CHAPTER 1
INTRODUCTION

1.1 Cement and Concrete

Concrete is a hard material that has cementitious medium within which aggregates are embedded [3,4,135,136,137]. With the development of concrete technology the use of concrete in the construction industries have gained pace. Cement is one of the major constituent of a concrete. Materials other than cement used in the manufacture of concrete are coarse and fine aggregates, admixtures and water. Cement is an extremely important constituent of a concrete as it binds together other materials. The raw materials used for the manufacture of cement consist mainly of lime, silica, alumina and iron oxide [84,136,137,138]. These oxides interact with one another in the kiln at high temperature to form four major complex compounds [137]. Concrete is strong and tough material. Reinforced concrete resists cyclones, earthquakes, blast and fires much better than timber and steel if designed properly [137]. The developments related to the concrete is used extensively in the production of buildings, bridges, harbours, runways, roads, etc. Concrete is an extraordinary and key structural material in the human history. As written by Brunauer and Copeland (1964), Man consumes no material except water in such tremendous quantities. It is no doubt that with the development of human civilization, concrete will continue to be a dominant construction material in the future. However, the development of modern concrete industries also introduce many environmental problems such as pollution, waste dumping, emission of dangerous gases, depletion of natural resources etc. The quality of concrete is determined by its mechanical properties as well as its ability to resist deteriorations. Hardened concrete can be considered to have three distinct phases i.e. the hardened cement paste (HCP) or matrix, the aggregate and the interfacial or transition zone (TZ) between HCP and the aggregate [136]. For optimum performance all the three phases should be considered explicitly. The HCP is about 30% to 40% of the volume of concrete and aggregates constitute 60% to 70% of the volume. Fig.1.1 shows the different constituents of concrete. Concrete also contains air which is also a part of paste phase. Concrete can be classified into various categories depending on its density.
and strength as recommended by IS 456: 2000 [146]. The aggregates used in making concrete contribute mainly to its density.

![Fig. 1.1: Constituents of Concrete (Source: A.R. Santhakumar [137])]()

Compressive strength is an important parameter which determines the characteristic of a concrete [4, 136, 137]. For the construction of high rise buildings and long span bridges the use of high strength concrete (compressive strength 60-100 MPa) were commercially started in the late 70’s. This made the concrete technologist to develop high performance concrete (HPC) which not only give high strength but also perform satisfactorily during its service period. The standard code of practice for plain and reinforced concrete IS: 456-2000 [146] has classified concrete on the basis of strength shown in Table 1.1

<table>
<thead>
<tr>
<th>Classification</th>
<th>Maximum Strength (MPa)</th>
<th>Type</th>
</tr>
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<tbody>
<tr>
<td>Ordinary Concrete</td>
<td>&lt; 20</td>
<td>Low strength</td>
</tr>
<tr>
<td>Standard Concrete</td>
<td>20-40</td>
<td>Medium strength</td>
</tr>
<tr>
<td>High strength Concrete</td>
<td>40-80</td>
<td>High strength</td>
</tr>
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The strength of concrete is the most important characteristic as it has strong relationship with quality. Strength as a parameter is used for controlling as well as evaluating other properties of concrete because of its relationship with durability and dimensional stability [137]. Various parameters that affect the strength of concrete are shown in Fig 1.2. Specimen parameter includes dimension, moisture state and shape of a specimen. Most important factor which affect the strength is the porosity which can result from either the matrix, aggregate, or the interfacial transition zone. Porosity in turn is influenced by w/c ratio, degree of hydration and air content.

![Diagram of Factors affecting the strength of concrete](image)

**Fig. 1.2:** Factors affecting the strength of concrete (Source: A.R. Santhakumar [137])

Small or large all types of construction uses concrete. Though conventional concrete is a widely used construction material, there are other materials that are being increasingly used for special purposes. Depending upon the need one may employed prestressed, self compacting or fiber reinforced concrete. Development in concrete industry can be classified into five major focus
areas as shown in the Fig 1.3. Recycling of demolition waste, use of industrial wastes such as fly ash and green building method are developments that have emerged from the need to conserve materials and obtain maximum output from them. Currently a large number of structures are built in very hostile environments to withstand severe and cyclic environmental and weather changes. Therefore durability of concrete is an important parameter in the recent development of concrete. Polymer and co-polymers are added to concrete to impart it new and improved properties in concrete.

Fig. 1.3: Developments in concrete industry (Source: A.R. Santhakumar [137])

1.2 Environmental concerns

Even though the embodied energy of concrete is among the lowest compared to other engineering materials [72], the concrete industry is still one of the greatest industrial pollutants. The cement industry alone is responsible for approximately 5 to 8% of the world’s CO₂ emissions [74]. Other
contributing factor is the total amount of materials consumed. A massive use of concrete in the 21st century is inevitable, and an increase in total concrete consumption is projected. In 2015, the main world producers among G20 countries produced approximately 3.5 billion tonne of cement [131], which was used to produce approximately 10 billion m$^3$ of concrete. The largest portions of the materials used in the concrete industry are still natural and non-renewable materials. Therefore, the concrete industry is still very linear, meaning that it uses a huge amount of natural materials and energy and, at the same time, creates significant emissions and waste because at the end of the service life most materials lose their value and are not treated as raw materials. At the same time, the concrete industry has a high potential for a positive shift toward a more sustainable circular production and lower ecological footprint. One strategy is to use waste materials and by-products from other industries as valuable raw materials in the concrete industry. Concrete is an extraordinary and key structural material in the human history. It is no doubt that with the development of human civilization, concrete will continue to be a dominant construction material in the future. However, the development of modern concrete industry also introduces many environmental problems such as pollution, waste dumping, emission of dangerous gases, depletion of natural resources etc. Presently, Portland cement and supplementary cementitious materials are cheapest binders which maintain enhance the performance of concrete. However, out of these binders, production of Portland cement is very energy exhaustive along with CO$_2$ production. About 1 tonne of CO$_2$ is produced in manufacturing of each tonne of Portland cement (PC). Thus, cement production accounts for about 5% of total global CO$_2$ emissions [94]. On the other side of the spectrum, in order to reduce the rate of climate change, a global resolution to an 8% reduction in greenhouse gas emissions by 2010 was set in the Kyoto Protocol in 1997. Developed countries are much aware for its need and a climate change tax was introduced by them. In this connection, UK Government also introduced same kind of tax on 1st April 2001, in order to achieve its target of a 12.5% reduction in greenhouse gas emissions which was the government’s domestic goal of a 20% reduction in CO$_2$ emissions by 2010.

Cement based materials are the most abundant of all manmade materials and are among the most important construction materials and it is most likely that they will continue to have the same importance in future. However these construction and engineering materials must meet new and higher demands. When facing issues of productivity, economy, quality and environment they
have to compete with other construction materials such as plastic, steel and wood. However, the development of a sustainable concrete is urgently needed for environmental reasons. It is clear that cement, the key binder ingredient in concrete has a high environmental impact. Presently about 10% of the total anthropogenic CO₂ is due to the cement production solely. Today innovation is leadingly being inspired by nature as a sustainable alternative. The main concern is that concrete is unsustainable due to the painful carbon footprint associated to it. It has been clear that cement, the key binder ingredient in concrete has a high environmental impact. The thumb rule for cement production goes as for every tonne of cement made a tonne of CO₂ is produced. After the Kyoto Protocol, several commitments have been made to reduce this through a series of frameworks-

(i) “Production efficiency,

(ii) Energy efficiency, especially in calcination phase as it accounts for the majority of the Energy consumption; and

(iii) Innovation in CO₂ capture and storage (CCS) technologies.

Presently to reach optimal levels of sustainability, several investigations are being made to reduce the environmental impact of concrete. Such as :

(i) Obtaining optimal strengths

(ii) Replacing Portland clinker with alternative cements; and

(iii) Increasing concrete durability.

Another reason for concrete having such an impactful carbon footprint is due to the huge quantities being used. Hence by obtaining optimal strengths the amount of concrete consumed to do the same job can be reduced. To achieve high strengths of concrete the water-cement ratio can be reduced to 0.16, as complete hydration is not needed if admixtures are added and as such attaining higher strengths than completely hydrated concrete. And in terms of threshold of workability due to lowered water amounts can be achieved using additives called plasticizers. However, the workability of the concrete is the only thing preventing from going below this ratio. Replacing Portland clinker, either partially or entirely, with alternative cements is also being investigated as an approach to tackling concrete’s CO₂ emissions. Waste materials, such as slag (from blast furnaces) and fly ash (from coal-fired power stations), are already being used as supplementary cementitious materials (SCMs) and have been for some decades. However, with
50% clinker replacement with fly ash, the early strength drops dramatically. Or even if the clinker were to be replaced entirely by slag, an alkali can be added to activate it. However, Alkali-Silica reactions is a more and more of a problem because as time goes by, it is being discovered that more and more aggregates are reactive. Concrete as a material is liable to crack formation and degradation. It has been observed that if 20% of cement content is reduced the durability improves because it is the cement paste that is most porous. So it is the cement that provides a route by which elements of exposure can go in and out, hence the less cement used the better the concrete. Pores in the material allow corrosive materials such as chlorides and sulphates to penetrate the structure and attack the metal reinforcement – the cause of over 90 percent of problems of reinforced concrete durability. However, ultimate strength of concrete is more important than short term CO₂ savings.

The world’s yearly cement production of 1.6 billion tons accounts for about 7% of the global loading of carbon dioxide into the atmosphere. Portland cement, the principal hydraulic cement in use today, is not only one of the most energy-intensive materials of construction but also is responsible for a large amount of greenhouse gases. Producing a ton of Portland cement requires about 4 GJ energy, and Portland cement clinker manufacture releases approximately 1 ton of carbon dioxide into the atmosphere. Furthermore, mining large quantities of raw materials such as limestone and clay, and fuel such as coal, often results in extensive deforestation and top-soil loss. Ordinary concrete typically contains about 12% cement and 80% aggregate by mass. This means that globally, for concrete making, we are consuming sand, gravel, and crushed rock at the rate of 10 to 11 billion tons every year. The mining, processing, and transport operations involving such large quantities of aggregate consume considerable amounts of energy, and adversely affect the ecology of forested area and riverbeds. The concrete industry also uses large amounts of fresh water; the mixing water requirement alone is approximately 1 trillion liter every year. Reliable estimates aren’t available, but large quantities of fresh water are being used as wash-water by the ready mixed concrete industry and for curing concrete. Besides the three primary components, that is, cement, aggregates, and water, numerous chemical and mineral admixtures are incorporated into concrete mixtures. They too represent huge inputs of energy and materials into the final product. What about batching, mixing, transport, placement, consolidation, and finishing of concrete? All these operations are energy-intensive. Fossil fuels
are the primary source of energy today, and the public is seriously debating the environmental costs associated with the use of fossil fuels. The environmental impact of the concrete industry can be reduced through resource productivity by conserving materials and energy for concrete-making and by improving the durability of concrete products. The task is most challenging but can be accomplished if pursued diligently. To examine how the concrete industry will have to restructure when the business paradigm shifts its emphasis from a culture of acceleration to a culture of resource productivity, I have subdivided the environmental impacts of modern concrete construction practice into several categories that are discussed separately as follows.

Cement conservation is the first step in reducing the energy consumption and greenhouse-gas emissions. Resource productivity consideration will require us to minimize portland cement use while meeting the future demands for more concrete. This must be the top priority for a viable concrete industry. Except for blended Portland cements containing mineral additions, no other hydraulic cements seem to satisfy the setting, hardening, and durability characteristics of portland cement-based products. Although there is steady growth in the use of portland cement blends containing cementitious or pozzolanic by-products, such as ground granulated blast-furnace slag and fly ash, vast quantities of these by-products still end up either in low-value applications such as landfills and road sub bases, or are simply disposed by ponding and stockpiling. The world cement consumption rate is expected to reach about 550 million tonne by the year 2020, and there are adequate supplies of pozzolanic and cementitious by-products that can be used as cement substitutes, thus eliminating the need for the production of more portland cement clinker. Interestingly, as will be discussed below, Portland cement blends containing 50% or more granulated blast furnace slag or fly ash can yield much more durable concrete products than neat portland cement, and this would also contribute to natural resource conservation. The slower setting and hardening rate of concrete containing a high-volume of a mineral admixture can be compensated for, to some extent, by reducing the water cementitious materials ratio with the help of a superplasticizer. Nevertheless, for most structural applications, somewhat slower construction schedules ought to be acceptable when resource maximization, not labor productivity, becomes the most important industry goal.
1.3 High Performance Concrete

It is important to note the high-strength and high performance concrete are not synonymous. Concrete is defined as high-strength concrete solely on the basis of its compressive strength measured at a given age. In the 1970’s, any concrete mixtures that showed 40 MPa or more compressive strength at 28-days were designed as high-strength concrete. Later, 60-100 MPa concrete mixtures were commercially developed and used in the construction of high-rise buildings and long-span bridges in many parts of the world. The definition of high-performance concrete is more controversial. The term, high performance concrete (HPC) was used for the first time for concrete mixtures possessing high workability, high durability and high ultimate strength. ACI defined high-performance concrete as a concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practice. It is mistaken to bestow that supplementary cementitious materials were used in the concrete only because of their availability and just for economic considerations. These materials present some unique desirable properties which cannot be met by using OPC only [135]. For producing high performance concrete (HPC), it is well recognized that the use of supplementary cementitious materials (SCMs), such as Silica Fume (SF), GGBS and Fly Ash (FA) are necessary. The concept of HPC has definitely evolved with time. Initially it was equated to high strength concrete (HSC), which certainly has some merit, but it does not show a complete and true picture. There is a need to consider other properties of the concrete as well which sometimes, may even take priority over the strength criterion. Various authors proposed different definitions for HPC. High Performance Concrete is a concrete which made with appropriate materials, combined according to a selected mix design; properly mixed, transported, placed, consolidated and cured so that the resulting concrete will give an excellent performance in the structure in which it is placed, in the environment to which it is exposed and with the loads to which it will be subjected for its design. Thus, HPC is directly related to durable concretes.

From the general principles behind the design of high-strength concrete mixtures, it is apparent that high strengths are made possible by reducing porosity, In homogeneity, and microcracks in the hydrated cement paste and the transition zone. The utilization of fine pozzolanic materials in high strength concrete leads to a reduction of the size of the crystalline compounds, particularly,
calcium hydroxide [137]. Consequently, there is a reduction of the thickness of the interfacial transition zone in high-strength concrete. The densification of the interfacial transition zone allows for efficient load transfer between the cement mortar and the coarse aggregate, contributing to the strength of the concrete. For very high-strength concrete where the matrix is extremely dense, a weak aggregate may become the weak link in concrete strength. Almost any ASTM portland cement type can be used to obtain concrete with adequate rheology and with compressive strength upto 60 MPa. In order to obtain higher strength mixtures while maintaining good workability, it is necessary to study carefully the cement composition and finenesses and its compatibility with the chemical admixtures. Experience has shown that low-C₃A cements generally produce concrete with improved rheology. In high-strength concrete, the aggregate plays an important role on the strength of concrete. The low-water to cement ratio used in high strength concrete causes densification in both the matrix and interfacial transition zone, and the aggregate may become the weak link in the development of the mechanical strength. Extreme care is necessary, therefore, in the selection of aggregate to be used in very high strength concrete. The particle size distribution of fine aggregate that meets the ASTM specifications is adequate for high strength concrete mixtures. If possible, using of fine aggregates with higher fineness modulus is advisable because high-strength concrete mixtures already have large amounts of small particles of cement and pozzolan, therefore fine particles of aggregate will not improve the workability of the mix. The use of coarser fine aggregates requires less water to obtain the same workability; and during the mixing process, the coarser fine aggregates will generate higher shearing stresses that can help prevent flocculation of the cement paste. The higher the targeted compressive strength, the smaller the maximum size of coarse aggregate. Up to 70 MPa compressive strength can be produced with a good coarse aggregate of a maximum size ranging from 20 to 28 mm. To produce 100 MPa compressive strength aggregate with a maximum size of 10 to 20 mm should be used. To date, concretes with compressive strengths of over 125 MPa have been produced, with 10 to 14 mm maximum size coarse aggregate. Using supplementary cementitious materials, such as blast furnace slag, fly ash and natural pozzolans, not only reduces the production cost of concrete, but also addresses the slump loss problem. The optimum substitution level is often determined by the loss in 12hr or 24-hr strength that is considered acceptable, given climatic conditions or the minimum strength required. While silica fume is usually not really necessary for compressive strengths under 70 MPa, most concrete
mixtures contain it when higher strengths are specified. The American concrete committee (ACI 1993) includes the following six criteria for material selections, mixing, placing and curing procedures for concrete.

i) Ease of placement
ii) Long term mechanical properties
iii) Early age strength
iv) Toughness
v) Life of severe environment
vi) Volume stability

Though the freezing thawing resistance is indicated as a measure of high performance concrete, the durability with respect to chloride ingress has been a very important parameter for marine exposed structures especially in India. At present there is virtually no structure in coastal regions in India that has achieved its designed life span without repairs. The following eight parameters are used by Federal Highway Administration (FHWA) in USA to grade HPC

i) Compressive strength
ii) Modulus of elasticity
iii) Creep
iv) Shrinkage
v) Freeze- Thaw resistance
vi) Abrasion
vii) Chloride permeability
viii) Scaling Resistance

“Better durability performance can be achieved by using high strength, low w/c ratio concrete. Though in this approach the design is based on strength and durability it is desirable that the high performance is addressed directly by optimizing critical parameters such as the particle size of the required materials. Two approaches to achieve durability through different techniques are shown in Fig 1.4”
1.4 Need for this Research

Concrete is a commonly used construction material formed by mixing cement (binder), aggregate, water and admixtures in different ratios depending on the function and strengths required. The oldest known surviving concrete is found in the former Yugoslavia and is thought to have been laid in 5600 BC using red lime as the cement. The first major concrete users were the Egyptians around 2500 BC; Egyptians used mud mixed with straw to bind dried bricks. Later the Romans since 300 BC made many developments in concrete technology including the use of slaked lime a volcanic ash called pozzolana; animal fat, milk, and blood were used as admixtures; and even built the Pantheon in 200 AD with lightweight aggregates in the roof. Even today this 43.3 m diameter dome is still the world’s largest non-reinforced concrete dome. After 400 AD the art of Concrete was lost with the fall of the Roman Empire. It was only in 1824 that modern concrete was developed by Joseph Aspdin. He patented what he called Portland cement which till date remains as the key ingredient in concrete. The work presented here aims at increasing the
knowledge on the effect of ultrafine particles in concrete. In the context of this work, ultrafine particles are particles with a grain size finer than cement. These particles may be inert and improve the packing density of the fines in concrete, or they may be pozzolanic and react with hydration products of the cement. The hypothesis of this work is that substantial amounts of cement can be replaced by suitable very fine grained materials without affecting mechanical properties or durability negatively. Cement itself is considered as a fraction of the complete particle mix that builds up the concrete. By application of suitable particle packing models to the entire concrete mix, the particle size distribution (PSD) of the entire mix can be adjusted in order to achieve mobility in the fresh state and adequate properties when hardened. Due to the fact that the ingredients of a concrete mix are particles with continuous size distributions, a model should be based on packing of continuous size distributions. A modification of concrete mixes with ultrafine particles affects the fresh and hardened properties of the concrete. The workability, hardening, mechanical properties and durability may be influenced indifferent ways. Reactive particles like silica fume may have different effects compared to inert particles. Synergy effects from combination of reactive and inert particles can be expected. Therefore, this investigation is done in several steps. First, a literature review on particle packing, cement hydration, load independent deformation and mechanical strength of concrete is done. These issues are considered to be of primary interest for the subject of the work. Particle packing is directly related to the introduction of other fine particles than cement into concrete. It may be used to provide knowledge on how to utilize ultrafine particles in the best way. The hydration of cement is known to be influenced by the presence of other particles. Load-independent deformations of concrete are known to be influenced by the content of fines, the cement content and reactive additives. The mechanical strength of concrete is strongly related to the porosity which in turn is influenced by hydration, particle packing and additives. The experimental section of this work concentrates on concrete experiments. In addition, the influence of the ultrafines on the hydration is examined on paste samples with the help of isothermal calorimetry. In the concrete experiments, different measures are taken in order to isolate the influence of inert and reactive ultrafine particles. First, different inert ultrafine particles are used to replace cement at constant water content and variable water content. Then, mix compositions are optimised towards low cement content with the help of inert ultrafines. The effect of high contents of reactive ultrafine particles on concrete properties is tested, also in combination with inert ultrafines. Then, concrete
compositions are optimized towards low binder content. The effect of different ultrafine particles on concrete properties is quantified by tests on compressive strength and calculation of shrinkage, and characterization of the microstructure by microscopy, mercury intrusion Porosimetry (MIP) and capillary suction as well as test of frost resistance. The results of this work shall contribute to an increased understanding of the effects of different very fine particles on concrete properties. Recommendations are given on how to include ultrafine particles in mix design. This work does not concentrate on concrete mixes that comply with recent concrete standards in which concrete properties are mainly related to the water-cement ratio. The results of this work are expected to be more useful for performance based design of concrete or in special applications. Further, it is not primarily the fresh concrete properties that are investigated. Workability of fresh concrete is of course an important issue but within the limitations of this work, super plasticizers were used to achieve workable mixes when necessary. The fine aggregate (0-8 mm) used in this work is of natural origin with well rounded particle shape. Crushed fine aggregate is not tested but it is likely that some adjustments are necessary when using this type of fine aggregate. There are other properties of hardened concrete, e.g. creep, E-modulus, chloride diffusion and carbonation which can be influenced by ultrafine particles but it is not possible to test all of them within this work. Neither is cost efficiency of the resulting mixes considered, at present time the cost of the used ultrafines may exceed the cost of the replaced cement. Additionally, many concrete plants may have problems handling ultrafines. However, the findings of this work can contribute to increased use of ultrafines in concrete and intensified research on suitable byproducts. In that way, cost efficiency can be achieved in the future.

1.4.1 Particle Packing Theory

Particle packing is fundamental to concrete. The better the packing of the particle system, the less binder is required in the concrete. The problem with concrete is, however, that concrete must flow and be compactable in the fresh state which stands in conflict with optimal packing. Introduction of large amounts of fine particles, in size of cement and below, into a concrete mix can solve this problem. Then, the particle size distribution of the whole mix composition, including cement, pozzolanas and/or fillers, should be taken into account when calculating the packing density. Particle packing is an important issue not only for concrete materials. Ceramics,
geotechnology, food processing industry and others do benefit from densely packed systems. The first investigations concerning particle packing were done more than 200 years ago. One of the most important properties of a particle system is its packing density; the volume percentage of solids for each volume unit. Looking into a certain system, the particle packing of this system is a function of particle size distribution, particle shape, and particle surface, ratio between system size and maximum grain size and presence of liquids, if any. In order to understand the existing theories and models for systems with multiple grain sizes, one ought to look into systems with only one grain size first. Systems consisting of only one grain size are called mono-dispersions; they are useful for modelling but rarely seen in reality. If perfect spherical particles of only one size are assumed, the packing density of the system depends on which structure is formed by the spheres. Practically one can select a combination of sizes such that the free space between the particles is reduced when the material is mixed. Fig. 1.5 explains the concept behind particle packing. Cubical particles are capable of being packed without any voids, but this is not possible for wet concrete in a colloidal suspension. Generally the key particle sizes affecting packing density are those smaller than 125 μm. These particles are smaller than the capillary pores. When they are well dispersed they will block the capillary pores. In addition the fine powder effect will augment the cement reaction. This increases the degree of hydration for a given period of curing. There are number of binders that can perform the particle packing job viz fly ash, GGBS, metakaoline, lime stone flour, silica fume and rice husk ash.

Let us consider a concrete mix composed of a single-sized aggregate and cement paste only. In order to fill up all the gaps between the aggregate particles so as to drive away the air voids in the concrete mix, the volume of cement paste must be larger than the volume of gaps within the aggregate skeleton. If, instead of a single-sized aggregate, a multi-sized aggregate is used, the smaller size aggregate particles would fill up the gaps between the larger size aggregate particles, leading to a smaller volume of gaps within the aggregate skeleton. This has two implications. Firstly, with a multi-sized aggregate used, the volume of cement paste needed to fill up the gaps within the aggregate skeleton would be reduced. Secondly, if the volume of cement paste is kept the same, the use of a multi-sized aggregate
would increase the volume of the excess paste (the portion of paste in excess of that needed to fill up the gaps within the aggregate skeleton), which disperses the aggregate particles, provides a coating of paste for each aggregate particle and renders workability to the concrete mix. Hence, the size distribution, or grading, of the aggregate has an important bearing on the paste demand and the workability of a concrete mix. That the grading of the aggregate can have a great influence on the performance of the concrete mix is actually well known long time ago. It is only that many parameters (the various size fractions of the aggregate) are needed to describe the grading and the effects of the various parameters are often blurred by the interaction between the
various parameters involved. Nevertheless, it is nowadays very clear that the single most important parameter influencing the performance of concrete is the packing density of the aggregate. The packing density of a given aggregate or a given lump of solid particles is the ratio of the volume of solids to the bulk volume of the solid particles. Since the bulk volume is equal to the volume of solids plus the volume of voids, a higher packing density means a smaller volume of voids to be filled and vice versa. The single-sized aggregate can be packed together to occupy only limited space, i.e. can achieve only a relatively low packing density. The multi-sized aggregate can be packed together much more effectively to achieve a much higher packing density. With the paste volume fixed, the increase in packing density of the aggregate could be employed to increase the workability of the concrete at the same water/cementitious ratio or increase the strength of the concrete by reducing the water/cementitious ratio while maintaining the same workability. Apart from increasing the excess paste at a given paste volume to improve the workability and/or strength of the concrete, the increase in packing density of the aggregate could also be employed to improve the dimensional stability of the concrete. In a concrete mix, it is the cement paste that generates heat of hydration causing thermal expansion/contraction during the early age and shrinks when subjected to drying in the longer term. Hence, the larger the paste volume is, the larger would be the changes in dimension of the hardened concrete due to early thermal expansion or contraction and long term drying shrinkage. The heat of hydration and drying shrinkage of the concrete are dependent also on the water/cementitious ratio, both being larger at higher water/cementitious ratio. The reduction in paste demand due to a higher packing density of the aggregate would for the same workability allow the use of a smaller paste volume at a fixed water/cementitious ratio or a lower water/cementitious ratio at the same paste volume, either of which would significantly improve the dimensional stability of the concrete. The concept of packing density can be extended to apply also to the cementitious materials, which may include cement and other supplementary cementitious materials, such as pulverized fuel ash (PFA), ground granulated blast-furnace slag (GGBS) and condensed silica fume (CSF) etc. Drawing analogy to the previous case of packing aggregate particles, the packing density of the cementitious materials should have similar effect on the water demand and the flow ability of the cement paste. The different types of cementitious materials are generally of different sizes. By mixing appropriate proportions of different cementitious materials together, the medium size particles would fill up the gaps between the larger size particles and the smaller size particles.
would fill up the gaps between the medium size particles and so forth. Hence, blending cementitious materials of different sizes together could increase the packing density of the cementitious materials and reduce the water demand. Recent research findings have provided positive support to the above theory. Further in the presence of a super plasticizer, the addition of GGBS, which has a higher fineness than cement, has shown improvement in the fluidity of cement paste through its filling effect. Research shows that during the development of high strength self-consolidating concrete that at a ratio lower than 0.28, the addition of CSF, which has a mean particle size of about 0.1 μm, could substantially increase the workability of the concrete mix, despite large increase in surface area of the cementitious materials. Such increase in workability may be explained by the ultra-high fineness of the CSF, which allowed the CSF particles to fill up the gaps between the cement grains thereby freeing more mixing water to lubricate the concrete mix. Study has showed that blending cement with an ultra-fine PFA, which has a mean particle size of about 3 μm, would reduce the water demand of the cementitious system, due most probably to the increase in packing density after adding the ultra-fine PFA. More recently, many authors have directly measured the packing density of blended cementitious materials and confirmed that the addition of CSF could significantly increase the packing density of the cementitious system. They have also demonstrated that at a water/cementitious ratio of 0.2, the increase in flow ability of the cement paste after addition of CSF could be quite dramatic. The packing density of the cementitious materials has great impact on the strength of the concrete produced. First of all, the reduction in water demand due to a higher packing density would allow the use of a lower water/cementitious ratio for achieving higher strength. Secondly, better packing would reduce the permeability of the bulk of cementitious materials and thus bleeding of the fresh cement paste. Thirdly, better packing would reduce the porosity of the transition zone by filling up the voids formed as a result of the wall effect of the aggregate with very fine particles. Both the reduced bleeding of the cement paste and the reduced porosity of the transition zone would substantially improve the quality of the transition zone, which, as the weakest link in concrete, has dominant effect on the strength of concrete. This phenomenon is often manifested by having trans granular failure (failure with fracture planes cutting through the aggregate particles) instead of transition zone failure (deboning failure at the transition zone) in high strength concrete made with densely packed cementitious materials containing CSF. More recent research has demonstrated that due to improved packing, blending cement with a rice husk ash
can lead to an increase in strength of the concrete and that because of the more significant improvement in packing density, the increase in strength is larger when the cement is 12 gap-graded. Apart from strength, an increase in packing density of the cementitious materials would also improve the overall performance of the concrete. For instance, at the same water/cementitious ratio, the flow ability of the cement paste and the workability of the concrete mix would be improved. Furthermore, with increased packing density, the cement paste would be more cohesive and the concrete mix would be less likely to segregate during placing. With the water demand reduced, the water content of the concrete mix might also be adjusted downwards to limit the drying shrinkage and improve the dimensional stability of the concrete. Lastly, with better packing, the permeability of the bulk of cementitious materials, both in fresh state and in hardened state, would be dramatically reduced leading to a much higher durability of the concrete. Summing up the above discussions, many authors are of the view that the packing density of the solid particles in the concrete mix is the key concept in the design of HPC mixes. Both the packing of the aggregate and the packing of the cementitious materials need to be considered. In fact, it is the grading or packing of the whole range of particles from the coarse aggregate to fine aggregate, to cement grains, and to fine and ultra-fine cementitious materials that determines the overall performance of a concrete mix.

1.5 Application of Ultrafine slag

As a result of growth in advance technology in concrete, high performance concrete (HPC) has gained worldwide popularity in the construction industry since 1990. In practice, high performance concrete, are generally characterized by high cement factors and very low W/C ratios. Such concrete suffer from two major weaknesses. It is extremely difficult to obtained proper workability, and to retain the workability for sufficiently long period of time with such concrete mixes. High dosage of high range water reducing agents (HRWR) then become a necessity, and resulting cohesive and thixotropic, sticky mixes are equally difficult to place and compact fully and efficiently. These problem indicate that there is probably a critical limit for the water content below which high HRWR dosage become not only essential but also unhelpful and undesirable, and often even harmful from a durability point of view. In high performance concrete applications, Silica Fume is generally proposed as the appropriate cement extender.
where high strength, low permeability are the prime requirements. Though silica fume is known
to improve durability, its addition in concrete is often negated by the increase water and/or
admixture dosage required to improve the workability and handling properties of the fresh
concrete. Ultra fine slag Alccofine 1203 is a specially processed product based on slag of high
glass content with high reactivity obtained through the process of controlled granulation. The raw
materials are composed primary of low calcium silicates. The processing with other select
ingredients results in controlled particle size distribution (PSD). The computed blain value based
on PSD is around 12000cm$^2$/gm and is truly ultra fine. Due to its unique chemistry and ultra fine
particle size, Alccofine 1203 provides reduced water demand for a given workability, even up to
70% replacement level as per requirement. The quality and impermeability of high performance
concrete are determined by the amount of water utilized in mix design i.e. the water/binder ratio.
High range water reducers (HRWR) are extensively used to ensure placement with low water
contents. The presence of extremely fine particles decreases the permeability and improves
durability. In order to measure the effect of Alccofine 1203 on the workability, water requirement
and HRWR dosages and based on past research concrete mixes were prepared.