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Cover: Concrete pavement. M.G. Road
(Ladyhill to Lalbagh), Mangalore
Client: Mangalore Municipal Corporation
Consultants: Dhanwant and Associates
Contractor: M.G. Hussain & Company
Jugul Construction Pvt Ltd
Cement used: ACC Suraksha
Photo courtesy: Mr B.S. Biradar, RMO, ACC, Bangalore

Technical papers

137 Performance of high-volume fly ash concrete pavements constructed since 1984
Taran R. Naik, Bruce W. Ramno and Rudolph N. Kraus

144 Design of RC slabs to satisfy both bending and deflection criteria
Sarat Kumar Das

148 Are increased covers of beams in accordance with IS 456 : 2000 desirable?
D. Sree Ramachandra Murty and N.V. Subba Rao

157 Concrete properties affecting corrosion of embedded rebars
A.K. Tiwari and P. Bandyopadhyay

164 Rapid assessment of chloride resistance of concrete using the chloride conductivity test
J.R. Mackechnie and M.G. Alexander

Features

129 Editorial: ACI : A century of distinguished service to concrete!

132 News and Events

131 Letters to the Editor

170 Point of View: Dual role of gypsum: Set retarder and strength accelerator
N. Bhanumathi and N. Kalidas

174 Engineering Education: Learning to "Learn": The forgotten pleasures of civilised education
Dhanada K. Mishra

177 ICJ index 2003

183 Earthquake Tip 17 : How do earthquakes affect reinforced concrete buildings?
This investigation was performed to evaluate the long-term performance of concrete pavements made with high volumes of Class F and Class C fly ash. Additional recent field performance investigations (2002) are reported in this paper since the prior publication in the ACI [1]. Six different mixtures, consisting of three mixtures with Class C fly ash having up to 70 percent cement replacement and three mixtures with Class F fly ash having up to 67 percent cement replacement, were used. Two series of tests were conducted to establish the long-term performance for all mixtures using core specimens from in-situ pavements. Long-term tests were conducted for compressive strength, resistance to chloride-ion penetration, and density. Test results revealed that both Class C and Class F fly ash contributed to high long-term compressive strength. Generally, the concrete mixtures containing Class F fly ash exhibited higher resistance to chloride ion penetration relative to mixtures containing Class C fly ash. Long-term compressive strengths of core specimens taken from in-situ pavements ranged from approximately 45 to 59 MPa. The highest long-term compressive strength was achieved by concrete mixtures incorporating 19 percent Class C fly ash at the age of 12 years (59 MPa) and 67 percent Class F fly ash at the age of 7 years (57 MPa). Visual observations revealed that the concrete pavement sections containing high-volumes of Class F fly ash (35 to 67 percent) performed well in the field with only minor surface scaling. Concrete pavement sections containing up to 70 percent Class C fly ash have experienced some surface damage due to abrasion and scaling, especially in an area where truck traffic makes a 90-degree turn.

Concrete is considered to be a two-phase material — aggregate and the cement paste — with a thin layer in between the two phases, known as the transition zone. It is now recognised that the interfacial transition zone between aggregate and hydrated cement paste is the weakest link in concrete [2]. The performance of concrete is adversely affected by the increase in size and number of microcracks in the transition zone, which govern the strength and durability characteristics of the material. Due to the presence of a higher water-cementitious material ratio compared to the bulk of concrete, the transition zone contains a large number of capillary voids as well as microcracks created during the processing and hardening of concrete. The size and number of microcracks are influenced by several factors including aggregate size and grading, water-cementitious materials ratio, cementitious material content, chemical admixtures, and mineral admixtures. Recently, attempts have been made to produce high-quality concrete by using large volumes of pozzolanic admixtures such as fly ash, ground granulated blast furnace slag (GGBFS), etc. In view of the widespread availability and low cost, coal fly ashes are the most commonly used in the manufacture of cement-based materials to improve their microstructure. Generally, strength development of concrete made with fly ash, especially Class F fly ash, is slower than concrete without fly ash. However, recent advances in concrete technology have solved this problem to a great extent by using appropriate mixture proportions at a low water-cementitious materials ratio, with the use of high-range water-reducing admixtures (HRWRA).

A number of researchers — Mehta [3], Mukherjee et al. [4], Malhotra and Painter [5], Sivasundaram et al. [6], Ravina and Mehta [7], Naik et al. [8], Yuan and Cook [9], Hooton [10], Naik and Ramme [11,12,13,14,15], Naik and Singh [16], Naik et al. [17] — have made attempts to demonstrate the use of high volumes of fly ash in the manufacture of structural and high-strength concrete (HSC) systems. Malhotra and his associates [4,10,17] were among the first to develop mixture proportions for the manufacture...
Table 1: Chemical and physical characteristics of fly ashes

<table>
<thead>
<tr>
<th>Chemical composition</th>
<th>Class F</th>
<th>Class C</th>
<th>ASTM C 618 limits, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fly ash, percent</td>
<td>Class F</td>
<td>Class C</td>
<td>Class F</td>
</tr>
<tr>
<td>Silicon dioxide, SiO₂</td>
<td>51.4</td>
<td>32.9</td>
<td>-</td>
</tr>
<tr>
<td>Aluminum oxide, Al₂O₃</td>
<td>26.3</td>
<td>19.4</td>
<td>-</td>
</tr>
<tr>
<td>Iron oxide, Fe₂O₃</td>
<td>15.3</td>
<td>5.4</td>
<td>-</td>
</tr>
<tr>
<td>Total, SiO₂ + Al₂O₃ + Fe₂O₃</td>
<td>93.0</td>
<td>57.7</td>
<td>70.0</td>
</tr>
<tr>
<td>Sulphur trioxide, SO₃</td>
<td>1.4</td>
<td>3.8</td>
<td>5.0</td>
</tr>
<tr>
<td>Calcium oxide, CaO</td>
<td>3.6</td>
<td>28.9</td>
<td>-</td>
</tr>
<tr>
<td>Magnesium oxide, MgO</td>
<td>1.1</td>
<td>4.8</td>
<td>-</td>
</tr>
<tr>
<td>Titanium dioxide, TiO₂</td>
<td>1.1</td>
<td>1.6</td>
<td>-</td>
</tr>
<tr>
<td>Potassium oxide, K₂O</td>
<td>1.9</td>
<td>0.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Sodium oxide, Na₂O</td>
<td>2.0</td>
<td>4.0</td>
<td>-</td>
</tr>
<tr>
<td>Moisture content</td>
<td>0.7</td>
<td>0.8</td>
<td>3.0</td>
</tr>
<tr>
<td>Loss on ignition</td>
<td>6.5</td>
<td>6.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Physical tests

- Fineness retained on no 325 sieve, percent: 25.7 max, 15.9 max, 34.0 max, 34.0 max
- Strength activity index with cement, 28-days: 93 max, 79 max, 75.0 min, 75.0 min
- Water requirement (percent of control): 103 max, 89 max, 105 min, 105 min
- Autoclave Expansion, percent: 0.0 max, 0.11 max, ±0.8 min, ±0.8 min
- Specific gravity: 2.34 max, 2.58 max

*Per ASTM C 618: The use of class F pulverized fuel ash or class C fly ash may be approved by the user if either acceptable performance records or laboratory test results are available.

Table 2: Concrete mixture proportions and fresh concrete test data

<table>
<thead>
<tr>
<th>Mixture no</th>
<th>A-1</th>
<th>B-5</th>
<th>C-4</th>
<th>D-2</th>
<th>E-3</th>
<th>F-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class C fly ash, percent</td>
<td>70</td>
<td>50</td>
<td>19</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Class F fly ash, percent</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>67</td>
<td>53</td>
<td>35</td>
</tr>
<tr>
<td>Cement, kg/m³, C</td>
<td>101</td>
<td>175</td>
<td>285</td>
<td>133</td>
<td>181</td>
<td>271</td>
</tr>
<tr>
<td>Fly ash, kg/m³, F</td>
<td>234</td>
<td>175</td>
<td>65</td>
<td>267</td>
<td>208</td>
<td>145</td>
</tr>
<tr>
<td>Water, kg/m³, W</td>
<td>N.A.*</td>
<td>92</td>
<td>101</td>
<td>125</td>
<td>119</td>
<td>98</td>
</tr>
<tr>
<td>W/C (F)</td>
<td>N.A.*</td>
<td>0.26</td>
<td>0.29</td>
<td>0.21</td>
<td>0.18</td>
<td>0.27</td>
</tr>
<tr>
<td>SSO sand, kg/m³</td>
<td>884</td>
<td>742</td>
<td>813</td>
<td>837</td>
<td>857</td>
<td>914</td>
</tr>
<tr>
<td>SSO coarse aggregates, kg/m³</td>
<td>1,086</td>
<td>1,086</td>
<td>1,145</td>
<td>1,127</td>
<td>1,127</td>
<td>1,095</td>
</tr>
<tr>
<td>Water reducing admixture, m³/m³</td>
<td>310</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Superplasticizer (HRWRA), m³/m³</td>
<td>0</td>
<td>N.A.**</td>
<td>0</td>
<td>217</td>
<td>178</td>
<td>194</td>
</tr>
<tr>
<td>Air entraining admixture, m³/m³</td>
<td>426</td>
<td>464</td>
<td>271</td>
<td>1,238</td>
<td>1,238</td>
<td>580</td>
</tr>
<tr>
<td>Sharp, mm</td>
<td>70</td>
<td>51</td>
<td>44</td>
<td>57</td>
<td>64</td>
<td>—</td>
</tr>
<tr>
<td>Air content, percent</td>
<td>5-6</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>5.8</td>
<td>5</td>
</tr>
<tr>
<td>Air temperature, °C</td>
<td>28.3</td>
<td>24.4</td>
<td>12.2</td>
<td>11.1</td>
<td>25</td>
<td>—</td>
</tr>
<tr>
<td>Concrete temperature, °C</td>
<td>31.1</td>
<td>28.0</td>
<td>17.0</td>
<td>17.8</td>
<td>31.7</td>
<td>—</td>
</tr>
<tr>
<td>Concrete density, kg/m³</td>
<td>2,352</td>
<td>2,304</td>
<td>2,339</td>
<td>2,339</td>
<td>2,308</td>
<td>—</td>
</tr>
</tbody>
</table>

*Not available; **HRWRA added; however, information is not available.

of good-quality, structural-grade concrete incorporating large quantities of ASTM Class F fly ash. Use of high volumes of Class C fly ash in manufacture of structural-grade concrete started at the University of Wisconsin-Milwaukee in 1984. Naik also reported the first case of concrete made in 1984 with 70 percent Class C fly ash as a replacement for cement for pavement construction in Wisconsin.

Naik and Singh reviewed literature on high-volume fly ash (HVFA) concrete systems incorporating ASTM Class C fly ash. Based on the information collected, they reported that HVFA concrete can be proportioned using large amounts of fly ash to meet strength and durability requirements for structural-grade as well as high-strength concrete. They further indicated that there is a lack of data on long-term strength properties and durability of HVFA concrete systems. Such data are needed for development of material specifications for HVFA concrete systems for their commercial applications. Therefore, a study was directed toward evaluating durability performance of concrete incorporating large amounts of Class C and Class F fly ashes.

This field study was undertaken to collect recent performance data about strength and durability data from in-situ concrete pavement, 1280-m long. The existing crushed stone road was used as a base and a 6-m wide, and 200-mm thick concrete pavement was placed over the base. The pavement was designed to comply with the State of Wisconsin Standard Specification for Road and Bridge Construction.

Research significance

Laboratory work on the use of high-volume fly ash in concrete is reported in literature. In this study, strength and durability performance (up to 18 years) of HVFA concrete pavements has been presented. Results of this study will be useful in understanding the long-term performance characteristics of HVFA pavements.

Materials

Type I portland cement conforming to the requirements of ASTM C 150 was used in this investigation. Both Class F and Class C fly ash were obtained from Wisconsin Electric Power Company's power plants located in Wisconsin. Physical and chemical test data of these fly ashes were determined in accordance with applicable ASTM standards, Table 1. Both the fly ashes met the ASTM C 618 requirements. Natural sand was used as fine aggregate and natural gravel was used as the coarse aggregate. These aggregates were obtained from local sources. Both aggregates met the ASTM C 33 requirements. Two chemical admixtures, a melamine-based superplasticizer (ASTM C 494, Type F) and an air-entraining admixture (AEA) (ASTM C 260), were used. The 70 percent Class C fly ash concrete mixture used a conventional water reducer. The dosage of AEA was varied to achieve the target level of air-entrainment required for the concrete mixes.

Mixture proportions

Six different mixture proportions were developed for this work. The control mixture was the standard 19 percent Class C fly ash concrete mixture having a 28-day compressive
strength of 24 MPa as specified by the State of Wisconsin Department of Transportation at the time of construction. Various high-volume fly ash concrete mixtures were proportioned from previous experience with structural-grade and paving-quality concrete mixtures developed by Naik and his colleagues. The details of the mixture proportions used in this project are presented in Table 2.

Each mixture was batched and mixed at a ready-mixed concrete plant in accordance with ASTM C 94. Test specimens were prepared to measure properties of each mixture, in accordance with ASTM C 31. Each mixture was tested for fresh and hardened concrete properties. The fresh concrete properties measured were slump (ASTM C 143), air content (ASTM C 231), concrete temperature (ASTM C 1064), and ambient air temperature. The hardened concrete was tested for compressive strength (ASTM C 39) using cylindrical specimens (ASTM C 39). All concrete mixtures developed in this investigation were used in the construction of various pavement sections (1984-1991). Core specimens were drilled from in-place pavements for measurement of compressive strength (ASTM C 39), resistance to chloride-ion penetration (ASTM C 1202), and hardened concrete density (ASTM C 642) for test data collected starting the seven-year age.

Results and discussion
Density of concrete mixtures
The fresh concrete density values are shown in Table 2. The hardened concrete density data from cores are shown in Table 3. The fresh density values of the concrete mixtures varied within a narrow range for all mixtures. The density of fresh concrete was similar to that obtained from hardened concrete density values for the mixtures. Density of the hardened concrete also did not significantly change when evaluated after an additional four years. Thus, both the fresh and hardened density values were not significantly influenced by the variations in fly ash content, type, or age within the tested range.

Compressive strength
The compressive strength test data are given in Tables 4 and 5, and shown in Figs 1 and 2. As expected, the compressive
strength increased with age. The rate of increase depended upon the level of cement replacement, type of fly ash, and age. In general, concrete strength decreased with increasing fly ash concentration at the very early ages for both types of fly ash. Generally the early-age strength of Class F fly ash concrete mixtures were lower compared to Class C fly ash concrete mixtures.

Mixture A-1 incorporating 70 percent Class C fly ash showed compressive strength increase from 15.1 MPa at 28 days to 45.5 MPa at the age of 14 years. This translates into approximately a 200 percent increase in the compressive strength in 14 years. The compressive strength achieved at the age of 18 years, 45.2 MPa, was approximately the same as the compressive strength obtained at 14 years. This indicates that the pozzolanic reaction probably had reduced at these later ages.

Mixture B-5 incorporating 50 percent Class C fly ash exhibited an increase in the compressive strength from 28.9 MPa at the age of 28 days to 52.1 MPa at 12 years. This is approximately an 80 percent increase in the compressive strength in about 12 years from the strength observed at the age of 28 days. The compressive strength of this mixture also increased approximately 6 percent between the ages of 8 and 12 years.

Mixture C-4 made with 19 percent Class C fly ash showed an increase in the compressive strength from 30.8 MPa at 28 days to 58.6 MPa at the age of 12 years. This indicates about 90 percent increase in the compressive strength in about 12 years compared to the compressive strength recorded at the 28-day age. There also was a significant increase in the average compressive strength obtained between the ages of 8 and 12 years, approximately 13 percent.

Mixture D-2 made with 67 percent Class F fly ash registered an increase in the compressive strength from 19.4 MPa at 28 days to 56.0 MPa at the age of 11 years. This translates into an increase in compressive strength of approximately 189 percent in 11 years relative to the 28-day age strength. The compressive strength observed at the ages of 7 and 11 years was relatively constant, with a difference of less than 1 MPa observed in the results.

Mixture E-3 containing 53 percent Class F fly ash showed an increase in the compressive strength from 24.8 MPa at 28 days to 53.9 MPa at the age of 11 years. This represents an increase in the compressive strength of 117 percent in about 11 years relative to the compressive strength recorded at the age of 28 days. A decrease of approximately 3 percent was observed in the compressive strength (1.6 MPa) between the ages of 7 and 11 years. However, the decrease was attributed to the large variation in the strength of the cores obtained at 11 years, over 4.8 MPa for only two tests.

Mixture F-6 containing 35 percent Class F fly ash exhibited an increase in the compressive strength from 30.0 MPa at 28 days to 51.9 MPa at the age of 12 years. This translates into a 72 percent increase in about 12 years relative to the 28-day compressive strength. Compressive strength of the hardened concrete also did not change significantly between the ages of 8 and 12 years, an increase of less than one percent in four years.

The results obtained in this investigation reveal that compared to the 28-day strength, the long-term strength gain by the high-volume Class F fly ash concrete system was at a higher rate (that is, up to 12 years) than comparable Class C fly ash concrete. Mixture A-1, 70 percent Class C fly ash, had the highest percentage increase in long-term compressive strength between the age of 28 days and 18 years, 200 percent. The higher percentage increase in long-term compressive strength of the mixtures containing Class F fly ash is most likely due to that fact that Class F fly ash concrete pavement was constructed in a colder weather climate (November) and also probably due to a greater contribution of pozzolanic C-S-H compared to Class C fly ash. This in turn resulted in a greater improvement in the microstructure of the concrete made with Class F fly ash compared to Class C fly ash, especially in the transition zone. Therefore, the use of Class F fly ash, which is abundantly available in India, is more desirable from the long-term perspective for the manufacture of high-performance...
Table 6: Chloride-ion penetration of concrete cores

<table>
<thead>
<tr>
<th>Mixture no</th>
<th>Fly ash (ASTM Class C), percent</th>
<th>Fly ash (ASTM Class F), percent</th>
<th>Age, years</th>
<th>Average charge passed, coulombs</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>70</td>
<td>50</td>
<td>14</td>
<td>113*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>18</td>
<td>111**</td>
</tr>
<tr>
<td>B-5</td>
<td>50</td>
<td>35</td>
<td>8</td>
<td>217*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>215**</td>
</tr>
<tr>
<td>C-4</td>
<td>19</td>
<td>53</td>
<td>7</td>
<td>566*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>11</td>
<td>646**</td>
</tr>
<tr>
<td>D-2</td>
<td></td>
<td>67</td>
<td>7</td>
<td>65*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>61*</td>
</tr>
<tr>
<td>E-3</td>
<td></td>
<td>53</td>
<td>7</td>
<td>77*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>11</td>
<td>82*</td>
</tr>
<tr>
<td>F-6</td>
<td></td>
<td>35</td>
<td>8</td>
<td>155*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>152*</td>
</tr>
</tbody>
</table>

ASTM C1202

<table>
<thead>
<tr>
<th>Charge passed, coulombs</th>
<th>Chloride ion penetrability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;4000</td>
<td>High</td>
</tr>
<tr>
<td>2,000-4,000</td>
<td>Moderate</td>
</tr>
<tr>
<td>1,000-2,000</td>
<td>Low</td>
</tr>
<tr>
<td>100-1,000</td>
<td>Very low</td>
</tr>
<tr>
<td>&lt;100</td>
<td>Negligible</td>
</tr>
</tbody>
</table>

*Average of three observations; **Average of nine observations

Concrete (HPC) because HPCs are required to possess both long-term high-strength properties and durability.

Limited data shows that the long-term strength gain correlation with the fly ash volume is better with Class F fly ash than that of Class C fly ash, as is evident from Fig 3, which shows the relationship between the ratio of compressive strength at seven or eight years and 28-day and fly ash percentages. It is clear from this figure that ratio of the compressive strength gain of Class C fly ash concrete mixtures remained constant, whereas ratio of compressive strength gain of Class F fly ash mixtures increased with the increase in fly ash content.

From the results of this investigation, it is clear that though concrete mixtures with Class C fly ash performed better than Class F fly ash mixtures at early ages, their long-term performances (at 7, 8, and 14 years) are comparable to Class F fly ash mixtures. Therefore, it does not really matter, what type of fly ash is being used by a design engineer. It would be economical to use readily available local fly ash, either Class C or Class F for long-term performance of concrete pavements.

**Resistance to chloride ion penetration**

Table 6 and Fig 4 show the chloride ion penetration data at the age of 7 and 11 years and/or 8 and 12 years for all the mixtures except for Mixture A-1, for which data is for 14 and 18 years. The resistance to chloride-ion penetration was determined based on charge passed through a concrete core test specimen in accordance with ASTM C 1202. Within a group of mixtures containing the same Class of fly ash, chloride ion penetration resistance increased as replacement rate of cement with fly ash increased. Mixtures D-2 (67 percent Class F fly ash) and E-3 (53 percent Class F fly ash) exhibited very low total charge of 61 to 65 Coulombs and 77 to 84 Coulombs, respectively. Table 6. Thus, these mixtures were relatively impermeable to chloride ions and were rated to have "negligible" chloride ion penetrability per ASTM C 1202. The remaining mixtures had a total charge that ranged between 111 and 646 Coulombs, which is classified as having a "very low" chloride ion penetrability in accordance with ASTM C 1202.

Considering the above results, all concrete mixtures tested in this investigation showed excellent resistance to chloride-ion penetration. The general performance trend with respect to resistance to chloride-ion penetration followed a similar trend as indicated by the compressive strength data reported earlier by Naik et al. Mixtures containing high volumes of Class F fly ash had the highest resistance to chloride ion penetration. Differences in the Coulomb values between mixtures are not significant with the exception of Control Mixture C-4, which had a total charge passed that was at least two times the values of other mixtures. The charge passed of the mixtures is more a reflection of the ionic concentration in the pores, which is a function of the fly ash volumes.

**General observations and recommendations**

Concrete pavements constructed for roadways and highways in very cold weather in Wisconsin since 1984 show that pavement design and concrete mixtures containing high-volumes of Class C or F fly ash can be readily and successful accomplished. For an exposure to typical climate in India, along with abundant amount of fly ash available in India, roadways, highways, and airfield pavements in India must use HVFA pavements. There are two issues, however, that must be addressed in order to succeed with HVFA pavement construction in India.

(i) Sub-base and base of the pavement must be carefully constructed with sufficient quality management during construction to assure that the desired,
specified, carefully spelled-out construction specifications are followed and implemented.

(ii) After the HVFA pavement is constructed, the curing of the concrete must continue for sufficient length of time, minimum 14 days or longer depending upon weather conditions.

HVFA concrete construction not only for pavements but also for footings, columns, walls, beams, and other structural components can be successfully adopted for sustainable developments of cement and concrete industry and management of our natural resources.

Conclusions

Based on the data recorded in this investigation, the following general conclusions may be drawn.

(i) Concrete density was not greatly influenced by either the type or the amount of fly ash or the age within the tested range.

(ii) The rate of early-age strength gain of the Class C fly ash concrete mixtures was higher compared to the Class F fly ash concrete mixtures. This was primarily attributed to greater reactivity of Class C fly ash compared to Class F fly ash.

(iii) Long-term pozzolanic strength contribution of Class F fly ash was somewhat greater compared to Class C fly ash, probably due to early age cold weather curing. Consequently, long-term compressive strengths of Class F fly ash concrete mixtures were higher than the strength obtained from concrete mixtures containing Class C fly ash.

(iv) Very little change in the compressive strength of concrete occurred between the ages of 8 to 12, 7 to 11, and 14 to 18 years. This indicates that the pozzolanic reaction of the ash has slowed at later ages.

(v) Concrete containing Class F fly ash exhibited higher long-term resistance to chloride-ion penetration compared to Class C fly ash concrete. The best long-term performance was recorded for both the 53 percent and 67 percent Class F fly ash and 70 percent of Class C fly ash concrete mixtures as they were found to be relatively impermeable to chloride ions in accordance with ASTM C 1202. Except for control mixture C-4, the differences in the Coulomb values of the high-volume fly ash mixtures are not significant. The values are more a reflection of the high concentrations in the pores, which is a function of the fly ash volumes. All fly ash concrete mixtures irrespective of the type and amount of fly ash, showed excellent performance with respect to chloride-ion penetration resistance.

(vi) Resistance to chloride ion penetrability did not significantly change in the hardened concrete at later ages (concrete ages of seven years or later).

(vii) Based on the results obtained in this investigation, it is desirable to use high-volumes of Class C or Class F fly ash in the manufacture of low-cost HPC concrete systems for improved long-term performance.

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References


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