Higher Performance Concrete

Prepared by Engineer

ASO ABDULGAFUR FAQE RAHIM

١) Introduction to High Performance Concrete

Concrete is a versatile material which consists of binder, aggregates and water. It was used in one form or the other by early civilizations. The Portland Cement Concrete we use today traces back to the first half of the ١٩th century when Portland cement was discovered in England. The rapid global development after World War II and advancement in engineering and material sciences necessitated to think beyond conventional concretes in order to achieve longer spans, durable and economical structures. This is where the story of High Performance Concrete (HPC) started.

High-performance concrete (HPC) is defined as concrete which meets specialperformance and uniformity requirements that cannot always be achieved by using onlythe conventionalmaterials and mixing, placing and curing practices. The performance Requirements involve enhancements of placement and compaction withoutsegregation, long-term mechanical properties, early-age strength, toughness, volumestability, or service life in severe environments.

Concretes designated as HPC should pass very strict performance criteria as compared to normal concretes. The most important aspect is the durability. Strength, ductility, modulus of elasticity, serviceability and long-term environmental effects are equally important. HPC can be either normal-strength or high-strength depending on the intended use; however, nearly all high-performance concretes aim at high durability. This is explained by the fact that, a high-strength low-durability concrete will eventually degrade if subjected to non-friendly harsh environments.

Different organizations suggest different guidelines to classify concrete as normal or high strength. For example, ACI defines high strength concretes as those having a cylinder compressive strength exceeding ٤٢ MPa. Globally, numerous buildings and bridges have been built using concretes of strength in excess of ١٥٠ MPa. In laboratories, even higher strengths have been achieved. However, it is worth noting that, the reinforcement to be used with high-strength concretes will show lower ductility. This sets limitations to the practical concrete strengths we can use without compromising on ductility(Nawy, ٢٠٠٠)

١.١ What are the main ingredients of HPC?

The main ingredients of High Performance Concrete are:

- Common but good quality aggregates of smaller size typically ١٠mm,
- Ordinary Portland cement (Type I) at a very high content ٤٥٠-٥٥٠ kg/m^٣ (rapid hardening Type III may be used when high early strength is required),
- Cementations Mineral Admixtures: Silica Fume, Fly Ash, GGBFS. The most important is the Silica Fume at ٥-١٥% by mass of the total cementations' materials.
- Super plasticizer: A high dosage of ٥-١٥ liters/m^٣ of concrete is used to reduce the water content by ٤٥-٧٥ kg/m^٣.
- Good quality mixing water and fine aggregates are also present. Some other admixtures may be used depending on the need for them, such as: polymers, epoxies, fibers, corrosion inhibitors, air-entraining admixtures.The main characteristic of HPCs is the very low water/cement ratio ٠.٢-٠.٣٥. This achieved by careful selection, proportion and production control of the above ingredients. It is worth noting, that the two most influential ingredients which differentiate HPC from conventional concretes are: Silica Fume and Super plasticizers(Neville, ١٩٩٥)

Figure ١.١: Higher – Performance Concrete is often used in (Bridge and Tall building)

١.٢Composition 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).

The Strategic Highway Research Programme (SHRP)

SHRP defined HPC as :

١. Concrete with a maximum water-cementitious ratio (W/C) of ٠.٣٥
٢. Concrete with a minimum durability factor of ٨٠%, asdetermined by ASTM C ٦٦٦
٣. Concrete with a minimum strength criteria of either
٤. - ٢١ Mpa within ٤ hours after placement (Very Early Strength, VES),
٥. - ٣٤ MPa within ٢٤ hours (High Early Strength, HES), or
٦. - ٦٩ MPa within ٢٨ days (Very High Strength, VHS)

High performance concrete can hence be defined as an engineered concrete with low water/binder concrete with an optimized aggregate/binder ratio to control its dimensional stability and which receive an adequate water curing.

١.٣ Comparison between the Microstructure of HPC and NSC

The microstructure of concrete can be described in threeaspects, 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. Thepore structure refers to the gel pores, capillary pores and voids, as well as their connections within thehardened 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, whichconsists of cement, aggregate and water. Figure ١.٢ shows the microstructure of NSC.(Büyüköztürk & Lau)

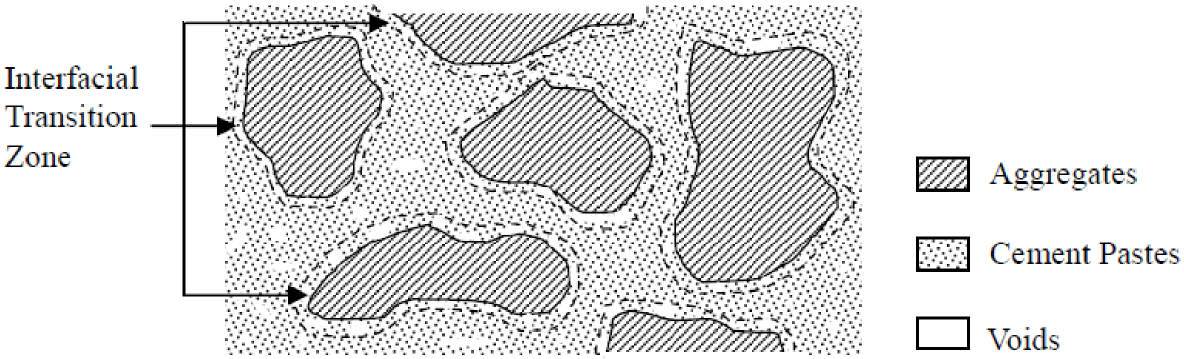


Figure ١.٢: Microstructure of NSC

The porosity in concrete is due togel pores, capillary pores and voids. Hence, C-S-H gel is low density phase which is space filling, butstrength limiting. For concrete with strength below ٥٠MPa, the increase in strength is primarilyattained by reducing the capillary porosity alone. However, only reducing the capillary porosity is notenough to generate a concrete strength higher than ٥٠MPa. The gel porosity should also be reducedtogether 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 crystallinephases, which eventually leads to the production of HPC. A high permeabilityusually means low durability as the inner part of concrete is more readily to be attacked by surroundingchemicals. However, with a high permeability, the concrete can get a higher early strength usingsuitable curing process because continuous hydration can be carried out with the permissible flow ofwater within the pore network. The porosity and the pore connectivity of NSC are usually higher thanthat of HPC due to the absence of fine particles (see Figure ١.٣)(Büyüköztürk & Lau)

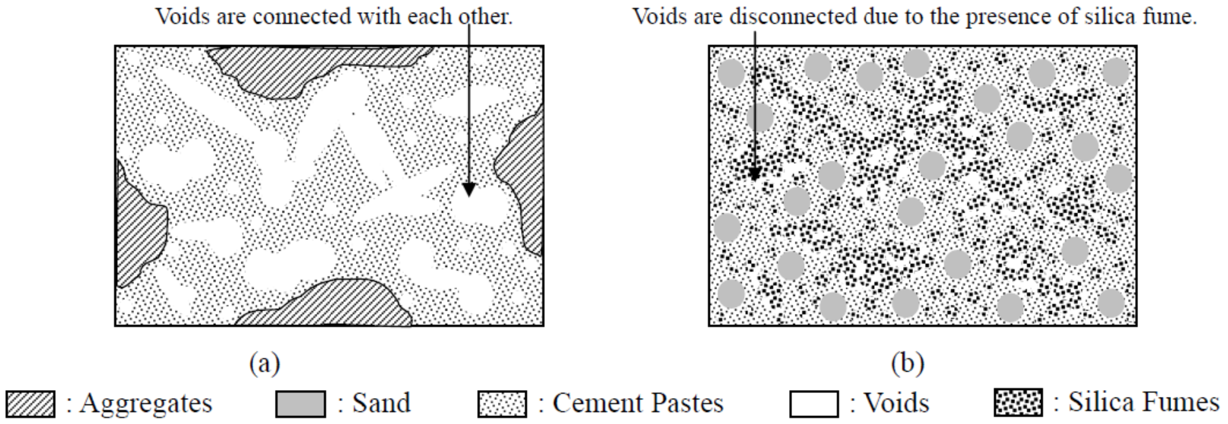


Figure ١.٣: Pore Connectivity in (a) NSC and (b) HPC

In order to improve the concrete performance, the following three aspects are considered: (a) thehydrated 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 asfollows. Firstly, the hydrated cement paste can be strengthened by reducing the gel porosity inside thepaste. As mentioned previously, the crystalline of C-S-H gel has a lower gel porosity compared toamorphous C-S-H gel. By adding suitable admixture (e.g. silica fume), crystalline C-S-H gel can beachieved. Secondly, the porosity in concrete can be lowered by adding suitable fine admixture whichcan fill up the empty space inside concrete. In HPC, very fine admixture, such as silica fume or flyash, 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 thecapillary network as shown in Figure ١.٣. Thirdly, the interfacial transition zone can be toughened bylowering 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 ٠.٢)become feasible to be adopted. Fine admixtures, like silica fume or fly ash is added as well toimprove the particle packing in the interfacial transition zone. It is noticed that in order to improvethe 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. Figure١.٤ 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 performanceare discussed in the following.Figure ١.٤: Microstructure of HPCSuperplasticizer.(Büyüköztürk & Lau)

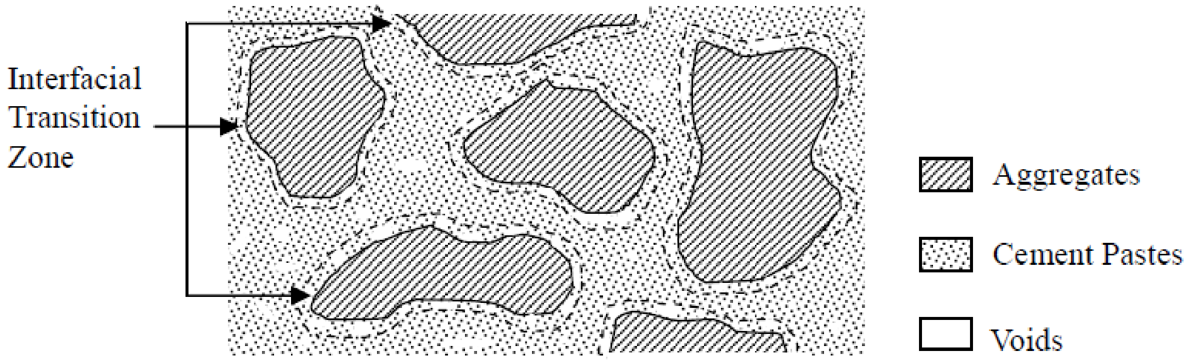


Figure ١.٤: Microstructure of HPC

١.٤ What is the difference between Special Concrete and HPC?

The most distinctive feature of HPC is that it performs well when subjected to the intended environment for the whole design life of the structure. On the other hand, special concrete are meant for achieving specific properties for special applications. For example, self-flowing concrete may be produced for use where access is difficult, reinforcement is congested, or high-workability is needed. This makes concrete placing in its fresh-state easy, but long-term hardened-state properties would not be improved if not initially intended for in mix-design and production. Differences between NSC and HSC

- In normal strength concrete, the micro cracks form when the compressive stress reaches ~ ٤٠% of the strength. The cracks interconnect when the stress reaches ٨٠-٩٠% of the strength
- For HSC, Iravani and Macgregor reported linearity of the stress-strain diagram at ٦٥ to ٧٠, ٧٥ to ٨٠ and above ٨٥% of the peak load for concrete with compressive strengths of ٦٥, ٩٥, and ١٠٥ MPa.Typical Classification:

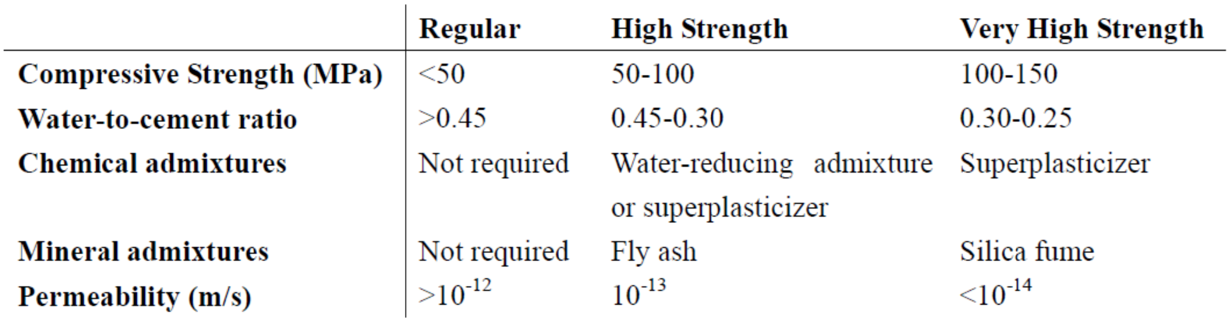
Normal Strength ٢٠-٥٠ MPa
High Strength ٥٠-١٠٠ MPa
Ultra High Strength ١٠٠-١٥٠ MP
Especial> ١٥٠ MPa

١.٥ Key Features of High Performance Concrete

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

١.٥.١ Strength

In practice, concrete with a compressive strength less than ٥٠MPa is regarded as NSC, while highstrength concrete (HSC) may be defined as that having a compressive strength of about ٥٠MPa.Recently, concrete with the compressive strength of more than ٢٠٠MPa has been achieved(Kreijger, ١٩٨٧).Such concrete is defined as ultra-high strength concrete. As the compressive strength of concrete hasbeen steadily increasing with ample experimental validation, the commercial potential of high strengthconcrete became evident for columns of tall buildings in ١٩٧٠s in the U.S..In general, the addition of admixture does not improve the concrete strength only. Usually, otheraspects of performance, like ductility and durability, are also enhanced. Hence, the characteristics ofHSC are very similar to those of HPC. Table ٢ shows the characteristics of different type of HS with various compositions(Aitcin, ١٩٩٤)



	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}	$<10^{-14}$

HSC is considerably more brittle than NSC. Meanwhile, HSC has a larger Young’s modulus thanNSC and the post-peak softening branch is steeper. HSC behaves linearly up to a stress levelwhich is about ٩٠% of the peak stress, whereas lower strength concrete shows nearly no linear part atall.

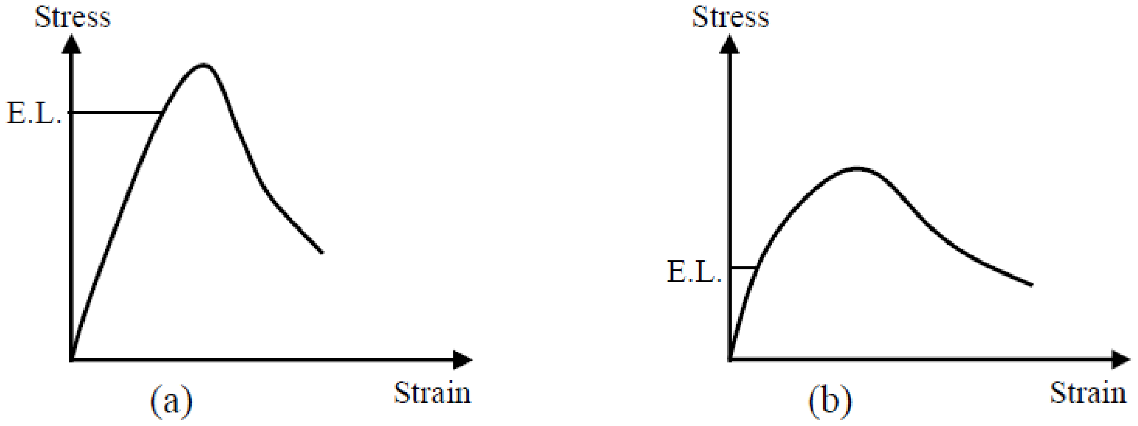


Figure١.٥: Schematic of Stress-strain Curve in (a) HPC and (b) NSC under Uniaxial Compression

١.٥.٢ 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 beimproved by applying a confining pressure on HPC. Besides confinement, the ductility of HPC canbe 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 behaviour of FRCcan be categorized into two classes by their tensile response: high performance FRC and conventionalFRC. The conventional FRC made by adding fibers in NSC only exhibits an increase in ductilitycompared 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 bothstrength and toughness compared with the plain matrix (see Figure ١.٦). Because of this increasedimprovement in terms of ductility, high performance FRC is referred to as ultra-ductile concrete as well.

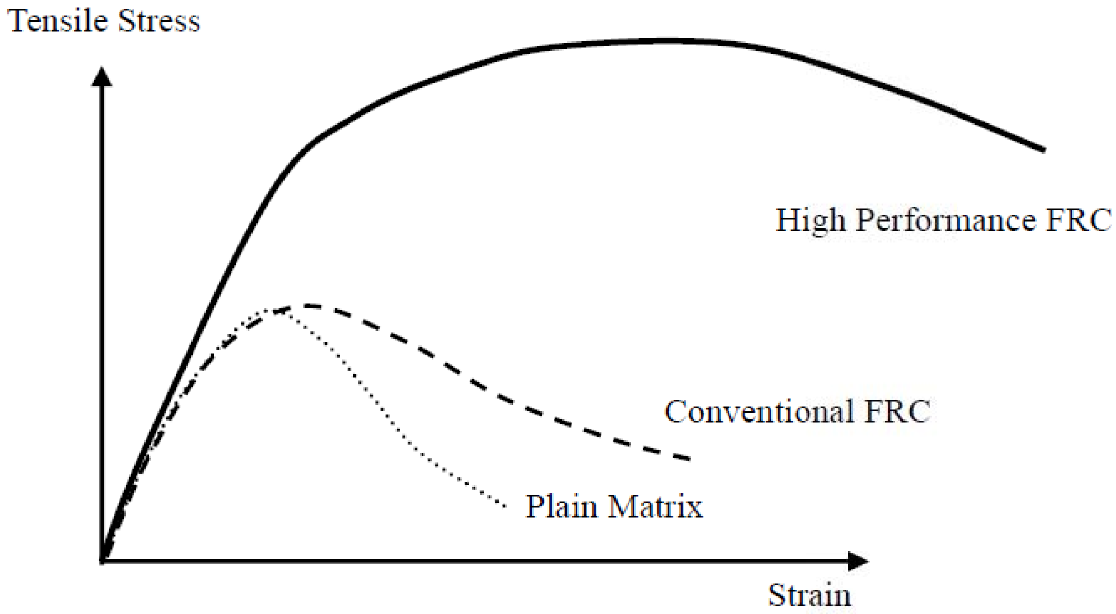


Figure ١.٦: Mechanical Behavior of FRC Compared with Plain Matrix

١.٥.٣ 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 [٢٧, ٢٨]. 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. 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 ٣, 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 the١٣aggregate volume, size and spacing.(Aitcin, ١٩٩٤)

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. A strength criterion ensures that concrete can resist the designstress without failure. A permeability criterion ensures that concrete has a limited flow penetrationrate so as to minimize vulnerability to water and chemical ion attack during the design period of servicelife. A crack resistance criterion ensures that concrete has a minimum capability to resist the crackingdue to environmental conditions, such as thermal and moisture shrinkage.(Aitcin, ١٩٩٤)

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 asthe permeability of cement paste approaches that of aggregate. Therefore, the permeability ofconcrete can be best controlled by governing the permeability of the cement paste. It wasdemonstrated that a decrease in the water-to cement ratio was accompanied by lower porosity. Adecrease in the porosity means that the 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.

HPCmust be cured differently from NSC. It has been demonstrated that insufficient curing increasespermeability and cause surface cracking. Due to the lower permeability of HPC, water curingmust be applied on HPC for at least seven days after casting.(Aitcin, ١٩٩٤)

١.٥.٣.١ Examples of Durability-Related Problems and their Solution:

Many durability problems arise during the life of the structural concrete. They happen at different times due to different causes, and we have to study their individual behavior and their overall effect on the ability of the concrete to resist them. Material-related problems can be either caused by physical or chemical mechanisms. Some of these are presented below (Mather,B. ٢٠٠٠):

- **Deterioration of hardened cement paste due to repeated cycles of freezing and thawing:**
  This appears in the first ١-٥ years in the form of scaling or map cracking, generally initiating near joints or cracks; with possible internal disruption of concrete matrix. It can be prevented or reduced by addition of air-entraining agent to establish protective air-void system.
- **Fracturing or excessive dilation of susceptible coarse aggregates due to freezing and thawing:**
  This appears in ١٠-١٥ years in the form of cracks parallel to joints and other cracks and later spalling; with possible presence of surface staining. It can be prevented by use of non-susceptible aggregates or reduction in maximum coarse aggregate size.
- **Deicer scaling and deterioration:**
  It takes ١-٥ years to appear in the form of scaling or crazing of the slab surface. Deicing chemicals can amplify deterioration due to freezing and thawing and may interact chemically with cement hydration products. It can be prevented by limiting w/c ratio to no more than ٠.٤٥, and providing a

minimum ٣٠-day “drying” period after curing before allowing the use of deicers.

- **Alkali-Silica Reactivity (ASR):**

  It appears in ٥-١٥ years in the form of map cracking over entire slab area with accompanying spalling .ASR is caused by reaction between alkalies in cement and reactive silica in aggregate resulting in an expansive gel and the degradation of aggregate particles. It can be prevented by use of non-susceptible aggregates, addition of pozzolans, limiting alkalies in cement, minimizing exposure to moisture, and addition of lithium salts.

- **Alkali-Carbonate Reactivity (ACR):**

  This is similar to ASR except that the expansive reaction occurs between alkalies in cement and carbonates in certain aggregates containing clay fractions.

- **External Sulfate Attack:**

  It appears in ١-٥ years in the form of fine cracking near joints and slab edges or map cracking over entire slab area. It is caused by expansive formation of ettringite that occurs when external sources of sulfate (e.g. groundwater, deicing chemical) react with chemically active aluminates in cement or fly ash. It can be prevented by minimizing tricalcium aluminate content in cement or using blended cements, Class F fly ash, or GGBFS.

- **Internal Sulfate Attack:**

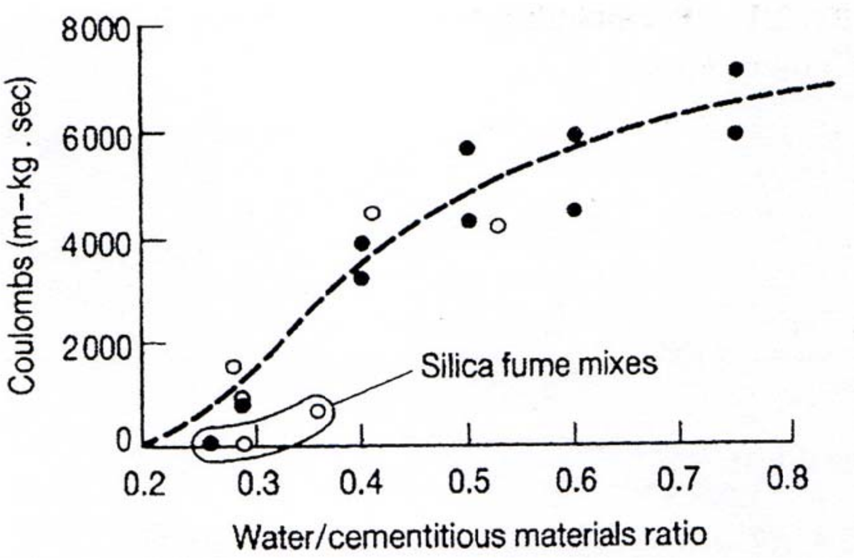
  Similar to above but ettringite is due to internal sources of sulfate. In addition to above, use low-sulfate cement and avoid high curing temperatures.

- **Corrosion of embedded steel:** It appears in ٣-١٠ years in the form of spalling, cracking, and deterioration of areas above or surrounding embedded steel. It is caused by chloride ions penetrating concrete. It can be prevented by reducing the permeability of the concrete, providing adequate concrete cover, and coating steel.

١.٥.٣.٢Factors affecting durability of concrete:

When concrete is placed to the service environment, it is subject to chemical, physical, and mechanical processes which can damage its durability. One of the main problems is the penetration of harmful substances in solution to the concrete. Permeability is the degree of this penetration and it is a function of void structure of the concrete matrix.

In order to get high-performance concrete, we must produce very compact, dense and impermeable concrete by using low-permeable aggregates, low-fineness pozzolanic materials such as Silica Fume, Fly Ash, and Ground Granulated Blast Furnace Slag (GGBFS). The use of Silica Fume decreases the permeability to minimum due to its high fineness, high pozzolanic reactivity, and elimination of bleeding. Fig ٢.١ shows that by using Silica Fume with low w/c ratio, the permeability can be substantially reduced (Nawy, ٢٠٠٠)



١.٥.٣.٣ Effect of Course and Fine Aggregates on durability

Aggregates are the main ingredient of concrete in terms of volume because they represent ٧٥-٨٥% of the total mass of concrete. There are different natural and artificial sources of aggregates which give different densities and qualities. Even recycled aggregates are nowadays used for economic and environmental reasons. Nevertheless, HPC needs strong and durable aggregates, and for this we have to study the properties of the specific aggregate in the laboratory. According to the type of aggregate used, concrete mixtures can be classified as:

١) Normal-weight aggregate concrete (normal density)
٢) Sand-lightweight aggregate concrete (medium density)
٣) All-lightweight aggregate concrete (low density)

Aggregate quality is one of the important factors which control long-term durability of both normal and high-strength concretes. We have to select an aggregate which is suitable for the intended environment. Generally, aggregates should have low permeability, high resistance to freezing, thawing, abrasion and expansion. They should exhibit low or no ASR or ACR as discussed in Section ٢.٢. If in some cases, we use reactive aggregates, then to reduce their reactivity we have to use blended cements or pozzolanic materials. All aggregates have to be well graded to achieve a workable and durable concrete(Nawy, ٢٠٠٠). One of the reasons of using aggregates is to reduce the plastic shrinkage of cement paste which results from moisture escape. Aggregates themselves should also have minimum drying shrinkage as this is a long process and the concrete may take several years to achieve complete drying. Following factors need to be considered during the selection of the coarse aggregates for minimizing shrinkage (NAWY, ٢٠٠٠).*Aggregate:* The aggregate acts to restrain the shrinkage of the cement paste depending on the properties of aggregate. Thus concretes containing high content of aggregates having high modulus of elasticity and rough surfaces are more resistant to shrinkage process.

١) *Water/cementitious material ratio*: as this goes higher, shrinkage effects increase.
٢) *Size of the concrete element*: Both the rate and total magnitude of shrinkage decrease with an increase in the volume of the concrete element. However, the duration of shrinkage is longer for larger members since more time is needed for drying to reach internal regions.
٣) *Medium ambient conditions*: The rate of shrinkage is lower at high states of relative humidity. Furthermore, the shrinkage becomes stabilized at low temperatures.
٤) *Amount of reinforcement*: Reinforced concrete shrinks less than plain concrete; the relative difference is a function of the reinforcement percentage.

٥) *Admixtures*: This effect varies depending on the type of the admixture. An accelerator such as calcium chloride and Pozzolans can increase the shrinkage, whereas air-entraining agents have little effect.

٦) *Type of cement*: Rapid-hardening cement concrete shrinks somewhat more than other types, while shrinkage-compensating cements minimize or eliminate shrinkage cracking if used with restraining reinforcement.

٧) *Carbonation*: Carbonation shrinkage results from the reaction between CO٢ present in atmosphere and that present in cement paste. If both carbonation and drying shrinkage take place simultaneously, less overall shrinkage develops.

٢.٢.١ Mineral admixture

The major difference between conventional cement concrete and High Performance Concrete is essentially the use of mineral admixtures in the latter. Some of the mineral admixtures are, Fly ash ,Silica fumes , Carbon black powder and Anhydrous gypsum based mineral additives Mineral admixtures like fly ash and silica fume act as puzzolonic materials as well as fine fillers, thereby the microstructure of the hardened cement matrix becomes denser and stronger. The use of silica fume fills the space between cement particles and between aggregate and cement particles. It is worth while noting that addition of silica fume to the concrete mix does not impart any strength to it, but acts as a rapid catalyst to gain the early age strength.

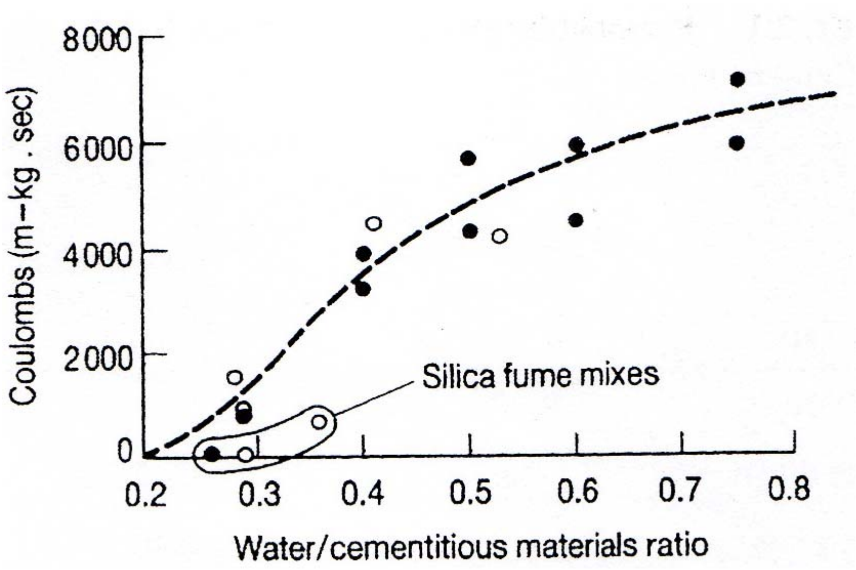


Figure ٢.١: chloride ion permeability vs. w/cm ratio, and the effect of silica fume in reducing permeability to a minimum ((Nawy, ٢٠٠٠)

١.٦ Serviceability Considerations

Serviceability comprises of two main elements i.e. cracking and deflection. Cracking is caused by shrinkage (plastic & drying), restraining from expansion/contraction, and flexural deformations induced by applied stresses. The gross moment of inertia decreases after the section cracks, thereby reducing stiffness and producing large deformations and deflections. Cracking results in surface deterioration and ingress of harmful substances which will attack the reinforcement and may ultimately cause the concrete to fail. To minimize cracking, we have to use code guidelines for reinforcement proportioning and placing, formwork design, handling of precast units to avoid overstressing, and use of non-chloride accelerators to prevent reinforcement corrosion. Proper material selection -especially aggregates- and the use of short discrete fibers can help in reducing shrinkage cracks.

Deflection, on the other hand, is caused by external loads, which, if excessive, may lead to increased deformations, cracks and ultimate failure. Deflection should be taken care of in the design stage by following respective code guidelines on deflection control, which in many cases control size of structural elements rather than strength requirement. There are some design techniques for proportioning members in order to control deflection e.g. increasing section depth or width, addition of compression or tension reinforcement, and prestressing (Nawy, ٢٠٠٠)

١.٦ Concrete Shrinkage

If water curing is essential to develop the potential strength of cement in plain concrete, early water curing is crucial for high performance concrete in order to avoid the rapid development of autogenously shrinkage and tocontrol concrete dimensional stability, as explained below.
Cement paste hydration is accompanied by an absolute volume contraction that creates a very fine pore network within the hydrated cement paste. This network drains water from coarse capillaries, which start to dry out if no external water is supplied. Therefore, if no drying is occurring and if no external water is added during curing, the coarse capillaries will be empty of water as hydration progresses, just as though the concrete was drying. This phenomenon is called self-desiccation. The difference between drying and self-desiccation is that, when concrete dries, water evaporates to the atmosphere, while during self-desiccation, water stays within concrete means it only migrates towards the very fine pores created by the volumetric contraction of the cement paste. In ordinary concrete with a high water/cement ratio greater than ٠.٥٠, for example, there is little cement and more water than is required to fully hydrate the cement particles present. A large amount of this water is contained in well connected large capillaries, in ordinary concrete. This means that the hydrated cement paste does not shrink at all when selfdesiccationdevelops. In the case of high performance concrete with a water/binder ratio of ٠.٣٠ or less, significantly more cement and less mixing water have been used, so that the capillary network that developed within the fresh paste is essentially composed of fine capillaries. When self-desiccation starts to develop as soon as hydration begins, the menisci rapidly develop in small capillaries if no external water is added. Since many cement grains start to hydrate simultaneously in high performance concrete, the drying of very fine capillaries, can

generate high tensile stresses that shrink the hydrated cement paste. This early shrinkage is referred to as autogenously shrinkage. Of course, autogenously shrinkage is as large as the drying shrinkage observed in ordinary concrete when these two types of drying develop in capillaries of the same diameter. But, if there is an external supply of water, the capillaries do not dry out as long as they are connected to this external source of water. The result is that no menisci, no tensile stress, and no autogenously shrinkage develops within the high performance concrete. Therefore, an essential difference between ordinary concrete and high performance concrete is that ordinary concrete exhibits no autogenously shrinkage whether or not it is water-cured, whereas high performance concrete can experience significant autogenously shrinkage if it is not water-cured during the hydration process. Autogenously shrinkage will not develop in high performance concrete if the capillaries are interconnected and have access to external water. When the continuity of the capillary system is broken, then and only then, will autogenously shrinkage start to develop within the hydrated cement paste of a high performance concrete. Aitcin*at el. (١٩٩٧)*

High performance concrete must be cured quite differently from ordinary concrete because of the difference in shrinkage behaviour described above. If HPC is not water-cured immediately following placement or finishing, it is prone to develop severe plastic shrinkage because it is not protected by bleed water, and later on develops severe autogenously shrinkage due to rapid hydration reaction. While curing membranes provide adequate protection for ordinary concrete (which is not subject to autogenously shrinkage), they can only help to prevent the development of plastic shrinkage in high performance concrete. They have no value in inhibiting autogenously shrinkage. Therefore, the most critical curing period for any HPC run from placement or finishing up to ٢ or ٣ days later. During this time, the most critical period is usually from ١٢ to ٣٦ hours. In fact, the short time during which efficient water curing must be applied to HPC can be considered a significant advantage over ordinary concrete. Those who specify and use HPC must be aware of the dramatic consequences of skipping early water curing. Initiating water curing after ٢٤ hours is too late because, most of the time, a great deal of autogenously shrinkage will already have occurred and, by this time, the microstructure will already be so compact that any external water will have little chance of penetrating very deep into the concrete. Water ponding, whenever possible, or fogging are the best ways to cure HPC; one of these two methods must be applied as soon as possible immediately following placement or finishing. The water curing can be stopped after ٧ days because most of the cement at the surface of concrete will have hydrated and any further water curing will have little effect on the development of autogenously shrinkage due to compactness of the HPC microstructure. Moreover, after ٧ days of water curing, HPC experiences little drying shrinkage due to the compactness of its microstructure and because autogenously shrinkage will have already dried out the coarse capillaries pores. Even then, the best thing to do is to paint HPC with an sealing agent so that the last remaining drops of water in the concrete can hydrate more cement particles. There is no real advantage to paint a very porous concrete since it is impossible to obtain an absolutely impermeable coating; painting HPC, however, is easier and more effective Aitcin*at el. (١٩٩٧)*

١.٧ General Parameters affecting HPC:

Many parameters must be considered in order to achieve a high-performance concrete. Most of these are incorporated in the mix design, but some of them depend on the actual production procedure and quality control. Nawy (٢٠٠٠) summarizes the major parameters to be considered as follows:

١ Quality and type of cement
٢ Proportion of cement in relation to water in the mixture
٣ Strength, size, and cleanliness of aggregate
٤ Interaction or adhesion between cement paste and aggregate
٥ Type of admixture chosen
٦ Adequate mixing of the ingredients
٧ Proper placing, finishing, and compaction of the fresh concrete

٨ Curing at a temperature not below ١٠C while the placed concrete gains strength

٩ Chloride content not to exceed ٠.١٥% in reinforced concrete exposed to chlorides in service and ٠.٥% for dry protected concrete.

١٠ Chemical Admixtures

١.٧.١ Materials – Cement

- ❖ Almost any ASTM Portland cement type can be used to obtain concrete with adequate rheologyand with compressive strength up to ٦٠ 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 chemicaladmixtures.
- ❖ Experience has shown that low-C٣A cements generally produce concrete with improved rheology.

١.٧.٢ Materials – Aggregate

- ❖ 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 theMatrix and interfacial transition zone, and the aggregate may become the weak link in theDevelopment 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, Aitcin recommends using fine aggregates with higher fineness modulus (around ٣.٠). His reasoning is as follows:

a. 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.

b. The use of coarser fine aggregates requires less water to obtain the same workability.
c. During the mixing process, the coarser fine aggregates will generate higher shearing stresses that can help prevent flocculation of the cement paste.

We will briefly discuss how the above factors can be manipulated to achieve high performance concrete through enhanced durability. Due to the limited scope of this mini-research, we cannot cover all aspects of HPC.

Guidelines for the selection of materials:

- The higher the targeted compressive strength, the smaller the maximum size of coarse aggregate.
- Up to ٧٠ MPa compressive strength can be produced with a good coarse aggregate of a maximum size ranging from ٢٠ to ٢٨ mm.
- To produce ١٠٠ MPa compressive strength aggregate with a maximum size of ١٠ to ٢٠ mmshould be used.
- To date, concretes with compressive strengths of over ١٢٥ MPa have been produced, with ١٠ to ١٤ 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 ١٢- or ٢٤-hour strength that is considered acceptable, given climatic conditions or the minimumstrength required.
- While silica fume is usually not really necessary for compressive strengths under ٧٠ MPa, most concrete mixtures contain it when higher strengths are specified.

١.٧.٣ Water/Cement or Water/Binder Ratio

Both expressions were deliberately used above, either singly or together, to reflect the fact that the cementitious component of high performance concrete can be cement alone or any combination of cement with supplementary cementitious materials, such as, slag, flyash, silica fume, metakaolin, rice husk ash, and fillers such as limestone. Ternary systems are increasingly used to take advantage of the synergy of supplementary cementitious materials to improve concrete properties in the fresh and hardened states and to make high performance concrete more economical.

Despite the fact that most high performance concrete mixtures contain at least one supplementary cementitious material, which should favour the use of more general expression water/binder ratio, the water/ binder and water/cement ratios should be alongside each other. This is because most of the supplementary cementitious materials that go into high performance concrete are not as reactive as Portland cement, which means that most of the early properties of high performance concrete can be linked to its water/ cement ratio while its long-term properties are rather linked to its water/binder ratio.

Concrete compressive strength is closely related to the density of the hardened matrix. High performance concrete has also taught us that the coarse aggregate can be the weakest link in concrete when the strength of hydrated cement paste is drastically increased by lowering the water/binder ratio. In such cases, concrete failure can start to develop within the coarse aggregate itself. As a consequence, there can be exceptions to the water/binder ratio law when dealing with high performance concrete. In some areas, decreasing the water/binder ratio below a certain level is not practical because the strength of the high performance concrete will not significantly exceed the aggregate's compressive strength. When the concrete's compressive strength is limited by the coarse aggregate, the only way to get higher strength is to use a stronger aggregate.

١.٧.٤ High performance Concrete: A Composite Material

Standard concrete can be characterized solely by its compressive strength because that can directly be linked to the cement paste's water/cement ratio, which still is the best indicator of paste porosity. Most of concrete's useful mechanical characteristics can be linked to concrete compressive strength with simple empirical formulas. This is the case with elastic modulus and the modulus of rupture (flexural strength), because the hydrated cement paste and the transition zone around coarse-aggregate particles constitute the weakest links in concrete. The aggregate component (especially the coarse aggregate) contributes little to the mechanical properties of ordinary concrete. As the strength of the hydrated cement paste increases in high performance concrete, the transition zone between the coarse aggregate and the hydrated cement paste practically disappears. Since there is proper stress transfer under these conditions, high performance concrete behaves like a true composite material.

١.٧.٥ Chemical Admixtures

Chemical admixtures are the essential ingredients in the concrete mix, as they increase the efficiency of cement paste by improving workability of the mix and there by resulting in considerable decrease of water requirement.

Different types of chemical admixtures are:

- Plasticizers
- Super plasticizers
- Retarders
- Air entraining agents

Plasticizers and super plasticizers help to disperse the cement particles in the mix and promote mobility of the concrete mix. Retarders help in reduction of initial rate of hydration of cement, so that fresh concrete retains its workability for a longer time. Air entraining agents artificially introduce air bubbles that increase workability of the mix and enhance the resistance to deterioration due to freezing and thawing actions.

٢) Practical Considerations and Conclusions

٣.١ Mixture Design:

Mixture design is the process of optimizing the contents of the concrete in order for the concrete to satisfy long-term performance criteriafor its intended function. Many guidelines are available in different textbooks and codes to make the process of mix design easier. Once we select the proportion of materials to achieve our requirements, we need to produce trial mixes for testing and study of properties before we finally select the appropriate mix formula.

There are many factors to bear in mind during the mix design which will ultimately control whether we achieve HPC or not. Nawy (٢٠٠٠) summarizes them as:

Appropriate structural compressive and tensile strengths

١. Good workability of the mixture
٢. Compactness and minimum permeability through proper mixing, vibration, and no aggregate segregation
٣. Resistance to freezing thawing
٤. Resistance to chloride penetration
٥. Minimum or no plastic shrinkage cracking or drying-shrinkage cracking
٦. Low shrinkage and low creep properties of the aggregates
٧. High abrasion resistance

Basically, HPC is achieved by careful selection and proportioning of the ingredients which include Portland cement, aggregates, water, mineral admixtures (such FA, SF, GGBFS), and chemical admixtures (such as High Range Water Reducers HRWRs). Nearly all HPCs are characterized by high cement content, low w/c ratio and smaller maximum size of aggregates.

The larger the size of coarse aggregates used, the lesser cementitious material needed. The nominal maximum size to be used depends on the size of the concrete element and the geometry of reinforcement. However, many experts in the field suggest the maximum aggregate size to be ١٠-١٢mm. The shape, grading, and quality of aggregates are as important as the size (Somayaji, S. ٢٠٠١)

٣.٢ Constructability Process:

The successful achievement of HPC depends on strict quality control in contrast to conventional concretes where less stringent procedures are acceptable. This is because HPC is sensitive to small variations in amounts and properties of its various constituents. The constructability steps that need to be followed are summarized below by (Moreno, J. and Albinger,J. ١٩٩٨):

١. **Preconstruction meetings:** The effects to be reviewed include time, temperatures, placing, curing, acceptance criteria, the manner in which these criteria will be established, as well as the capabilities of the contractor.

٢. **Material selection and processing:** Lowest water/cementitious material ratio is to be maintained. Arriving at the optimum combination of aggregate, cement, pozzolans, chemical admixtures, and HRWRs and their interaction becomes a trial-and-adjustment process until the desired mixture is achieved.

٣. **Material control:** The consistency of the constituent components should be controlled. If variations become excessive, the required average strength may become unattainable.

٤. **Mixing:** The most important factor is the blending of all the constituent materials into a homogenous concrete mixture. We have to control the sequence of loading materials into the mixer, the efficiency of the mixer, mixing time, and the temperature of the concrete.

٥. **Transportation:** there should not be any significant change in the slum, w/cm ration, air content, consistency, and temperature during transportation from mixer to site. Certified mixer trucks should be used, and delays in delivery should be prevented.

٦. **Placement:** Segregation of the coarse aggregates should be prevented. Use proper vibratory equipment, and avoid over-vibration.

٧. **Finishing:**The desired concrete surface should be produced with minimum manipulation. The concrete should not be troweled while water is present on surface. No water should be introduced for finishing process because w/cm ratio and subsequently hardened-state properties would be adversely affected.

٨. **Curing:** Proper curing is crucial for achieving desired properties in both normal- and high-performance concrete. HPC are extremely dense and special curing method must be adopted to prevent moisture loss, shrinkage and thermal cracking.

٩. **Job Site Control:** This can be achieved if coordination is planned and exercise between concrete supplier and construction contractor. Time of concrete delivery from truck loading to discharge should be limited to ٨٠ minutes.

٣.٣ Quality Control:

Concrete is a non-homogenous material and its properties depend on many variables. It is unlike the mechanized production in factories where the quality of end-product is easily controlled. Among the important factors are the humans who are involved in concrete production and use. The performance of the personnel in a quality-oriented system depends on knowledge, training and communication at all levels. A smooth flow of correct information among all participants and a shared systematic understanding of the developing problems lead to increased motivation toward improved solutions and hence improved quality control and assurance (NAWY, ٢٠٠٠)

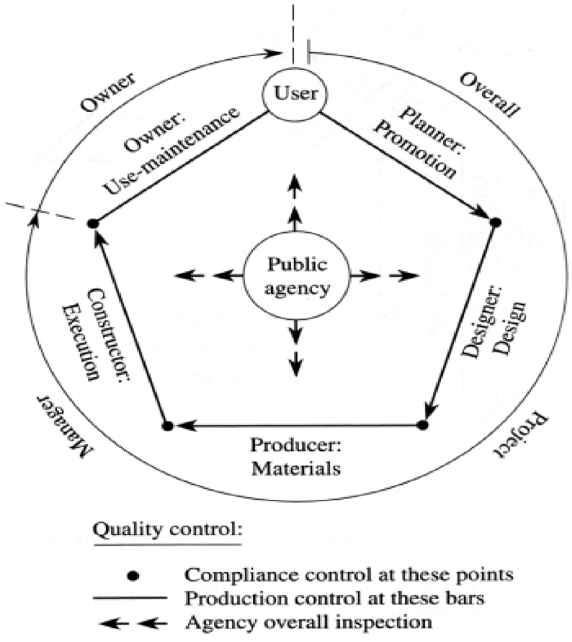


Fig ٣.١: Components of a quality control &assurance system

٣.٤ Advantages and Disadvantages of using HPC:

By using High-Strength High-Performance Concrete we are able gain many advantages which can are not available with conventional concretes. This will of course increase the initial cost due to higher cost of materials, labor, and quality control procedures. However, the long-term benefits of HPC will, in many cases, balance the higher initial cost of HPC as compared to Conventional Concretes.Nawy (٢٠٠٠)summarize some of the advantages of using HPC:

- Reduced member size with decrease in dead-loads, amount of concrete needed, construction time required, formwork area and cost, number and size of foundations required, and Increase in usable space
- Ability to construct higher number of stories with accompanying saving in land costs
- Bridges with longer spans and lesser number of beams
- Great stiffness as a result of a higher modulus, E_c
- Improved durability and long-term performance criteria
- Reduced maintenance costs
- Smaller depreciation due to the longer usable life of the structure

On the other hand, HPC has some disadvantages such as:

- Low shear strength
- Low ductility or small failure strain i.e. brittle failure
- Increased creep and shrinkage due to higher amounts of cement and lower amounts of aggregates as compared to ordinary concrete
- Increased initial cost

٣.٥ Conclusions & Suggestions:

The rapid development and industrialization of many countries around the world raised the need for innovative materials which must satisfy performance requirements of today’s mega construction projects. One answer to that problem was the introduction and growth of HPC concept.

It seems that at least for our current century, there is no in sight a material which can replace concretes in general and HPC in particular. Although a lot of research was focused on HPC in developed countries, our knowledge is far from perfection. As a consequence, the research on this innovative material is expected to grow and get much attention.

In the last half century, developed countries were mainly using HPC for the following three applications:

١. **Rehabilitation of existing infrastructure**
٢. **Aggressive environments** e.g. marine structures, structures subjected to deicing salts…
٣. **Skyscrapers** (reduce size of columns) &**long-span bridges** (for durability & for longer spans)

Developing countries like Malaysia are facing the same needs today. The rapid development of Malaysian infrastructure especially in the last two decades raises the need for maintenance and rehabilitation solutions. On the other hand, more than ٩٠% of Malaysian oil and gas production comes from offshore installations. These structures need special and high-performance concretes in order for them to be durable over their design life.

For successful technology transfer, we need to consider many underlying issues and base our decisions on pre-planned reasonable criterion. I am hereby discussing some of the factors which are pertinent to Malaysia and similar developing countries:

- Most of the professionals in the local construction industry lack an updated knowledge of concrete technology. They are reluctant to learn about and use the latest advances in this rapidly growing field.
- Curriculum of most universities and technical schools is not sufficient in the sense that most of their graduates lack the real understanding of theoretical and experimental knowledge of concrete materials technology.
- As a solution to the above, I suggest that there is a need to setup a new Advanced Concrete Technology Center in order to do the following:
    - Employ renowned researchers in this field in order to conduct and supervise the research going in the Center.
    - Develop a comprehensive advanced concrete technology curriculum which reflects the state-of-the-art knowledge on the subject, and which may be recommended for other learning institutions in Malaysia.
    - Develop partnership relationships with similar centers in developed countries for getting updates and feedback.

- Conduct a sustained research for HPC applications in Malaysia. Issues to be considered include the use of local materials and industrial by-products for producing durable concretes, types of durability problems in local environments around Malaysia, monitoring the existing structures using HPC for further research, etc.
- Raise awareness of the construction industry in particular and the public in general about the benefits of using HPC through conferences, field trips, journals, etc.

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