HIGH-VOLUME FLY ASH CONCRETE

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ABSTRACT
This investigation was carried out to review high-volume fly ash concrete technologies developed to date. This paper includes literature information concerning mixture proportioning techniques, fresh concrete properties, and hardened concrete properties. The properties of fresh concrete include workability, pumpability, cohesiveness, bleeding, water demand, time of set, etc. The hardened concrete properties reviewed are compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, shrinkage, creep, fatigue strength, permeability, and abrasion resistance.

Previous studies have substantiated that performance of high-volume fly ash concrete systems are either comparable to or better than that for concrete without fly ash with respect to strength properties and durability of concrete. Long-term strength and durability performance data on fly ash concrete systems are lacking, especially high-volume fly ash concrete systems. Therefore, more research is needed to develop a data bank on mechanical properties and durability of HVFA concrete to establish mixture proportions for commercial production.
INTRODUCTION

Coal combustion by-products are generated due to the combustion of coal in coal-fired electric power plants. At the present time, nearly 80 million tons of solid by-products are generated each year in the United States. These by-products are primarily composed of fly ash and bottom ash. Fly ash comprises over 80% of these waste solids generated. Fly ash is captured by particulate collection devices such as mechanical collectors, electrostatic precipitators from the flue gases, etc. The fly ash particles can be classed as carbon from unburnt coal, fire polished sand, thin-walled hollow spheres and their fragments, magnetic iron-containing spherical particles, and spherical glassy particles [1-3]. The small size glassy particles take part in pozzolanic reaction in concrete. In accordance with ASTM C 618, fly ash can be divided into two classes: Class F and Class C. The Class F fly ash is mostly composed of less than 10% analytical CaO, whereas Class C fly ash generally contains 15% to 35% analytical CaO. The Class C ashes are produced from combustion of either lignite or subbituminous coal. The Class F ashes are produced from combustion of anthracite and bituminous coals. Due to high calcium content, the Class C ashes exhibit both cementitious and pozzolanic properties. Thus, these fly ashes are classified as cementitious and pozzolanic admixtures. The Class F ashes possess primarily pozzolanic properties and are classified as normal pozzolans. In general, Class C fly ashes have higher CaO + MgO + SO₃ and lower Al₂O₃ + SiO₂ compared to Class F fly ashes[2].
Approximately 25% of the total fly ash produced in the United States is utilized. Consequently, a huge amount of fly ash finds its way into landfills. This results in increased disposal costs to the producer, lost resources and energy, and environmental problems. To solve these problems, it is essential to develop high-volume applications for fly ash. One of the applications in which large amounts of fly ash can be consumed is the creation of construction materials, especially concrete [4].

Properties of fresh as well as hardened concrete are greatly improved by adding fly ash. The degree of influence depends on physical, chemical, and microstructural properties of fly ash. The major objective of this investigation was to evaluate state-of-the-art information on high-volume fly ash concrete systems.

MIX PROPORTIONING METHODS
A number of mixture proportioning methods have been used in the manufacturing of fly ash concrete systems [3,5,6]. Generally, three basic mixture-proportioning techniques have been used, as presented below [3,5]:

1. Partial replacement of cement: the simple replacement method
2. Addition of fly ash as fine aggregate: the addition method
3. Partial replacement of cement, fine aggregate, and water.

The simple replacement method involves direct replacement of a portion of the portland cement with fly ash. Past experience has shown that any percentage replacement of the cement in concrete with fly ash on a one-for-one basis (either by volume or by
mass) causes decreases in compressive and flexural strengths up to about three months of moist curing [5]. Beyond six months, strength development may become equal or higher relative to no-fly ash concrete.

The addition method involves adding fly ash to the mixture without a corresponding reduction in the quantity of cement used [3,5]. Consequently, the effective cementitious content of the concrete is increased by this method. Mostly, addition of fly ash by this technique enhances compressive strength in concrete at all ages.

The third method requires partial replacement of cement by a greater mass of fly ash, with adjustments made in fine aggregate and water content [5]. In this technique, two different types of mixture proportioning systems are followed. These are the modified replacement and rational proportioning methods. In the modified method, the total weight of cement plus fly ash of a mix exceeds the total weight of portland cement used in a comparable non-fly ash concrete mixture. This method of mixture proportioning produces early age compressive strengths of fly ash concrete similar to that of concrete without fly ash. The rational mixture proportioning technique assumes that each fly ash possess a unique cementing efficiency. A mass of fly ash (F) is converted to an equivalent mass of cement as $KF$, where $K$ is a fly ash cementing efficiency factor. The required strength and workability of fly ash concrete are obtained by applying Abrams’ relationship between strength and water-to-cement ratio ($W/(C + KF)$) and adjusting the volume ratio of cementitious particles to water and aggregate. However, the value of $K$ is found to vary with type of cement, curing conditions, strength level of
concrete, etc. [5]. Because of this and because adjustments are required in aggregate content due to varying water demands of fly ash/cement to achieve desired workability, this method is not appropriate for most practical applications.

Gopalan and Haque [6] studies the influence of design methods on the strength development of concrete. They used three mixture designs: (1) partial replacement of cement by fly ash on a direct weight to weight basis; (2) direct addition of fly ash to the mixture as fine aggregate; and (3) partial replacement of cement with an excess amount of fly ash. Their test results revealed that the amount of fly ash required for developing higher strength depends on the grade of the concrete, and that the amount of fly ash required progressively decreased as the strength of the concrete increased.

PROPERTIES OF FRESH CONCRETE
Numerous studies [2,3,7,8,9] have shown that inclusion of fly ash to concrete and mortar mixtures causes reduction in water demand, increased workability, better pumpability, and decreased bleeding. The majority of early investigations [2,3,8,9,10] have reported that the reduction in water requirement is due to ball-bearing effects of spherical fly ash particles, especially fly ash containing fine particles. However, water requirements can increase with an increase in carbon content and other porous materials, and presence of coarse fly ash particles. Helmuth [7], based on analysis results of previous investigations, concluded that water reduction is a result of adsorption of the fine fly ash particles on cement particles, which in turn causes dispersion of cement particles. Similar to that of water reducing add mixtures.
Naik and Ramme [11] studied workability and setting characteristics of concrete incorporating large amounts of Class C fly ash. Their results substantiated that workability increased and the water demand decreased due to addition of the fly ash. For constant workability, the water-to-cementitious materials ratio decreased substantially when the fly ash level was increased from zero to 60%. The results further demonstrated that initial and final set times were not greatly influenced for cement replacement by fly ash in the range of 35-55% [11]. However, many investigations [2,3,5,8,9] observed higher initial and final set times for fly ash concrete relative to reference concrete without fly ash. Dodson [12] reported reduction in time of setting due to the cement replacement with a Class C fly ash up to 40 percent.

Several researchers [2,3,5,8,9,13] have substituted that the inclusion of fly ash in concrete increases the air entraining agent (AEA) requirement relative to plain portland cement concrete mixture. Inclusion of other mineral admixtures can also influence AEA requirements. Some portland cement can also increase demand for AEAs in concrete mixture [5].

Gebler and Klieger [14] demonstrated that concrete containing Class C fly ash demanded less air entraining admixture (AEA) compared to concrete incorporating Class F fly ash. They also reported that all fly ash concrete mixes containing either Class C or Class F fly ash at 25% or higher cement replacement levels required higher air entraining admixtures relative to the reference concrete without fly ash. Their
studies indicate that an increase in organic matter content, carbon content, and loss on ignition (LOI) of fly ashes increased demand for air entraining admixtures.

PROPERTIES OF HARDENED CONCRETE
Addition of fly ash in concrete mixtures affects the resultant properties of hardened mass. The improvement in properties of hardened concrete occurs due to improved microstructure of concrete resulting from formation of pozzolanic C-S-H. The improvement in properties of concrete would depend upon the type of fly ash and its properties, including physical, chemical, and mineralogical properties.

Strength Properties
This section mainly deals with compressive strength, tensile strength, flexural strength, and Poisson's ratio of concrete. Generally, the rate of strength development in concrete is reduced due to addition of fly ash, especially ASTM Class F fly ash. This occurs primarily due to dilution effects. The rate of strength gain due to inclusion of Class C fly ash in concrete mostly exceeds the rate shown by concrete around without fly ash at 14 days and beyond. At later ages, higher rate of strength development are attributed to pozzolanic contributing of the fly ash.

Numerous investigations have been carried out to quantify the effects of fly ash on properties of mortars and concretes [16-43]. Swamy et al. [15] reported that concrete mixtures incorporating 30 percent fly ash (ASTM Class F) by weight of total cementitious materials could be proportioned to attain sufficient fluidity or workability
and early one-day strength and elastic modulus for structural applications. The dosage of admixtures or superplasticizers was adjusted to obtain cohesiveness and workability with slumps in excess of 100 mm for easy placing in structural members with steel reinforcement.

Swamy and Mahmud [16] described development of superplasticized concrete having 50% cement replacement with Class F fly ash at water-to-cementitious materials ratios of 0.32 to 0.42. All fly ash concreted attained about 50 - 100% higher strength at one year age compared to their strengths at 28-day age.

Several investigations [17-22, 37] at CANMET have been directed toward development of high-volume ASTM Class F fly ash concrete for structural applications. Mukerjee et al. [17] manufactured high volume fly ash concrete through the aid of three different superplasticizers. They concluded that high-strength concrete can be manufactured using large quantities of ASTM Class F fly ash and superplasticizers. Their study revealed super performance of concrete containing 37% low-calcium fly ash compared to the reference concrete without fly ash. Malhotra and Painter [18] showed an optimum low-calcium fly ash content of 200 kg/m$^3$ for structural grade concrete with respect to compressive strength.

Giaccio and Malhotra [19] evaluated properties of superplasticized concrete containing high-volume of Class F fly ash and ASTM Type I and III cements. The mechanical properties determined were compressive strength, splitting tensile strength, and flexural
strength. The results sustained that concrete containing high volumes of Class F fly ash possessed excellent mechanical properties appropriate for manufacture of structural concrete elements, especially for massive sections.

Sivasundaram et al. [20] studied performance of concrete mixtures incorporating large amounts of low-calcium fly ash, superplasticizer, and air entraining admixture. The results showed best performance at a water-to-cementitious materials ratio of about 0.32. The concrete produced had high compressive strength at both early and later ages. The 91-day strengths of test specimens were about 40 MPa at water-to-cementitious materials ratio of 0.33 and 53 MPa at water-to-cementitious materials ratio of 0.28. Both small blocks cast under laboratory conditions and large block cast under field conditions did not develop any observable thermal cracks, and their compressive strengths were comparable to those obtained for laboratory specimens. In other studies, Sivasundram et al. [21, 37] observed excellent long term performance of high-volume fly ash concrete with respect to compressive strength.

Armaghani et al. [40] reported that rate of strength gain of concrete without fly ash was higher than that of concrete with low-calcium fly ash up to 28 days. However, a reverse trend was noticed after 91 days. Yong and Peng [42] studied AEP (Aggregate Enveloped in Cement Paste) mixing technique to improve structure of interfacial regions of aggregate and hydrated cement paste. In this method, first cement, fly ash, and water was mixed to form a paste at a low w/c ratio. Thereafter, both coarse and fine aggregates was added to the paste and mixed for two minutes. Finally, the remaining
water was added to this mix and mixing was preformed for an additional 40 seconds. The authors reported that 28-day compressive strength of concrete made by using AEP technology can be over 15% higher than the strength of concrete manufactured with normal mixing technology.

Wilbert et al. [22] concluded that maximum fly ash percentages might range between 55 and 60 percent of total cement content in order to produce structural grade concrete. Taniguchi et al. [23] indicated that strength development of high-volume fly ash concrete was significantly influenced by type and dosages of chemical activators and curing conditions. Their results revealed that high-volume fly ash concrete with NaCl as a chemical activator attained high initial strength and significant increase in compressive strength with age. Langley [38] determined long-term strength development of concrete containing high-volume of low-calcium fly ash. This concrete showed substantial increase in compressive strength with age beyond 28 days.

Naik et al. [24] evaluated performance of superplasticized concrete incorporating high-volume of ASTM Class F fly ashes obtained from two different sources. Concrete mixtures were proportioned to have cement replacement by fly ash between zero and 60% for a 28-day design strength of 41 MPa. The water-to-cementitious materials ratio was ranged between 0.32 and 0.44. Both compressive and tensile strength increased with age and decreased with addition of fly ash. However, the compressive strengths obtained in this study were in excess of 30 MPa at 28 days even at 60% cement replacement by fly ash. The authors concluded that concrete containing up to
60% ASTM Class F fly ash can be proportioned for structural applications.

Ghosh and Timusk [25] proportion concrete incorporating Class C fly ash for strength levels of 21, 35 and 55 MPa. The effects of parameters such as carbon content of fly ash (6 to 18 percent), ash to cement ratio (0.2, 0.4 and 1.0), and fineness of fly ash on the concrete performance were studied. The early-age compressive strengths of fly ash concretes were compared to the reference concrete without fly ash. Except for 55 MPa concrete, all fly ash concrete higher compressive strength than reference concrete at later ages.

Yuan and Cook [26] investigated strength properties of both air entrained and non-air entrained concrete made with a ASTM Class C fly ash at water-to-cementitious materials ratio of 0.45. Fly ash content was varied between zero and 50 percent by the weight of total cement used. The results sustained that the rate of strength development for fly ash mixtures was comparable to the fly ash-free concrete.

Cuijuan et al. [27] studied the effects of dosage of high-calcium fly ash on strength development of concrete. Their test results indicated that concrete, with less than 25% fly ash substituted for cement, attained higher compressive strength compared to non-fly ash concrete. The concrete containing 40% fly ash showed strength levels either comparable to or higher than non-fly ash concrete at both the 90-day and 180-day ages.

Papayianni [28] investigated behavior of superplasticized concrete containing fly ash
levels of 0, 30, 40, 50, 60, 70, 80, 90, and 100% of the total cementitious materials. The water-to-cementitious material ratio ranged from 0.55 to 0.75. Based on the results obtained, the author recommended cement replacement up to 30-40% by Class C fly ash for reinforced concrete, and up to 70% for plain concrete.

Hooton [29] showed that presence of high-alkali lignite fly ash (6 to 7% NA$_2$O) in concrete did not initiate an alkali-silica reaction. Compressive strength of concrete up to 35% cement replacement by the fly ash was lower at 1-day age and comparable at and beyond 7 days. Long-term and compressive and tensile strengths were significantly higher than reference concrete without fly ash. Manz and McCarthy [30] indicated that with certain Western United States high-lime fly ashes, similar strength levels were obtained for cement replacements by either 25 or 75% fly ash.

Naik and Ramme [11,31,32] developed mixture proportions to have 28-day compressive strengths of 21 MPa, 28 MPa, and 35 MPa. Fly ash concrete mixtures were also proportioned to substitute fly ash for various levels of cement replacement (20, 30, 40, 50, and 60%). They maintained the ratio of fly ash to cement replaced at 1.25 for all the test mixtures. The authors concluded that structural grade concrete could be made with at least 40% cement replacement by fly ash in order to produce concrete appropriate for structural applications.

Naik and Ramme [31,32] used high volumes of fly ash in two different construction projects. The first demonstration project was constructed in September 1984, and
involved paving 430 meters of a truck access road in Kenosha County, Wisconsin. The pavement construction involved 765 cu. m. of concrete. The concrete mixture for the project was proportioned to have 70% replacement by Class C fly ash. The mix proportions consisted of 100 kg cement (Type I), 213 kg Class C fly ash, 883 kg fine aggregate, and 1085 kg coarse aggregate per cu. m. of concrete. An air-entraining agent was used to produce air content in fresh concrete in the range of 5 to 6%, and a water reducing admixture was also used to improve workability. The approximate cost of the in-place concrete was $98 per cu. m. The rate of strength gain was found to be slower than expected. The average compressive strengths at 7-day, 28-day and 56-day were 7.9, 15.2, and 24.1 MPa, respectively. The road was kept closed to traffic longer than expected. Another problem noted was the occurrence of a crack in each section between saw cuts joint, due to excessive shrinkage. This can be solved by providing saw cuts at 3 m. intervals. The truck road is still in service. The second project was conducted in November 1984. This involved over 38 cu. m. of concrete for three electric transformer foundations. The mix was the same as that used in the previous project but without any water reducer. The average compressive strengths at 7-day, 28-day, and 84-day were 14, 28, and 39 MPa, respectively. No problems were encountered in the second project. Though substantial variations in strength gain occurred between the two projects, the potential usefulness of high-volume of Class C fly ash in concrete was demonstrated.

Naik and Ramme [33] determined Poisson’s ratio of concrete having cement replacement by fly ash in the range of 35-55% by weight at three different strength
levels. The water-to-cementitious materials ratio varied between 0.45 and 0.65. The values of static Poisson's ratio were found to be in the range of 0.15 - 0.20. Rodway and Fedirko [36] indicated that concrete containing Class C fly ash up to 68% of total cementitious materials attained compressive strength greater than 50 MPa at slumps appropriate for structural applications.

Recently, Naik and Singh [34,35] conducted an investigation to determine performance of superplasticized concrete containing Class C fly ash. A reference portland cement concrete was proportioned to have 28-day compressive strength of 40 MPa. Fly ash concretes were proportioned to have cement replacement of 40, 50, 60, and 70% by weight, maintaining cement to fly ash ratio of 1:1.25. The water-to-cementitious materials ratio varied between 0.29 and 0.33. The superplasticized fly ash concrete at the 28-day age outperformed the reference portland cement concrete up to 70% cement replacement with respect to compressive strength. The fly ash concrete showed tensile strength identical to that of no-fly ash concrete up to cement replacement of 50 percent.

Naik et al. [41] developed three paving concrete mixtures. These were a control mixtures containing 20% Class C fly ash, a mixture containing 50% Class C fly ash, and a mix containing 40 percent Class F fly ash of the total cementitious materials. All the mixtures had total cementitious materials of about 270 kg., and contained an air entraining agent and a superplasticizer. The water-to-cementitious materials ratio varied between 0.34-0.40 for the mixtures tested. Workability of the mixtures was
approximately (51 ± 25 mm.). The authors concluded that paving grade air entrained concrete can be produced with 40% of the cement replaced with Class F fly ash at a water to cement ratio below 0.36. The concrete mixture incorporating 50% Class C fly ash was also found suitable for highway paving work.

Gopalan [43] proportioned concrete mixtures having water-to-cementitious materials ratio in the range of 0.30 - 0.65 by weight. The author reported that optimum fly ash content was dependent upon the method of mixture design. He further reported that optimization based on the cementing efficiency of fly ash was unreliable. The author indicated that strength development in concrete was strongly correlated to the gel/space ratio. The results further revealed that the best compressive strength can be contained at an optimum gel/space ratio of 0.70.

Mostly, the rate of strength development in concrete tends to be only marginally affected by inclusion of Class C fly ashes. The majority of researchers have reported that high-volume Class C fly ash concrete can be made without any significant effect on compressive strength.

Concrete incorporating Class F generally shows lower early strength compared to non-fly ash concrete because of low reactivity. However, at later ages (> 56 days) they can approach the strength gain comparable to fly ash free concrete. A summary of some typical values of compressive and tensile strengths of HVFA concrete is presented in Table 1.
In general, flexural strength of concrete increases as its compressive strength increases. However, the rate of increase in flexural strength is lower than that for compressive strength. A relationship between these strengths, suggested by ACI is as follows.

\[ F_t = K (F_c)^{1/2} \]

Where \( F_t \) is Flexural Strength, \( K \) is an empirical constant, and \( F_c \) is compressive strength.

Some investigators [48,49,50] found almost identical flexural for concrete made without fly ash. Costa and Massazza [49] indicated that the ratio for \( F_t/F_c \) for fly ash concrete were significantly greater compared to reference concrete containing no fly ash.

Sivasundaram et al. [37] observed flexural strength of high volume fly ash concrete as 4-5 MPa at 14 days and 5-6 MPa at 91 days. The results further indicated lower flexural modulus of air-cured specimens compared to cured specimens. Langley [38] reported flexural strength of concrete having 55% cement replacement by low-calcium fly ash at the water-to-cementitious materials ratios maintained were at 0.27 and 0.49. The flexural strength increased from 7.2 to 7.5 MPa for the water-to-cementitious materials ratio of 0.27 and from 5.6 to 6.3 MPa for the water-to-cementitious materials ratio of 0.49 when lab curing period was increased from 91 to 365 days.

Naik et al. [41] determined flexural strength of concretes containing large quantities of Class F and Class C fly ashes. The 28-day flexural strength of fly ash concretes ranged from 4.0 to 4.7 MPa and 56-day results ranged from 4.4 to 4.9 MPa. Some typical values of flexural strength of HFFA concrete derived from previous investigations are shown in Table 2.
Table 1 Typical Values of Compressive Strength and Tensile Strength of HVFA Concrete

<table>
<thead>
<tr>
<th>Cement Type</th>
<th>Amount kg/m³</th>
<th>Fly Type</th>
<th>Ash Replacement (%)</th>
<th>W/C + FA</th>
<th>Compressive Strength (MPa) 7d</th>
<th>Tensile Strength 28d MPa</th>
<th>Admixture Type</th>
<th>Reference No.</th>
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<tbody>
<tr>
<td>I 365</td>
<td>F</td>
<td>59</td>
<td>0.32</td>
<td>22</td>
<td>28d 36 47 3.4</td>
<td>R,A</td>
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<tr>
<td>I 450</td>
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<td>R,A</td>
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<td>I 1300</td>
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<td>32 42</td>
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<tr>
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<td>51 66</td>
<td>R,A</td>
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<tr>
<td>I 345</td>
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<td>R</td>
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<td>8</td>
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<td>I 275</td>
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<td>9 15 1.6</td>
<td>R,S</td>
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<tr>
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<td>Type</td>
<td>Replac. Percent</td>
<td>28-day MPa</td>
<td>28-day MPa</td>
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Conversions:  

1 kg/m³ = 1.69 lb/yd³

1 MPa = 145 psi
Modulus of Elasticity

In general, with and without fly ash modulus of elasticity of concretes increases with compressive strength up to certain strength levels, after which it comes approximately constant. Most test data have shown that the type and amount of fly ash used in concrete do not significantly influence the ratio of modulus of elasticity to compressive strength.

Crow and Dunstan [51] evaluated the properties of 36 concretes incorporating fly ashes from different sources. They concluded that the elastic properties of fly ash concretes were similar to that of non-fly ash concrete.

Sivasundaram et al. [20] evaluated elastic modulus of fly ash concrete incorporating 56% low-calcium fly ash of total cementitious materials. Their results showed modulus values ranging from $3.78 \times 10^4$ to $4.34 \times 10^4$ MPa at 91 days for cast cylinders and $4.55 \times 10^4$ MPa for drilled core specimens at 365 days. In another study Sivasundaram et al. [37] reported that fly ash concretes made with 58% of total cementitious materials showed 15 to 20 percent higher modulus than that of a conventional limestone concrete of comparable strength. An extensive study by Dunstan Inc [47] found modulus values of fly ash concretes slightly lower or comparable reference concrete without fly ash.

Naik et al. [24] determined secant modulus of elasticity of concrete containing high-volume of ASTM Class F fly ashes. The fly ashes were obtained from two different sources. The results showed that modulus values for fly ash concretes were
sufficient for structural applications up to 60% cement replacement by fly ash. A number of studies [5,8,25,34] substantiated that inclusion of Class C fly ash in concrete mixture does not effect its elastic behavior.

Ghosh and Timusk [25] evaluated chord modulus of elasticity of fly ash concrete at compressive strength levels of 21, 35, and 55 MPa. The modulus of elasticity values of fly ash concrete was comparable to non-fly ash concrete. All concrete mixtures tested in their investigation showed higher modulus compared to the prediction by the ACI formula.

The modulus of elasticity of concrete incorporating 45% cement replacement by fly ash was determined by Naik and Ramme [33]. The 28-day average elastic modulus values for non-air entrained concrete obtained were 3.28, 3.48, and $3.37 \times 10^4$ MPa at respective nominal strength levels of 21, 28, and 38 MPa. The modulus values corresponding to these strength levels for air entrained concrete were 2.91, 2.88, and $3.03 \times 10^4$ MPa. The authors reported that the difference between the experimental modulus values and the values computed by the ACI 318 was insignificant. Naik and Singh [35] determined modulus of elasticity of superplasticized fly ash concrete containing high volumes of Class C fly ash. The test data demonstrated that concrete containing fly ash up to 70% cement replacement had high modulus suitable for structural applications. Some modulus data derived from previous studies for high-volume fly ash concretes are summarized in Table 3.
Shrinkage and Creep

Drying shrinkage refers to volume change in concrete due to loss of moisture in hardened concrete. Increase in strain with time under a constant application of load is defined as creep. A limited amount of work has been done on shrinkage and creep of concrete incorporating high volumes of fly ash [5,8,52].

Because of lower specific gravity fly ash, replacement of cement with fly ash on an equal weight basis results in an increase in paste volume of the fresh concrete mixture. If the water demand of the fly ash concrete increases compared to fly ash free concrete, the shrinkage of HVFA concrete can be higher compared to concrete without fly ash. On the other hand, if water demand decreases due to addition of fly ash, shrinkage can decrease.

Ghosh and Timusk [25] reported that for the same maximum size of aggregate and for all strength levels, the shrinkage of concrete containing fly ash was lower than that of non-fly ash concrete. Yuan and Cook [26] concluded that shrinkage of concrete is not greatly influenced by addition of fly ash.
Table 3: Modulus of Elasticity of HVFA Concrete

<table>
<thead>
<tr>
<th>Cement Type</th>
<th>Fly Ash</th>
<th>W/C+F</th>
<th>Compressive Strength 28d. (MPa)</th>
<th>Modulus of Elasticity (MPa x 10^4)</th>
<th>Reference No.</th>
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<td>I 365 F 59</td>
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<tr>
<td>I 362 F 60</td>
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Conversions:  
1 kg/m³ = 1.69 lbs/yd³  
1 MPa = 145 psi
High-volume fly ash concrete (58% cement replacement) exhibited shrinkage identical to non-fly ash concrete after 7 days of curing in lime-saturated water [37]. However, beyond 91 days of curing, shrinkage of fly ash concrete was significantly lower compared to non-fly ash concrete. Torii and Kawamuza [45] reported that shrinkage of HVFA concrete decreased with the increase in the low-calcium fly ash content.

Dunstan, Inc. [53] reported that as compared to reference concrete, fly ash concrete having fly ash with: (1) calcium content less than 20% reduced shrinkage; (2) calcium content between 20-25% produced similar shrinkage; and (3) calcium contents higher than 25% slightly increased shrinkage.

Naik and Ramme [33] evaluated drying shrinkage of non-air entrained as well as air entrained fly ash concretes incorporating 45% Class C fly ash. The drying shrinkage data were obtained for nominal strength levels of 21, 28, and 35 MPa at ages of 4-day, 7-day, 14-day, and 28-day. In general, drying shrinkage decreased with increasing strength levels for the air entrained concretes compared to the corresponding non-air entrained concretes.

Swamy and Mahmud [54] studied creep of concretes containing 50% fly ash of total cementitious materials. The specified compressive strength for the concretes were 20, 40, and 60 MPa. The results indicated that creep increased with decreasing concrete strength, and increasing stress-strength ratio. The results further indicated that creep of HVFA concrete could be expressed as a linear function of the stress-strength ratio.
Ghosh and Timusk (25) indicated that most fly ash concretes exhibited lower creep compared to reference concrete. Yuan and Cook (26) reported identical creep data for both fly ash concrete with 20% cement replacement and ash-free concrete. Beyond 20% cement replacement, the creep of fly ash concrete increased with fly ash content.

Nasser and Al-Manaseer (55) investigated creep of sealed and unsealed concrete containing Type I cement and 50% lignite fly ash. The creep data were recorded at various stress/strength ratio for a maximum of 112 days. In their study, the 50% lignite fly ash mixture exhibited lower creep compared to non-fly ash concrete. The results revealed that creep of concrete made with 50% fly ash could be represented by a linear function of stress/strength ratio.

**Permeability of Concrete**

Concrete permeability is greatly affected by several parameters, including amount of cementitious materials content, water-to-cementitious materials ratio, porosity, etc. Properly proportioned concrete with fly ash exhibit a more homogeneous microstructure and increase of density in the interfacial zone resulting from pozzolanic contribution of fly ash compared to non--fly ash mixture. The improved microstructure of concrete leads to increased resistance to penetration of water, gases or other aggressive chemicals from getting in, thereby improving durability. Rodway and Fedirko (36) reported a very low coefficient of $3.65 \times 10^{-12}$ m/s concrete having 68% Class C fly ash of total cementitious materials.

Davis (56) observed higher permeability of fly ash concrete compared to fly ash-free concrete at 28 days. However, a reverse trend was observed at an age of six months. Kanitakis [57] reported that incorporation of fly ash was more effective in retarding
diffusion of chloride ions in concretes compared to increasing strength.

Amaghani et al. (40) reported a good correlation ($r = 0.88$) between water permeability and resistance to chloride-ion penetration. Ellis et al. (39) indicated that increasing the amount of Class C or F fly ash concrete at a fixed quantity of cement can reduce chloride permeability to a marked extent. In their study, concrete with Class F fly ashes exhibited higher resistance to chloride-ion compared to concrete made with Class C fly ash. Krell (50) evaluated oxygen permeability of concrete containing 37% cement replacement by fly ash. The oxygen permeability of fly ash concrete decreased with increasing concrete strength. Sivasundaram et al. (37) exhibited greatly improved resistance to chloride-ion penetration at ages of 91 days and beyond.

**Abrasion**

Concrete resistance to abrasion depends heavily on parameters such as water-to-cementitious material ratio, compressive strength, surface finish, and curing conditions. Tikalsky and Carrasquillo (61) reported that, at equal strength or later ages, the abrasion resistance of fly ash concrete was found to be superior to that of non-fly ash concrete. Their results further showed that concrete containing Class C fly ash at 35% cement replacement level exhibited superior abrasion resistance compared to that of either plain portland cement concrete or concrete containing Class F fly ash.

Liu (62) showed similar abrasion resistance for both fly ash concrete (29% fly ash) and non-fly ash concrete when tested for periods up to 36 hours. The fly ash concrete
showed almost 25% more mass loss due to abrasion-erosion compared to the non-fly ash reference concrete. Ukita et al. (63) observed increased abrasion of resistance of concrete with the fineness of fly ash. At a fly ash content of 30%, the abrasion resistance of fly ash concrete was lower compared to reference cement concrete without fly ash. Barrow et al. (64) substantiated that the concrete containing either Class C or Class F fly ash (35% by volume) had equivalent abrasion resistance to that of concrete without fly ash at equal strengths.

Naik and Singh (65) studied the effects of temperature and inclusion of low-calcium fly ash on concrete strength and abrasion resistance under simulated hot weather conditions. Test data were collected at four levels of fly ash content, ranging between 0-30% by weight of cement used, and three temperature levels of 23, 35 and 49°C with varying relative humidity (20-80%) depending upon age and temperature during curing. Two different concretes, A and B, with respective design strengths of 17 MPa and 31 MPa were tested for compressive strength. Concrete A (17 MPa) only was tested for abrasion resistance. The resistance to abrasion increased with increasing fly ash content at 23°C. However, the abrasion resistance at higher temperatures was adversely affected by inclusion of low-calcium fly ash. More recent investigations at UWM Center for by-Products Utilization have shown excellent resistance of concrete made with or without fly ash.

**Fatigue Strength**

Fatigue strength data are needed for design of structures subjected to cyclic loads. Concrete structures such as pavements, bridges, offshore structures, etc. need to be designed based on fatigue strengths. The stress at which a material fails due to cyclic
loading is called fatigue strength.

The fatigue strength is less than the material's ultimate strength. There is a minimum load for most materials below which a load can be repeatedly applied an indefinitely large number of times. This limiting stress is termed as endurance limit. The ratio of endurance limit to static strength is called the endurance ratio. Numerous investigations have been directed toward characterizing fatigue behavior of plain portland cement concrete. However, very little is known about fatigue behavior of concretes containing large amounts of fly ash [66,67].

Tse et al. [66] conducted an experimental investigation to evaluate compressive fatigue characteristics of concrete under compressive mode of loading. The variables considered were type of fly ash (low-calcium and high-calcium fly ashes), cement content, cement replacement levels by fly ash, and water-to-cement ratio. Their results revealed that fatigue strength of concrete with 25% or 50% cement replacement by high-calcium fly ash is higher than that for plain concrete without fly ash. However, the fatigue strength of concrete containing class F fly ash was significantly lower compared to non-fly ash concrete. The authors concluded that portland cement replacement by fly ash should be 25% for low-calcium fly ash and 50% for high-calcium fly ash in order to achieve equal or higher compressive and fatigue strengths compared to the strengths attained by no-fly ash concrete. Ramakrishnan et al. (76) determined flexural fatigue behavior of concrete containing high volume of low-calcium fly ash. They reported that the endurance limit was 7% higher for the
high-volume fly ash concrete compared to the non-fly ash concrete. However, the modulus of rupture and fatigue strength were higher in the case of concrete without fly ash. However, ongoing research at the UWM Center for By-Products have shown fatigue behavior of high-volume fly ash concrete similar to reference concrete without fly ash.

CONCLUSIONS

Based on analysis of test data derived from previous investigations, the following main conclusions can be drawn.

FRESH CONCRETE PROPERTIES

1. Inclusion of fly ash particles in concrete mixtures improves rheological properties of fresh concrete. These include improvement in workability, pumpability, and cohesiveness, and reduction in bleeding and segregation.

2. Generally, fly ash concrete mixtures have lower water requirements compared to mixtures without fly ash.

3. As compared to concretes containing Class C fly ash, Class F fly ash concretes demand greater amounts of air entraining admixtures. However, fly ash concrete requires higher dosages of air entraining admixture compared to concrete without fly ash.
4. In general, both initial and final times of setting of fly ash concrete mixtures are higher compared to non-fly ash concrete.

HARDENED CONCRETE PROPERTIES

1. In general, the rate of strength gain is lower for mixtures containing fly ash, especially at early ages due to the dilution effects.

2. Beyond 28-day age, the strength gain for Class F fly ash concrete may equal or exceed the strength gain by non-fly ash concrete due to improved concrete structure resulting from formation of pozzolanic C-S-H.

3. The rate of strength gain for Class C fly ash concrete mixtures is higher than that for Class F fly ash concretes. Compressive strength of Class C fly ash can exceed the compressive strength of plain concrete beyond 14-day age, up to 35-40% cement replacement.

4. Splitting tensile strength of high-volume fly ash (HVFA) concrete system is mostly lower compared to reference concrete without fly ash.

5. The flexural strength of HVFA concrete is comparable to that of non-fly ash concrete.
6. The modulus of elasticity of HVFA concrete is practically the same as that for fly ash-free concrete.

7. Inclusion of fly ash to concrete mixture does not cause appreciable affect on shrinkage behavior of concrete.

8. Numerous studies have substantiated that fly ash concrete exhibit lower creep compared to fly ash-free concrete, especially at later ages.

9. Recent investigations have revealed that fatigue behavior or fly ash concrete is similar to that of reference concrete containing no fly ash.

10. Properly proportioned fly ash concrete should exhibit lower permeability, thus improved durability compared to reference concrete without fly ash.

11. Abrasion resistance of fly ash concrete is comparable to non-fly ash concrete up to 30-40% fly ash content.

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