influencing creep is the load intensity as a function of time. However, the composition of the concrete, environmental conditions, and the size of the specimen also influences the creep.

In normal weight aggregate concrete, the source of creep is the hardened cement paste since the aggregate is not liable to creep at the level of stress existing in concrete. Because the aggregate is stiffer than the cement paste the main role of aggregate is to restrain the creep is the cement paste. The composition of concrete can be defined by the w/c ratio, aggregate and cement types and quantities. Therefore, as with shrinkage, an increase in w/c ratio and in cement content generally results in an increase in creep. Also, as with shrinkage, the aggregate induces a restraining effect so that an increase in aggregate content and stiffness reduces creep.

Numerous tests have indicated that creep deformations are proportional to the applied stress at low stress levels. The valid upper limit of the relationship can vary between 0.2 and 0.5 of the compressive strength. This range of the proportionality is expected due to the large extent of micro cracks in concrete at about 40 to 45% of the strength. A widely used predictive equation for creep strain at time t days after loading is that given by ACI Committee [131].
2.4.2.5 Thermal Properties:

The important thermal properties of concrete are thermal conductivity, thermal diffusivity, specific heat and coefficient of thermal expansion. The thermal properties of concrete are more complex than for most other materials, because not only is concrete a composite material whose components have different thermal properties, but its properties also depending on moisture content and porosity.

Data on thermal properties of high performance concrete is limited, although the thermal properties of high strength concrete fall approximately within the same range as those of lower strength concrete, for characteristics such as specific heat, diffusivity, thermal conductivity and coefficient of thermal expansion [132].

2.4.3 Fatigue strength:

There are two types of failure in fatigue can takes place in concrete. In the first, failure occurs under sustained loads or slowly increasing load. Under repeated loads, concrete suffers damages which results progressive growth of internal micro cracks. After a sufficient number of load repetitions, concrete fails at a load less than its static strength. The fatigue strength of concrete is therefore a fraction of its static strength that the concrete can support repeatedly for a given number of load cycles.

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 very high strength concrete could be vulnerable to fatigue loading. However, in case of high strength concrete, the elastic modulus of the paste and aggregate are more similar, thereby reducing stress concentrations at the interface of aggregate paste, which causes the high strength concrete less susceptible to fatigue loading.
2.4.4 Durability:

When properly designed and carefully produced with good quality control, concrete is inherently a durable material. However, under adverse conditions, concrete is potentially vulnerable to deleterious attacks such as frost, sulfate attack, alkali-aggregate reaction, and corrosion of steel. Each of these processes involves movement of water or other fluids, transporting aggressive agents through the pore structure of concrete. Therefore, porosity and permeability are important properties which affect the durability of concrete.

2.4.4.1 Porosity and Permeability:

An excellent review of the pore structure and its influence on permeability of cement paste and concrete has been presented by Young [133]. It is generally agreed that for normal-weight concrete, its porosity resides principally in the cement paste. The pore structure of the paste can be classified into two types: (1) intrinsic pores in the cement gel resulting from hydration; and (2) capillary pores originating from the space initially filled with water. The size and distribution of these pores cover a very large range, from much less than 2.5 nm to 10,000 nm. Typically, the size of the gel pores is less than 10 nm whereas the size of the capillary pores is more than 10 nm. Pores of 10,000 nm or larger are classified as air voids.

The basic information on how porosity and permeability are affected by W/C ratio, curing, mineral and chemical admixtures has been presented by Zia et al. [91]. Various methods commonly used to measure porosity and permeability has been discussed. In the past several years, a large number of porosity and permeability studies have been reported in the literature. Some of these studies will be summarized in the following sections.
2.4.4.1.1 Porosity:

Fresh cement paste is a plastic network of particles of cement in water. But once the paste has set, it’s apparent or gross volume remains approximately constant. Winslow and Lui [134] demonstrated that the cement paste in concrete and mortar has a pore size distribution different from that of plain paste hydrated without aggregate. For mortar and concrete, additional porosity occurs in pore sizes larger than the plain paste's threshold diameter as measured by mercury intrusion. Based on the assumption that these larger pores are essentially present only in the interfacial zones surrounding each aggregate, Winslow et al., [135] designed an experimental program in which the volume fraction of sand in a mortar was varied in a systematic fashion and the resultant pore system probed using mercury intrusion porosimetry. The intrusion characteristics were observed to change drastically at a critical sand content of 48.6% volume fraction. Similar results were observed for a series of mortar specimens in which the cement paste contained 10% silica fume. To better interpret the experimental results, a hard core/soft shell computer model was developed to simulate percolation of the interfacial zones in mortar and concrete specimens. The interfacial zone thickness (15-20 mm) provided by the mercury intrusion experiment and computer model for mortar was somewhat less than that conventionally measured using the SEM imaging technique but the difference was to be expected given the inherent differences in the two measurement methods.

The computer model indicated that for an interfacial zone thickness of about 20 mm, interfacial zone percolation would occur in most typical construction concrete mixes. This observation was supported by the generally large permeability of concrete relative to plain paste. By decreasing the interfacial zone thickness or the porosity in the interfacial zone or reducing the quantity of aggregates in a concrete, the
probability of interfacial zone percolation would be reduced. Thus they suggested that the engineering of interfacial zone microstructure and aggregate content and size distribution might be critical in increasing the service life of concrete. [136].

2.4.4.1.2 Permeability:

There is no recognized standard test method to measure the permeability of concrete. Different investigators have used different techniques and procedures. In general, there are three categories of methods: air (or gas) permeability, hydraulic permeability, and chloride ion permeability. An excellent review of different methods for measurement of permeation properties of concrete on site has been presented by Basheer et al. [137]

Reinforced concrete structures exposed to a marine environment often deteriorate in the early stages of their service life. The main reason is corrosion of the reinforcing steel due to the penetration of chloride ions through the concrete. Therefore, the chloride penetration resistance of concrete is a critical parameter in determining the long-term performance of structures in a marine environment. Several standardized tests can be used to determine the resistance to chloride penetration in concrete. The short-term conductivity test, Rapid Chloride permeability (RCP) is one of the most widely used because its results correlate reasonably, well with those from long-term 90 days ponding test. Hence in the present investigation Rapid Chloride Ion Permeability Test (RCPT) is used for measuring permeability.

This research is therefore set out to investigate not only the applicability of NRL into concrete, but also to determine appropriate quantity of latex to be added without impairing strength characteristics as well as evaluating the impact of concrete grade on its efficiency.
2.5. Closure:

From the detailed review presented it can be noted that latex addition in concrete can improve flexural strength substantially and compressive strength to certain extent. It is also reported that latex addition can improve the durability of concrete. Though research has been carried out to study the effect of latex addition on ordinary concrete, very little research has been carried out to investigate the effect of latex addition on strength and durability characteristics of High Performance Concrete.

Normally high performance concrete becomes brittle due to its very high strength. Steel fibres and Natural Rubber Latex can be incorporated into the HPC to make it ductile and durable. Thus there is urgent need to study the effect of Natural Rubber Latex (NRL) addition on workability, strength and durability characteristics of fibre reinforced High Performance Concrete.

The present investigation proposes to address these issues by conducting a detailed experimental program on Natural Rubber Latex Modified Fibre Reinforced High Performance Concrete with locally available materials, indigenously produced mineral admixtures, Steel fibres and Natural Rubber Latex. Polymer latexes are being increasingly used in civil engineering applications as modifiers especially for the purpose of improving the workability, drying shrinkage and strength characteristics and durability properties of cement products as per Ohama [138] and Bala [139]. Even if the addition of fibres in a concrete mix mainly affects the tensile behavior, improvements of the compression behavior also occur. In particular the results of experimental tests conducted by Soroushian [140] have shown the favorable effects of fibres in increasing the post peak ductility, the energy absorption capacity and, to some extent, the strength of concrete.