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Properties of Concrete Containing Ultra-Fine Fly Ash

by Karthik H. Obla, Russell L. Hill, Michael D. A. Thomas, Surali G. Shashiprakash, and Olga Perebatova

Fly ash and silica fume are two pozzolans that have been widely used for improved concrete strength and durability. Silica fume displays a greater pozzolanic reactivity than fly ash primarily due to its finer particle size. The reactivity of fly ash can be improved by reducing its particle size distribution. This paper discusses the fresh and hardened properties of concrete made with an ultra-fine fly ash (UFFA) produced by air classification. Durability testing for chloride diffusivity, rapid chloride permeability, alkali-silica reaction (ASR), and sulfate attack was also conducted. It was found that at a given workability and water content, concrete containing UFFA could be produced with only 50% of the high-range water-reducer dosage required for comparable silica fume concrete. Similar early strengths and durability measures as silica fume concrete were observed when a slightly higher dosage of UFFA was used with a small reduction (10%) in water content.

Keywords: alkali-silica reaction; cracking; durability; fly ash; shrinkage; sulfate attack; workability.

INTRODUCTION

The beneficial properties that pozzolans can impart to concrete include increased ultimate strength, reduced permeability, and improved durability. Within the broad category of pozzolans, two of the most commonly used classes of materials are fly ash (FA) and silica fume (SF). While both materials are alike in the fact that they exhibit pozzolanic properties, each material possesses unique characteristics, such that one product may be more suitable for a given application than the other. For instance, SF's high amorphous silica content, coupled with an extremely small particle size (high surface area), makes for a highly reactive pozzolan that offers increased concrete strength and reduced permeability at early ages. These same material characteristics, however, also influence concrete rheology. Concrete containing SF will have a higher water demand for a given workability and will exhibit placement and finishing characteristics differing considerably from portland cement concrete.[1] Because of these issues, as well as availability and economic considerations, SF is not used as widely as FA and remains a specialized pozzolan.

This paper reports on an attempt to enhance the performance of the FA so that it too functions as a highly reactive pozzolan. FA reactivity is a result of, among other things, particle size.[2,3] A FA particle distribution will typically consist of particles ranging from slightly greater than 150 micrometers to submicron size. Mehta has reported that a majority of the reactive particles in FA are actually less than 10 micrometers in diameter.[4] A typical Class F FA (produced from bituminous coal) will consist of fewer than 25% (by volume) of particles with a particle diameter of 10 micrometers or less. Research has shown that increasing the fineness of FA by grinding improves reactivity to a point but eventually leads to increased water demand.[5,6] The increased water demand results from the increased surface area offered by the finer, irregularly shaped, ground particles.[6,7] Others have shown success in the laboratory by using a variety of other classification systems to produce an enhanced FA. Processed FA with improved reactivity and no negative consequences due to increased water requirements has been demonstrated on a laboratory scale.[8-12]

This paper provides physical and chemical characteristics, as well as performance data for a FA that has been engineered to provide both improved reactivity and improved rheological behavior. The improvements are achieved by producing an optimum particle size distribution through the use of a commercial-scale, selective, air-classification system. Concrete testing indicates that the combination of increased reactivity and improved water-reducing capacity of this material can be used advantageously to produce high-performance concrete. The unique properties of this ultra-fine fly ash (UFFA) qualify it for acceptance as a highly reactive pozzolan.

The chemical and physical properties of a particular UFFA are reported herein. Fresh properties—that is, slump, water demand, and set time—and hardened properties—that is, shrinkage and compressive strength of concrete containing SF and UFFA—are reported. Durability properties are also reported herein and these include chloride permeability, electrical resistivity, chloride diffusion, resistance to alkali-silica reaction (ASR), resistance to external sulfate attack, and resistance to freezing and thawing cycling and deicer-salt scaling.

RESEARCH SIGNIFICANCE

Laboratory investigations around the world have shown that when FA particle size is reduced, its performance in concrete is improved. This is the first comprehensive study that shows that significant improvements in concrete strength and durability without loss in workability can be achieved with a commercially available UFFA. The concrete test results clearly show that performance levels similar to that of SF concrete can be achieved. For the practicing engineer, UFFA can be an alternative to SF when specifying concrete for demanding environments where high durability or strength is required.

Materials

Materials used for the production of concrete specimens included an ASTM Type I portland cement, river sand, crushed stone with a maximum size of 19 mm, a tall oil-based ASTM C 260 air-entraining agent (AEA), a lignin-based ASTM Type A water reducer, a naphthalene-sulfonate-based high-range water reducer (HRWR) (40% solids), a densified

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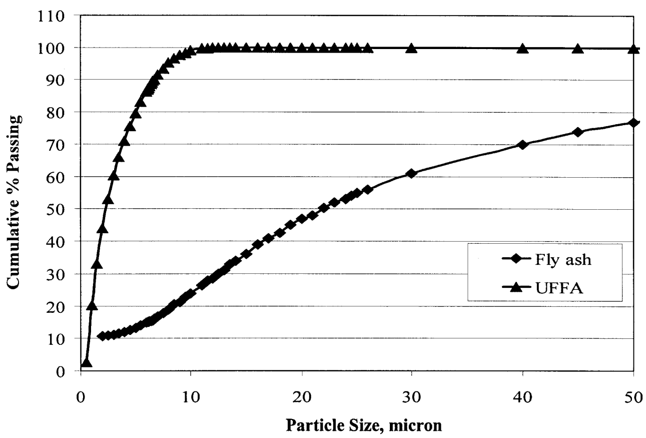

Fig. 1—Particle size distribution of UFFA as compared with regular FA.

SF, UFFA, and a Class F FA (source of UFFA). The chemical and physical properties of the cement, unclassified Class F FA, UFFA, and a typical Class C FA are given in Table 1. Mortar specimens for ASR and sulfate-resistance tests were produced using a Type I cement with a high alkali (1.0% Na_2O_2) and high C_3A (11%) content, respectively. This cement is identified as Cement^A in Table 1. A reactive siliceous limestone from a quarry in Ontario, Canada, was used for ASR tests and standard Ottawa sand was used for the sulfate resistance tests.

UFFA

The UFFA is manufactured by a proprietary separation system that includes selective air classification. The commercially available product typically has a mean particle diameter of about 3 micrometers, with over 90% of the material (by volume) having a particle diameter less than 7 micrometers (as measured by a laser interferometer). This is significantly finer than typical FA as demonstrated in Fig. 1 and 2. Chemical and physical analyses for the UFFA are compared with the parent, unprocessed FA and a typical Class C FA in

Table 1—Chemical and physical properties of cement and UFFA

	Cement	Cement^{A*}	UFFA	Unclassified Class F	Typical Class C
Silicon dioxide (SiO_2), %	20.86	20.20	50.66	53.60	36.12
Aluminum oxide (Al_2O_3), %	4.60	5.68	27.24	26.00	18.96
Iron oxide (Fe_2O_3), %	3.47	3.10	3.06	3.10	6.91
Sum of SiO_2, Al_2O_3, Fe_2O_3, %	28.93	28.98	80.96	82.70	61.99
Calcium oxide (CaO), %	64.34	63.20	11.80	11.17	25.01
Magnesium oxide (MgO), %	1.21	2.77	2.51	2.34	5.46
Sulfur trioxide (SO_3), %	2.79	0.49	1.03	0.49	1.40
Moisture content, %	—	—	0.09	0.06	0.05
LOI, %	1.29	1.10	0.28	0.16	0.21
Amount retained on No. 325 (45 μm) sieve, %	6.9	6.9	2.03	18.66	17.95
Blaine surface area, m^2/kg	370	—	800	330	—
BET surface area, m^2/kg	—	—	3500	830	—
Specific gravity	3.15	3.15	2.57	2.37	2.70
Strength activity index with portland cement at 28 days % of control	—	—	127.20	96.37	105.25
Strength activity index with cement at 7 days	—	—	110.03	87.33	93.15
Water required % of control	—	—	88.13	93.49	91.23
Autoclave soundness (% expansion)	0.04	—	0.19	0.01	0.00
Available alkalies (as equivalent Na_2O), %	0.46	1.01	0.35	0.28	1.86
Tricalcium silicate (C_3S)	63.35	—	—	—	—
Tricalcium aluminate (C_3A)	10.33	11.10	—	—	—

*Cement was used only in ASR and sulfate testing.

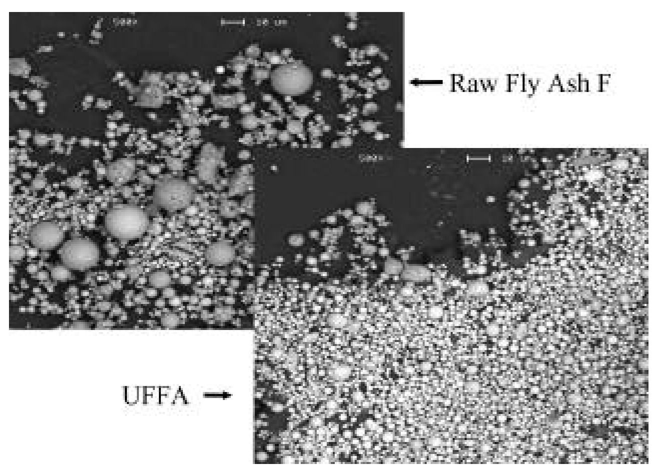

Fig. 2—SEM micrograph of typical sample of UFFA compared with regular FA.

Table 1. Processing has little impact on the bulk chemistry of the FA, which would be designated as Class F by ASTM C 618 terminology. Semiquantitative, x-ray diffraction data suggest that the UFFA contains more than 20% higher proportion of amorphous silica as compared with the parent FA (Fig. 3). The semiquantitative analysis was carried out by measuring and comparing the relative area under the curves of the glass humps centered around 26 degree two-theta in the x-ray diffraction patterns. The high calcium oxide measured in the parent FA as well as the UFFA may also lead to an

Table 2—Mixture proportions, fresh properties, and compressive strength results

Material	360 C	360 SF8	360 UF12.1	360 UF8	360 UF12.2	360 UF12.3
Cement, kg/m^3	360	331	331	331	331	331
SF, kg/m^3	0	29	0	0	0	0
UFFA, kg/m^3	0	0	43	29	43	43
Total CM, kg/m^3	360	360	374	360	374	374
Water, kg/m^3	142	143	141	130	129	120
w/cm	0.40	0.40	0.38	0.36	0.35	0.32
HRWR, mL/100 kg	655	1047	524	589	655	818
Fresh properties						
Slump, mm	200	190	185	165	210	190
Air content, %	6.4	5.0	5.6	5.4	5.4	6.5
Temperature, C	18	18	18	19	20	22
Initial set, hr:min	5:11	5:29	5:49	5:37	5:44	5:42
Compressive strength, MPa						
1 day	13.9	13.4	12.7	14.2	15	24.7
3 days	25.1	26.4	31.1	29.3	30.8	37.1
7 days	33.6	40.8	36.8	36.9	41.6	49.3
28 days	39.2	47.9	45.1	44.8	50.7	57.3
90 days	46.3	53.9	53.6	54.6	56.9	60.5
180 days	47.9	56.6	63.2	55.9	62.9	63.7

Table 3—Concrete mixture proportions for chloride penetrability, electrical resistivity, and chloride diffusion tests

Material	PC	8 UFFA	12 UFFA	16 UFFA	8 SF	12 SF
Cement, kg/m^3	375	345	330	315	345	330
UFFA, kg/m^3	—	30	45	60	—	—
SF, kg/m^3	—	—	—	—	30	45
Total CM, kg/m^3	375	375	375	375	375	375
Water, kg/m^3	150	150	150	150	150	150
w/cm	0.40	0.40	0.40	0.40	0.40	0.40
HRWR, mL/100 kg	625	438	364	313	813	938
Slump, mm	145	135	160	135	190	145

altered glass network with increased reactivity as described by Diamond,[13] Hemmings and Berry,[14] and Pietersen.[15] These intrinsic properties, along with the increased surface area of this engineered product, contribute to the rather dramatic increase in strength activity index (SAI), displayed by the UFFA in Table 1. The increased reactivity and improved water reduction exhibited by the UFFA combine to provide an SAI that is 25 to 30% higher than the unprocessed FA.

Mixture proportions

The experimental program was divided into three phases. Phase I of the program focused on measurement of basic fresh (slump and set time) and hardened (compressive strength) concrete properties and was conducted by Boral Material Technologies. Phase II of the program focused on durability testing such as the ASTM C 1202 (also known as rapid chloride permeability [RCP]), chloride diffusion, electrical resistivity, ASR, sulfate resistance, freezing and thawing resistance, and deicer-salt scaling and was conducted at the University of Toronto. Phase III of the program focused on testing on autogenous

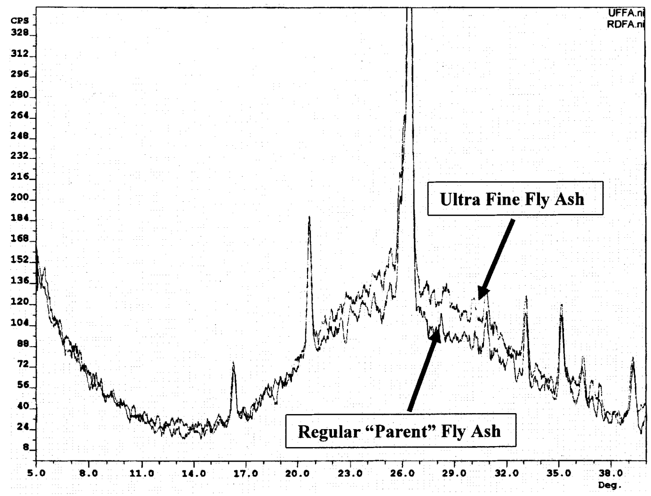

Fig. 3—X-ray diffraction data for UFFA and regular parent FA.

shrinkage, drying shrinkage, and cracking related to that shrinkage and was conducted at Northwestern University.

The concrete mixture proportions used in Phase I of the experimental program are shown in Table 2. Six concrete mixtures were prepared. Cementitious contents were approximately 360 kg/m^3, respectively. Mixture 360 C is the portland cement control. Mixture 360 SF8 had SF at an 8% replacement (by mass) and similar water content as the portland cement control. The other four mixtures contained UFFA at various levels and were designed to use the water-reducing properties of this material. The water-cementitious material ratio (*w/cm*) of the UFFA mixtures ranged approximately between 0.32 and 0.38 as compared with 0.40 for the control and SF mixtures. The amount of HRWR was adjusted to give a slump of 150 to 225 mm. The air content was maintained between 5 and 7%. The experimental measurements in concrete were slump, air content, unit weight, temperature, set time, and compressive strength at various ages (average of two values). Compressive strength was measured on cylinders that were 102 mm in diameter and 203 mm in height.

The concrete mixture proportions used in Phase II of the experimental program are shown in Table 3. The mixtures had different levels of UFFA or SF with a cementitious materials content of 375 kg/m^3 and a water content of 150 kg/m^3, thereby yielding a *w/cm* of 0.40. For these mixtures, the dosage of HRWR was adjusted to produce a slump in the range of 125 to 175 mm. A second series of three mixtures were cast with the same proportions of cementitious materials and *w/cm* as mixtures PC, 12 UFFA, and 8 SF shown in Table 3. These three mixtures were air entrained with air contents in the range of 5 to 7% and concrete specimens from these mixtures were used for freezing and thawing and deicer-salt scaling tests.

In Phase III of the experimental program, three concrete mixtures were prepared with a *w/cm* of 0.40, an aggregate volume fraction of 0.71, and a cementitious content of 400 kg/m^3. The mixtures were an ordinary portland cement control, 8% SF replacement, and 9.3% UFFA replacement.

Mixing and curing

Concrete was prepared according to ASTM C 192 except that mixing was extended by 2 min. The HRWR was added after the concrete achieved a plastic state with 13 mm slump. Immediately after preparation the compressive strength specimens were placed in a 100%

humidity room. They were demolded at 24 h and placed in the humidity room until the test age. The curing conditions for the RCP, resistivity, and chloride diffusion test specimens were as follows: 24 h in molds under wet polythene, then demolded and placed in a 100% humidity room until the test age. Freezing and thawing and scaling test specimens were cured according to their respective ASTM specifications. The shrinkage specimens were covered with a thin plastic sheet and immediately placed in an environmental chamber that was maintained at 30 °C and 40% relative humidity. The specimens were demolded approximately 24 h after casting and stored in the environmental chamber until tested.

Testing

Compressive strength testing was carried out in accordance with ASTM C 39, and rapid chloride permeability tests were performed using the procedures of ASTM C 1202. The sulfate resistance of the UFFA blended with high-C_3A cement (C_3A = 11%) at various replacement levels was assessed using ASTM C 1012. Freezing and thawing tests were conducted in accordance with ASTM C 666 and deicer-salt scaling tests were conducted in accordance with ASTM C 672.

The efficacy of the UFFA in controlling ASR was evaluated using a modified version of the ASTM C 1260 and ASTM C 1293 tests. The only variation from the standard ASTM tests was that portland cement was substituted on an equal mass basis with various pozzolans. The aggregate used was a crushed and graded siliceous limestone from the quarry in Ontario. The alkalis in the pozzolans were disregarded for the purpose of calculating the appropriate NaOH dose in the ASTM C 1293 test and sufficient NaOH was added to bring the portland cement component of the mixture to 1.25% Na_2O_e. The fine aggregate used for the ASTM C 1293 test was a locally available concreting sand that has been shown by testing to be nonreactive.

Bulk chloride diffusion tests were initiated at 28 days. After curing for 28 days in the fog room at 23 °C, 100 mm-diameter x 50 mm-thick test specimens were cut (from concrete panels), the curved surfaces and one flat face were sealed with epoxy and the specimens were then vacuum saturated. After saturation, specimens were immersed in a chloride solution (165 g NaCl per L) in a sealed container at laboratory temperature (nominally 23 °C). After various immersion periods specimens were retrieved from the salt solution and were sampled by precision profile grinding. This technique[16] involved grinding successive layers from the exposed surface of the specimen in 1 mm depth increments down to a depth of 10 mm or greater. The resulting powder samples were then collected and subjected to a total chloride analysis using nitric-acid digestion and subsequent titration against silver nitrate solution. The resulting output of the test is a profile of chloride concentration versus depth from the exposed surface.

The penetration of chlorides into saturated concrete has been shown to follow Fick's second law. The established chloride concentration profile can be fitted to a standard boundary condition solution to Fick's second law, using

$$\frac{C_{x,\,t}}{C_s} = 1 - erf\left(\frac{x}{2\sqrt{D_a \cdot t}}\right) \qquad (1)$$

where C_s = chloride concentration at the surface; C_x = chloride concentration at distance x; x = depth from the surface, m; and D_a = apparent diffusion coefficient, m^2/s.

The unknown values of C_s and D_a are found by fitting Eq. (1) to the experimental data.

The DC-resistivity measurement was carried out using an alternating DC potential similar to the method proposed by Monfore.[17] The test was carried out on specimens immediately prior to testing (the same specimens) in the RCP test. Thus, the preparation of specimens (that is, sealing the curved surfaces and achieving vacuum saturation) followed the detailed procedures outlined in ASTM C 1202. Briefly, the test involves attaching two circular electrodes to the flat surfaces of the test specimen (a 100 mm-diameter x 50 mm-thick disc), applying a DC voltage between the electrodes and measuring the current flow. The voltage is cycled between 3 and 5 volts every 5 s to compensate for polarization effects at the electrodes. The resistivity was calculated as follows

$$\text{Resistivity (ohm.cm)} = \frac{(V_5 - V_3) \times A}{(I_5 - I_3) \times L} \qquad (2)$$

where V_5 = average applied voltage for 5 volts (volts); V_3 = average applied voltage for 3 volts (volts); I_5 = average current for 5 volts (amperes); I_3 = average current for 3 volts (amperes); A = specimen cross sectional area (cm^2); and L = specimen thickness (cm).

In the restrained shrinkage test, a 35 mm-thick annulus of concrete is cast around a rigid steel cylinder with a diameter of 300 mm and a height of 140 mm. The concrete ring contracts due to drying and autogenous shrinkage but is restrained by the rigid steel ring and hence develops tensile stresses and may ultimately crack. Daily visual inspections were performed and the age at first crack was noted.

RESULTS AND DISCUSSIONS

Workability improvement

Fly ashes generally reduce water demand and improve concrete workability.[18] Processing of the FA to produce ultra-fine material further improves these properties. The strong water-reducing performance of the UFFA is in direct contrast to the increased water demand generally associated with other highly reactive pozzolans. Table 2 provides concrete testing results indicating that for a given slump, UFFA reduced the water demand compared with the portland cement control, while SF increased water demand. At slumps of 165 to 210 mm, the UFFA mixtures needed 40% less HRWR and 10% less water as compared with the SF concrete mixture. When the UFFA concrete mixture had 16% less water, it still required only approximately 80% of the HRWR dosage necessary to produce a slump equivalent to that measured in the SF concrete. An examination of Phase II concrete test results (Table 3) also shows the beneficial effect of the UFFA on concrete workability. The required dosage of HRWR decreases significantly as the level of UFFA present in the mixture increases. This trend is in stark contrast to that observed for SF, the addition of which leads to substantial increases in admixture demand. Results from recent cement paste rheological tests also confirm that UFFA, in contrast to SF, results in significant reductions in HRWR and water contents at similar workability levels.[19]

Reasons for improved workability

It is commonly understood that the use of a fine powder will increase the water demand due to the increase in surface area. This reasoning has typically been used to account for

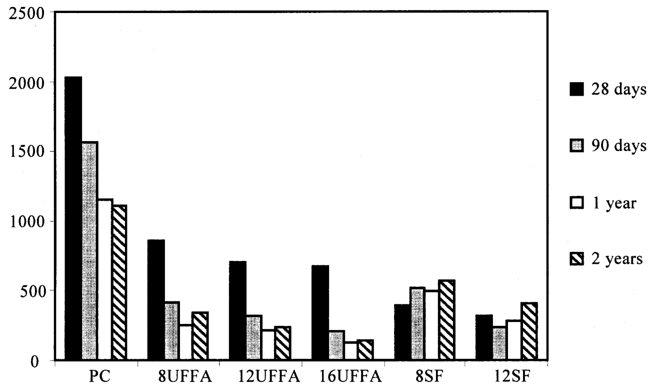

Fig. 4—RCP (ASTM C 1202) test results.

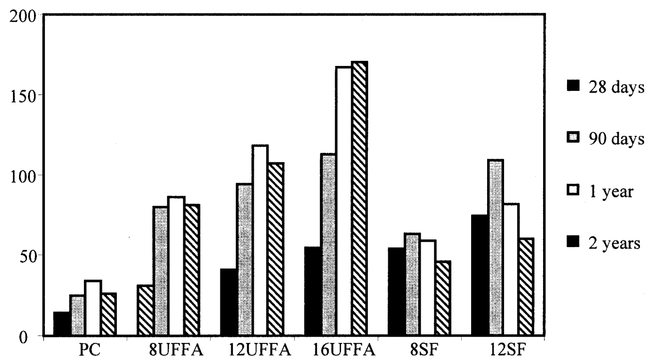

Fig. 5—Results of DC resistivity tests.

the increase in water demand exhibited by Type III cement and SF. Processing of FA to produce UFFA appears to actually enhance the water-reducing properties of the FA. The reasons for this are not completely clear at this time, but several potential contributing factors can be identified. First, it should be noted that the surface area of the UFFA, while increased dramatically compared with ordinary FA, is much lower than typical values reported for SF (3 to 5m^2/g versus 20 to 30 m^2/g). Secondly, a popular hypothesis for the rheological properties offered by FA states that FA spherical particles can easily roll over one another, reducing interparticle friction. Microscopic observations indicate that this UFFA has a higher proportion of spherical particles than its parent FA.[20] The use of UFFA also broadens the particle size distribution (PSD) of the overall cementitious system, thus potentially improving packing features. Higher packing densities and increased sphericity, in theory, should result in an increased availability of free water, leading to improved workability.[21] On the other hand, Helmuth[22] rejected the shape and packing argument and suggested that submicron particles of FA adsorb on the surface of the cement grains and prevent flocculation, thus reducing water demand. The UFFA obviously contains a higher proportion of submicron material than the parent FA. Regardless of the exact mechanism, the concrete testing reported in this paper clearly marks the water-reducing properties of the UFFA.

Compressive strength behavior

Results from compressive strength testing in Table 2 indicate that both the UFFA and SF concrete mixtures display higher strengths than the portland cement control. For similar early-age compressive strengths (as compared with SF concrete mixtures, 360 SF8), it is apparent that more UFFA is required than SF. A 10% reduction in water content was also necessary for equal early-age strength. Later age strengths (28 days and beyond) were comparable at similar pozzolan dosages and water contents. Higher compressive strengths (higher than Mixture 360 SF8) were achieved when the water-reducing capabilities of the processed pozzolan were further used (Mixture 360 UFFA12.3).

Rapid chloride permeability testing

The RCP test (ASTM C 1202) gives a rapid indication of the concrete's resistance to the penetration of chloride ions. Concrete specimens were tested at 28 and 91 days and 1 and 2 years. Results are presented in Fig. 4.

It is clear that the presence of UFFA has a very beneficial effect on the chloride permeability of concrete with significant reductions in the charge passed being observed as the level of UFFA increases. At 28 days, the RCP test value of concretes with 8 to 16% UFFA are higher than those recorded for SF concrete of the same *w/cm*. After 91 days, however, generally similar results are observed for all the concretes with either UFFA or SF. In fact, the lowest RCP test value was recorded for the mixture with 16% UFFA.

Concrete containing UFFA exhibited further reductions in the RCP test value between 91 days and 1 year. Between 1 and 2 years, however, small increases were found in the charge passed for the mixtures containing UFFA. Similar trends were observed for the concrete containing SF, although the magnitude of the increase was much greater. In fact, the charge passed for the concrete with 8% SF has been increasing since the first measurement was made at 28 days. The value at 2 years is 572 Coulombs compared with 393 Coulombs at 28 days; this represents an increase of almost 50% in the chloride permeability. The concrete with 12% SF showed a 29% increase during the same period. While the differences in the RCP test values may be within the experimental error of the test, the consistent increase with time for both mixtures and the fact that a similar trend has been observed in a separate study,[23] indicates that the general trend of increasing electrical conductance is a real phenomenon. This may result, however, from a change in the ionic concentration of the pore solution rather than a change in the pore structure. Shehata and Thomas[24] have reported significant increases with time in the alkali concentration of the pore solution of pastes containing SF. In spite of the increase in RCP test value, the concrete still satisfies a very low chloride permeability level, according to ASTM 1202.

Electrical resistivity

Concrete specimens were tested for DC resistivity at 28 and 91 days and at 1 and 2 years. Figure 5 summarizes the data from DC resistivity tests. Essentially, the trends observed are similar to those observed for the RCP test. The RCP test basically measures electrical conductivity, which is the reciprocal of electrical resistivity. Consequently, increases in resistivity are observed with increasing UFFA and SF content, and with increasing age (as opposed to the decreases observed with the RCP test data). The mixtures with UFFA show inferior performance to the mixtures with SF after 28 days curing, but generally improved performance (especially compared with the concrete with 8% SF) after 91 days.

A number of the mixtures showed a decrease in the electrical resistivity between 1 and 2 years; and this is consistent with the RCP test data, although, again, the trends were not expected. The extent of the reduction is more

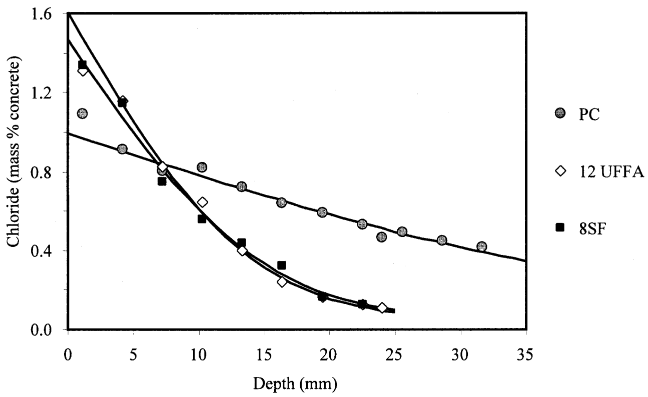

Fig. 6—Chloride profiles after 2 years of immersion.

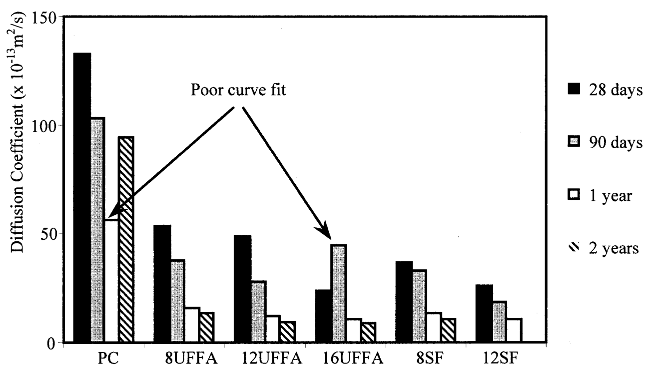

Fig. 7—Results of bulk diffusion tests.

marked for the specimens containing SF and, as observed with the RCP test, the 2-year-old concrete with either 8 or 12% SF showed inferior performance compared with the 28-day-old samples.

Chloride diffusion

Typical chloride profiles measured on concrete specimens after immersion in NaCl solution for 2 years are shown in Fig. 6. Figure 7 summarizes the apparent diffusion coefficients calculated for the different concrete mixtures after immersion periods of between 40 days and 2 years. These data show the same general trends as the RCP and resistivity data except that improvements in performance continued throughout the 2 year test period. Increasing levels of UFFA and SF lead to very significant reductions in the chloride diffusivity compared with plain portland cement concrete. The diffusion coefficients for the UFFA concrete are higher than those for SF concrete after a 40-day soaking period, but the values obtained for both types of concrete are generally similar for immersion periods of 91 days or more. In two cases, the calculated diffusion coefficient did not follow the general trend of the data; and in both cases, there was a poor fit between the theoretical solution (Eq. (1)) and the experimental profile. The reasons for this are not clear.

RESISTANCE TO ASR

Accelerated mortar bar tests

Results from modified ASTM C 1260 tests are shown in Fig. 8. The behavior of the UFFA is almost identical to that of SF with regard to controlling expansion in this test. It is interesting to compare the performance of the UFFA with the source FA. It is clear that the finer FA is significantly more efficient in controlling ASR expansion. Replacement levels of

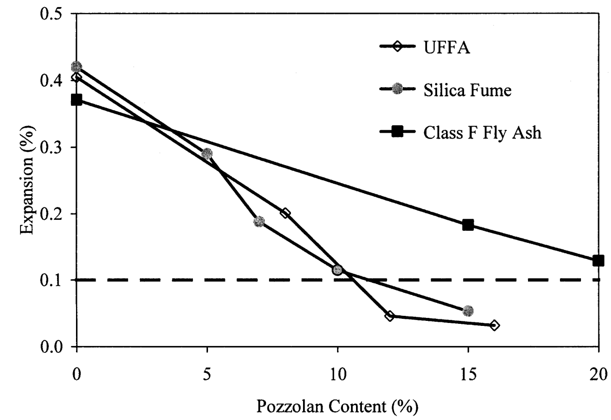

Fig. 8—Results of accelerated mortar bar test (ASTM C 1260).

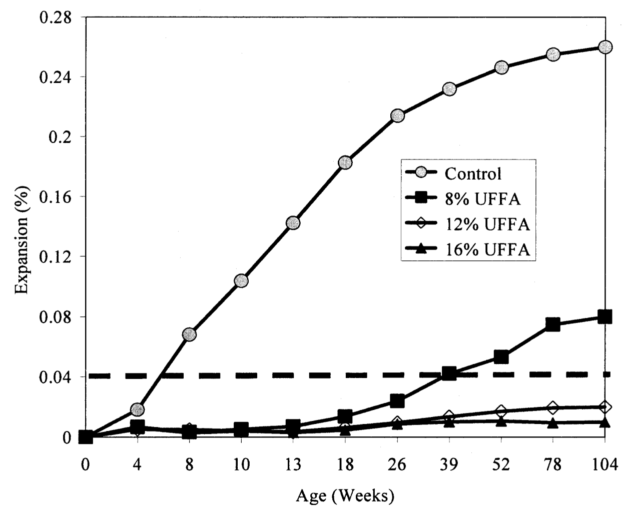

Fig. 9—Results of concrete prism test (ASTM C 1239).

12 or 16% UFFA, 15% SF, or 25% Class F FA were sufficient to reduce the expansion to less than 0.10% at 14 days.

Concrete prism tests

Test results up to 2 years from the modified ASTM C 1293 tests are shown in Fig. 9. The results from this test are consistent with those from the accelerated test. Concrete with 12 or 16% UFFA expanded by less than 0.04% at 2 years and mortars with the same amounts of UFFA expanded by less than 0.10% at 14 days. Conversely, concrete with 0 or 8% UFFA expanded by more than 0.04% at 2 years and the equivalent mortars expanded by more than 0.10% at 14 days. The correlation between the concrete and mortar tests is consistent with the findings of Thomas and Innis[25] for a wider range of pozzolans, slag, and reactive aggregate types.

Sulfate resistance

Expansion results are shown in Fig. 10. It should be noted that commonly used criteria for sulfate resistance are as follows:

Sulfate resistance	Criteria	Standards (ASTM)
Moderate	< 0.10% at 6 months	C 618, C 989, C 1240, C 1157
High	< 0.05% at 6 months	C 618, C 989, C 1240, C 1157
	< 0.10% at 12 months	C 1157
Very high	< 0.05% at 12 months	C 1240

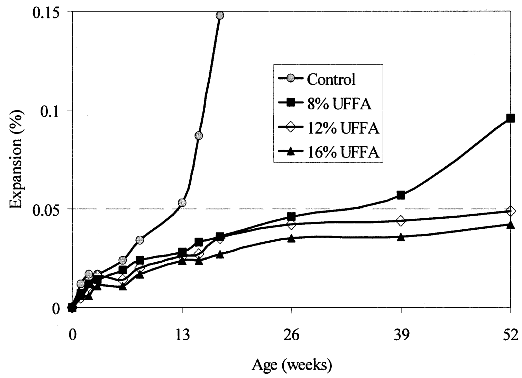

Fig. 10—Results of sulfate resistance test (ASTM C 1012).

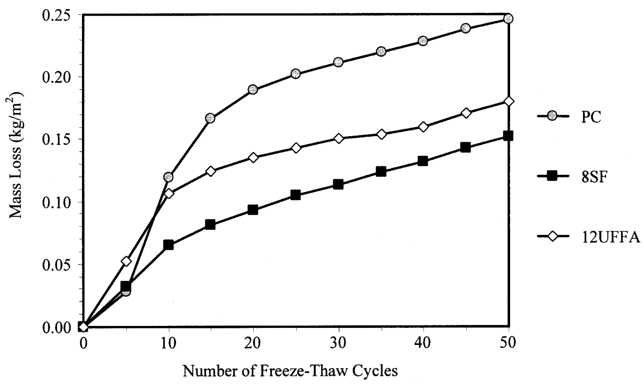

Fig. 11—Results of salt scaling test (ASTM C 672).

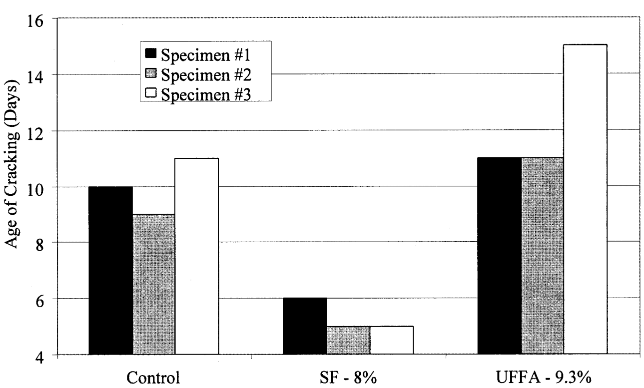

Fig. 12—Restrained shrinkage cracking behavior of SF and UFFA concrete.

Based on these criteria, it can be seen that the high-C_3A cement when used by itself does not offer any level of sulfate resistance. Combinations of the same cement with 8% UFFA meet both limits for high resistance, whereas blends with higher levels of UFFA (that is, 12 and 16%) meet the limits for very high resistance. Although no testing was carried out with the regular Class F FA, previous research has indicated that replacement levels of 20% or more are typically necessary to achieve a high level of sulfate resistance.[18]

Resistance to freezing and thawing and deicer-salt scaling

Samples from air-entrained mixtures PC (control), 8 SF (8% SF), and 12 UFFA (12% UFFA) were subjected to 900 cycles of freezing and thawing. There was no significant reduction in the dynamic modulus during testing; indeed, durability factors after 900 cycles were greater than 100% for all three concrete mixtures tested.

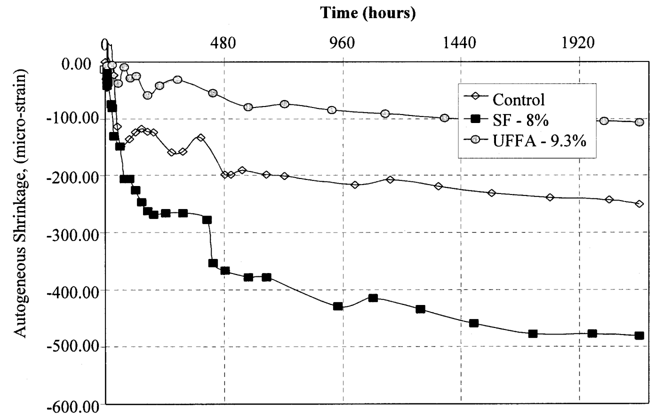

Fig. 13—Autogenous shrinkage behavior of SF and UFFA concrete.

Concrete slabs prepared from the same three mixtures were also tested for scaling resistance in accordance with ASTM C 672. Figure 11 shows the progressive loss of mass from the finished surface of the slabs during testing. The mass loss after 50 cycles of freezing and thawing in the presence of deicing salts was low (150 to 250 g/m^2) for all three mixtures and a visual rating of zero to 1 was recorded for all the slabs tested. Concrete with 8% SF or 12% UFFA showed slightly lower mass loss than the control mixture although there was no noticeable difference in the visual appearance.

Restrained shrinkage test results

Restrained shrinkage test results are plotted in Fig. 12. It can be observed that the concrete containing UFFA cracked at a slightly later age (12.3 days) as compared with the control concrete mixture (10 days). The SF concrete mixture cracked at an earlier age (5.3 days). Further investigation showed that the fracture resistance, elastic moduli, and drying shrinkage values were similar for all three mixtures. The SF mixture, however, had a much higher rate of increase in autogenous shrinkage at early ages (Fig. 13).[26] This suggests that the rate of stress development in the early ages is very high in the SF mixture when the material is still relatively weak. Because the fracture resistance of all mixtures was comparable, SF mixture had the highest potential for failure due to early cracking. It has been reported, however, that SF concrete may not crack earlier if the specimens are subjected to 7 days of moist curing prior to exposure to a drying environment.[27]

Discussions on durability test results

The benefits of using Class F FA in concrete in terms of improved durability have been recognized for many decades. Previous research, however, has shown that for satisfactory control of ASR and sulfate attack, replacement levels in the range of 20 to 30% are usually required.[18] The UFFA used in this study was able to control the expansion of mortars or concrete containing reactive aggregates or of mortars immersed in sulfate solution at relatively modest levels of replacement (for example, 8 to 16%). Indeed, the UFFA appears to provide equivalent performance to SF in these tests.

The use of FA is an effective means for reducing the permeability and chloride penetrability of concrete. These benefits, however, are usually manifested at later ages with little improvement being observed at ages of 28 days or so.[18] The use of UFFA results in very substantial reductions in chloride permeability (electrical conductivity) in concrete at 28 days and the differences between concrete with and without UFFA appear to become more marked at later ages. The diffusion coefficient after just 40 days ponding is between 2.5 to 5.5 times lower in concrete with between 8 to 16% UFFA compared with the control concrete (PC) at the same *w/cm*. After 2 years ponding, the diffusion coefficients of the concrete with UFFA are between 7 to 11 times lower than the control. Although not considered in this paper, these reductions in chloride permeability should lead to very dramatic increases in the service life of reinforced concrete elements exposed to chlorides.

At early ages, the concretes with SF appear to offer a slightly higher resistance to chloride penetration as assessed by the rapid chloride permeability, electrical resistivity, and chloride diffusion tests. Beyond approximately 90 days, however, there is little to separate the concretes with UFFA and SF, and by 2 years it is possible that the concretes with UFFA offer slightly greater resistance. Overall, it is not unreasonable to suggest that the use of moderate levels of UFFA (for example, 8 to 12%) will provide equivalent performance to the use of 8% SF.

These tests were carried out at equal cementitious material and water contents (that is, equal *w/cm*). No advantage was taken of the water-reducing properties of the UFFA.

SUMMARY AND CONCLUSIONS

A UFFA is being commercially manufactured with a mean particle diameter of approximately 3 microns. The high silica content and sum of oxides (SiO_2 + Al_2O_3 + Fe_2O_3) are similar to what would be expected for a Class F FA as per ASTM C 618 designation.

1. The UFFA can produce concrete strength comparable with that produced with a highly reactive pozzolan such as SF. To reach the performance levels of SF concrete at early age, generally the concentration of UFFA must be slightly greater than the SF content, and the total water in the concrete must be reduced by about 10%;

2. UFFA displays a strong tendency to reduce water demand. For comparable workability as SF concrete, a 10% reduction in total water content, together with as much as a 40% reduction in HRWR, was possible;

3. UFFA concrete also displays a lower tendency towards cracking due to drying and autogenous shrinkage compared with SF concrete; and

4. Processing FA into an ultra-fine material with a refined particle size distribution clearly improves its performance as a durability-enhancing admixture. The practical significance of the increased reactivity, from a concrete technology perspective, is that a given improvement in performance can be achieved at a lower level of replacement (that is, the ultra-fine material is more efficient) compared with an unprocessed FA and at an earlier age. As such, the UFFA may offer a viable alternative to SF in certain applications.

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