# HIGH-PERFORMANCE, HIGH-VOLUME FLY ASH CONCRETE FOR SUSTAINABLE DEVELOPMENT

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## Abstract

For a variety of reasons, the concrete construction industry is not sustainable. First, it consumes huge quantities of virgin materials. Second, the principal binder in concrete is portland cement, the production of which is a major contributor to green-house gas emissions that are implicated in global warming and climate change. Third, many concrete structures suffer from lack of durability which has an adverse effect on the resource productivity of the industry. Because the high-volume fly ash concrete system addresses all three sustainability issues, its adoption will enable the concrete construction industry to become more sustainable.

In this paper, a brief review is presented of the theory and construction practice with concrete mixtures containing more than 50% fly ash by mass of the cementitious material. Mechanisms are discussed by which the incorporation of high volume of fly ash in concrete reduces the water demand, improves the workability, minimizes cracking due to thermal and drying shrinkage, and enhances durability to reinforcement corrosion, sulfate attack, and alkali-silica expansion. For countries like China and India, this technology can play an important role in meeting the huge demand for infrastructure in a sustainable manner.

## 1. Introduction

How to meet the housing and infrastructural needs of society in a sustainable manner is, unquestionably, the most important challenge confronting the concrete industry today. Among the sustainability issues, the three major ones that are widely discussed in the published reports may be summarized as follows:

**Climate change**—In many parts of the world, extreme weather patterns are occurring with greater frequency. Most scientists believe that this phenomenon is associated with the high emission rates of green-house gases, primarily carbon dioxide, the environmental concentrations of which has increased from 280 to 370 parts per million volume mainly during the industrial age (1, 2). The transportation industry and the portland cement industry happen to be the two largest producers of carbon dioxide. The latter is responsible for approximately 7% of the world's carbon dioxide emissions (2).

**Resource productivity—**The concrete industry is the largest consumer of virgin materials such as sand, gravel, crushed rock, and fresh water. It is consuming portland and modified portland cements at an annual rate of about 1.6 billion metric tons. The cement production consumes vast amounts of limestone and clay besides being energy-intensive.

Obviously, large amounts of energy and materials, in addition to financial resources, are wasted when structures deteriorate or fail prematurely which, in fact, has been the case with many recently built reinforced concrete bridge decks, parking garages, and marine structures throughout the world (3). Traditionally, most concrete structures are designed for a service life of 50 years. With the advent of high-performance concrete mixtures, some structures are now being designed and built for a service life of 100 years. In the long run, sustainable development of the concrete industry will not take place until we are able to make even more dramatic improvements in our resource productivity. In this context, it should be noted that the Factor Ten Club, a group of scientists, economists and business people have made a declaration that, within one generation, nations can achieve a tenfold increase in their resource productivity through a 90% reduction in the use of energy and materials (4).

**Industrial ecology**—Achieving a dramatic improvement in resource productivity through durability enhancement of products is, of course, a long-term solution for sustainable development. A short-term strategy that must be pursued simultaneously is to practice industrial ecology at a larger scale than is the case today. Simply defined, the practice of industrial ecology by a manufacturing industry involves the reclamation and re-use of its own waste products and, to the extent possible, the waste products of other industries which are unable to recycle them in their own manufacturing process.

Reportedly, over 1 billion tons of construction and demolition waste is generated every year. Cost-effective technologies are available to recycle most of the waste as a partial replacement for the coarse aggregate in fresh concrete mixtures. Similarly, industrial wastewaters and non-potable waters can substitute for municipal water for mixing concrete unless proven harmful by testing. Blended portland cements containing fly ash from coal-fired power plants, and ground-granulated slag from the blast-furnace iron industry provide excellent examples of industrial ecology because they offer a holistic solution for reducing the environmental impact of several industries.

The construction industry already uses concrete mixtures containing cement replacement materials, such as 15% to 20% fly ash or 30% to 40% slag by mass. As discussed in this paper, with conventional materials and technology, it is now possible to produce high-performance concrete mixtures containing 50% to 60% fly ash by mass of the blended cementitious material. Note that fly ash is readily available in most parts of the world. China and India, the two countries that consume large amounts of cement, together produce over 300 million tons of fly ash per year.

## 2. High-Performance Concrete

What is high-performance concrete? According to a recent paper by Aitcin (5), *what was known as high-strength concrete in the late 1970s is now referred to as high-performance concrete (HPC) because it has been found to be much more than simply stronger*. ACI defines HPC as a specially engineered concrete, one or more specific characteristics of which have been enhanced through the selection of component materials and mix proportions. Note that this definition does not cover a single product but a family of high-tech concrete products whose properties have been tailored to meet specific engineering needs, such as high workability, very-high early strength (e.g. 30-40 MPa compressive strength in 24 hours), high toughness, and high durability to exposure conditions.

A major criticism against the ACI definition of HPC is that durability of concrete is not mandatory; it is one of the options. The misconception that high-strength will automatically lead to high-durability has probably resulted in many cases of cracking and premature deterioration of HPC structures, as reported in the published literature (6, 7). The reason lies in the mix proportions used to achieve very high-strength; for example, commercial high-strength concrete mixtures are often designed to obtain 50-80 MPa compressive strength at 28-day and at times high early-strength values on the order of 25-40 MPa at 1-day, together with 150-200mm slump for ease of constructability if the structure is heavily reinforced. Typically, these mixtures are composed of a high cement content, viz 450-500 kg/m$^3$ portland or blended portland cement containing a relatively small amount of silica fume and fly ash or slag, a low water/cement on the order of 0.3 (with the help of a superplasticizing admixture), and an air-entraining agent when it is necessary to protect the concrete from cycles of freezing and thawing. Field experience shows (6, 7) that the foregoing high-strength concrete mixtures are prone to suffer early cracking from a variety of causes, such as a large thermal contraction due to the high portland cement content, a large autogenous shrinkage due to the low water-cementitious ratio, and a high drying shrinkage due to the high cement paste-aggregate ratio.

Aitcin (5) prefers to define HPC as a low water/binder concrete with an optimized aggregate-to-binder ratio to control its dimensional stability (i.e. drying shrinkage), and which receives an adequate water-curing (to control autogenous shrinkage). This definition adequately addresses the potential for lack of durability of HPC concrete except with massive structural members that may be subject to thermal cracking. In this regard, an earlier definition proposed by Mehta and Aitcin (8) stated that the term HPC should be applied to concrete mixtures possessing the following three characteristics: high workability, high strength, and high durability.

The above critical examination of the commercial practice and the perceived meaning of the term, *high-performance concrete*, is essential to answer the question whether or not HPC is a sustainable product. Most of the conventional HPC products will not qualify to be classified as "sustainable" because they are not likely to be highly durable and may contain a high content of portland cement and a relatively small amount of pozzalanic and cementitious by-products for cement replacement. However, the high-volume fly ash (HVFA) system, discussed next, represents an emerging technology for producing *sustainable HPC mixtures.*

## 3. High-Volume Fly Ash Concrete

Fly ash, a principal by-product of the coal-fired power plants, is well accepted as a pozzolanic material that may be used either as a component of blended portland cements or as a mineral admixture in concrete. In commercial practice, the dosage of fly ash is limited to 15%-20% by mass of the total cementitious material. Usually, this amount has a beneficial effect on the workability and cost economy of concrete but it may not be enough to sufficiently improve the durability to sulfate attack, alkali-silica expansion, and thermal cracking. For this purpose, larger amounts of fly ash, on the order of 25%-35% are being used.

Although 25%-35% fly ash by mass of the cementitious material is considerably higher than 15%-20%, this is not high enough to classify the mixtures as HVFA concrete according to the definition proposed by Malhotra and Mehta (9). From theoretical considerations and practical experience the authors have determined that, with 50% or more cement replacement by fly ash, it is possible to produce sustainable, high-performance concrete mixtures that show high workability, high ultimate strength, and high durability. The following text containing a brief description of the composition and properties of HVFA concrete is adapted from Malhotra and Mehta's book on HVFA concrete (9).

### 3.1 What is high-performance concrete?

The characteristics defining a HVFA concrete mixture are as follows:

- Minimum of 50% of fly ash by mass of the cementitious materials must be maintained.
- Low water content, generally less than 130 kg/m$^3$ is mandatory.
- Cement content, generally no more than 200kg/m$^3$ is desirable.

- For concrete mixtures with specified 28-day compressive strength of 30 MPa or higher, slumps >150 mm, and water-to-cementitious materials ratio of the order of 0.30, the use of high-range water-reducing admixtures (superplasticizers) is mandatory.
- For concrete exposed to freezing and thawing environments, the use of an air-entraining admixture resulting in adequate air-void spacing factor is mandatory.
- For concrete mixtures with slumps less than 150 mm and 28-day compressive strength of less than 30 MPa, HVFA concrete mixtures with a water-to-cementitious materials ratio of the order of 0.40 may be used without superplasticizers.

### 3.2 Mixture proportions

Adapted from a recent paper by Malhotra (10), typical range of component materials for different levels of strength in high-performance, HVFA concrete is shown in Table 1. Note that the control of water content is most essential because the amount of water is varied within a narrow range between 100-130 kg/m$^3$ by using a combination of one or more tools such as a superplasticizing admixture, a high-quality fly ash, and well-graded aggregate. Depending on the desired strength levels, the content and the fly ash/cement ratio of the binder can be varied. As the water content between the different strength levels does not vary much, it is necessary to increase the cementitious materials substantially to achieve higher strength. When very high strength is needed at an early age, it can be obtained by adopting one or more of the following methods: a higher ratio between portland cement and fly ash, substitution of a high-early strength portland cement for ordinary portland cement, and replacement of a portion of the fly ash with a more reactive pozzolan such as silica fume or rice-husk ash.

Table 1: Typical mix proportions for different strength levels

| **Strength level (MPa)** | Low | Moderate | High |
|---|---|---|---|
| 28 days | 20 | 30 | 40 |
| 90 days to 1 year | 40 | 50 | 60 |
| **Mix proportions (kg/m$^3$)** | | | |
| Water | 120-130 | 115-125 | 100-120 |
| Cement, ASTM Type I/II | 100-130 | 150-160 | 180-200 |
| Fly ash, ASTM Class F | 125-150 | 180-200 | 200-225 |
| Water/cement | 0.40-0.45 | 0.33-0.35* | 0.30-0.32* |
| Coarse aggregate, 19 mm max. | 1100-1200 | 1100-1200 | 1100-1200 |
| Fine aggregate | 800-900 | 800-900 | 800-900 |

* Moderate and high-strength concretes need a superplactisizer to obtain a low water/cement ratio. Also, some adjustments in water/cement will be needed when an air-entraining agent is used for protection against freezing and thawing cycles.

### 3.3 Mechanisms by which fly ash improves the properties of concrete

A good understanding of the mechanisms by which fly ash improves the rheological properties of fresh concrete and ultimate strength as well as durability of hardened concrete is helpful to insure that potential benefits expected from HVFA concrete mixtures are fully realized. These mechanisms are discussed next.

**Fly ash as a water reducer**

Too much mixing-water is probably the most important cause for many problems that are encountered with concrete mixtures. There are two reasons why typical concrete mixtures contain too much mixing-water. Firstly, the water demand and workability are influenced greatly by particle size distribution, particle packing effect, and voids present in the solid system. Typical concrete mixtures do not have an optimum particle size distribution, and this accounts for the undesirably high water requirement to achieve certain workability. Secondly, to plasticize a cement paste for achieving a satisfactory consistency, much larger amounts of water than necessary for the hydration of cement have to be used because portland cement particles, due to the presence of electric charge on the surface, tend to form flocs that trap volumes of the mixing water.

It is generally observed that a partial substitution of portland cement by fly ash in a mortar or concrete mixture reduces that water requirement for obtaining a given consistency. Experimental studies by Owen (10) and Jiang and Malhotra (12) have shown that with HVFA concrete mixtures, depending on the quality of fly ash and the amount of cement replaced, up to 20% reduction in water requirements can be achieved. This means that good fly ash can act as a superplasticizing admixture when used in high-volume. The phenomenon is attributable to three mechanisms. First, fine particles of fly ash get absorbed on the oppositely charged surfaces of cement particles and prevent them from flocculation. The cement particles are thus effectively dispersed and will trap large amounts of water, that means that the system will have a reduced water requirement to achieve a given consistency. Secondly, the spherical shape and the smooth surface of fly ash particles help to reduce the interparticle friction and thus facilitates mobility. Thirdly, the “particle packing effect” is also responsible for the reduced water demand in plasticizing the system. It may be noted that both portland cement and fly ash contribute particles that are mostly in the 1 to 45 μm size range, and therefore serve as excellent fillers for the void space within the aggregate mixture. In fact, due to its lower density and higher volume per unit mass, fly ash is a more efficient void-filler than portland cement.

**Drying shrinkage**

Perhaps the greatest disadvantage associated with the use of neat portland-cement concrete is cracking due to drying shrinkage. The drying shrinkage of concrete is directly influenced by the amount and the quality of the cement paste present. It increases with an increase in the cement paste-to-aggregate ratio in the concrete mixture, and also increases with the water content of the paste.

Clearly, the water-reducing property of fly ash can be advantageously used for achieving a considerable reduction in the drying shrinkage of concrete mixtures.

The significance of this concept is illustrated by data in Table 2 which shows mixture proportions of a conventional 25 MPa concrete compared to a superplasticized HVFA concrete with similar strength but higher slump. Due to a significant reduction in the water requirement, the total volume of the cement paste in the HVFA concrete is only 25% as compared to 29.6% for the conventional portland-cement concrete which represents a 30% reduction in the cement paste-to-aggregate volume ratio.

Table 2: Comparison of cement paste volumes

| | Conventional concrete | | HVFA concrete | |
|---|---|---|---|---|
| | $kg/m^3$ | $m^3$ | $kg/m^3$ | $m^3$ |
| Cement | 307 | 0.098 | 154 | 0.149 |
| Fly ash | – | – | 154 | 0.065 |
| Water | 178 | 0.178 | 120 | 0.120 |
| Entrapped air (2%) | - | 0.020 | - | 0.020 |
| Coarse aggregate | 1040 | 0.385 | 1210 | 0.448 |
| Fine aggregate | 825 | 0.305 | 775 | 0.287 |
| **Total** | **2350** | **0.986** | **2413** | **0.989** |
| w/cm | 0.58 | – | 0.39 | – |
| Paste: volume | – | 0.296 | – | 0.254 |
| Percent | – | 30.0% | – | 25.7% |

**Thermal cracking**

Thermal cracking is of serious concern in massive concrete structures. It is generally assumed that this is not a problem with reinforced-concrete structures of moderate thickness, e.g. 50-cm thick or less. However, due to the high reactivity of modern cements cases of thermal cracking are reported even from moderate-size structures made with concrete mixtures of high-cement content that tend to develop excessive heat during curing. The physical-chemical characteristics of ordinary portland cements today are such that very high heat-of-hydration is produced at an early age compared with that of normal portland cements available 40 years ago. Also, high-early strength requirements in modern construction practice are usually satisfied by an increase in the cement content of the concrete mixture. Further, there is considerable construction activity now in the hot-arid areas of the world where concrete temperatures in excess of 60°C are not uncommon within a few days of concrete placement.

For unreinforced mass-concrete construction, several methods are employed to prevent thermal cracking, and some of these techniques can be successfully used for mitigation of thermal cracks in massive reinforced-concrete structures. For instance, a 40-MPa concrete mixture containing 350 kg/m$^3$ portland cement can raise the temperature of concrete by approximately 55-60°C within a week if there is no heat loss to the environment. However, with a HVFA concrete mixture containing 50% cement replacement with a Class F fly ash, the adiabatic temperature rise is expected to be 30-35°C. As a rule of thumb, the maximum temperature difference between the interior and exterior concrete should not exceed 25°C to avoid thermal cracking. This is because higher temperature differentials are accomplished by rapid cooling rates that usually result in cracking. Evidently, in the case of conventional concrete it is easier to solve the problem either by keeping the concrete insulated and warm for a longer time in the forms until the temperature differential drops below 25°C or by reducing the proportion of portland cement in the binder by a considerable amount. The latter option can be exercised if the structural designer is willing to accept a slightly slower rate of strength development during the first 28 days, and the concrete strength specification is based on 90-day instead of 28-day strength.

**Water-tightness and durability**

In general, the resistance of a reinforced-concrete structure to corrosion, alkali-aggregate expansion, sulfate and other forms of chemical attack depends on the water-tightness of the concrete. The water-tightness is greatly influenced by the amount of mixing-water, type and amount of supplementary cementing materials, curing, and cracking resistance of concrete. High-volume fly ash concrete mixtures, when properly cured, are able to provide excellent water-tightness and durability. The mechanisms responsible for this phenomenon are discussed briefly below.

When a concrete mixture is consolidated after placement, along with entrapped air, a part of the mixing-water is also released. As water has low density, it tends to travel to the surface of concrete. However, not all of this "bleed water" is able to find its way to the surface. Due to the wall effect of coarse aggregate particles, some of it accumulates in the vicinity of aggregate surfaces, causing a heterogeneous distribution of water in the system. Obviously, the interfacial transition zone between the aggregate and cement paste is the area with high water/cement and therefore with more available space that permits the formation of a highly porous hydration product containing large crystals of calcium hydroxide and ettringite. Microcracks due to stress are readily formed through this product because it is much weaker than the bulk cement paste with a lower water/cement.

It has been suggested that microcracks in the interfacial transition zone play an important part in determining not only the mechanical properties but also the permeability and durability of concrete exposed to severe environmental conditions. This is because the rate of fluid transport in concrete is much larger by percolation through an interconnected network of microcracks than by diffusion or capillary suction. The heterogeneities in the microstructure of the hydrated portland-cement paste, especially the existence of large pores and large crystalline products in the transition zone, are greatly reduced by the introduction of fine particles of fly ash. With the progress of the pozzolanic reaction, a gradual decrease occurs in both the size of the capillary pores and the crystalline hydration products in the transition zone, thereby reducing its thickness and eliminating the weak link in the concrete microstructure. In conclusion, a combination of particle packing effect, low water content, and pozzolanic reaction accounts for the eventual disappearance of the interfacial transition zone in HVFA concrete, and thus enables the development of a highly crack-resistant and durable product.

### 3.4 Concrete construction practice

Due to the high volume of fines and a low water content, fresh concrete mixtures of the HVFA system are generally very cohesive and show a little or no bleeding and segregation. They show excellent pumpability and workability at slumps as low as 75 mm, however higher slump values may be specified with heavily reinforced structures. The material moves well to fill space without much effort and behaves almost like a self-consolidating concrete. Consequently, the surface finish is usually smooth, pleasing, and without honeycombs and bugholes.

Due to the lower portland cement content, HVFA concrete mixtures may take one to two hours longer to set. Accelerating admixtures should not be used unless their compatibility with the actual concrete mixture has been adequately tested. In such cases, the use of a rapid-hardening portland cement offers a better solution.

Usually HVFA concrete mixtures do not suffer excessive slump loss in a short period. Jobsite retempering of ready-mixed HVFA concrete is permissible to restore severe slump loss with a small amount of superplacticizer or water, provided the water/cement does not exceed the specified limit.

Low water/cement, non-bleeding concrete mixtures are vulnerable to plastic shrinkage cracking as well as autogenous shrinkage cracking. With slabs-on-grade, concrete surfaces must be protected from any water loss by operating a water-fogger around the structure during the placement, or by covering the surface with a heavy plastic sheet immediately after the placement and screeding operations are over. A minimum of 7 days of moist-curing is mandatory to achieve the optimum strength and durability characteristics that are possible from the use of HVFA concrete. With slabs, foundations, piers, columns and beams, leaving the form work in place for at least a week is acceptable in lieu of moist-curing.

**3.5 Field experience**

Case histories of the application of HVFA concrete for a variety of structures in Canada and the United States are discussed in several reports. One of the first applications consisted of an unreinforced concrete pavement in Wisconsin in the 1970s (13). In Canada, beginning with a massive concrete foundation built in 1987 for testing of components for communication satellites, reinforced columns, beams, and floor slabs of an office complex were installed in 1988, and drilled caisson piles for a wharf in 1990. Details of their applications and others in Canada are described by Langley and Leaman (14). Mehta and Langley (15) have discussed the construction experience with a large (36 by 17 by 1.2 m), monolith, HVFA concrete foundation that has remained crack free until today (for almost three years after its installation). Similar experience with large foundation slabs, cast-in-place drilled piers, and caissons is reported from recently built structures in Houston and Chicago (15). Mehta (16) and Manmohan and Mehta (17) have also documented the construction experience with another HVFA concrete project involving a reinforced belt foundation, shear walls, and collector beams for the seismic upgrade of a building at the University of California campus at Berkeley.

**3.6 Properties of concrete**

Based on field experience and laboratory tests, the properties of HVFA concrete, when compared to conventional portland cement concrete, can be summarized as follows:

- Easier flowability, pumpability, and compactability.
- Better surface finish and quicker finishing time when power finish is not required.
- Slower setting time, which will have a corresponding effect on the joint-cutting and lower power-finishing times for slabs.
- Early-strength up to 7 days, which can be accelerated with suitable changes in the mix design when earlier removal of formwork or early structural loading is desired.
- Much later strength gain between 28 days and 90 days or more. (With HVFA concrete mixtures, the strength enhancement between 7 and 90-day often exceeds 100%, therefore it is unnecessary to overdesign them with respect to a given specified strength.)
- Superior dimensional stability and resistance to cracking from thermal shrinkage, autogenous shrinkage, and drying shrinkage. In unprotected concrete, a higher tendency for plastic shrinkage cracking.
- After three to six months of curing, much higher electrical resistivity, and resistance to chloride ion penetration, according to ASTM Method C1202.

- Very high durability to the reinforcement corrosion, alkali-silica expansion, and sulfate attack.
- Better cost economy due to lower material cost and highly favorable life-cycle cost.
- Superior environmental friendliness due to ecological disposal of large quantities of fly ash, reduced carbon-dioxide emissions, and enhancement of resource productivity of the concrete construction industry.

## 4. Concluding Remarks

Throughout the world, the waste disposal costs have escalated greatly. At the same time, the concrete construction industry has realized that coal fly ash is relatively inexpensive and widely available by-product that can be used for partial cement replacement to achieve excellent workability in fresh concrete mixtures. Consequently, in the modern construction practice 15%-20% of fly ash by mass of the cementitious material is now commonly used in North America. Higher amounts of fly ash on the order of 25%-30% are recommended when there is a concern for thermal cracking, alkali-silica expansion, or sulfate attack. Such high proportions of fly ash are not readily accepted by the construction industry due to a slower rate of strength development at early age.

The high-volume fly ash concrete system overcomes the problems of low early strength to a great extent through a drastic reduction in the water-cementitious materials ratio by using a combination of methods, such as taking advantage of the superplactisizing effect of fly ash when used in a large volume, the use of a chemical superplactisizer, and a judicious aggregate grading. Consequently, properly cured high-volume concrete products are very homogenous in microstructure, virtually crack-free, and highly durable. Because there is a direct link between durability and resource productivity, the increasing use of high-volume concrete will help to enhance the sustainability of the concrete industry.

In conclusion, the high-volume concrete offers a holistic solution to the problem of meeting the increasing demands for concrete in the future in a sustainable manner and at a reduced or no additional cost, and at the same time reducing the environmental impact of two industries that are vital to economic development namely the cement industry and the coal-fired power industry. The technology of high-volume fly ash concrete is especially significant for countries like China and India, where, given the limited amount of financial and natural resources, the huge demand for concrete needed for infrastructure and housing can be easily met in a cost-effective and ecological manner.

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