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## CORROSION OF REINFORCEMENT IN HVFA CONCRETE

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### ABSTRACT

The use of concrete containing high volumes of fly ash (HVFA) has recently gained popularity as a resource-efficient, durable, and sustainable option for a variety of concrete applications. In this study, two HVFA mixtures, one containing Class C fly ash the other Class F fly ash, were compared with TDOT Class A general use mixtures using the same class of fly ash at a smaller replacement percentage. The HVFA mixtures reached similar to higher long term compressive strengths, due to the pozzolanic properties of the fly ash and the lower w/cm ratios. Also, the water permeable void contents and absorptions were lower for the HVFA mixtures at all ages, indicating that the durability of the HVFA is much better than that of the TDOT mixtures. The setting times for the HVFA mixtures were approximately two hours longer than those of the TDOT Class A mixtures at laboratory conditions (72°F (22°C)). Also, the costs of the HVFA mixtures were slightly higher. Overall, the use of HVFA mixtures would be ideal for warm weather placements; when compared with the TDOT Class A mixtures, the HVFA mixtures exhibit comparable costs, increased compressive strengths, and enhanced durability properties

## I. INTRODUCTION

### History of High volume fly ash concrete

The use of high volume fly ash (HVFA) concretes has recently gained popularity as a resource efficient, durable, cost-effective, sustainable option for many types of portland cement concrete (PCC) applications. Any concrete containing a fly ash content that is greater than 50 percent by mass of the total cementitious materials is considered HVFA PCC. The production of portland cement is not only costly and energy-intensive, but it also produces large amounts of carbon dioxide. With large quantities of fly ash available around the world at low costs, the use of HVFA seems to offer the best short term solution to rising cement demands. In 2003, 70 million tons of fly ash were produced in the United States, and only 38 percent were recycled into useful applications. Also, LEED points, which are points awarded based on environmental performance, are available for any mixture that replaces up to 40 percent of the cement in concrete with fly ash.

Fly ash is commonly used in concrete in replacements ranging from 0 to 30 percent by mass of the total cementitious material. However, research has shown that using a 50 percent or greater replacement of fly ash can have a wide range of benefits. Fly ash is a by-product and therefore less expensive than portland cement; it is also known to improve workability and reduce internal temperatures. The improved workability is a result of the “ball bearing” action of the spherical fly ash particles. Fly ash improves the grading in the mixture by smoothing out the fine particle size distribution. Also, fly ash has been shown to reduce the amount of water required. Fly ash from modern power

plants used in large volumes can reduce the water content by 15 to 20 percent. However, research has shown that the properties of HVFA concrete are strongly dependent on the characteristics of the cement and fly ash used.

While HVFA has a wide range of benefits, possibly the most attractive property of all is durability. The improvements in durability are a result of the reduction in calcium hydroxide, which is the most soluble of the hydration products, and from changes in the pore structure. Research has shown that HVFA concrete is more crack resistant than conventional PCC, due to the decreased shrinkage. This is a result of the decreased mixing water, decreased water to cementitious materials (w/cm) ratio, and also a decrease in the total volume of cement paste that is required in HVFA. Also, decreased heat of hydration at early ages reduces potential for thermal shrinkage and cracking. One indicator of the durability of concrete is the permeability; the more water that can penetrate the concrete, the more potential for freeze/thaw damage. Also, the rate of water absorption by capillary suction has been shown to be a good measure of the potential durability of concrete. Research has shown that the water permeability of HVFA is lower than that of normal PCC.

While HVFA concretes do have a wide range of benefits, they also have a few drawbacks. Generally, the strength development of concretes with high volumes of fly ash is slower than concrete without fly ash. It has been suggested that a compressive strength of 750 psi (5.2 MPa) at one day, which HVFA has been found to obtain, is adequate for formwork removal when

no early loads are applied. Also, even though the short term strengths are usually lower than those of normal concrete, the pozzolanic properties of fly ash result in long-term strengths comparable to or better than conventional PCC. The rate of increase in compressive strength is dependent on the level of cement replacement, type of fly ash, and age of the concrete. It has been observed that the rate of early-age strength gain of Class C is higher than that of Class F fly ash. However, the long-term pozzolanic strength contribution for Class F fly ash is greater than Class C, resulting in higher long-term compressive strengths. Overall, higher long term strengths have been observed for HVFA due to the dense microstructure and smaller size of capillary pores, which result from the pozzolanic reactions. Adequate curing is essential to ensure that later-age strength development will occur.

The rate of strength variation is also dependent upon the consistency and presence of different chemical admixtures. Many researchers agree that the use of a super plasticizer or water reducer is necessary in HVFA to ensure workability, especially when low w/cm ratios are used. In cases where frost resistance is necessary, the use of an air-entraining admixture is required. However, special caution must be taken when using air-entrainers and large amounts of fly ash. Fly ashes having very high carbon content require much higher dosages of air-entraining admixtures. Also, the effectiveness of air-entrained decreases with an increase in the fly ash to cementitious materials ratio.

**Scope**

In this study, two different HVFA mixtures were studied, one containing Class C fly ash and the other Class F fly ash. The HVFA mixtures were each compared with a Tennessee Department of Transportation (TDOT) Class A general use mixture containing the same class of fly ash at a much lower replacement percentage. The compressive strength, water absorption, water permeable void content, setting time, and cost were compared. The goal was to produce an HVFA mixture with properties that were comparable to or better than a TDOT Class A mixture.

**II. Material**

Most investigations on high volume fly ash concrete were carried out at a Canada centre for mineral and energy technology (CANMET). The typical mix proportion used and optimised on the basis of investigations are shown below

The HVFA mixtures contained higher dosages of air-entrainer than the TDOT lass A mixtures. As stated in the literature, this was necessary due to the reduced effectiveness of air-entrainer that results from high volumes of fly ash. The HVFA mixture containing F

Ash also required a greater dosage of air-entrained than the C Ash mixture due to the higher carbon content.

*Table No 1. Typical (HVFA) Mix Proportions*

	Low Strength	Medium Strength	High Strength
<b>Water</b>	115 kg/m <sup>3</sup>	120 kg/m <sup>3</sup>	110 kg/m <sup>3</sup>
<b>ASTM Type I cement</b>	125 kg/m <sup>3</sup>	155 kg/m <sup>3</sup>	180 kg/m <sup>3</sup>
<b>Class F Fly ash</b>	165 kg/m <sup>3</sup>	215 kg/m <sup>3</sup>	220 kg/m <sup>3</sup>
<b>C.A.</b>	1170 kg/m <sup>3</sup>	1195 kg/m <sup>3</sup>	1110 kg/m <sup>3</sup>
<b>F.A.</b>	800 kg/m <sup>3</sup>	645 kg/m <sup>3</sup>	760 kg/m <sup>3</sup>
<b>Air-entraining Admixture</b>	200 ml/m <sup>3</sup>	200 ml/m <sup>3</sup>	280 ml/m <sup>3</sup>
<b>Super plasticizer</b>	3.0 l/m <sup>3</sup>	4.5 l/m <sup>3</sup>	5.5 l/m <sup>3</sup>

**Effect of super plasticizer on the performance of high volume fly ash concrete**

Super plasticized high-volume fly ash concretes with 50% of Portland cement replacement were manufactured by using two different chemical admixtures based on sulfonated naphthalene (*SN*) or acrylic polymer (*AP*).

Portland cement with a Blaine fineness of about 400 or 500 m<sup>2</sup>/Kg was replaced by 50% of ground or un-ground fly ash. The content of the cementitious material (Portland cement + fly ash) was about 470 kg/m<sup>3</sup>. The concretes with *SN* were manufactured with a slump in the range of 190-200 mm, whereas the slump of the concretes with *AP* was in the range of 220-230 mm. Due to the different effect of the superplasticizers, the water-cementitious material ratio (*w/c*) was 0.32 or 0.29 for the *SN* or *AP* admixture respectively, although the dosage was slightly lower for the latter. Cube specimens were cured at 5°C or 20°C and compressive strength was measured at 1 to 90 days. Due to the lower *w/cm*, the strength of the concretes with the acrylic polymer was significantly higher with respect to those with *SN*. The better performance of the *AP* superplasticizer, in terms of compressive strength, was obtained at early and later ages independently of the curing temperature (5 and 20°C) and the fineness of the portland cement and fly ash.

Due to the lower *w/cm* in concrete with the *AP* admixture with respect to those with the *SN* superplasticizer, the durability behavior of high-volume

fly ash concrete can be furtherly improved in terms of lower penetration rate of CO<sub>2</sub> or chloride ions. Antonio Borsoi is a laboratory technician of Enco. He is active in the area of concrete mixture design. He is author of several papers in the field of superplasticized concrete mixtures. Silvia Collepari is a research civil engineer of Enco, Spresiano, Italy. She is working in the field of concrete durability and superplasticized concrete mixtures and has published several papers in this area. Luigi Coppola is a research civil engineer and technical director of Enco, Spresiano, Italy. He has authored numerous papers on various aspects of concrete technology, durability and mix-design. He was acknowledged by a CANMET-ACI award for his contribution to the fundamental knowledge of concrete durability.

### III. Properties of HVFA concrete Compressive Strength

The plastic properties for the batches used for compressive strength testing are given in Table 3. The slump and air content for the Class C ash mixtures were similar, as were those for the Class F ash mixtures. As shown in Figure 1, the HVFA mixture containing Class C ash obtained greater compressive strengths than the TDOT Class A mixture with 25 percent C ash replacement.

The strength of the HVFA mixture was greater than that of the TDOT Class A mixture at all ages. It would seem that the HVFA mixture would have lower strengths at early ages, due to the decreased cement available for reactions. However, it appears that the low w/cm ratio and the increased Type A admixture overcome the adverse effect of increased fly ash. Class C fly ash also has some cementitious properties which contribute slightly to the compressive strengths at early ages. As expected, the long term strengths were greater for HVFA due to the pozzolanic properties of the Class C ash and the lower w/cm ratios. The rate of strength gain for the two mixtures appears to be similar.

The long term compressive strengths for the HVFA mixture containing Class F ash were similar to those of the TDOT Class A mixture with 20 percent F ash replacement, as illustrated in Figure 2. Unlike the C ash mixture, the strengths of the HVFA mixture containing F ash were slightly lower than those of the TDOT Class A mixture at early ages. This was the expected behavior due to the large amount of Class F fly ash, which possesses pozzolanic properties but no cementitious properties. Even though the early strength of the HVFA mixture was lower, it still exceeded 750 psi (5.2 MPa) at one day which has been suggested as an acceptable limit for formwork removal. After approximately three weeks, the compressive strength of

the HVFA mixture surpassed that of the TDOT Class A mixture, due to the pozzolanic properties of the F ash.

However, at later ages, the compressive strength of the HVFA mixture dropped slightly below that of the TDOT Class A mixture; an explanation for the drop in strength is unclear. It appears from the graph that the rate of strength gain for the HVFA mixture was equal to that of the TDOT Class A mixture, due to the pozzolanic properties.

Figure 1. Compressive Strength vs. Time – C Ash Mixtures

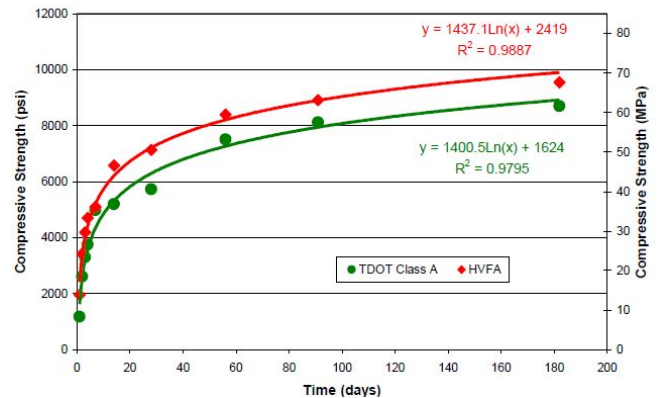
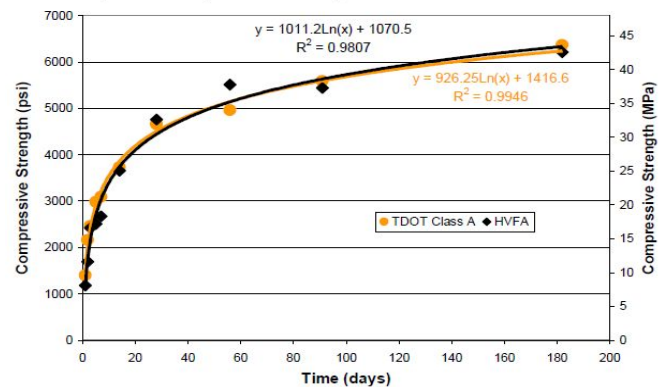


Figure 2. Compressive Strength vs. Time – F Ash Mixtures



### Durability Properties

The water absorption and permeable void contents were determined as per ASTM C 642. The water absorption for each of the four mixtures is shown in Figure 3. Both of the HVFA mixtures had significantly less absorption than the TDOT Class A mixtures. Also, Figure 4 illustrates the water permeable void content for each of the mixtures. The HVFA mixtures also had a lower percentage of water permeable voids than the TDOT Class A mixtures. This indicates that the HVFA mixtures will probably exhibit better durability than the TDOT Class A general use mixtures. This is consistent with the literature, which states that the durability of

concrete containing large amounts of fly ash is superior to that of normal PCC. The high volumes of fly ash provide a denser microstructure that is less permeable, resulting in enhanced durability.

Figure 3. Water Absorption vs. Time

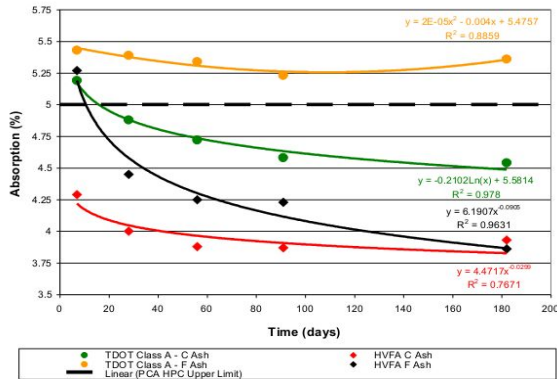
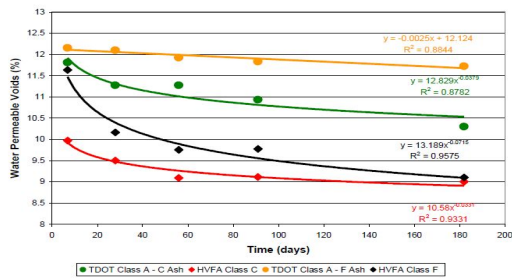


Figure 4. Water Permeable Void Content vs. Time



#### IV. Corrosion

Corrosion is the disintegration of an engineered material into its constituent atoms due to chemical reactions with its surroundings. In the most common use of the word, this means electrochemical oxidation of metals in reaction with an oxidant such as oxygen. Formation of an oxide of iron due to oxidation of the iron atoms in solid solution is a well-known example of electrochemical corrosion, commonly known as rusting. This type of damage typically produces oxide(s) and/or salt(s) of the original metal. Corrosion can also refer to other materials than metals, such as ceramics or polymers, although in this context, the term degradation is more common.

In other words, corrosion is the wearing away of metals due to a chemical reaction. Many structural alloys corrode merely from exposure to moisture in the air, but the process can be strongly affected by exposure to certain substances (see below). Corrosion can be concentrated locally to form a pit or crack, or it can extend across a wide area more or less uniformly corroding the surface. Because corrosion is a diffusion controlled process, it occurs on exposed surfaces. As a

result, methods to reduce the activity of the exposed surface, such as passivation and chromate-conversion, can increase a material's corrosion resistance. However, some corrosion mechanisms are less visible and less predictable.

Corrosion of rebars in reinforced concrete (RC) structures is recognised as a major problem in the maintenance of the structural integrity. The most important causes for initiation of corrosion of reinforcing steel are the ingress of chloride ions and carbon dioxide to the steel surface. Chloride ion causes local destruction of the passive film leading to localised corrosion. Carbon dioxide, on the other hand, reacts with the hydrated cement matrix, leading to a decrease in pH and subsequent loss of steel passivity and to corrosion initiation. The need to extend concrete durability has led to the use of several admixtures and modifications to the concrete composition. Addition of fly ash as an additive to concrete has become common practice in recent years. The fly ash particles react with calcium hydroxide, producing November 2004 \* The Indian Concrete cementitious products that strongly decrease concrete porosity<sup>2-1</sup>. This effect leads to an increase of the concrete resistivity and consequently to a decrease of the diffusivity coefficients of some elements, such as oxygen and chloride through the concrete<sup>5-7</sup>. It has been reported that a reduction of chloride diffusivity in immersed concrete to half its value was observed in concrete incorporating 50 percent of fly ash, consequently, the corrosion process in the presence of chlorides was delayed. This behaviour was revealed in previous work on fly ash concrete immersed in sodium chloride solutions<sup>8</sup>. The use of 30 percent fly ash as partial substitution of cement has led to a significant increase of induction time and to a reduction of the corrosion rate by one order of magnitude.

#### Common corrosion types

Crevice corrosion is a localized form of corrosion usually associated with a stagnant solution on the micro-environmental level. Such stagnant microenvironments tend to occur in crevices (shielded areas). Oxygen in the liquid which is deep in the crevice is consumed by reaction with the metal. Oxygen content of liquid at the mouth of the crevice which is exposed to the air is greater, so a local cell develops in which the anode, or area being attacked, is the surface in contact with the oxygen-depleted liquid.

Pitting -Theories of passivity fall into two general categories, one based on adsorption and the other on presence of a thin oxide film. Pitting in the former case arises as detrimental or activator species, such as Cl<sup>-</sup>, compete with O<sub>2</sub> or OH at specific surface sites. By the oxide film theory, detrimental species become incorporated into the passive film, leading to its

local dissolution or to development of conductive paths. Once initiated, pits propagate auto-catalytically according to the generalized reaction,

$M^{+n} + nH_2O + nCl^- \rightarrow M(OH)_n + NaCl$ , resulting in acidification of the active region and corrosion at an accelerated rate ( $M^{+n}$  and  $M$  are the ionic and metallic forms of the corroding metal).

#### Reasons of corrosion

The two most common causes of reinforcement corrosion are (i) localized breakdown of the passive film on the steel by chloride ions and (ii) general breakdown of passivity by neutralization of the concrete, predominantly by reaction with atmospheric carbon dioxide. Sound concrete is an ideal environment for steel but the increased use of deicing salts and the increased concentration of carbon dioxide in modern environments principally due to industrial pollution, has resulted in corrosion of the rebar becoming the primary cause of failure of this material. The scale of this problem has reached alarming proportions in various parts of the world.

Following are the contributing factors leading to corrosion :

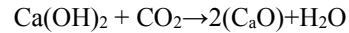
**Loss of Alkalinity due to Carbonation** It is well known that if bright steel is left unprotected in the atmosphere a brown oxide rust quickly forms and will continue to grow until a scale flakes from the surface.

This corrosion process will continue unless some external means is provided to prevent it. One method is to surround the steel with an alkaline environment having a pH value within the range 9.5 to 13. At this pH value a passive film forms on the steel that reduces the rate of corrosion to a very low and harmless value. Thus, concrete cover provides chemical as well as physical protection to the steel. However, alkalinity can be lost as a result of:

(a) Reaction with acidic gases (such as carbon dioxide) in the atmosphere.

(b) Leaching by water from the surface.

Concrete is permeable and allows the slow ingress of the atmosphere; the acidic gases react with the alkalis (usually calcium, sodium and potassium hydroxides), neutralising them by forming carbonates and sulphates, and at the same time reducing the pH value. If the carbonated front penetrates sufficiently deeply into the concrete to intersect with the concrete reinforcement interface, protection is lost and, since both oxygen and moisture are available, the steel is likely to corrode. The extent of the advance of the carbonation front depends, to a considerable extent, on the porosity and permeability of the concrete and on the conditions of the exposure. In the case of carbonation, atmospheric carbon dioxide ( $CO_2$ ) reacts with pore water alkali according to the generalized reaction,



#### V. Corrosion testing techniques

There are several non-destructive techniques available for the investigation of corrosion in reinforced concrete. In order to get a reliable assessment of the corrosion of reinforcing steel, three corrosion evaluation techniques were used in this study. They were half-cell potential, linear polarization and AC impedance methods.

##### Half-cell potential method -

The half-cell potential method has been widely used because of its simplicity and cost effectiveness. This method allows the evaluation of the probability of corrosion activity through the measurement of the potential difference between a standard portable reference electrode and the reinforcing steel. The data analysis guidelines described in ASTM C876-99 provide general principles for the evaluation of the probability of corrosion of reinforcing steel in concrete structures.

##### Linear polarisation method –

The linear polarisation technique was used to determine the polarisation resistance and the corrosion rate of reinforcing steel bars embedded in concrete. The potential of the steel electrode was scanned at a slow rate of 0.1 to 0.05 mV/s. The tests were initiated at 20 mV below the corrosion potential,  $E_{wrr}$ , and terminated at 20 mV above it, while recording the polarisation current (1). These tests were conducted with one of the following potentiostats, EG&G 273 or 6310, Gamry CMSI00, and Solartron 1286 or 1287.

##### AC impedance method –

The measurement of AC impedance spectroscopy provides information on the electrical resistivity and the dielectric properties of the concrete cover, the corrosion rate and the mechanism of reaction on the steel concrete interface. This technique is frequently used in the laboratory to study the corrosion of steel in concrete. Experimental investigations have shown a close relationship between the corrosion rate determined by weight loss and the values calculated from AC impedance measurements.

#### VI. CONCLUSION

HVFA concretes ( $w/cm = 0.32$ ) and control concrete ( $w/c = 0.32$ ) performed excellently in the corrosion test reported. The reinforcing steel bars with a cover of 25 mm or greater were in a passive state after 5.3 years of exposure in 3.4 percent NaCl solutions. As most specifications for structural concrete exposed to aggressive media specify a minimum cover of 37 mm, the test results obtained indicate no likelihood of corrosion of reinforcing steel in HVFA concrete with  $w/c$  of 0.32 during the service life of concrete structure. The data reported in this investigation together with

chloride-ion profiles in concrete slabs can be used to develop prediction model for service life of concrete structures exposed to chloride-ions.

### **Specific**

The corrosion of reinforcing steel bars embedded in the concrete slabs containing high volume fly ash was investigated by half-cell potential, linear polarisation and AC impedance techniques, The performance of these concrete

slabs and concrete cover depths in delaying corrosion of reinforcing steel bars was evaluated after 5.3 years of ponding with a 3.4 percent NaCl solution. Their performance was compared to conventional portland cement concrete and concrete slabs with high w/c. The results obtained by these different techniques were in very good agreement. The concrete slab N2 had the best performance. The corrosion of the reinforcing steel bars was initiated only on the steel bars with 13 mm concrete cover and the corrosion rate was lower than that obtained in the control slab N3 (w/c =0.32).

The control slab N3 (control concrete, w/c = 0.32) and slab N1 (containing high volumes of Class F fly ash) also had a good performance. The corrosion of the reinforcing steel bars with a 13mm concrete cover depth was in the moderate to high corrosion state, but the reinforcing steel bars with thicker concrete covers were still in the passive condition, according to the measured corrosion rates. The corrosion of reinforcing steel bars embedded in portland cement concretes with high water/cement ratios (w/c=0.43 and 0.55) was significant. Substantial corrosion of the reinforcing steel bars was found in slab N4 (w/c =0.43) with a 50 mm cover and in slab N5 (w/c = 0.55), even with a 75 mm concrete cover.

### **VII. Acknowledgement**

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