

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/239925229>

High Performance Concrete: Fundamentals and Application

Article · November 2007

CITATIONS

2

READS

1,416

2 authors, including:



Denvin Lau

City University of Hong Kong

89 PUBLICATIONS 576 CITATIONS

SEE PROFILE

Some of the authors of this publication are also working on these related projects:



Special issue on "Thermosetting polymeric adhesives: Durability issues" [View project](#)

High Performance Concrete: Fundamentals and Application

Oral Büyüköztürk* and Denvid Lau**

Department of Civil and Environmental Engineering
Massachusetts Institute of Technology
77 Mass. Ave., Room 1-280
Cambridge, Massachusetts 02139

Abstract

When the general performance of concrete is substantially higher than that of normal type concrete, such concrete is regarded as high performance concrete (HPC). Three of the key attributes to HPC are discussed in this paper. They are: strength, ductility and durability. In order to know the intrinsic differences between normal type concrete and high performance concrete, micro-structure and composition of HPC are studied. Stress strain behavior of HPC under biaxial and triaxial loading are described. Finally, the application of HPC in tall building construction is discussed. This paper provides a general overview of the development of HPC, covering the topic from the laboratory testing to the industrial application.

1 Introduction

Traditionally, high performance concrete (HPC) may be regarded as synonymous with high strength concrete (HSC). It is because lowering of water-to-cement ratio, which is needed to attain high strength, also generally improves other properties. However, it is now recognized that with the addition of mineral admixtures HPC can be achieved by further lowering water-to-cement ratio, but without its certain adverse effects on the properties of the material. Hence, it is important to understand how concrete performance is linked to its microstructure and composition. In fact, performance can be related to any properties of concrete. It can mean excellent workability in fresh concrete, or low heat of hydration in case of mass concrete, or very quick setting and hardening of concrete in case of spray concrete which is used to repair roads and airfields, or very low imperviousness of storage vessels. However, from a structural point of view, one understands usually that high strength, high ductility and high durability, which are regarded as the most favorable factors of being a construction material, are the key attributes to HPC. Decades ago, HSC was only tested in laboratory without real applications because there were still many uncertainties on the structural behavior of HSC at that time. Up to the present, HPC has been widely used in tall building

* Professor

** Graduate Student

construction. In this paper, the key attributes will be evaluated in details so as to better understand how HPC differs from normal strength concrete (NSC). These key attributes are strength, ductility and durability. Interrelationships between microstructure and properties of HPC will be discussed. Finally, the application of HPC in tall buildings will be shown through the example “Taipei 101”.

2 Composition of High Performance Concrete

The composition of HPC usually consists of cement, water, fine sand, superplasticizer, fly ash and silica fume. Sometimes, quartz flour and fiber are the components as well for HPC having ultra strength and ultra ductility, respectively. The key elements of high performance concrete can be summarized as follows:

- Low water-to-cement ratio,
- Large quantity of silica fume (and/or other fine mineral powders),
- Small aggregates and fine sand,
- High dosage of superplasticizers,
- Heat treatment and application of pressure which are necessary for ultra high strength concrete after mixing (at curing stage).

3 Comparison between the Microstructure of HPC and NSC

What makes HPC to be different from NSC? In order to answer this question, the microstructure of the material should be studied. Interrelationships between microstructure and properties of both HPC and NSC need to be established. The microstructure of concrete can be described in three aspects, namely composition of hydrated cement paste, pore structure and interfacial transition zone. The hydrated cement paste is in fact the hydration products when cement is reacted 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. Figure 1 shows the microstructure of NSC.

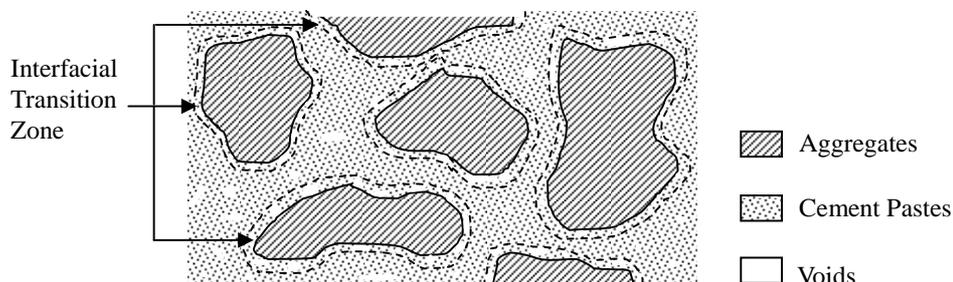


Figure 1: Microstructure of NSC

The hydrated cement paste is referred to as cementitious calcium silicate hydrate (C-S-H) gel

which is the main product of hydration of cement and water. The hydrated cement paste of NSC is dominated by amorphous C-S-H gel which is intrinsically porous. The porosity in concrete is due to gel pores, capillary pores and voids. Hence, C-S-H gel is low density phase which is space filling, but strength limiting. For concrete with strength below 50MPa, the increase in strength is primarily attained by reducing the capillary porosity alone. However, only reducing the capillary porosity is not enough to generate a concrete strength higher than 50MPa. The gel porosity should also be reduced together with the capillary pores so that there is a substantial reduction in the total porosity of concrete. Further reductions in gel porosity require a change in chemistry to convert C-S-H to more crystalline phases, which eventually leads to the production of HPC [1].

While total porosity of the cement paste matrix has a great influence on the strength of concrete, the pore structure and its connectivity have a significant impact on permeability. A high permeability usually means low durability as the inner part of concrete is more readily to be attacked by surrounding chemicals. However, with a high permeability, the concrete can get a higher early strength using suitable curing process because continuous hydration can be carried out with the permissible flow of water within the pore network. The porosity and the pore connectivity of NSC are usually higher than that of HPC due to the absence of fine particles (see Figure 2).

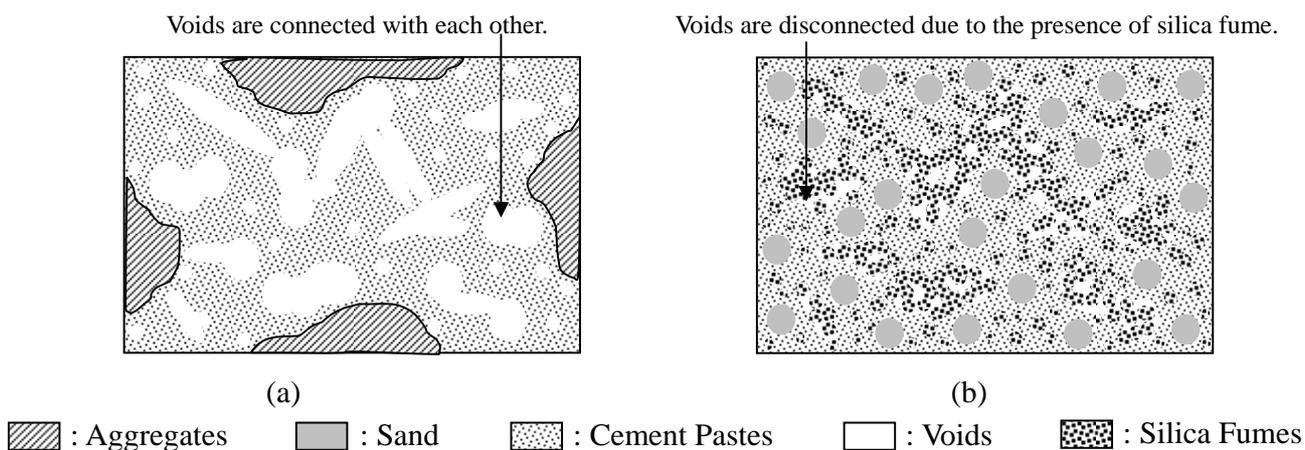


Figure 2: Pore Connectivity in (a) NSC and (b) HPC

In concrete, the zone of cement paste adjacent to the surface of embedded components, like aggregates and steel fibers, has a modified structure when compared to C-S-H gel. This is called the interfacial transition zone, which is about 2-3mm wide on average. This zone is characterized by a higher porosity than the bulk paste matrix as a result of poor packing of cement particles adjacent to the embedment surface. The higher porosity interfacial transition zone is subjected to accumulation of water leading to a locally higher water-to-cement ratio in these regions. Therefore, the interfacial transition zone in NSC may be weaker than other regions in the concrete system. Various interfacial transition zones may adversely affect the permeability of the bulk material. With prolonged moisture curing, the interfacial transition zone may gradually be filled up with hydration products. This

process may improve the bonding between the paste and the embedded materials. 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 promotes bond cracking along the boundaries of aggregates under external loading.

In order to improve the concrete performance, the following three aspects are considered: (a) the hydrated cement paste should be strengthened, (b) the porosity in concrete should be lowered, and (c) the interfacial transition zone should be toughened. These three aspects are evaluated one by one as follows. Firstly, the hydrated cement paste can be strengthened by reducing the gel porosity inside the paste. As mentioned previously, the crystalline of C-S-H gel has a lower gel porosity compared to amorphous C-S-H gel. By adding suitable admixture (e.g. silica fume), crystalline C-S-H gel can be achieved. Secondly, the porosity in concrete can be lowered by adding suitable fine admixture which can fill up the empty space inside concrete. In HPC, very fine admixture, such as silica fume or fly ash, is added into the design mix so that the empty space inside concrete can be reduced significantly. Meanwhile, the pore connectivity is lowered because the very fine particles effectively block the capillary network as shown in Figure 2. Thirdly, the interfacial transition zone can be toughened by lowering the locally high water-to-cement ratio and by improving the particle packing in this zone. Superplasticizer is added into the concrete mix so that a very low water-to-cement ratio (less than 0.2) become feasible to be adopted. Fine admixtures, like silica fume or fly ash, is added as well to improve the particle packing in the interfacial transition zone. It is noticed that in order to improve the concrete performance, admixture is a necessary component which must be added into the design mix in order to generate HPC. Hence, its microstructure is quite different from that of NSC. Figure 3 shows the microstructure of HPC. Three most important admixtures are mentioned here: superplasticizer, fly ash and silica fume. Their properties and impacts on the concrete performance are discussed in the following.

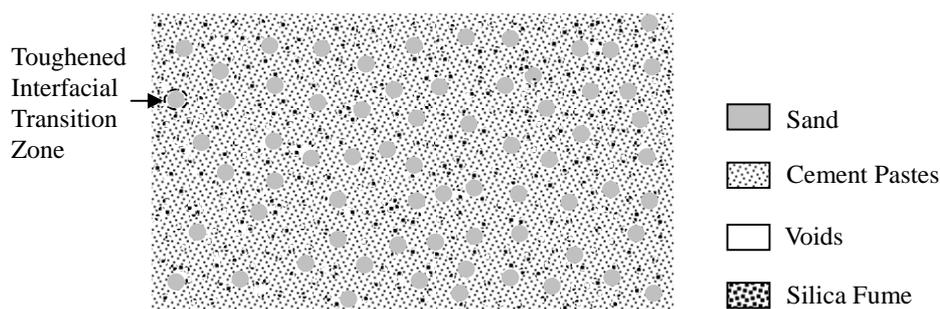


Figure 3: Microstructure of HPC

Superplasticizer

Superplasticizer can increase the workability of concrete mix and reduce the amount of water needed. Therefore, it enables the use of very low water-to-cement ratio and thus produce HPC. The principal active components in superplasticizer are surface-active agents. During mixing, these agents

are absorbed on the cement particles, giving them a negative charge which leads to repulsion between the particles and results in a more uniform dispersion of cement grains. With the addition of superplasticizers, concrete can be successfully produced and placed with a water-to cement ratio as low as 0.2. However, this value is not the lowest possible value in concrete. Further lowering of water-to-cement ratio can be achieved by adding other mineral admixtures, like fly ash or silica fume.

Fly ash

Fly ash with suitable spherical morphology can improve the workability and permits lowering the water-to-cement ratio to 0.3 in favorable cases. Fly ash should have low alkali contents and should not exhibit cementitious properties on their own, which means that the early formation of hydrates, leading to a negative impact on flow behavior, can be prohibited. Cement pastes containing fly ashes also develop a finely divided capillary pore system. The super fine fly ash, having a specific surface of 2000-4000sq.m/kg, was found to have a significant improvement on the compressive strength, tensile strength, permeability, acid resistance and chloride resistance compared with the NSC [2]. Recently, it has been found that volcanic ash, which is similar to fly ash but is more abundant in volcanic disaster areas, can also be used as partial cement replacement material to manufacture HPC [3]. In fact, the most important effects on cementitious paste microstructure due to these fine particles are changes in pore structure produced by the reduction in the grain size caused by the pozzolanic reactions and the obstruction of pores and voids by the action of the finer grains [4] as shown in Figure 2(b).

Silica Fume

Silica fume, which has a similar function as fly ash, is very effective in lowering the water-to-cement ratio needed for workable concrete in conjunction with superplasticizers because its sub-micron particle size allows it to pack between the cement grains [5]. The spaces between cement grains that would normally have to be occupied by water are now partially filled with other solid particles. This is the basis of castable densified with small particle (DSP) systems, which can have a water-to-cement ratio as low as 0.16 with a compressive strength more than 150MPa [6, 7]. In such a high strength concrete, the C-S-H gel formed by conventional hydration reacts with silica fume at high temperature to form crystalline hydrate which is a dense phase without intrinsic porosity. It is found that the workability of high strength concrete can be maintained when 6% of the cement (by weight) is replaced by silica fume [8]. In pastes with higher water-to cement ratios, silica fume is adept at subdividing the pore system [9]. Very fine silica fume is effective in eliminating the interfacial transition zone because of its good particle packing characteristics. It is found that the silica fume, in combination with superplasticizers, improves the bonding between paste and aggregate due to the formation of a dense microstructure in the interfacial transition zone [10]. Hence, there is little or no interfacial porosity resulting in a strong paste-aggregate bond in HPC.

It is noticed that the admixtures and the sand present in HPC are all very fine. The small sizes of these particles are essential in generating HPC. The basic concept of adding fine particles into the concrete mix is based on packing theory. It is found that packing density of concrete governs the performance of concrete to a large extent. Effective particle packing depends on the relative size of particles and the number of different sizes [11]. Ternary systems can give denser packing configurations than binary system (see Table 1). In principle, calcined clays, such as metakaolin, should be able to achieve dense packing configurations. However, these materials are not as effective because of their plate morphology, in contrast to the spherical morphology of silica fume particles.

Table 1: Comparison of Packing Densities [1]

Type of Packing	Size Ratios	Relative Density
Binary	1 : 7	0.86
	1 : 10	0.88
Ternary	1 : 7 : 7	0.88
	1 : 10 : 10	0.89
	1 : 100 : 100	0.92
Quaternary	1 : 7 : 7 : 7	0.91
	1 : 10 : 10 : 10	0.93
	1 : 100 : 100 : 100	0.94

4 Key Features of High Performance Concrete

HPC should have a better performance when compared to normal strength concrete. Three of the key attributes to HPC are discussed in this part. They are: strength, ductility and durability. We identify these three areas for discussion because they are the most important performance that a construction material should possess.

4.1 Strength

In practice, concrete with a compressive strength less than 50MPa is regarded as NSC, while high strength concrete (HSC) may be defined as that having a compressive strength of about 50MPa. Recently, concrete with the compressive strength of more than 200MPa has been achieved [12, 13]. Such concrete 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. [14].

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. Table 2 shows the characteristics of different type of HSC with various compositions. To illustrate the composition of the ultra high strength concrete, two examples are given in Table 3 [12, 13].

Table 2: Characteristics of High Strength Concretes

	Regular	High Strength	Very High Strength
Compressive Strength (MPa)	<50	50-100	100-150
Water-to-cement ratio	>0.45	0.45-0.30	0.30-0.25
Chemical admixtures	Not required	Water-reducing admixture or superplasticizer	Superplasticizer
Mineral admixtures	Not required	Fly ash	Silica fume
Permeability (m/s)	$>10^{-12}$	10^{-13}	$<10^{-14}$

Table 3: Composition (by weight) of Concrete with Compressive Strength of 200MPa

	Sauzeat et al. [12]	Aitcin and Richard [13]
Cement	1	1
Water	0.28	0.15
Superplasticizer	0.06	0.044
Silica fume	0.33	0.25
Fine sand	1.43	1.1
Quartz flour	0.3	N/A

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 [15]. 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 [16]. 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 4.

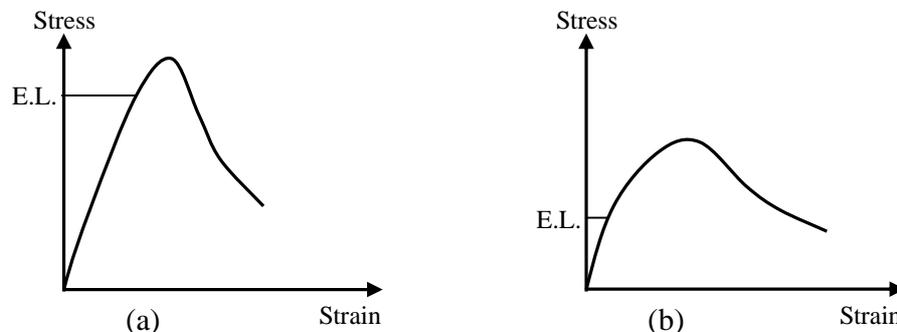


Figure 4: Schematic of Stress-strain Curve in (a) HPC and (b) NSC under Uniaxial Compression

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 are discussed. Biaxial testing with brush loading platen has been reported by Hussein and Marzouk [17]. Three concrete grades have been tested with all the combinations of compression and tension in the two major axes. Figure 5 shows the biaxial strength envelopes for three types of concrete. 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.

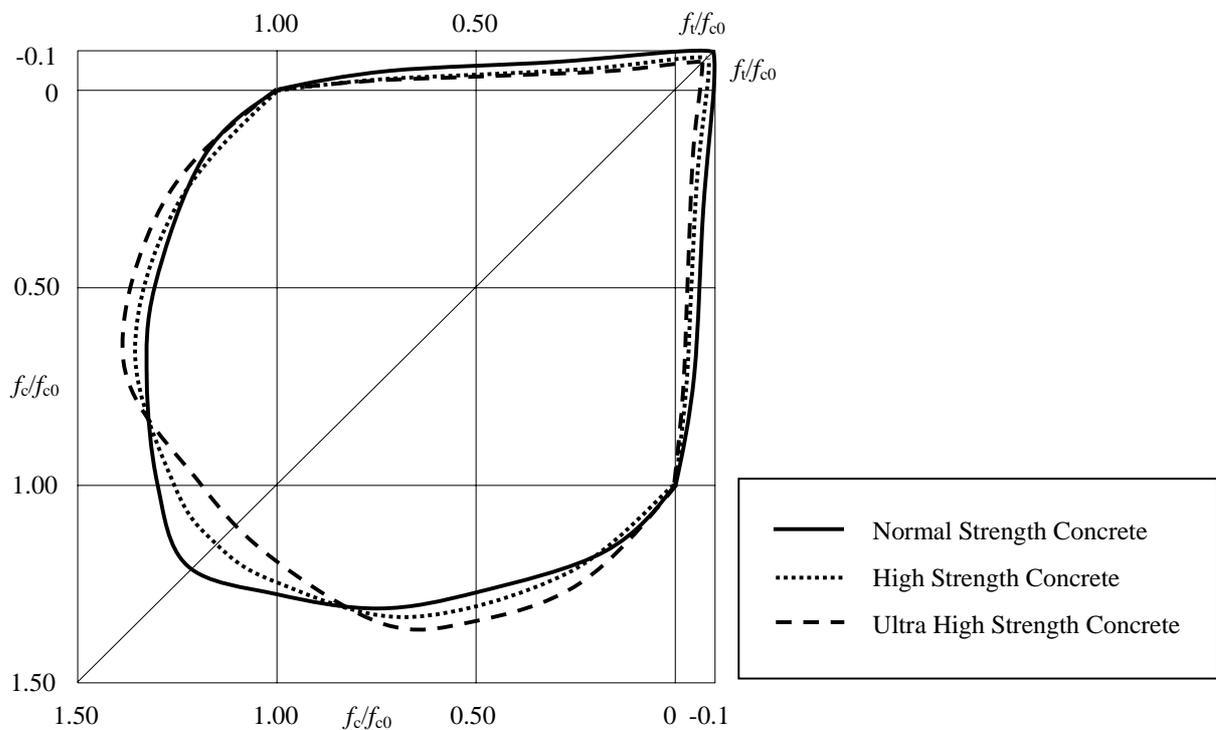


Figure 5: Biaxial Strength Envelops for Three Types of Concrete

It is known that compressive strain in the loading direction is accompanied by tensile strain in the lateral direction due to Poisson's effect. When the HPC is confined in the lateral direction either by active loading or passive constraint, the ultimate load is increased. The main effect of lateral constraint is to suppress cracks from opening and extension. Hence, it is anticipated that normal strength concrete benefits more from lateral constraint than high strength concrete does. Such expectation has been confirmed in triaxial confined test [18]. A model for evaluating the triaxial strength of concrete has been proposed by Newman [19]:

$$\frac{f_c}{f_{c0}} = \left(A \frac{\sigma_{conf}}{f_{c0}} + 1 \right)^B \quad (1)$$

Here f_c = triaxial strength, f_{c0} = uniaxial strength, σ_{conf} = confining pressure, A and B are empirical constants. For high strength concrete, B = 0.45, and for normal strength concrete, B = 0.63. This means that the relative strength increase is smaller for high strength concrete than for normal strength concrete. For practical purposes, a simplified relation can be used which is similar to the classical one proposed by Richart et al. [20]:

$$\frac{f_c}{f_{c0}} = 1 + 3 \frac{\sigma_{conf}}{f_{c0}} \quad (2)$$

This linear relationship is a lower bound of results from numerous tests.

When high strength concrete is confined by lateral compressive stresses, the material becomes more ductile. Triaxial tests on a high strength concrete with cube compressive strength of 80MPa have been carried out using brush loading platens either with two equal lateral stresses [16]. The setup of the test is shown in Figure 6. The loading condition is equivalent to that of the specimen which is initially under hydrostatic stresses, and tested to failure by increasing the stress in the axial direction. Figure 7 shows the relation between the applied stress in axial direction which equals the stress difference $\sigma_1 - \sigma_3$, and the displacement in three directions. When comparing some existing data from uniaxial and hydrostatically triaxial experiments, it is found that the displacements increase by two orders of magnitude with lateral confining stress 100MPa [16].

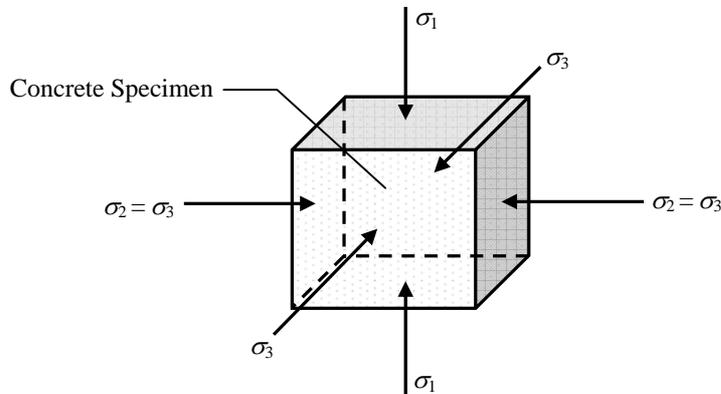


Figure 6: Experimental Setup of the Triaxial Test (Schematic)

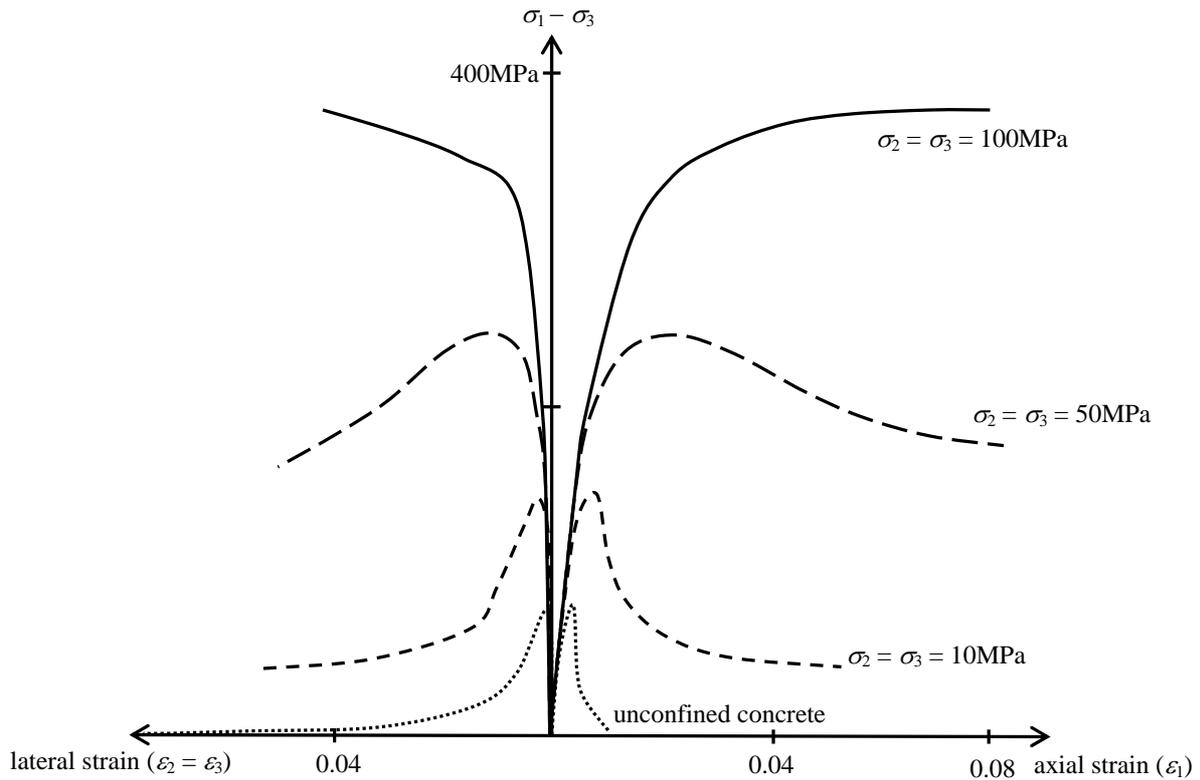


Figure 7: Stress-displacement Curve of High Strength Concrete in Hydrostatic Loading

4.2 Ductility

HPC is usually more brittle when compared with NSC, especially when high strength is the main focus of the performance. Based on the above discussion, it is known that the ductility can be improved by applying a confining pressure on HPC. Besides confinement, the ductility of HPC can be improved by altering its composition through the addition of fibers in the design mix. Concrete with fibers inside is regarded as fiber reinforced concrete (FRC). The mechanical behavior of FRC can be categorized into two classes by their tensile response: high performance FRC and conventional FRC. The conventional FRC made by adding fibers in NSC only exhibits an increase in ductility compared with the plain matrix, whereas high performance FRC made by adding fibers in HPC exhibits substantial strain hardening type of response which leads to a large improvement in both strength and toughness compared with the plain matrix (see Figure 8). Because of this increased improvement in terms of ductility, high performance FRC is referred to as ultra ductile concrete as well. In order to examine the scope of high performance FRC, it is useful to identify two performance related parameters: a) elastic limit, and b) strain hardening response. The elastic limit refers to the point of first cracking. The strain hardening response refers to the plastic region.

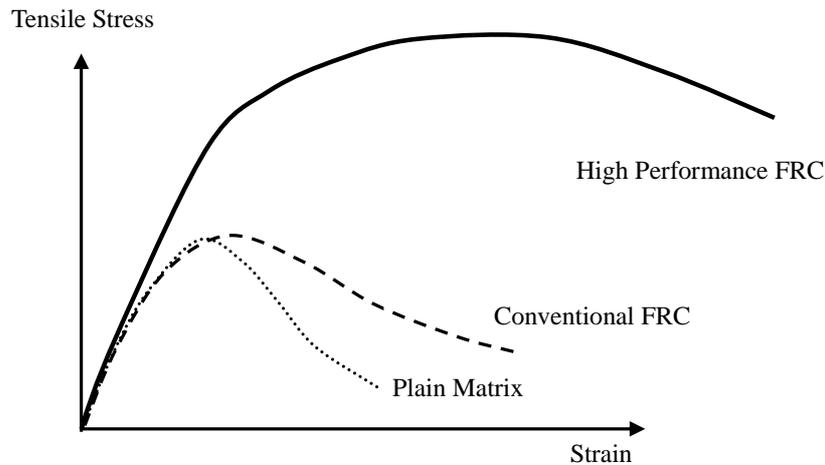


Figure 8: Mechanical Behavior of FRC Compared with Plain Matrix

Elastic Limit

Traditionally, it was assumed that the elastic limit of FRC is influenced by the tensile strength of the matrix itself and that the fibers primarily control deformation after cracking. Recently, it was reported that fibers can enhance the elastic limit provided that they effectively bridge the matrix microcracks [14]. The effectiveness of the fiber-bridging action will depend on volume fraction, length, diameter, and distribution of fibers, as well as the properties of the fiber matrix. It was found that the inherent tensile strength and strain capacity of the matrix itself was enhanced when small fibers were used [12]. When 4% (by volume) of carbon fibers were added, the first cracking, indicating the elastic limit, was observed at about 30% of the maximum tensile load [21].

Strain Hardening

Strain hardening is caused by 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 fiber pullout and fiber rupture. Uniform distribution of the fibers affects the stress distribution in the matrix and hence, higher stress is required to propagate the crack [22]. After the first crack starts, distributed multiple matrix cracking follows. The width of the cracks is usually between 1-3mm [21]. 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 fibers should be increased as well. Meanwhile, the fibers should be closely spaced and well distributed [23, 24, 25]. However, it is difficult to mix such a high content of fibers 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 fibers [26]. It was reported that the FRC obtained from extrusion exhibits substantial higher strain hardening response, higher toughness and higher flexure and tensile strengths when compared with that obtained from cast processing. Under the scanned electron microscope (SEM), it is found that extruded composite has longer fibrils and the rougher fiber surfaces when compared with the cast composite. This indicates that there is a stronger fiber-matrix bond in the extruded composite. Meanwhile, it is known that the size and amount of pores are significantly higher for the cast FRC. It is concluded that the strong fiber-matrix bond and the low porosity of the extruded FRC lead to a better mechanical performance.

The effect of fiber length on tension and flexural behavior of cast and extruded composite has also been studied [27]. It was found that the decreasing fiber length significantly enhances the tension and flexure response of the extruded FRC. In general, short fibers are advantageous when using cast process because they are easier to handle during mixing and result in less broken fibers and better dispersion in the FRC. It was also found that the distribution of the smaller fibers in the extruded FRC cross-section was more homogeneous than that of larger fibers. The same trends but to a lesser extent were observed with the cast FRC [28].

4.3 Durability

Many researchers have conducted investigations related to concrete durability and have identified that the majority of concrete durability problems are related to the resistance of concrete to permeation of water and chemical ions. Such problems include corrosion of steel reinforcement, freeze-thaw damage, and alkaline-silica reaction. The durability evaluation of concrete may be inferred by measuring the resistance of cover layer to transport mechanisms such as diffusion coefficient, coefficient of permeability, rate of absorption, concrete resistivity and corrosion rate [27, 28].

The permeability of concrete is a key factor influencing the durability of concrete. Concrete permeability is dependent on permeability of each constituent material and its geometric arrangement. The permeability of cement paste is primarily related to pore structure, which includes porosity, pore size and connectivity; while pore structure is a function of the water-to-cement ratio and the degree of hydration. The aggregates have a much lower permeability than cement pastes. However, they affect the permeability of concrete in four ways: dilution, tortuosity, interfacial transition zone and percolation [29]. The dilution effect occurs because the aggregates are less permeable than the paste. As a result, the aggregate particles block the flow paths and effectively reduce the permeable area in a cross section of concrete. The tortuosity effect occurs as a result of the impermeability of the aggregates which forces flow around the aggregate particles, and therefore increasing the length of flow paths and decreasing the flow rate. As discussed in section 3, the interfacial transition zone has a high permeability due to the high porosity in this region. The term percolation describes the flow path connecting the interfacial transition zones. The degree of percolation mainly depends on the

aggregate volume, size and spacing.

In view of the durability characteristic of HPC, it is proposed that to achieve a durable concrete, three criteria may need to be considered in concrete mix design. The three criteria are strength, permeability and crack resistance [30]. A strength criterion ensures that concrete can resist the design stress without failure. A permeability criterion ensures that concrete has a limited flow penetration rate so as to minimize vulnerability to water and chemical ion attack during the design period of service life. A crack resistance criterion ensures that concrete has a minimum capability to resist the cracking due to environmental conditions, such as thermal and moisture shrinkage.

In HPC, the interfacial transition zone effect may be reduced as a result of the improved aggregate interface properties. In addition, the effects of dilution, tortuosity and percolation can be reduced as the permeability of cement paste approaches that of aggregate. Therefore, the permeability of concrete can be best controlled by governing the permeability of the cement paste. It was demonstrated that a decrease in the water-to cement ratio was accompanied by lower porosity [31]. A decrease in the porosity means that there is a decrease in pore size and a disconnection among pores. The permeability of concrete decreases accordingly. The addition of mineral admixtures, especially silica fume, can improve both the pore structure and interfacial transition zone. It turns out that there is a drastic reduction in permeability. Although HPC generally demonstrates an increased strength and a decreased permeability, HPC may not be durable due to early age shrinkage cracking. Hence, besides a good concrete mix, it must be emphasized that good construction practice, including good curing, is essential to produce durable concrete. Self-desiccation in HPC can be very harmful to the durability if it is not controlled in the early phase of the development of hydration reaction. HPC must be cured differently from NSC. It has been demonstrated that insufficient curing increases permeability and cause surface cracking [32]. Due to the lower permeability of HPC, water curing must be applied on HPC for at least seven days after casting [33].

It is argued that water will not be able to penetrate from outside into the dense matrix of HPC and thus will not reach most cement in the interior of the structural part because of the low permeability of HPC. In order to solve this problem, it is suggested to cure the concrete from the inside core. It is found that autogenous curing is very effective in improving the durability of HPC [34, 35]. Lightweight expanded clay aggregates with high moisture content are added as an internal water reservoir so as to support the continuous hydration. This kind of concrete is named as “self-curing concrete”. In practice, self-curing concrete does not require external curing. It means that external curing due to inadequate workmanship would not impair the concrete.

5 Application of HPC in Tall Buildings

Since 1960, with the advent of high- and ultra-high-strength concrete, there has been a growing realization that building a concrete or composite column is more economical than building the column

with pure steel. In fact, studies in North America indicate that concrete or composite columns are four to five times less expensive than all-steel columns [36]. The favorable economics of HPC combined with its high performances has led to its marriage with steel, which has its own advantages namely strength, speed of construction, long span capability and lightness.

In tall building structures, the dead load plays a very severe effect on structural members, especially the columns near the ground level which are required to resist a tremendous axial load which is mainly due to the accumulated dead load from all the floors above. In fact, in a normal medium rise building (20-30 stories high), the size of the column at the ground floor may have a diameter more than three meters when normal strength concrete is used. It can be imagined that there will be no space in the ground level if normal strength concrete is used for a very tall building (more than 60 story). Hence, it is a normal trend to adopt HPC in tall building construction due to its advantages, such as high strength, high ductility and high durability. HPC may be used in all structural components of tall building, such as slabs, beams, columns and foundations; and it is usually combined with structural steel to form a composite structural element which is more effective in resisting load. The application of HPC in tall building structures can be best described through case studies. In this paper, Taipei 101 is used as an example to demonstrate how HPC is adopted in a tall building construction.

Currently, Taipei 101 Tower in Taipei, the capital city of Taiwan, R. O. C, still holds the records for the highest structural top, highest roof and highest occupied floor. These heights are: 509m at the top of the structural spire (see Figure 9), 449m at the highest roof, and 439m at the highest floor (101st floor) respectively. It should be noticed that these records were achieved despite the tower's location which is in one of the most active seismic and typhoon regions in the world. In order to reach these heights and still meet the rigidity and flexibility demands of the extreme lateral loads (earthquakes above magnitude seven and winds above 60m per second), a design of composite high rise building construction using steel and HPC was adopted.

For tall buildings, both gravity and lateral loads are very critical for the vertical members, like columns and shear walls. In Taipei 101, gravity loads are carried vertically by a variety of columns;

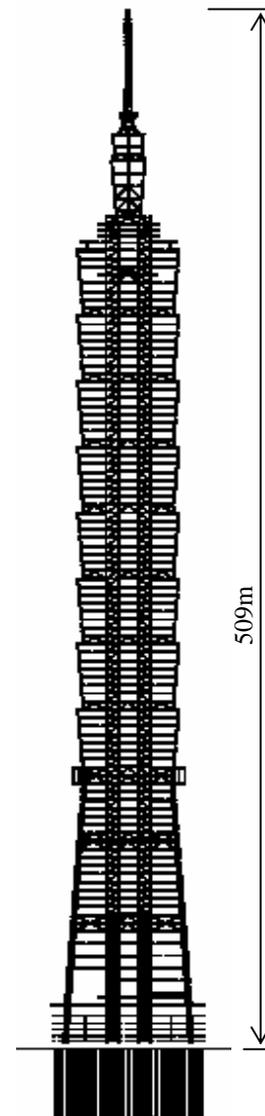
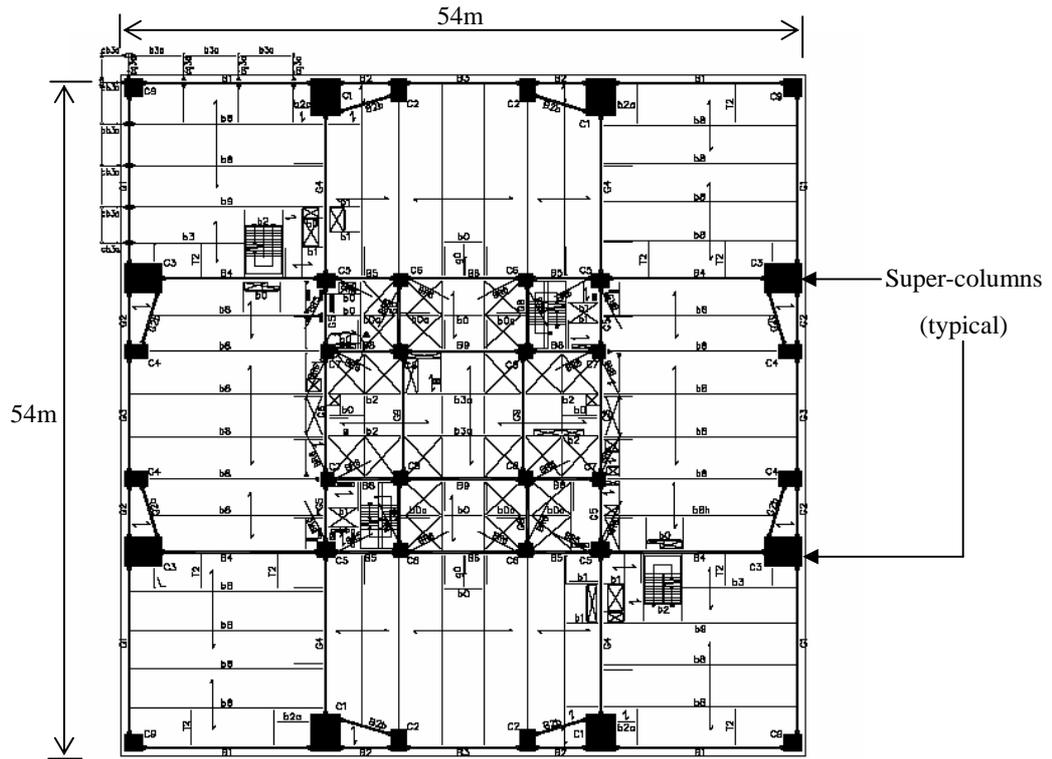


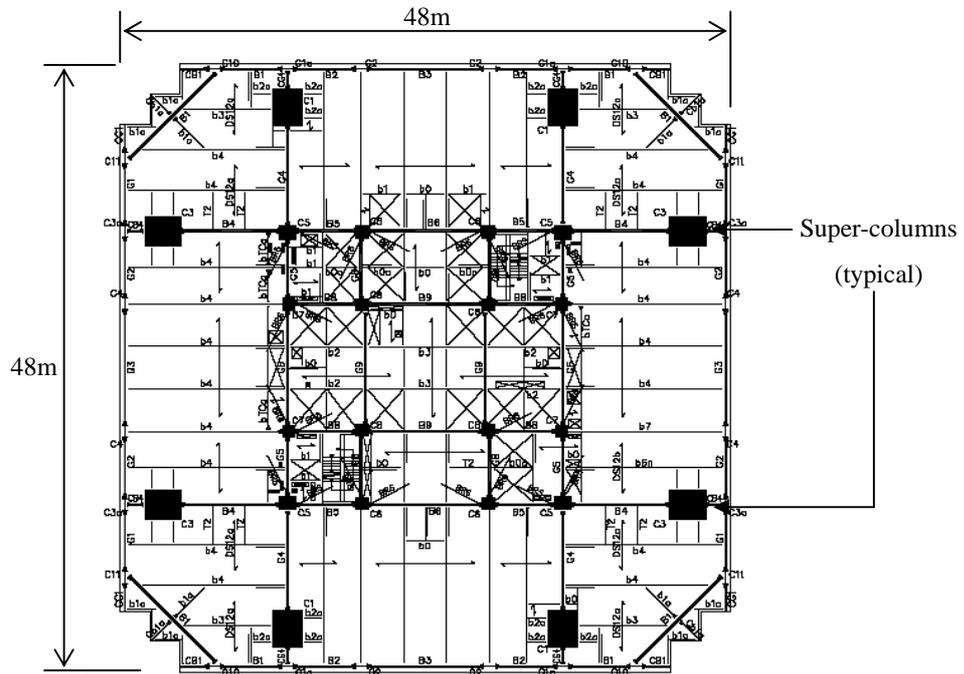
Figure 9: Frame Elevation [37]

while lateral forces will be resisted through a combination of braced frames in the core, outriggers from core to perimeter, 'super-columns' and moment resisting frames in the perimeter and other selected locations. Within the core, sixteen columns are located at the crossing points of four lines of bracing in each direction. The columns are box sections constructed of steel plates, filled with concrete for added strength as well as stiffness at the 62nd floor and below. On the perimeter, up to the 26th floor, each of the four building faces has two 'super-columns,' two 'sub-super-columns,' and two corner columns. Each face of the perimeter above the 26th floor has the two 'super-columns' continuing upward. The 'super-columns' and 'sub-super-columns' are steel box sections, filled with 10,000psi (about 70MPa) HPC on lower floors for strength and stiffness up to the 62nd floor; while the columns above level 62 are steel columns for reducing the gravity loads. The balance of perimeter framing is a sloping Special Moment Resisting Frame (SMRF) which is a rigidly-connected grid of stiff beams and H shape columns following the tower's exterior wall slope down each 8 story module (see Figure 9). At each setback level, gravity load is transferred to 'super-columns' through a story-high diagonalized truss in the plane of the SMRF. The topmost section of the building above the 91st floor is much smaller in plan. The loadings on these floors transfer to the core columns directly. Two typical floor framing plans of low story and high story are shown in Figure 10 which describe the locations of columns.

It is noticed that the super-columns are the most critical structural element in Taipei 101 to make the structure stands vertical on the ground with more than half kilometer and HPC plays an important role in the fabrication of these columns. Steel box column serves as the form of filled-in concrete while the overall column stiffness and strength are enhanced by the concrete. The cross section of a typical 'super-column' at lower level is shown in Figure 11. Even though HPC is used in these 'super-columns', the size of the column is still 3m×2.4m. The design strength of high performance filled-in concrete of the Taipei 101 is 10,000psi. However, high concrete strength is not the only performance which HPC used in Taipei 101 possesses. Many tests were performed to confirm that the concrete mixture proportion is able to meet the design requirements on the strength, shrinkage and other performance. For the construction, the high performance concrete was pumped from the bottom of the column, so the flowability is crucial to ensure there is no air trapped underneath the continuity steel plates. A high slump flow of 60±10cm is specified to ensure good workability. Bleeding and segregation are also not permitted. Design age is 90 days to keep autogenous shrinkage to as low as 300×10^{-6} m/m and increase durability through low water and low cement usage. Two mock-up tests were performed prior to construction to confirm the quality and workability of the concrete. The actual concrete proportion is listed in Table 4 and the actual slump flow is 65~70 cm. Concrete strength at the design age is about 12,000psi (about 83MPa) and still increasing.



Level 10 – Tower Framing Plan



Level 32 – Tower Framing Plan

Figure 10: Typical Floor Framing Plans [37]

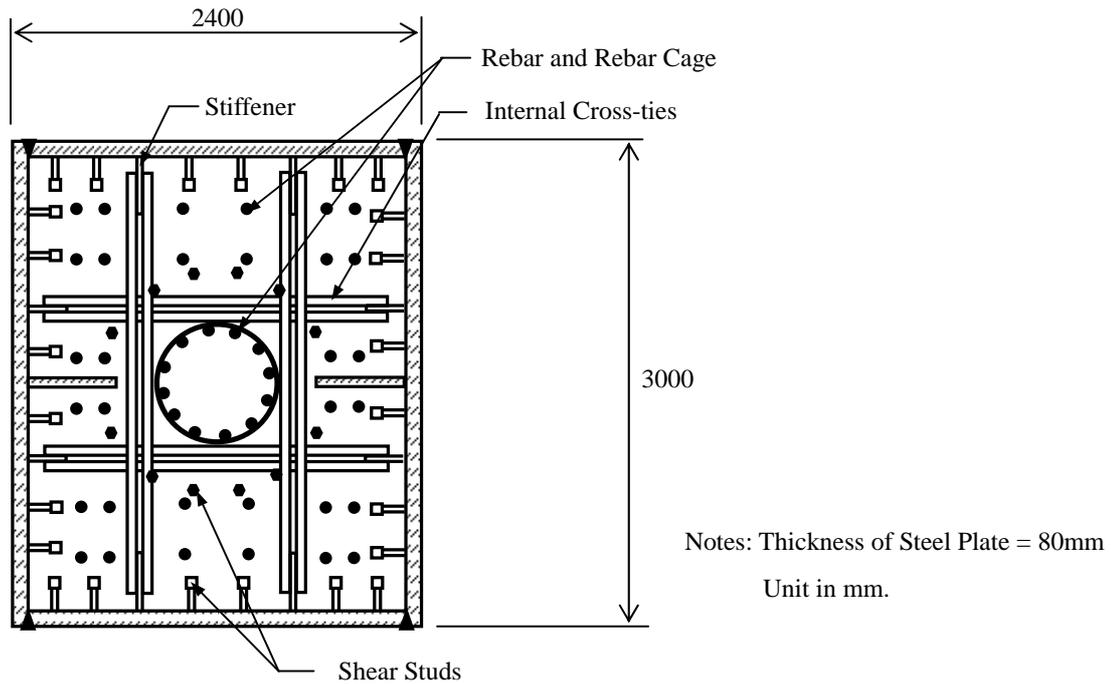


Figure 11: Typical Cross-section of Super-column at the level between 8th and 17th Floor. [37]

Table 4: 10,000psi Concrete Mixture Proportion used in Taipei 101 [37]

Design Strength (90days)	Slump	Slump Flow	Max. Dia. of Coarse Aggregates	Unit Quantity (kg/m ³)								
				Water	Cementitious Materials			Aggregates			Admixture	
	Water Cementitious Ratio	Cement	Slag		Silica Fume	Coarse Agg.	Fine Agg.	Limestone				
	(cm)	(cm)	(in)	W	W/(C+F)	C	F1	F2	G	S	LS	HP
10,000psi (HPC)	25±2	60±10	0.5	160	0.31	340	150	30	760	957	--	6.24
	25±2	60±10	0.5	160	0.31	340	130	30	772	920	80	7.25

Undoubtedly, the structural innovations in the Taipei 101 Tower cannot be accomplished without the use of HPC. The use of HPC allows that reasonable free floor space in tall building can be maintained. As a result, it gives a possibility to construct a tall building which has a height more than half kilometer. Such height is impossible to be achieved if normal strength concrete is used. In the coming few years, newer buildings in Dubai and China will be constructed and these buildings probably will cede the various height crowns from Taipei 101. New structural and material innovations will be required for the construction of tall buildings higher than Taipei 101.

6 Conclusion

This paper provides an overview of the fundamentals of high performance concrete (HPC) and its application in tall buildings. The microstructure of HPC and its influence on concrete performance is presented. In manufacturing the material the use of densified small particle systems contribute to the high strength and low permeability of HPC. The three key attributes of HPC, strength, ductility and durability are discussed. Fly ash, silica fume and superplasticizer are important ingredients to manufacture high strength concrete. In order to produce HPC with high ductility, fiber is a critical element which should be present in the design mix. In order to create durable HPC, it is necessary to use a proper mix design and apply an effective curing. It is suggested that three criteria should be considered to produce durable concrete. These criteria are strength, permeability and cracking resistance. Because of its advantageous characteristics, HPC is now widely used in tall building construction. In this paper, Taipei 101 is used as an example to demonstrate the application of HPC in tall building construction.

7 References

- [1] Young, J.F. (2000), "The Chemical and Microstructural Basis for High Performance Concrete", *Proceedings of High Performance Concrete – Workability, Strength and Durability*, Hong Kong, v 1, 2000, p 87-103
- [2] Malathy, R. (2003), "Role of super fine fly ash on high performance concrete", *Role of Concrete in Sustainable Development - Proceedings of the International Symposium dedicated to Professor Surendra Shah - Celebrating Concrete: People and Practice*, 2003, p 425-434
- [3] Hossain and Lachemin (2007), "Strength, ductility and micro-structural aspects of high performance volcanic ash concrete", *Cement and Concrete Research*, v 37, p 759-766
- [4] Isaia, G.C., Gastaldini, A.L.G. and Moraes, R. (2003), "Physical and pozzolanic actions of mineral additions on the mechanical strength of high performance concrete", *Cement and Concrete Composite*, v 25, p 69-76
- [5] Kwan, A.K.H (2000), "Use of condensed silica fume for making high-strength, self-consolidating concrete", *Canadian Journal of Civil Engineering*, v 27, n 4, Aug, 2000, p 620-627
- [6] Wise, S., Satkowski, J.A., Scheetz, B., Rizer, J.M., McKenzie, M.L. and Double, D.D. (1985), "The development of a high strength cementitious tooling/molding material", *Proceedings of Materials Research Society Symposium*, v 42, p 253-264
- [7] Richard, P. and Cheyrezy, M. (1995), "Composition of reactive powder concretes", *Cement and Concrete Research*, v 25, n 7, p 1501-1511
- [8] Hsieh, H.Y. (1992), "*Packing Characteristics and Interfacial Microstructure of DSP Cement*

Mortars”, MS Thesis, University of Illinois, Urbana IL.

- [9] Sellevold, E.J. and Nilsen, T. (1987), “Condensed silica fume in concrete: a world review”, *Supplementary Cementing Materials for Concrete*, ed. By V.M. Malhotra, CANMET, Ottawa, Canada, p167-246
- [10] Lee, K.M. and Buyukozturk, O. (1995), “Fracture toughness of mortar-aggregate interface in high-strength concrete”, *ACI Materials Journal*, v 92, n 6, p 634-642
- [11] Gray, W.A. (1968), “*The Packing of Solid Particles*”, Chapman & Hall, London, U.K.
- [12] Sauzeat, E., Feylessoufi, A., Villieras, F., Yvon, J., Cases, J. and Richard, P. (1996), “Textural analysis of reactive powder concretes”, *4th International Symposium on Utilization of High-strength / High-performance Concrete*, Paris.
- [13] Aitcin, P. and Richard, P. (1996), “The pedestrian/bikeway bridge of Sherbrooke”, *4th International Symposium on Utilization of High-strength/High-performance Concrete*, Paris.
- [14] Shah, S. and Ahmad, S. (1994), “*High performance concrete applications*”, Edward Arnold, London.
- [15] Dahl, K.K.B. (1992), “*A constitutive model for normal- and high-strength concrete*”, ABK Report No. R 287, Dept. Struct. Eng., TU Denmark, Lyngby.
- [16] van Geel, E. (1998), “*Concrete Behavior in Multiaxial Compression, Experimental Research*”, Doctorate Thesis, TU Eindhoven.
- [17] Hussein, A. and Marzouk, H. (2000), “Behavior of high-strength concrete under biaxial stresses”, *ACI Materials Journal*, v 97, n 1, p 27-36
- [18] Setunge, S., Attard, M.M., Darvall, P. and Le, P. (1993), “Ultimate strength of confined very high strength concrete”, *ACI Structural Journal*, v 90, n 6, p 632-641
- [19] Newman, J.B. (1979), “Concrete under complex stress”, Chapter 5 in *Developments in Concrete Technology-1*, ed. By F.D. Lydon, Appl. Sci. Publ., Barking, p 151-219
- [20] Richart, F.E., Brandtzaeg, A. and Brown, R.L. (1929), “*Failure of plain and spirally reinforced concrete in compression*”, Bulletin 190, Illinois Eng. Exp. St., University of Illinois, Champaign.
- [21] Shao, Y and Shah, S.P. (1997), “Mechanical Properties of PVA Fiber Reinforced Cement Composites Fabricated by Extrusion Processing”, *ACI Material Journal*, v 94, n 6, p 555-564
- [22] Kazuhisa, S., Noayoshi, K. and Yasuo, K. (1998), “Development of carbon fiber reinforced cement”, *Advanced Materials: The big Payoff National SAMPE Technical Conference*, Publ by SAMPE, Covina, CA, U.S.A, p 789-802
- [23] Land, D.A., Ouyang, C. and Shah, S.P. 1996, “Behavior of cement based matrices reinforced by randomly dispersed microfibers”, *Advanced Cement Based Materials*, v 3, p 20-30
- [24] Bentur, A. (1989), “Fiber reinforced cementitious materials”, *Material Science of Concrete*, ed. by J.P. Skalny, The American Ceramic Society, p 223-279
- [25] Balaguru, P.N. and Shah, S.P. (1992), “*Fiber Reinforced Cement Composites*”, McGraw Hills, Inc., Publishers, New York.

- [26] Shah, S.P. (2000), “High performance concrete: past, present and future”, *Proceedings of High Performance Concrete - Workability, Strength and Durability*, Hong Kong, v 1, p 3-29
- [27] Dhir, R.K., Jones, M.R. and Ng, L.D. (1993), “PFA concrete: chloride diffusion rates”, *Magazine of Concrete Research*, v 45, n 182 p 1-9
- [28] Francy, O. and Francois, R. (1998), “Measuring chloride diffusion coefficient from non-steady state diffusion tests”, *Cement and Concrete Research*, v 28, n 7 p 947-953
- [29] Wang, K., Igusa, T. and Shah, S.P. (1998), “Permeability of concrete – relationships to its mix proportion, microstructure, and microcracks”, *Material Science of Concrete: Sidney Diamond Symposium, Special Volume*, Wiley.
- [30] Shah, S.P. and Wang, K. (1997), “Microstructure, Microcracking, Permeability, and Mix Design Criteria of Concrete”, *The Fifth International Conference on Structural Failure, Durability and Retrofitting*, p 260-272, Singapore, November 27-28, 1997.
- [31] Powers, T.C. and Brownyard, T.L. (1948), “Studies on the physical properties of Hardened Portland Cement Paste”, *PCA Research Bulletin* 22, March 1948.
- [32] Guse, U. and Hilsdorf, H.K. (1995), “Surface cracking of high strength concrete”, *High Performance Concrete: Material Properties and Design*, ed. by F.H. Wittmann and P. Schwesinger, Aedificatio, Freiburg, Germany.
- [33] Aitcin, P.C. (2003), “The durability characteristics of high performance concrete: a review”, *Cement and Concrete Composite*, v 25, p 409-420
- [34] Weber, S. and Reinhardt, H.W. (1997), “A new generation of high performance concrete: concrete with autogenous curing”, *Advanced Cement Based Materials*, v 6, p 59-68
- [35] Reinhardt, H.W. and Weber, S.(1998), “Self-curing high performance concrete”, *Journal of Materials in Civil Engineering*, Nov 1998, p 208-209
- [36] Taranath, B.S. (1998), *Steel, Concrete, & Composite Design of Tall Buildings*, McGraw-Hill
- [37] Shieh, S.S., Chang, C.C. and Jong, J.H. (2003), “Structural Design of Composite Super-columns for the Taipei 101 Tower”, *Proceedings of International Workshop on Steel and Concrete Composite Constructions*, National Center for Research on Earthquake Engineering of Taiwan, 8-9 October 2003, p 25-33