USE OF SUPERPLASTIZERS IN TIF FOR HVFA CONCRETE FOR INDUSTRIAL PARK ROADS WITH MINIMUM LIFE-CYCLE COSTS

By Tarun R. Naik, John H. Tews, Bruce W. Ramme, and Shiw S. Singh

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Use of Superplastizers in TIF for HVFA Concrete for Industrial Park Roads with Minimum Life-Cycle Costs*

By

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Synopsis: This research was primarily carried out to demonstrate the application of HVFA concrete systems to minimize overall costs of road pavements. The research was completed in two phases. Phase I work was primarily devoted toward development of superplasticized concrete mixtures through laboratory investigation. Phase II work was directed toward demonstration of HVFA concrete application in paving roads. For Phase I work, six different concrete mixtures were proportioned using a Class C fly ash as cement replacement in the range of 18-74% of total cementitious materials. Each concrete mixture was evaluated with respect to compressive strength, tensile strength, flexural strength, modulus of elasticity, shrinkage, abrasion resistance, chloride ion permeability, salt scaling resistance, and freezing and thawing durability. The results indicated that concrete mixtures incorporating fly ash up to 56% are appropriate for paving and structural applications. On the basis of the results of this and other investigations, a 40% percent fly ash mixture was selected for Phase II investigation to demonstrate technical and economic feasibility of using HVFA concrete in construction of pavements. Test data collected to-date have shown excellent results for pavements made with 40% fly ash concrete.

Keywords: Abrasion; compressive strength; concrete; deicing salt scaling; flexural strength; freezing and thawing; pavement; permeability; shrinkage.
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soil and groundwater remediation technologies including bioremediation.

**INTRODUCTION**

Coal-fired electric plants generate nearly 81 million tonnes (90 million tons) of coal-combustion by-products in the USA. Of these, fly ash constitute a major component, about 50 million tonnes/year (55 million ton/year). Only about 25% of the fly ash produced is utilized in various applications. The remainder of the fly ash is landfilled. A large volume of fly ash can be consumed in cement-based materials. Low utilization of fly ash in cement-based materials in the United States is primarily attributed to regulatory and institutional constraints. Moreover, there is a lack of information about fly ash properties, especially mineralogical and structural properties, and their long-term performance in cement-based materials. To enhance rate of fly ash utilization, development of high-volume fly ash concrete has been a major subject of several investigations during the last 10-15 years.

Malhotra and his co-workers at CANMET [1-3] made valuable contributions toward development of structural grade concrete containing high volumes of Class F fly ash. Naik and his associates [4-6] made significant contribution in the development of high-volume Class C fly ash concrete systems at the University of Wisconsin–Milwaukee in cooperation with CANMET. Based on these investigations, a number of attempts have been made to demonstrate use of fly ash in paving and other applications [4-10].

It is estimated that large amounts of fly ash can be consumed in pavement construction.
Therefore, this work was carried out with a view to demonstrate technical and economical feasibility of using high-volumes of Class C fly ash in construction of concrete pavements. The results of this investigation would help in developing material specifications for large-scale commercialization of high-volume fly ash concrete technology in paving roads.

**TIF AND HVFA CONCRETE CONSIDERATIONS**

Tax Incremental Financing (TIF) is a capital financing tool available in forty-four states in the USA in one form or another. Eight of these states refer to TIF by another name such as "Division of Tax Revenue" or "Tax Allocation" in the enabling state legislation. Common to different versions of TIF is the idea that property taxes, or other property related revenues, resulting from the increase in tax base value in a specific area, can be used to repay the costs of investment which improve that specific area. Funds may be used to pay for infrastructure improvements or to subsidize land write-down to private investors.

TIF life can be as long as 23 years or until all improvement are paid for. Construction costs of the improvements must be expended in the first seven years. If the debts of a TIF district are not paid off in 23 years, the cost of the balance of the improvements is placed on the general property tax roll. Of course, this is not desirable; and can be avoided with proper design, planning, and construction in the TIF district.

In Phase II work, TIF district roads were constructed with HVFA concrete pavements at the
Sussex Industrial Park, Village of Sussex, Wisconsin. The Village of Sussex TIF districts are typically paid off in 14-16 years. Since concrete pavement does not normally require any significant maintenance for 30-50 years (except perhaps crack filling), it was selected over asphalt pavement because the Industrial Park would not supply any tax dollars for maintenance until the TIF district is paid off and closed. Asphalt pavement only lasts for about 10-15 years with crack filling. They then typically require replacement or, at the least, milling and resurfacing.

The advantages and disadvantages of using the 40% HVFA vs. no-fly ash concrete for the TIF districts are:

1. Set Time:
   (a) The HVFA concrete has a slower set. More time has to be allowed before cutting expansion/contraction joints, however, the actual cutting time does not change.
   (b) The slower set is excellent for hotter climates and hot summer working conditions.
   (c) An additional hour is added to the useful work time.
   (d) Caution has to be exercised if the daytime temperature drops below 7°C (45°F).

2. Workability: The HVFA concrete mixture workability is equivalent or better than conventional concrete.

3. Hardened Concrete Properties:
(a) Superior compressive, flexural, and tensile strength results.
(b) Equivalent de-icing salt scaling resistance.
(c) Reduced permeability to chloride ion penetration.
(d) Less expensive.

When combined with Tax Incremental Financing:

1. Long life before significant maintenance costs. The actual user helps pay for the initial low maintenance before the TIF district status ends.
2. Better total life cycle cost when compared equally to alternative asphalt pavement.
3. Saves energy (cost of producing cement)
4. Reduces the need for landfill space for fly ash burial - preserves the environment.

**EXPERIMENTAL PROGRAM**

This research was completed in two phases. Phase I work was designed to develop high-quality concrete (HQC) containing fly ash for use in paving through laboratory investigations. Phase II investigation was primarily concerned with demonstration of high-volume fly ash (HVFA) concrete use technology for use in paving roads. To meet the objective of Phase I, various fly ash concrete mixtures were proportioned. A reference concrete without fly ash was proportioned to have the 28-day compressive strength of 41 MPa. Each mixture was evaluated with respect to compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, shrinkage, chloride ion permeability, abrasion resistance, salt scaling resistance, and freezing and thawing resistance.

Based upon the results of Phase I work, and other UWM-CBU and CANMET
investigations, a 40% fly ash mixture was selected for use in Phase II. This mixture was used in construction of roads at the Sussex Industrial Park by the Village of Sussex, Wisconsin. On the basis of work completed in this investigation as well as other investigations (4-11), it was concluded that the 40% mixture would exhibit excellent strength and durability-related properties. Additionally, in the above investigations, a high correlation was obtained between compressive strength and durability-related properties. Therefore, it was decided to measure only compressive strength of the 40% fly ash paving concrete to evaluate its performance in Phase II.

**ROAD DESIGN AND CONSTRUCTION**

Concrete pavement was designed for use by the Sussex Industrial Park in accordance with the State of Wisconsin Standard Specification for Road and Bridge Construction. Fig. 1 shows a plan of the project site. The Sussex Industrial Park is a new 89 hectare (220 acre) business park development for small, light industry and business offices. It includes approximately 8 hectare (20 acre) of commercial shopping area. The concrete pavements (229 mm thick) were paved with an integrated concrete curb and gutter section over a 150 mm limestone base course. Approximately 1,286 linear meter of dual (8.5 m) lane divided concrete boulevard, and 1,286 linear meter of 11 m wide concrete pavements were placed for the Industrial Park roadways. The concrete crown surface was sloped at about 2% from the centerline to the edge of the roadway to provide good drainage. The minimum 28-day compressive strength was specified at 28 MPa and the fresh concrete air content was specified to be 5% to 7% by volume, as required by the Village of Sussex.
A self propelled auto grader was used to plane and level the crushed limestone base material. The base was then compacted using a vibratory roller. Concrete was batched at a remote central ready-mixed concrete plant and transported to the site in conventional ready-mixed concrete trucks. The concrete was discharged in front of a typical highway slip-form paver and was placed full width over a 27-day period in October 1995. The concrete was sprayed with a curing compound and contraction joints were saw cut at 6 m intervals after the concrete had reached the desirable strength for saw cutting. The road was opened to traffic within 10 days of paving completion, and has been providing good service without significant defects through one Wisconsin winter.

MATERIALS

For this Investigation, Type I portland cement meeting ASTM C 150 requirements was used. Properties of the cement used are given in Table 1. ASTM Class C fly ash obtained from the Pleasant Prairie Power Plant, Kenosha, Wisconsin, was used. Chemical and physical properties of the fly ash are reported in Table 1. A natural sand with a 6.35 mm maximum size meeting ASTM C 33 grading requirements was used as the fine aggregate. A crushed limestone conforming to ASTM C 33 grading requirements was used as the coarse aggregate for this investigation. Physical properties of these aggregates are presented in Table 2. A commercially available air-entraining agent conforming to ASTM C 260 was used. A melamine-based superplasticizer conforming to ASTM C 494, Type F, was used throughout this investigation. For each concrete mixture, the amount of the superplasticizer was varied to obtain desired level
of consistency and workability at a low water to cementitious materials ratio.

**CONCRETE MIXTURE PROPORTIONS**

For the Phase I work, a total of six different concrete mixtures were proportioned. One of them was the control mixture, and the other five contained Class C fly ash. The mixture proportions were developed for producing concrete having a ratio of fly ash addition to cement replaced of approximately 1.25. Five different levels (18%, 35%, 40%, 56%, and 74%) of fly ash were used in mixture proportioning of concrete (Table 3). The control mixture (Mix C-3) without fly ash was proportioned to have the 28-day compressive strength of 41 MPa. The water to cementitious materials ratio \( W/(C+FA) \) was maintained at about 0.35 ± 0.02 and air content was kept at 6 ± 1%. Concrete batches of 0.6 cu.m. each were mixed in a power-driven revolving-paddle mixer according to ASTM C 192.

For the investigation in Phase II, one 40% fly ash concrete mixture was proportioned to have a minimum 28-day compressive strength of 28 MPa and an average flexural strength of 2.2 MPa at 7 days of age. The mixture was composed of 214 kg/m\(^3\) cement, 142 kg/m\(^3\) fly ash, 79 kg/m\(^3\) water, 837 kg/m\(^3\) sand, 534 kg/m\(^3\) 19 mm crushed stone (#1), and 534 kg/m\(^3\) 38 mm crushed stone (#2). Approximately 518 ml/m\(^3\) of air entraining admixture was added to entrain an air content in the 5 to 7% range. The amount of the superplasticizer (HRWR) was varied to obtain a slump of 50 ± 25mm.

For Phase II work, the 40% fly ash mixture was batched at a remote ready-mixed concrete plant and transported to the site in conventional ready-mixed concrete trucks and discharged at
the project site in a mechanized paver.

**CASTING AND CURING OF TEST SPECIMENS**

For Phase I work, all test specimens were cast in accordance with ASTM C 192 at the Advance Cast Stone Company, Random Lake, WI. Cylinders (150 x 300 mm) were made from each mixture to evaluate compressive strength, splitting tensile strength, and modulus of elasticity. Prism specimens of (75 x 100 x 400 mm) were cast for flexural strength, freezing and thawing durability, and shrinkage measurements. Cylinders (100 x 200 mm) were cast for measurement of chloride ion permeability. Slab specimens (300 x 300 x 100 mm) were cast for measurements of abrasion resistance and deicer salt scaling resistance.

The test specimens were covered with plastic immediately after casting to minimize their moisture loss. These specimens were stored at a temperature of about 23EC in the casting room area of the precast concrete plant (the Advanced Cast Stone Company). After 24 hours, the specimens were demolded. They were then brought to the UWM-CBU test laboratory and put into a moist curing room at 23EC temperature and 100 percent relative humidity until the time of test.

For Phase II work, specimens for compressive strength measurements were cast in accordance with ASTM C 31.

**TESTING OF SPECIMENS**
Phase I Investigation

Fresh Concrete Properties -- Slump (ASTM C 143), unit weight (ASTM C 138), temperature (ASTM C 1064), and air content (ASTM C 231) for each concrete mixture were determined (Table 3).

Hardened Concrete Properties -- All compressive strength measurements were made in accordance with ASTM C 39. Tensile strength test was carried out in accordance with ASTM C 496. Flexural strength measurements were made using the third-point loading in accordance with ASTM C 78. Modulus of elasticity of concrete was determined per ASTM C 469. Water storage test method was used to evaluate the shrinkage behavior of concrete specimens in accordance with ASTM C 157. Chloride ion permeability of concrete was determined in accordance with ASTM C 1202.

Abrasion tests were conducted on the molded surface of the slab specimens to maintain uniform finish surface quality for these specimens. All the specimens were tested at dry condition using a modified ASTM C 944 test method that was developed at the University of Wisconsin-Milwaukee (7). After the surface was subjected to abrasion treatment, its abrasion resistance was evaluated in accordance with ASTM C 779. Specimens (300 x 300 x 100 mm) were tested for deicer salt scaling resistance in accordance with ASTM C 672. Prism specimens were tested for freezing and thawing resistance of concrete in accordance with ASTM 666, Procedure A.
Phase II Investigation

Fresh concrete properties such as slump (ASTM C 143), temperature (ASTM C 1064), and air content (ASTM C 231) were determined. Compressive strength of concrete was measured in accordance with ASTM C 39. Visual observations of the pavements were made to check for cracks, surface deterioration, or any other pavement distress due to traffic or other loads one year after the construction.

TEST RESULTS AND DISCUSSION

Phase I Results

Compressive Strength -- The test data on compressive strength of concrete mixtures are presented in Fig. 2. At early ages up to 3 days, all the fly ash concrete mixtures exhibited lower strength relative to the non-fly ash mixture; and, it decreased with increasing fly ash content. Up to 56% fly content, compressive strength values were in excess of 30 MPa at 28 days. In general, performance of fly ash concrete improved greatly with age due to the pozzolanic contribution of the fly ash.

Splitting Tensile Strength -- The tensile strength increased with age but it decreased with increasing fly ash content, particularly beyond about 35% fly ash content (Fig. 3). The concrete mixtures having fly ash content varying between 35% and 56% exhibited tensile strength in the range of 2.9 to 3.8 MPa at 28 days.
**Flexural Strength** -- The flexural strength was measured at ages of 3, 7, 28, 56, and 365 days (Fig. 4). The flexural strength ranged from 4.2 to 5.5 MPa at 28 days when the fly ash content was varied between 35% and 56% of total cementitious materials.

**Modulus of Elasticity** -- The secant modulus of the concrete mixtures are given in Fig. 5. The modulus of elasticity values for the mixtures varied from 22.9 to 27.9 GPa at 28 days for fly ash contents ranging from 35% to 56% of total cementitious materials.

**Shrinkage** -- The water-stored shrinkage strain test results for the concrete mixtures are presented in Fig. 6. All high-volume fly ash mixtures showed a very low level of shrinkage within the tested range.

**Abrasion Resistance** -- Test results [7] indicated high abrasion resistance of all concrete mixtures with and without fly ash (fly ash addition up to 56%) in accordance the ASTM requirement. However, beyond 35% fly ash content, abrasion resistance of the fly ash concretes became slightly lower relative to the reference concrete mixture.

**Chloride Ion Permeability** -- The chloride ion permeability test results are presented in Fig. 7. In general, all fly ash mixtures, except the 74% fly ash mixture, exhibited lower chloride ion permeability compared to the reference concrete at all test ages.
**Deicer Salt Scaling Resistance** -- The concrete mixtures containing up to 45% fly ash showed no surface scaling after being subjected to deicer salt scaling tests in accordance with ASTM C 672 [11]. The 56% fly ash concrete mixture achieved a rating of 2, representing "slight to moderate" scaling per ASTM C 672. The 74% fly ash concrete showed severe salt scaling.

**Freezing and Thawing** -- All mixtures with or without fly ash passed durability requirement per ASTM 666, Procedure A [11]. The fly mixture containing up to 35% fly ash showed freezing and thawing durability equivalent to the reference mixture.

**Phase II Results**

Soon after mixing, each concrete batch was tested for slump (ASTM C 143), concrete temperature (ASTM C 1064), and air content (ASTM C 231). The results are shown in Table 4. Compressive strength of the 40% fly ash mixture was measured to evaluate its performance for paving application. Visual observations were also made to see if any damage to the fly ash concrete pavements occurred due to traffic and other loads one year after construction.

The 40% fly ash concrete mixture showed excellent performance with respect to compressive strength. The early-age (3-day) strength of the mixture was in excess of 23 MPa (Fig.9). A rapid rate of strength gain was observed. At the 7-day age, the mixture attained a compressive strength of 38 MPa. This is about 37% higher than the minimum required at the 28-day age. At the age of 28 days, the mixture showed compressive strength equivalent to a high-
strength concrete (44 MPa).

Visual observations did not exhibit any pavement distress after one-year period of service.

Based on these laboratory results and field data, it was concluded that the 40% fly ash mixture is appropriate for construction of pavements in a northern climate.

**ECONOMIC ANALYSIS**

An economic analysis was carried out to evaluate cost-effectiveness of using Class C fly ash in HVFA concrete. It is well known that the use of fly ash as a component of cementitious materials reduces the cost of material significantly. The cost saving increases, with the amount of increase of fly ash. Additional saving is also realized by the producer of fly ash due to avoided disposal costs. Therefore, total cost savings are sum of cost saving due to the material cost plus cost saving due to avoided disposal cost.

Cost of fly ash to a concrete producer varies depending upon transportation cost, cost of storage, additional hardware needed at the ready-mixed plant, etc. For this study, the market cost of Class C fly ash was $25 per tonne. Disposal cost was estimated at $35, on an average it varies between 25 to $60 per tonne. Cost of cement was $85 per tonne, on an average it varies between $70 and $95 per tonne.

The potential cost savings due to use of fly ash as cement replacement is presented in
Table 5 and Fig. 10. In the U.S.A., use of concrete in pavement construction is estimated to be 65 million m$^3$ (85 million cubic yards) per year. As compared to non-fly ash concrete pavement, the use of the 40 percent fly ash mixture will result in potential total cost savings of $969 million/year, based on estimated use of 65 million m$^3$ of concrete in pavement construction alone. The Sussex Industrial Park realized a material cost saving of $42,000 due to the use of fly ash (based on 7,646 m$^3$).

Properly proportioned and placed fly ash concrete is expected to have increased service life and reduced maintenance costs compared to portland cement concrete. Due to these factors coupled with lower initial cost, high-volume concrete pavement would provide a significantly lower life-cycle cost relative to conventional concrete pavement containing no fly ash. Additionally, use of fly ash in lieu of portland cement in concrete saves energy, and prevents emissions of pollutants such as NO$_x$, SO$_x$, CO, etc. due to avoided cement manufacture.

**SUMMARY AND CONCLUSION**

This project was carried out to evaluate technical and economic feasibility of using high-volume fly ash concrete for paving roads. The research program was divided into two phases. Phase I work was conducted to establish paving concrete mixtures through prototype concrete making and laboratory experimental investigation. Phase II study was primarily undertaken to demonstrate suitability of using a high-volume fly ash concrete system in construction of pavements.
In Phase I investigation, six concrete mixtures were proportioned. One of them was a reference mixture which was proportioned to have the 28-day strength of 41 MPa. The other five mixtures contained fly ash ranging between 18-74% of total cementitious materials. Each mixture was tested for strength and durability-related properties. The concrete mixtures containing up to 56% fly ash exhibited adequate performance with respect to the above strength and durability-related properties.

For the Phase II study, a 40% fly ash concrete mixture (by mass of total cementitious materials) was selected based on Phase I results and other investigations completed at CBU in order to produce a high-quality paving concrete. Compressive strength of the 40% fly ash paving mixture was measured to evaluate its performance in the field investigation. One year after the pavement construction, visual observations were made to evaluate performance of the fly ash concrete pavement constructed in Phase II. The compressive strength data showed excellent performance of the 40% of fly ash mixture paving concrete. Visual observations of the pavement showed no sign of any pavement distress during the one-year service period.

An economic analysis was carried out to demonstrate economic feasibility of using Class C fly ash in concrete. The results indicated that the use of fly ash provided large saving in material cost, and saving in disposal cost to the producer of fly ash. Moreover, the use of fly ash as a replacement of cement in concrete provides energy savings and decreased emissions of pollutants (CO₂, NOₓ, CO, etc) in the air because of avoided cement manufacture.

ACKNOWLEDGEMENTS
Initial work of Phase I HVFA concrete was developed in cooperation with CANMET. The authors express their gratitude to EPRI and Advance Cast Stone Company for providing additional support for the work related to the Phase I investigation. The Phase II investigation financial support was provided by the Village of Sussex, Wisconsin.

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The help provided by staff of the Center for By-Products Utilization and former graduate students (Mohammed M. Hossain, Wenyi Hu, and Congli Ye) in data collection and analysis in Phase I investigation is gratefully acknowledged.

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1. Mukherjee, P.K., Loughborough, M.T., and Malhotra, V.M., "Development of High-


Table 1: Properties of Cement and Fly Ash

<table>
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<tr>
<th>Chemical Composition</th>
<th>Cement, Percent</th>
<th>ASTM C 150, Type I</th>
<th>Fly Ash, Percent</th>
<th>ASTM C 618, Class C</th>
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<tbody>
<tr>
<td>Silicon Oxide, SO₂</td>
<td>20.2</td>
<td>-</td>
<td>30.5</td>
<td>-</td>
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<tr>
<td>Aluminum Oxide, Al₂O₃</td>
<td>4.7</td>
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<td>17.2</td>
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<td>0.3</td>
<td>-</td>
<td>5</td>
<td>-</td>
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<tr>
<td>Total, SiO₂ + Al₂O₃ + Fe₂O₃</td>
<td>25.2</td>
<td>-</td>
<td>53.2</td>
<td>50.0 Min.</td>
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<td>-</td>
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<td>64.1</td>
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<td>28.6</td>
<td>-</td>
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<td>0.9</td>
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<td>5.0 Max.</td>
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<td>-</td>
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<td>Potassium Oxide, K₂O</td>
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<td>Loss on Ignition</td>
<td>-</td>
<td>3.0 Max.</td>
<td>0.3</td>
<td>6.0 Max.</td>
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Physical Properties of Cement

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<tr>
<th>Property</th>
<th>Cement, Percent</th>
<th>ASTM C 150, Type I</th>
<th>Fly Ash, Percent</th>
<th>ASTM C 618, Class C</th>
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<td>Air Content (%)</td>
<td>7.1</td>
<td>12 Max.</td>
<td>-</td>
<td>-</td>
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<td>Fineness (m²/kg)</td>
<td>396</td>
<td>280 Min.</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Autoclave Expansion (%)</td>
<td>0.03</td>
<td>0.8 Max.</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Specific Gravity</td>
<td>3.16</td>
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<td>-</td>
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<tr>
<td>Compressive Strength, MPa</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1-day</td>
<td>16.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>3-day</td>
<td>25.7</td>
<td>12.4 Min.</td>
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<tr>
<td>7-day</td>
<td>31.5</td>
<td>19.3 Min.</td>
<td>-</td>
<td>-</td>
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<td>28-day</td>
<td>37.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Vicat Time of Initial Set (min)</td>
<td>145</td>
<td>45 Min.,</td>
<td>375 Max.</td>
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<td>Physical Properties of Fly Ash</td>
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<tr>
<td>Fineness, Retained on No. 325 Sieve (%)</td>
<td></td>
<td></td>
<td>18.6</td>
<td>34 Max.</td>
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<td>Pozzolanic Activity Index with Cement, 28-day (% of control)</td>
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<td>105</td>
<td>75 Min.</td>
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<td>Water Requirement (% of control)</td>
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<td></td>
<td>90.4</td>
<td>105 Max.</td>
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<td>Autoclave Expansion (%)</td>
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<td></td>
<td>0.02</td>
<td>0.8 Max.</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td></td>
<td></td>
<td>2.78</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 (cont.): Properties of Cement and Fly Ash
Table 2: Physical Properties of Aggregates

<table>
<thead>
<tr>
<th>Fine Aggregates</th>
<th>Coarse Aggregates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sieve Size</td>
<td>% Passing</td>
</tr>
<tr>
<td>#4</td>
<td>100</td>
</tr>
<tr>
<td>#8</td>
<td>91</td>
</tr>
<tr>
<td>#16</td>
<td>74</td>
</tr>
<tr>
<td>#30</td>
<td>49</td>
</tr>
<tr>
<td>#100</td>
<td>4</td>
</tr>
</tbody>
</table>

Aggregate Physical Properties

<table>
<thead>
<tr>
<th>Aggregate</th>
<th>Physical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bulk Specific Gravity</td>
</tr>
<tr>
<td>Fine</td>
<td>2.25</td>
</tr>
<tr>
<td>Coarse</td>
<td>2.76</td>
</tr>
</tbody>
</table>
Table 3: Mixture Proportions Using ASTM Class C Fly Ash - 41 MPa Specified Strength at 28-Day Age.

<table>
<thead>
<tr>
<th>Mix Number</th>
<th>C-3 (P)</th>
<th>P4-2 (P)</th>
<th>P4-3 (P)</th>
<th>P4-6 (P)</th>
<th>P4-7 (P)</th>
<th>P4-8 (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (kg/m³)</td>
<td>375</td>
<td>259</td>
<td>220</td>
<td>320</td>
<td>179</td>
<td>110</td>
</tr>
<tr>
<td>Fly Ash (kg/m³)</td>
<td>0</td>
<td>139</td>
<td>182</td>
<td>71</td>
<td>226</td>
<td>316</td>
</tr>
<tr>
<td>Cement/ (Cement + F.A.)</td>
<td>0</td>
<td>35</td>
<td>45</td>
<td>18</td>
<td>56</td>
<td>74</td>
</tr>
<tr>
<td>Water (kg/m³)</td>
<td>135</td>
<td>133</td>
<td>150</td>
<td>129</td>
<td>136</td>
<td>155</td>
</tr>
<tr>
<td>[W/ (C+FA)]</td>
<td>0.36</td>
<td>0.34</td>
<td>0.37</td>
<td>0.33</td>
<td>0.33</td>
<td>0.36</td>
</tr>
<tr>
<td>Sand, SSD (kg/m³)</td>
<td>682</td>
<td>677</td>
<td>659</td>
<td>693</td>
<td>655</td>
<td>607</td>
</tr>
<tr>
<td>25 mm max. aggregates, SSD(kg/m³)</td>
<td>1182</td>
<td>1172</td>
<td>1153</td>
<td>1180</td>
<td>1139</td>
<td>1145</td>
</tr>
<tr>
<td>Slump (mm)</td>
<td>120</td>
<td>160</td>
<td>120</td>
<td>145</td>
<td>115</td>
<td>120</td>
</tr>
<tr>
<td>Air Content (%)</td>
<td>6.3</td>
<td>5.2</td>
<td>6.4</td>
<td>6.7</td>
<td>7.0</td>
<td>6.4</td>
</tr>
<tr>
<td>Superplasticizer (L/m³)</td>
<td>2.9</td>
<td>2.8</td>
<td>2.7</td>
<td>2.8</td>
<td>2.7</td>
<td>2.6</td>
</tr>
<tr>
<td>Air Entraining Admixture (ml/m³)</td>
<td>270</td>
<td>250</td>
<td>515</td>
<td>420</td>
<td>885</td>
<td>1380</td>
</tr>
<tr>
<td>Air Temperature (EC)</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Concrete Temperature (EC)</td>
<td>23</td>
<td>23</td>
<td>26</td>
<td>21</td>
<td>26</td>
<td>25</td>
</tr>
<tr>
<td>Fresh Concrete Density (kg/m³)</td>
<td>2480</td>
<td>2395</td>
<td>2360</td>
<td>2400</td>
<td>2335</td>
<td>2365</td>
</tr>
<tr>
<td>Hardened Concrete Density, SSD (kg/m³)</td>
<td>2470</td>
<td>2430</td>
<td>2415</td>
<td>2440</td>
<td>2340</td>
<td>2325</td>
</tr>
</tbody>
</table>
Table 4: Test Data for the HVFA Concrete (40% Class C fly ash mixture) Used in Phase II for the Industrial Park Road Paving

<table>
<thead>
<tr>
<th>Test Parameter</th>
<th>No. of Tests</th>
<th>Average Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump (mm)</td>
<td>72</td>
<td>28</td>
</tr>
<tr>
<td>Concrete Temperature (EC)</td>
<td>72</td>
<td>19.4</td>
</tr>
<tr>
<td>Air Content (%)</td>
<td>72</td>
<td>6.1</td>
</tr>
<tr>
<td>Compressive Strength (MPa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-Day</td>
<td>4</td>
<td>23.5</td>
</tr>
<tr>
<td>4-Day</td>
<td>13</td>
<td>27.6</td>
</tr>
<tr>
<td>5-Day</td>
<td>7</td>
<td>31.0</td>
</tr>
<tr>
<td>6-Day</td>
<td>4</td>
<td>30.7</td>
</tr>
<tr>
<td>7-Day</td>
<td>58</td>
<td>38.9</td>
</tr>
<tr>
<td>16-Day</td>
<td>9</td>
<td>39.2</td>
</tr>
<tr>
<td>28-Day</td>
<td>56</td>
<td>43.7</td>
</tr>
</tbody>
</table>
Table 5: Economics of Using Class C Fly Ash in Concrete

Total Cementitious Materials: 356 kg/m$^3$

<table>
<thead>
<tr>
<th>Fly Ash Content (%)</th>
<th>Fly Ash Content (kg/m$^3$)</th>
<th>Cement Content (kg/m$^3$)</th>
<th>Cost of Fly Ash ($/m^3$)</th>
<th>Cost of Cement ($/m^3$)</th>
<th>Total Cost of C + FA ($/m^3$)</th>
<th>Cost Saving ($/m^3$)*</th>
<th>Avoided Disposal Cost ($/m^3$)</th>
<th>Total Cost Savings ($/m^3$)*</th>
<th>Projected Total Cost Savings in USA (million$/year)***</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>356</td>
<td>0</td>
<td>33.35</td>
<td>33.35</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>71</td>
<td>285</td>
<td>1.96</td>
<td>26.68</td>
<td>28.64</td>
<td>4.71</td>
<td>2.74</td>
<td>7.45</td>
<td>484</td>
</tr>
<tr>
<td>30</td>
<td>107</td>
<td>249</td>
<td>2.96</td>
<td>23.35</td>
<td>26.29</td>
<td>7.06</td>
<td>4.12</td>
<td>11.18</td>
<td>727</td>
</tr>
<tr>
<td>40</td>
<td>142</td>
<td>214</td>
<td>3.92</td>
<td>20.01</td>
<td>23.93</td>
<td>9.42</td>
<td>5.49</td>
<td>14.91</td>
<td>969</td>
</tr>
<tr>
<td>50</td>
<td>178</td>
<td>178</td>
<td>4.90</td>
<td>16.68</td>
<td>21.58</td>
<td>11.77</td>
<td>6.87</td>
<td>18.64</td>
<td>1211</td>
</tr>
</tbody>
</table>

*Cost saving due to use of fly ash as a replacement of cement.
**Total cost savings = cost saving due to lower cost fly ash compared to cement plus disposal cost saving.
***Cost savings on national level based on total concrete used in pavement.