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USE OF CLASS C FLY ASH IN CEMENT-BASED CONSTRUCTION MATERIALS

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Synopsis: This paper provides the state-of-the-art information on high-calcium, ASTM Class C fly ash use in cement-based construction materials, such as high-performance concrete, ready-mixed concrete, and low-strength flowable concrete and slurry. The major topics included are: properties of fly ash; effects of fly ash inclusion on properties of fresh and hardened concrete and controlled low-strength materials (CLSM); and, future research needs. The fresh concrete properties discussed are workability, water requirement, bleeding, segregation, air content, time of setting, and temperature rise. The hardened concrete properties such as compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, creep and shrinkage, permeability, carbonation and corrosion of steel in concrete, abrasion resistance, freezing and thawing resistance, salt-scaling resistance, alkali-silica reaction, sulfate resistance, and fatigue strength are described.

It is shown that high-strength/high-durability/high-performance concrete containing significant amounts (up to 75 % cement replacement levels) of Class C fly ash can be manufactured for strength levels of up to 100 MPa. Future research efforts should be directed toward the use of Class C fly ash in blended cements with minimum (less than 10 %) portland cement in the blend.

Keywords: abrasion resistance; alkali-silica reaction; carbonation; concrete; corrosion; fatigue strength; fly ash; freezing and thawing durability; strength; sulfate resistance.

INTRODUCTION

Coal is the most widely used source of energy for power production. Its combustion in electric power plants produces large amounts of coal combustion products (CCPs), which include fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) products. In 1992, over 370 million tonnes (Mt) of fly ash and 90 Mt of bottom ash and boiler slag were produced; and, about 150 Mt (33 %) were utilized [1]. In 2000, over 59 Mt of CCPs were produced in Europe and about 95 % was utilized [2]. Production and utilization of CCPs in some countries in 2000 were as follows: Canada, 8 Mt, 23 %; India, 95 Mt, 13 %; Israel 1.3 Mt, 98 %; Japan, 10 Mt, 84 %; and Turkey, 20 Mt, unknown % [3]. In 2001, USA produced about 110 Mt of CCPs and about 32 % was utilized [4].

In accordance with ASTM C 618, coal fly ash is classified into two main categories: Class F fly ash (low-calcium) and Class C fly ash (high-calcium). Class F fly ash is produced from combustion of anthracite and bituminous coal, and Class C fly ash is generated from burning of lignite and subbituminous coal [5].

Class F fly ash has been used in concrete for more than 60 years. Substantial amount of data regarding Class F fly ash use in concrete are available including the effect of Class F fly ash on strength and durability characteristics of concrete. Since the late 1970s, Class C fly ash has become available in the USA and Canada due to burning of lignite and subbituminous coal. High-calcium fly ashes are also available in other countries including Spain, Poland, and Greece. Combustion of low-sulfur coals produces improved, low-sulfur, emissions. As a result, due to strict environmental regulations, it is expected that a large number of electric power plants in the USA and elsewhere will utilize low-sulfur coals in the future, which will result in increased production of Class C fly ash.

Relatively little work had been conducted on the use of Class C fly ash in concrete and other construction materials until the early 1980s. Research related to the application of large quantities of Class C fly ash in structural grade concrete began at the University of Wisconsin-Milwaukee in 1984 and extensive research work has been conducted for evaluation of long-term strength and durability performance of concrete containing large amounts of Class C fly ash. Work for production of structural-grade concrete containing high-volume of Class F fly ash was also performed by Malhotra and his co-workers [6,7,8]. This paper provides an extensive review of the Class C fly ash use in cement-based materials developed to-date and future research needs.

PROPERTIES OF FLY ASH

Fly ash is a heterogeneous mixture of particles varying in shape, size, and composition. Typical particles of a fly ash are shown in Fig. 1. The particle types may include fire-polished sand, thin-walled hollow spheres and fragments from their fracture, magnetic iron containing spherical particles, glassy particles, and unburned coal. [9]. Fly ash is predominately composed of spherical particles, which can be less than 1 μm to more than 1 mm [10,11,12,13]. Mehta [11] determined particle size distribution of a number of fly ashes. ASTM Class C fly ashes are relatively finer than ASTM Class F fly ashes. The nitrogen adsorption surface area of fly ash particles varies in the range of 300 to 500 m^2/kg [12]. Density of Class C fly ash normally varies between 2.4 to 2.8 g/cm^3 .

In general, ASTM Class C fly ashes are characterized by higher CaO, somewhat higher MgO, and lower Al_2O_3 and SiO_2 contents compared to ASTM Class F fly ashes. Typically Class C fly ashes contain 20 to 50 % SiO_2 , 15 to 20 % Al_2O_3 , 15 to 30 % CaO, 5 to 10 % Fe_2O_3 , and up to 8 % alkali. Major mineralogical components of the fly ash are a silico-aluminate glass

containing Fe_2O_3 , CaO , and MgO , and certain other oxide minerals. The Class F fly ashes contain less than 5 % of CaO . Over 40 % CaO was found in some fly ashes from Europe.

Crystalline mineral phases present in a Class C fly ash may include quartz, periclase, lime, calcium aluminate, calcium sulfate, alkali sulfate, in addition to glass which ranges between 60 to 90 % [12,13,14]. The presence of lime in Class C fly ashes can activate cementitious behavior in the presence of water by the ash itself [14]. Additionally, the calcium compounds and the alkali sulfates can participate in cementitious and pozzolanic reactions in concrete in the presence of moisture.

To a large extent, performance of fly ash in concrete is dependent upon its physical, chemical, and mineralogical characteristics. Glassy particles are of special importance because they participate in pozzolanic reactions in concrete. In general, reactivity of these particles increases with decreasing particle size [15]. The performance parameters of fly ash in concrete are known to be poorly correlated with chemical compositions of fly ash expressed in terms of its total oxides [12,16].

MIXTURE PROPORTIONING METHODS

Three basic mixture-proportioning techniques have been generally used for fly ash concrete systems [10]. These are: (1) the partial replacement of cement, the simple replacement method; (2) the addition of fly ash as fine aggregate, the addition method; and, (3) the partial replacement of cement, fine aggregate, and water. A variation of the first method is to replace cement by fly ash by mass and reduce the water content to obtain equal workability. The simple replacement method requires direct replacement of a portion of the portland cement with fly ash either on a mass or volume basis. Generally early age strength is decreased when this method is used, particularly for Class F fly ash. The addition method involves adding fly ash to the

mixture without reducing the cement content in comparison with the no-fly ash concrete mixture. In general, this method increases strength and overall quality at all ages, but does not provide any saving on the cement cost.

In the third method, partial amount of cement is replaced by a larger mass of fly ash with or without adjustments made in fine aggregate, and water content is reduced for a specified workability. This method can be further divided into two techniques: modified replacement, and rational proportioning methods. In the modified technique, the total mass of cement plus fly ash for a concrete mixture exceeds the total mass of portland cement used in a comparable no-fly ash mixture. This method produces early age compressive strengths of fly ash concrete comparable to or greater than plain portland cement concrete without fly ash. Authors have found this method to be very effective in producing concrete with the specified early strength and higher later age strength of fly ash concrete relative to concrete without fly ash [17]. Because of simplicity and effectiveness, this method is probably the best in assuring the specified concrete performance for the fly ash concrete system. Desired high-strength and high-durability is maintained by adding superplasticizer to the concrete to produce high-quality, high-strength, high-durability concretes at low water-cementitious materials ratios.

The rational mixture proportioning technique assumes that each fly ash possesses 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. For simplicity K is normally assumed to be one, particularly for good quality Class C fly ash [18]. The required strength and workability of fly ash concrete are obtained by applying Abrams' relationship between strength and water-cementitious materials ratio ($W/(C + KF)$) [10]. Since the value of K varies greatly with the type of cement and fly ash, curing conditions, strength level of concrete, and other

factors, adjustments are required in aggregate content due to varying water demands of fly ash-to-cement ratio to achieve the desired workability. This method, however, may not be readily adoptable to field applications. This method is similar to the method proposed in the new European specification CEN 450.

PROPERTIES OF CONCRETE

Addition of fly ash to concrete alters both fresh and hardened concrete properties. Effects of incorporation of fly ash on concrete properties are discussed in the following sections.

Fresh Concrete Properties

Workability, Cohesiveness, Bleeding, and Segregation

Replacement of cement with fly ash enhances rheological properties of fresh concrete. In general, workability and cohesiveness are improved, and bleeding and segregation are reduced. Incorporation of fly ash in concrete reduces water requirements for a given consistency and increases density of concrete (particularly the transition zone between aggregate and mortar is densified). Consequently, the reduction in water requirement due to fly ash addition causes reduction in bleeding and segregation, and improvement in impermeability. However, a well-dispersed mixture of cement and fly ash particles is needed to decrease the size of bleed channels and improve the aggregate-paste transition zone microstructure [15]. In order to accomplish this, water reducing admixtures have been used in concrete. Helmuth [19] reported that fly ash particles cause dispersion of cement particles in a manner similar to that observed for conventional water-reducing admixtures.

Many past investigations had substantiated that inclusion of fly ash in concrete causes decreased water demand, increased workability and pumpability, and decreased bleeding [9-13,17-20]. In general, the decrease in water requirement for a given workability is attributed to

the ball-bearing effect of spherical fly ash particles by a large number of investigators [18,19,20]. However, Helmuth [19] suggested that this occurs not only because of the ball-bearing effect but also due to improved dispersion of cement particles caused by fly ash particles.

Air-Entrainment

In order to improve freezing and thawing durability of concrete, air-entrainment is required in concrete. Studies have shown that the use of fly ash in concrete increases the air-entraining agent (AEA) dosage requirements relative to the control concrete without fly ash [12,19]. Similar to fly ash, other mineral admixtures also affect AEA requirements. Some portland cements have also been found to demand high doses of AEA [10]. The primary reason for the increased AEA dosage rate for fly ash concrete is said to be due to the presence of unburned coal, as measured by loss on ignition (LOI), or increased fineness of fly ash compared to cement, or both.

Gebler and Klieger [21] reported that concrete containing Class C fly ash demanded less air-entraining agent (AEA) compared to concrete with Class F fly ash. They also reported that all fly ash concrete mixtures containing either Class C or Class F fly ash at 25 % or higher cement replacement levels required higher air-entraining admixtures dosages relative to the portland cement concrete without fly ash. In their study, an increase in organic matter and carbon content, as measured by the loss on ignition (LOI) of fly ashes, caused substantial increase in the air-entraining admixture requirements.

Various factors such as the type of AEA and cement type, duration of mixing, concrete temperature, concrete consistency, carbon content and fineness of fly ash, and use of other mineral additives with fly ash are known to influence air-entraining admixture requirements.

Therefore, an optimum amount of the air-entraining admixture should be established through necessary pretesting for each given source of concrete constituent materials including fly ash.

Time of Setting

It is generally accepted that concrete setting may be retarded when Class F fly ash is added to concrete mixtures. Class C fly ashes have shown mixed behavior in regards to setting characteristics of concrete. The initial and final setting times measured in accordance with ASTM C 403 may increase, decrease, or remain unaffected due to inclusion of Class C fly ash [13,18,22,23].

Naik and Ramme [8] studied workability and setting characteristics of high-fly ash content concretes using a Class C fly ash. Mixture proportions were developed for concrete by maintaining a fly ash-to-cement replacement ratio of 1.25. For control mixtures without fly ash, water-cementitious materials ratios of 0.45, 0.55, and 0.65 were used. Their results showed that addition of fly ash in concrete mixtures increased workability and decreased water demand. For a constant workability, the water-cementitious materials ratio decreased substantially when the level of cement replacement by fly ash was increased from zero to 60 %. The results further indicated that the initial and final set times were not significantly affected for cement replacements by Class C fly ash in the range of 35 to 55 % for all the concrete mixtures tested in the investigation [18].

Dodson [22] found that incorporation of a high-calcium fly ash in concrete for cement replacements of up to 40 % caused reduction in setting time. However, a reverse trend was generally observed for very high (greater than 60 %) cement replacement levels [18]. Ramakrishnan et al. [24] observed higher time of set for mixtures made with a Class C fly ash

relative to mixture containing no fly ash. The increase in setting time was found to be lower with ASTM C 150 Type III cement than with Type I cement.

Recent investigation [23] at the UWM Center for By-Products Utilization, University of Wisconsin-Milwaukee has revealed that the setting time of concrete was retarded up to a certain level of cement replacement (typically about 60 %), beyond which a reverse trend was noticed. The former was attributed to the dilution effects, whereas the latter was probably due to the flash set and/or a reduction in total gypsum in the mixture. Results showed that at extremely high cement replacement, above 60 %, high dosages of set retarding admixture should be considered to keep concrete workable throughout the mixing through placing period.

Temperature Rise

During the cement hydration process, the temperature of concrete rises due to generation of heat from the chemical reaction between the cement and water. The rise in temperature, especially in mass concrete and large-volume concrete sections, results in a temperature gradient in the concrete which is a function of cement type, source, and quantity, concrete temperature, air temperature, and ambient relative humidity. The tensile stresses generated due to thermal gradients could cause cracking in concrete elements. In addition to structural implications, the increase in permeability due to such cracking may result in durability-related problems. To a significant extent, addition of Class F or Class C fly ash reduces the temperature rise due to lower heat of hydration of the Class F or C fly ash concrete mixtures. Some Class C fly ashes, when they contain large amounts of C_3A or free lime, have shown an increase in heat of hydration and also to cause quick set in concrete mixtures according to Mehta [12].

Hardened Concrete Properties

Concrete microstructure is greatly improved due to inclusion of fly ash, especially the transition region between hydrated cement paste and aggregates of the concrete [15]. This results in improved properties of the hardened concrete. However, the improvement in properties of concrete depend upon the type of fly ash and its properties. In the following sections, properties of hardened Class C fly ash concrete such as strength, elastic modulus, creep and shrinkage, and durability are discussed.

Compressive Strength, Splitting Tensile Strength, and Flexural Strength

Incorporation of Class C fly ash in concrete up to a certain optimum cement replacement level (at about 35 to 40 %) shows a rate of strength development either higher or comparable to that of no-fly ash concrete at all ages. However, several variables can influence the rate of strength development of a fly ash concrete system. These include mixture proportioning technique, fly ash content, water-cementitious materials ratio, curing, type and dosage of chemical admixtures, and type of cement. With Class C fly ash up to a cement replacement level of about 40 %, early age strength is generally improved or remains unchanged [17]. Beyond this level, the early age strength may be reduced. In order to improve the early age strength, lower amount of water (water-cementitious materials ratio of about 0.32 ± 0.02) with a superplasticizer is generally used. Even at high cement replacement levels, above 40 %, the strength gain by fly ash concrete generally exceeds that shown by no-fly ash concrete at 7-day age and beyond. Significant increases in concrete strength due to improvement of concrete microstructure resulting from pozzolanic reactions occur beyond 14-day age. The pozzolanic reactions are primarily governed by mineralogical properties of the fly ash used. Class C fly ashes participate in both cementitious and pozzolanic reactions in concrete. As a result, at normal rates of cement

replacement (up to 40 %), early-age strength as well as later-age strength of properly proportioned Class C fly ash concrete is higher compared to concrete mixtures without fly ash.

Since pozzolanic reaction is more sensitive to curing conditions, the strength development of concrete with fly ash is more adversely affected compared to a portland cement only concrete, when proper curing is not provided. This is especially true for Class F fly ash concrete. At high cement replacement levels (above 40 %), care must also be taken to ensure proper curing for Class C fly ash concrete.

Ghosh and Timusk [25] evaluated strength properties of concrete containing Class C fly ash. Concrete mixtures were proportioned for strength levels of 21, 35 and 55 MPa. The effect of high carbon content of fly ash (6 to 18 percent as measured by LOI), fly ash-to-cement plus fly ash ratio (16.7 %, 28.6 %, and 50 %), and fineness of fly ash, on the concrete performance was studied. Test data showed slightly lower early age compressive strength for fly ash concrete relative to the reference concrete containing no fly ash. However, at later ages, except for 55 MPa concrete, fly ash concrete showed higher compressive strength compared to the reference concrete without fly ash. Yuan and Cook [26] determined strength properties of both air-entrained and non-air-entrained concrete containing Class C fly ash at a water-cementitious materials ratio of 0.45. Their results showed that the strength development for mixtures containing fly ash (up to 50 %) was comparable to the reference concrete without fly ash.

Cuijuan et al. [27] determined the effects of dosage of a calcium-enriched Class F fly ash on strength development of concrete. The test results showed that concrete, with less than 25 % fly ash as a replacement of cement, attained higher compressive strength compared to the no-fly ash concrete. At 40 percent cement replacement with the fly ash, concrete either exceeded or approached the strength levels indicated by the no-fly ash concrete, at both 90 and 180-day ages.

Papayianni [28] used a ground Greek lignite (Class C) fly ash in concrete to replace cement in the range of zero to 100 %. The water-cementitious materials ratio ranged between 0.55 through 0.75. From the results obtained, it was concluded that the fly ash could be used in structural concrete requiring strength levels in the range of 15 to 30 MPa. The author recommended up to 30 to 40 % replacement of cement with the fly ash for reinforced concrete.

Performance of a high-alkali lignite (Class C) fly ash in concrete was reported by Hooton [29]. This fly ash contained alkali in the range of 6 to 7.5 % Na₂O equivalent. The results indicated that the presence of high-alkali in the fly ash did not aggravate the alkali-silica reaction. Compressive strength of concrete with up to 35 % cement replacement by the fly ash was lower at one-day age but was similar at 7 days. Both long-term compressive and splitting tensile strengths were higher relative to no-fly ash concrete. Manz and McCarthy [16] indicated that with certain western United States high-calcium fly ashes, similar strength levels were obtained for both 25 % and 75 % fly ash concretes.

Naik and Ramme [18,30,31] carried out an investigation to develop optimum mixture proportions for high-performance structural grade concretes. Concretes without fly ash were proportioned to have the 28-day compressive strengths of 21 MPa to 35 MPa. Concrete mixtures were proportioned for cement replacement levels of 10 to 60 percent with Class C fly ash. They showed that with proper mixture proportioning, even at 60 % cement replacement, fly ash concretes attained higher strength compared to their respective no-fly ash concretes at 28 days and beyond.

Naik and Ramme [30,31] also demonstrated successful application of a large amount of Class C fly ash in concrete (fly ash-to-cement plus fly ash ratio of 70 %) in two different construction projects.

Naik and Ramme [17] carried out investigations at precast/prestressed concrete plants to identify optimum mixture proportions for production of high-early strength concrete with high fly ash contents. Tests were carried out on a concrete with a nominal 28-day compressive strength of 35 MPa, and the 12-hour form stripping strength of 21 MPa, in which up to 30 percent of cement was substituted with Class C fly ash (Table 1). The results revealed that replacement of cement with Class C fly ash increased early strength compared to the concrete without fly ash (Table 2) for all fly ash concretes. The early strength was 24 MPa at 11-hour age, and 68 MPa at 28-day age for concrete mixture made with 30 % of cement replaced by fly ash, compared to 22 MPa, and 54 MPa, respectively, for the no-fly ash concrete. Therefore, it was concluded that concrete mixtures with Class C fly ash, with at least up to 30 % cement replacement, can be used to produce high-early strength concrete for making precast/prestressed concrete products. For all the cement replacement mixtures, with the same workability, the water-cementitious materials ratio decreased (0.40 to 0.35) as the fly ash content was increased. The results of this research led to commercial use of Class C fly ash in precast and prestressed concrete products. The producers are realizing a total saving of up to approximately 3,000 tons of cement per year (1992 data).

Naik and Singh [2,33] conducted an investigation to determine the performance of superplasticized concrete containing Class C fly ash. A reference portland cement concrete was proportioned to have the 28-day compressive strength of 41 MPa. Fly ash concretes were proportioned to have cement replacements of 40, 50, 60, and 70 % by mass, maintaining an amount of cement replaced to fly ash ratio by mass of 1:1.25. Total amount of cementitious material was kept at about 360 kg/m^3 with a water-cementitious materials ratio of 0.31 ± 0.02 for all the concrete mixtures. Desired workability was achieved with the aid of a superplasticizer.

The 7-day compressive strength, with up to 50 % cement replacement, was almost identical to that of concrete without fly ash. With respect to the 28-day compressive strength, the superplasticized fly ash concrete outperformed the reference concrete for up to 70 % cement replacement. It also showed adequate equivalent performance with respect to tensile strength.

Naik et al. [34] developed a high-strength concrete containing Class C fly ash and/or silica fume. Three different mixtures, Mixture 1, 2, and 3, were proportioned for the 28-day design strengths of 70, 75, and 85 MPa, respectively. Mixture 1 consisted of 356 kg of cement and 208 kg of Class C fly ash per cubic meter of concrete. Mixture 2 contained 415 kg of cement, 59 kg of Class C fly ash, and 42 kg of silica fume per cubic meter of concrete. Mixture 3 was composed of 415 kg of cement, 59 kg of Class C fly ash, and 59 kg of silica fume per cubic meter of concrete. The water-cementitious materials ratio of these mixtures was maintained at about 0.30. The 28-day compressive strength and tensile strength were measured. The average 28-day compressive strengths observed were 70 MPa for Mixture 1, 74 MPa for Mixture 2, and 86 MPa for Mixture 3. The corresponding splitting tensile strengths were 5 MPa, 6 MPa, and 6 MPa. At the 91-day age, concrete strength exceeded 100 MPa (the load capacity of the testing machine for 150 x 300 mm cylinders).

Naik et al. [35] determined mechanical properties of paving concrete incorporating both Class C and Class F fly ash for cement replacements in the range of 20 to 50 %. A 40 % Class F fly ash mixture with a superplasticizer was also used. The water-cementitious materials ratio ranged between 0.34 - 0.40 for the Class C fly ash mixtures. All mixtures contained 353 kg/m³ of cement plus fly ash. Test results showed compressive strength at 28 days in excess of design strength of 24 MPa for all of the Class C fly ash mixtures (20 and 50 % cement replacements), while it was 24 MPa for the 40 % Class F fly ash mixtures. The average splitting tensile strength

was found to vary from 2.3 to 3.4 MPa at 28 days and from 3.0 to 3.7 MPa at 56 days. This study showed average flexural strength for mixtures tested varying from 4.0 to 4.7 MPa at 28 days, 4.4 to 4.9 MPa at 56 days, and 5.2 to 6.3 MPa at 128 days.

The mixture proportions of a more recent investigation by Naik et al. [36] are shown in Table 3. The results showed that the concrete microstructure as determined by SEM improved with fly ash addition for up to 30 % cement replacements (i.e. fly ash-to-cement plus fly ratio of 0.35), beyond which the concrete microstructure deteriorated especially at high cement replacements of 50 % and above [36]. However, for up to 50 % cement replacements, fly ash concretes showed strength properties, such as compressive strength, splitting tensile strength, and flexural strength, very suitable for structural applications. In general, for up to 30 % cement replacement, this Class C fly ash concrete produced early as well as later age strength either similar or higher than a comparable portland cement concrete. Similar results have also been reported by others [37].

The UWM Center for By-Products Utilization at University of Wisconsin-Milwaukee [38] was also involved in developing low-cost high-performance concrete systems incorporating significant amounts of fly ash and silica fume. These mixtures were proportioned to contain Class C fly ash, Class F fly ash, or a combination of these fly ashes and low amounts of silica fume. The 28-day design strengths of the mixtures ranged from 70-100 MPa. Each concrete mixture was subjected to standard moist curing at 23 °C as well as to a Variable Temperature Curing Environment (VTCE) up to 45 °C. The result showed that low-cost high-performance concrete containing large amounts of fly ash can be produced with excellent mechanical properties.

Modulus of Elasticity

As expected, elastic modulus of concrete increased with concrete strength and vice versa. Generally, modulus of elasticity had very little effect from the inclusion of Class C fly ash in concrete [12,19,23,25,34,36].

Ghosh and Timusk [25] determined modulus of elasticity of fly ash concrete at strength levels of 21, 35 and 55 MPa. The concretes made with Class C fly ash showed results that were identical to those of comparable no-fly ash concretes. All concrete mixtures tested in their study showed higher modulus compared to that determined by the ACI 318 Building Code equation. Naik and Ramme [39] determined elastic modulus for concrete incorporating fly ash for 45 % cement replacement. They observed the 28-day average elastic modulus value for non-air-entrained concrete as 3.28×10^4 , 3.48×10^4 , and 3.37×10^4 MPa at respective nominal strength levels of 21, 28, and 35 MPa. The corresponding modulus values of air-entrained concrete mixtures were 2.91×10^4 , 2.88×10^4 , and 3.03×10^4 MPa. No significant difference was found between the experimental values and the values computed by the ACI 318 Building Code formula up to the 35 MPa concrete tested.

Naik and Singh [32,33] determined modulus of elasticity of superplasticized fly ash concrete containing high volumes of Class C fly ash in the range of zero to 70 % cement replacements. Concrete mixtures were proportioned to have the 28-day compressive strength of 41 MPa at a water-cementitious materials ratio of 0.31 ± 0.02 . The concrete containing Class C fly ash for cement replacements up to 70 % exhibited adequate modulus for structural applications even at the 7-day age.

Naik et al. [34] studied modulus of elasticity of high-strength concrete containing Class C fly ash and/or silica fume. The modulus of elasticity data were obtained for nominal

compressive strength of 70, 75, and 85 MPa concrete mixtures (Table 4). The modulus values predicted by the ACI 318 Equation were significantly higher than the experimental values obtained in their investigation at all the strength levels tested.

Naik and Ramme [39] evaluated Poisson's ratio of concrete containing fly ash with cement replacement in the range of 35 to 55 % by mass at three different strength levels. The water-cementitious materials ratio varied between 0.45 and 0.65. The static Poisson's ratio was measured to be in the range of 0.15 to 0.20.

Creep and Shrinkage

Relatively little work has been done in regards to creep and shrinkage behavior of concretes made with Class C fly ash [37]. Creep characteristic of concrete is influenced by parameters such as casting and curing temperature and moisture condition, concrete strength, aggregate content, and maximum size of coarse aggregates [13]. The major factors affecting drying shrinkage are volume fraction of paste, water-cementitious materials ratio, aggregate properties, concrete strength, curing environment, and maximum size of coarse aggregates.

Ghosh and Timusk [25] investigated creep and shrinkage of high-volume Class C fly ash concretes at strength levels of 21, 35 and 55 MPa. In general, they found lower creep and shrinkage for fly ash concretes compared to concretes without fly ash.

Naik and Ramme [39] measured drying shrinkage of non-air-entrained as well as air-entrained concretes containing 45 % Class C fly ash. The drying shrinkage data were obtained at nominal strength levels of 21, 28, and 35 MPa at ages varying from 4 to 28 days. In general, drying shrinkage decreased with increasing strength levels for the air-entrained concretes compared to the corresponding non-air-entrained concretes.

Yuan and Cook [26] studied shrinkage and creep behavior of concrete made with Class C fly ash at a water-cementitious materials ratio of 0.38. The results revealed that shrinkage strains for fly ash concretes were comparable to that for concrete without fly ash. Creep strains of fly ash concrete with 20 % cement replacement and the control concrete containing no fly ash were essentially the same. However, above 20 % cement replacement, the creep of fly ash concrete increased with the increase in fly ash content. Nasser and Al-Manaseer [40] studied creep and shrinkage behavior of sealed and unsealed concrete containing Type I cement and 50 % lignite fly ash. They predicted lower creep for concrete containing 50 % lignite fly ash in comparison to portland cement concrete. However, shrinkage of the fly ash concrete was higher compared to the no-fly ash concrete. In another study, Nasser and Al-Manaseer [41] presented the influence of temperature on shrinkage and creep behavior of concrete incorporating 50 % lignite fly ash. Combined shrinkage and creep of unsealed specimens were found to decrease with an increase in temperature from 21 °C to 177 °C, beyond which they increased slightly; whereas, creep of sealed specimens increased with an increase in temperature from 21 °C to 71 °C and then decreased. The authors indicated that in the case of unsealed specimens, the decrease in creep was associated with increased strength resulting from the strength contribution of the accelerated hydration and pozzolanic reactions. Whereas, in the case of sealed specimens, due to the presence of adsorbed water, creep increased up to about 71 °C, and then decreased due to the increased strength and rigidity resulting from the accelerated hydration and pozzolanic reaction similar to that observed in the case of unsealed specimens.

Naik et al. [35] reported low shrinkage of high-volume fly ash concrete mixtures. They found lower shrinkage for the 40 % Class F fly ash mixture compared to Class C fly ash mixtures having 20 to 50 percent cement replacement.

Investigation on high-volume concrete systems has been conducted at CANMET using mainly low-calcium, Class F fly ashes and two high-calcium fly ashes. The concrete mixtures contained 58 % Class F fly ash as a replacement of cement at a low water-cementitious materials ratio of 0.33. These high-volume fly ash concrete systems exhibited very low values of creep and shrinkage [42].

A study [43] on wetting shrinkage of high-volume Class C fly ash concrete was conducted at the UWM Center for By-Products Utilization, University of Wisconsin-Milwaukee. In general, wetting shrinkage decreased with fly ash inclusion up to 70 % cement replacement, especially at ages beyond 14 days of moist curing. This may be attributed to the decrease in the amount of water content per unit volume of the material with increasing fly ash content, and increased C-S-H crystals due to cementitious and pozzolonic reactions resulting from the presence of a significant amount of Class C fly ash.

Durability of Concrete

Durability of concrete is generally measured in terms of its resistance to corrosion of the embedded steel, abrasion, freezing and thawing, salt-scaling, alkali-aggregate reaction, and sulfate attack; and its permeability. To a significant extent, degree of deterioration by these factors is dictated by concrete permeability and ingress of water and/or chemicals [12].

Permeability of Concrete

Permeability dictates the rate at which aggressive agents such as gases (CO_2 , SO_x , and NO_x), liquids (acid rain, road salt-bearing water, sea water, sulfate-bearing water, snow and ice water, and river or lake flowing water), and chloride and sulfate ions penetrate into the concrete that can lead to various types of undesirable physical and/or chemical reactions. The primary

variables influencing concrete permeability are water-cementitious materials ratio, grading and size of aggregates, compaction of concrete, and curing.

Rodway and Fedirko [44] measured the coefficient of water permeability of concrete, having 68 % cement replacement with Class C fly ash. The results exhibited a very low coefficient of permeability of fly ash concrete of the order of 3.65×10^{-12} m/s. Ellis et al. [45] reported that increasing the amount of Class C or F fly ash concrete with a fixed quantity of cement reduces chloride-ion penetration considerably. Concrete containing Class F fly ash attained significantly lower chloride-ion penetration than concrete made with Class C fly ash.

Bilodeau et al. [46] determined water permeability and chloride-ion penetrability of six low-calcium and two high-calcium fly ashes using two different cements. The water and cement contents were kept low at 115 and 155 kg/m³, respectively. Fly ash content varied from 55 to 60 percent of the total cementitious materials. All mixtures were air-entrained and superplasticized at water-cementitious materials ratio of about 0.33. The coefficients of permeability for all mixtures were low, ranging from 1.6×10^{-14} to 5.7×10^{-13} m/s. The authors reported that the high volume fly ash concrete attained a very good resistance to chloride-ion penetration measured in accordance with ASTM C 1202, less than 650 coulombs at 91 days of age. These values are comparable with chloride-ion penetration attained by silica fume concretes.

Naik et al. [47] evaluated rapid chloride-ion penetrability of concrete containing mineral admixtures. ASTM Class C and Class F fly ashes, and silica fume were used as mineral admixtures in their study. Tests were conducted on concretes made in laboratory as well as in field conditions. Both air-entrained and non-air-entrained concretes were tested. Three different series of tests were carried out to determine the effects of addition of mineral admixtures on concrete chloride-ion penetration resistance. Mixture proportions for these three series (A, B,

and C) are given in Table 5. In general, fly ash concrete mixtures showed very low (between about 200 and 1,000 Coulombs at the age of 91-day and beyond) chloride-ion penetration values measured in accordance with ASTM C 1202 (Tables 6 to 8).

Naik et al. [48] evaluated permeability of concrete incorporating Class C fly ash for cement replacement levels of up to 70 %. The reference concrete was proportioned to have the 28-day strength of 41 MPa. Each mixture was evaluated for water permeability, air permeability, and chloride-ion penetration. Air and water permeabilities were evaluated by using the Figg method. At early ages, air permeability of concrete was slightly increased with fly ash addition beyond 50 % cement replacement. However, at later ages, especially at 91-day age, the lowest air permeability was obtained for concrete proportioned to replace 50 % cement with the Class C fly ash. All concrete mixtures showed fair resistance to water permeability at ages of up to 40 days. At 91 days, minimum water permeability values were obtained for the 30 % fly ash concrete mixture. All the mixtures containing the fly ash for cement-replacement varying from 30 to 50 % showed excellent resistance to water permeability. Chloride-ion penetration was measured in accordance with ASTM C 1202. All mixtures except the 70 % fly ash mixture attained moderate to low chloride permeability per ASTM C 1202 designation. Again, up to 50 % fly ash mixture showed very good results with respect to chloride-ion penetration. The 70 % fly ash mixture showed higher resistance to penetration of chloride ions than the no-fly ash concrete mixture at the 2-month age.

A study [38] by Olson evaluated the effects of variable temperature curing on chloride-ion penetration of high-performance concretes incorporating various combinations of Class C fly ash, Class F fly ash, and silica fume. In general, chloride-ion penetration decreased with

increasing compressive strength and age. The variable temperature curing cycles improved the resistance of concrete to chloride-ion penetration.

Carbonation and Corrosion

To a significant extent, the corrosion of steel reinforcement in concrete is governed by the resistance of concrete to carbonation and penetration of water, with or without chloride-ions.

Carbonation is a chemical reaction between CO₂ and cementitious-materials hydration products such as calcium hydroxides, calcium silicates, and calcium aluminates. The rate of carbonation is heavily dependent upon permeability of cementitious-materials paste, temperature, relative humidity, and the concentration of CO₂ in the air. Such a reaction increases drying shrinkage and reduces pH of concrete, which in turn increase the susceptibility to corrosion of the embedded steel. In order for the electrochemical reactions involving steel corrosion to occur, presence of air and water at the steel surface is required. It is believed that due to low permeability of fly ash concrete, the penetration of water and air is restricted which leads to reduced corrosion potential of the reinforcement in concrete.

Cuijuan et al. [27] carried out an investigation to evaluate carbonation and corrosion characteristics of steel reinforcement made for concrete incorporating a high-calcium fly ash. The carbonation was measured in a closed automatic carbonator at CO₂ concentration of 20 ± 2 % and relative humidity of 60 to 70 %. The carbonation depth was measured under laboratory as well as normal exposure conditions. Corrosion resistance of the steel reinforcement in concrete specimens cured in the carbonator for three months was also measured. The results revealed identical carbonation depth for concrete with or without fly ash. However, the mass loss and corrosion rate of the reinforcement in high-calcium fly ash concrete was lower than that in portland cement concrete.

Swamy [49] reported that fly ash concrete having a water-cementitious materials ratio in the range of 0.30 to 0.45 would not experience enough carbonation damage to initiate corrosion of the reinforcement. The author further indicated that the addition of fly ash at high replacements of cement does not result in large reductions in the pH value due to the pozzolanic reaction, and, therefore, susceptibility to the corrosion of the reinforcement is not greatly affected by inclusion of fly ash. In general, properly proportioned concretes with either Class C or Class F fly ash show better resistance to corrosion than concrete without fly ash.

Abrasion Resistance

Significant variables that influence abrasion resistance of concrete are compressive strength, surface finish, aggregate properties, surface treatments, curing, and maximum size of aggregates. Nanni [50] used fifty percent cement replaced by Class C fly ash mixture for abrasion resistance measurements of roller compacted concrete in accordance with ASTM C 779. A typical concrete mixture consisted of 310 kg/m^3 cementitious material, and fine and coarse crushed limestone aggregates each weighing about 957 kg/m^3 . The total water content was maintained at approximately 5 percent of the dry mass of materials (approximately 0.36 water-cementitious materials ratio). The test results revealed that: (1) testing under air dry conditions produced approximately 30 to 50 percent less wear than under wet conditions; (2) the addition of fibers (synthetic or steel fibers) did not cause an appreciable change in abrasion resistance; and, (3) improper moist-curing conditions produced more negative effects on surface quality than on compressive strength.

Gebler and Klieger [21] determined abrasion resistance of concrete made with ten different sources of Class F and Class C fly ashes. Cementitious materials for all the mixtures were 307 kg/m^3 . Fly ash concrete mixtures contained 25 % fly ash by mass of total cementitious

materials. The results revealed that abrasion resistance of Class C fly ash concrete was superior to Class F fly ash concrete. Tikalsky and Carrasquillo [51] evaluated abrasion resistance of concrete incorporating Class F and Class C fly ash in the range of 0 to 35 % as cement replacements. Concrete with Class C fly ash exhibited superior abrasion resistance to that of either no-fly ash portland cement concrete or concrete containing Class F fly ash. They concluded that improved performance of Class C fly ash concrete was due to reduced bleeding resulting from lower water requirements for fly ash concretes for equal workability. This caused an increase in surface hardness.

Langan et al. [52] determined strength and durability of concrete incorporating substitute materials at 50 % replacement level by mass of cement, at a water-cementitious material ratio of 0.47. Seven fly ashes (sub-bituminous, bituminous, and lignite), together with a limestone powder as an inert filler material, were used as replacement materials. The results showed that the presence of fly ash at high levels of cement replacement increased the mass loss due to abrasion at all ages compared to portland cement concrete.

Naik et al. [35] investigated abrasion resistance of high-volume fly ash concrete systems. Concrete mixture proportions developed for paving concrete had 20 % and 50 % cement replacements with Class C fly ash and 40 % cement replacement with Class F fly ash. The abrasion test results indicated that the 50 % Class C fly ash concrete mixture was as resistant to abrasion as the 20 % Class C fly ash concrete that used as a reference mixture for this study. The 40 % Class F fly ash concrete mixture showed decreased abrasion resistance compared to the Class C fly ash mixtures.

Barrow et al. [53] evaluated abrasion resistance of concrete incorporating Class F and Class C fly ashes to replace cement (25 or 50 %) by volume. Concrete was cured by maintaining

combinations of 10 °C, 24 °C, and 39 °C temperatures with 50 % and 100 % relative humidities. They reported that, due to lack of proper curing, abrasion resistance of fly ash concretes was less than the reference concrete.

Carette et al. [42] determined abrasion resistance of air-entrained and superplasticized concrete with six low-calcium and two high-calcium fly ashes. The amount of fly ash ranged from 55 to 60 % of total cementitious materials at a water-cementitious materials ratio of 0.33. This study did not find a good correlation between abrasion resistance and strength for the fly ash concrete mixtures tested.

An extensive research project to evaluate influence of Class C fly ash on abrasion resistance was completed at the UWM Center for By-Products Utilization, University of Wisconsin-Milwaukee [36]. Due to high abrasion resistance of concretes tested in this project, depths of wear observed were low (less than 1 mm) when tested in accordance with ASTM C 944. As a result, an accelerated test method was developed at the Center and was used to evaluate abrasion resistance of high-strength concretes [36]. This method used the abrasion test equipment grinding wheels with smaller size washers, and a constant amount (10 g) of Ottawa sand was applied to the surface being abraded at an interval of one minute. The accelerated test results showed that abrasion resistance of concrete with cement replacements of 0 to 30 % was essentially the same. Beyond 30 % cement replacement, the fly ash concretes exhibited slightly lower resistance to abrasion relative to the no-fly ash concrete. The 70 % fly ash mixture showed the least abrasion resistance. As expected, abrasion resistance increased (i.e. the depth of wear decreased) with increased compressive strength.

Freezing and Thawing Durability

Tensile stresses generated due to freezing and thawing actions can cause damage to concrete. For acceptable performance under freezing and thawing, concrete should have 4 to 7 % air content with air bubble spacing factor less than 200 μm and specific surface greater than 24 mm^2/mm^3 [12]. A number of studies [16,26,36,54,55,56,57,58] have reported satisfactory performance of Class C fly ash concrete against freezing and thawing actions.

Yuan and Cook [26] examined freezing and thawing durability of fly ash concrete incorporating fly ash up to 50 % of the total cementitious materials. Fly ash concrete with 6.3 % and 6.9 % entrained air showed excellent freezing and thawing durability. Air-entrained concretes with or without fly ash did not show considerable loss either in mass or in dynamic modulus up to 400 freezing and thawing cycles. However, beyond 400 cycles, significant scaling damage to the concrete containing 50 % fly ash occurred.

Naik and Ramme [54] determined freezing and thawing durability of 28 MPa concrete having 45 % cement replacement with Class C fly ash. As was expected, non-air-entrained concrete showed very poor freezing and thawing durability. Concrete specimens with 5.6 % air content showed high durability as the test specimens did not “fail” even after 300 cycles of freezing and thawing.

Mather [55] reported that irrespective of addition of fly ash, concrete will be durable against freezing and thawing if: (1) it is not critically saturated; (2) it is properly air-entrained; (3) it has attained about 28 MPa compressive strength when subjected to freezing and thawing environment; (4) it is made with sound aggregates; and, (5) proper construction practices, in particular surface finishing operations, are followed. He concluded that concrete will be immune to the effects of freezing and thawing even when critically saturated with water if it is made with

sound aggregates, has a proper air-void system, and has matured so as to have a compressive strength of above 28 MPa. Several other researchers have also supported this conclusion [56,57,58]. Tyson [56] reported that freezing and thawing durability of fly ash concrete in field application is identical to that of no-fly ash concrete.

Johnson [57] studied the effects of cement replacement (up to 42 %) with Class C fly ash on the resistance of concrete to freezing and thawing. He reported that cement replacement with Class C fly ash does not affect freezing and thawing performance greatly when dosages of air-entraining admixture are adequate to achieve air-void spacing factor of less than 250 μm even at a water-cementitious materials ratio of about 0.53.

Naik et al. [35] investigated the resistance of concrete to freezing and thawing actions. They replaced 40 % cement with Class F fly ash, and 20 and 50 % cement with a Class C fly ash. Both the high-volume fly ash concrete mixtures showed excellent resistance to freezing and thawing actions. Similar results have also been obtained at CANMET [10,42] with fly ash concretes containing high-volumes of fly ash.

An extensive research has been completed at the UWM Center for By-Products Utilization, University of Wisconsin-Milwaukee to evaluate freezing and thawing durability of high-volume fly ash concrete systems incorporating several Class C fly ashes. All concrete mixtures (up to 70 % cement replacement) passed freezing and thawing performance requirement in accordance with ASTM C 666, Procedure A [36].

Salt-Scaling Resistance

Salt-scaling resistance of concrete depends significantly upon properties of the surface layer of the concrete. Soroushian and Hsu [59] indicated that salt-scaling resistance of concrete is decreased if the freshly-placed concrete is subjected to excessive vibrations, trowelled too

early and too long, and subjected to plastic shrinkage and/or excessive bleeding. This occurs because concrete produced under such conditions experiences increased microcracking and bleed channels, which in turn increase the penetration of salt solutions in concrete. To avoid these problems proper mixture proportioning, finishing, and curing must be implemented.

Very limited number of investigations have been conducted to quantify the effects of Class C fly ash inclusion on salt-scaling resistance of concrete. Gebler and Klieger [21] carried out an investigation to establish the effects of Class C and Class F fly ash on salt-scaling resistance of concrete. The fly ash to cement plus fly ash ratio was varied between 0.4 and 0.45 with two levels of total cementitious content, 307 and 282 kg/m³. In this study, Class C and Class F fly ashes indicated identical deicing salt-scaling resistance at the curing temperature of 23 °C. In general, no-fly ash concrete exhibited better performance compared to fly ash concretes irrespective of type of curing technique used. Tikalsky and Carrasquillo [51] examined salt-scaling resistance of Class C fly ash concrete having cement replacement in the range of 0 to 35 % under varying curing conditions. The scaling resistance was evaluated in accordance with ASTM C 672. The results concerning the influence of compressive strength and curing practices on the deicing salt-scaling resistance of the concrete were not conclusive.

Carette et al. [42] evaluated salt-scaling resistance of concrete containing 58 % Class F or Class C fly ashes at a water-cementitious materials ratio of 0.33. In general, these high-volume fly ash concrete mixtures experienced severe scaling (visual rating of 5 per ASTM C 672) after 50 cycles of freezing and thawing treatment.

Naik et al. [35] measured salt-scaling resistance of fly ash concrete systems in accordance with ASTM C 672. Three concrete mixtures were proportioned to incorporate: (1) Class C fly ash to replace 20 % of cement; (2) Class C fly ash to replace 50 % of cement; and, (3) Class F fly

ash to replace 40 % of cement. The water-cementitious materials ratio varied between 0.25 and 0.35. At 50 cycles of freezing and thawing treatments, the salt-scaling resistance for the 20 % Class C and the 40 % Class F mixtures was rated as 2, and that for the 50 % Class C fly ash mixture was rated as 4 according to ASTM C 672 visual rating. Thus, the high-volume Class C fly ash performed poorer than the other two fly ash concrete mixtures in regards to salt-scaling resistance. However, field observation of these concrete pavements do not show increased salt-scaling in these three types of concretes.

A study was conducted at the UWM Center for By-Products Utilization, University of Wisconsin-Milwaukee, to evaluate salt-scaling resistance of concrete incorporating several Class C fly ashes in the range of 0 to 70 % cement replacements [36]. The scaling resistance was evaluated per ASTM C 672. The test data showed no scaling for concretes up to 40 % cement replacements. The 50 % mixture experienced some surface scaling damage, which was rated as 2 (slight to moderate scaling) per ASTM C 672. Severe scaling damage (scaling rating of 5) occurred to concrete at 70 % cement replacement with fly ash.

Mehta [12] indicated that probably due to finer pore structures of the concrete incorporating mineral admixtures, such concrete is more susceptible to surface scaling compared to concrete without mineral admixture. From the investigations conducted at the UWM Center for By-Products Utilization, University of Wisconsin-Milwaukee, it appears that cement replacement with Class C fly ash should not exceed 40 % to have satisfactory performance against salt-scaling [36].

Alkali-Silica Reaction

The alkali hydroxides generated during cement hydration process can react with amorphous-silica containing aggregates, causing formation of expansive products. This

expansion can produce stresses high enough to cause failure of the concrete. It is generally accepted that addition of Class F fly ash eliminates or reduces the danger of alkali-silica reactions in concrete when used in the range of 25 % or more. Probably a greater amount of Class C fly ash may be needed to reduce these reactions [12]. When Class C fly ash, containing large amounts of water-soluble alkali sulphates, is added to concrete, it can participate in the alkali-silica reactions. However, these reactions may not cause appreciable expansion, if the value of total amounts of water-soluble alkalis in concrete from all sources is less than 2.5 kg/m³ [12].

Lee [60] studied the effect of high-calcium fly ash on alkali-aggregate reactions. He replaced a low-alkali cement (0.49 % Na₂O equivalent) by three fly ashes (2.26, 3.39 and 7.37 % Na₂O equivalent). The addition of these fly ashes caused reduction in expansion from 1.5 % to 0.9 %, 0.7 %, and 0.5 %, respectively, after 8 weeks of exposure to alkalis from external sources (such as deicing salt and sea water). Further reduction in the expansion occurred when the high-alkali fly ash concentration was increased from 20 % to 40 %. Increase in expansion was found to be inversely related to Na₂O/SiO₂ molecular mass ratio. Using similar mixtures, in another study, Lee [61] found that replacement of small amounts of high-alkali cement and up to 40 % of low-alkali cement with a high-calcium fly ash increased the amount of expansion measured in accordance with ASTM C 441. The author reported that the maximum expansion can occur at the total equivalent Na₂O/SiO₂ molecular mass ratio of the cementitious materials at a critical value which varies from fly ash to fly ash.

Sulfate Resistance

Several investigators reported that inclusion of Class F fly ash in concrete increased the resistance of concrete to sulfate attack, whereas Class C fly ash reduced it [13,62,63].

Dunstan [62] evaluated sulfate resistance of fly ash concrete using ASTM Class C and Class F fly ashes. He developed an empirical model for representing sulfate resistance factor (R), a measure of concrete resistance to sulfate attack, as $R = (C-5)/F$, where C is percent CaO and F is percent Fe_2O_3 in the fly ash. He reported that when R is less than 1.5, the sulphate resistance of fly ash concrete was improved, and when the value of R exceeds 3.0, the sulfate resistance decreased.

Tikalsky and Carrasquillo [63] studied the effect of fly ash composition, fly ash type and content, slump, air content, cement type, and moist curing time on concrete resistance to sulfate attack. They reported that fly ashes with high amounts of calcium oxide and amorphous calcium aluminate increased susceptibility of concrete containing the fly ash to sulfate attack, whereas low amount of calcium oxide containing fly ashes reduced it. Other parameters did not significantly influence fly ash concrete resistance to sulfate attack.

Mehta [12,64] reported that R factor is not a reliable parameter to describe sulfate resisting characteristics of fly ash in concrete. Based on extensive microscopic investigation of blended cement pastes containing several fly ashes, he concluded that “irrespective of the calcium content or the R-factor, it is the amount of reactive alumina contributed by a fly ash (from the dissolution of the aluminosilicate glass and hydration of crystalline compound, such as C_3A and C_4A_3), which controlled the presence of the mineral highly vulnerable to sulfate attack (such as the monosulfate hydrate and calcium aluminate hydrates).” Mehta [64] found that some high-calcium fly ashes formed ettringite as a stable product of hydration. As a result, these fly ashes did not experience the expansion and strength loss due to sulfate exposure. Similar results in regards to sulfate resistance of Class C fly ash in concrete were obtained by Manz and McCarthy [16].

Fatigue Strength

Concrete fatigue strength is influenced by a large number of variables including rate of loading, range of loading, load history, rest period, material properties, and frequency of loading. Not much work has been conducted concerning fatigue behavior of fly ash concretes, especially concrete containing Class C fly ash. Tse et al. [65] studied fatigue behavior of fly ash concretes under compression mode of loading. The results revealed that concrete with equivalent or higher compressive fatigue strength can be manufactured with cement replacement of 25 % by mass of low-calcium fly ash, or 50 % by mass of high-calcium fly ash, compared to the reference concrete without fly ash. An extensive study has been completed at the UWM Center for By-Products Utilization, University of Wisconsin–Milwaukee, for evaluation of fatigue behavior of high volume Class C and Class F fly ash concrete systems. Test results [43,66] showed that endurance limit of high-volume Class C fly ash concrete systems under flexural fatigue loading was about 0.55.

CONTROLLED LOW-STRENGTH MATERIALS (CLSM)

CLSM is defined by the ACI Committee 229 as a cementitious material having compressive strength of less than 8.3 MPa at 28 days. CLSM is a suitable material for pipe bedding, utility duct envelopes, road base, backfills, foundation support, and other similar applications. Studies have been conducted to develop and use low-strength material (CLSM) produced by using either high- or low-calcium fly ashes [67,68,69,70]. Naik et al. [68] developed mixture proportion for low-strength concrete containing high volumes of Class C fly ash and necessary water to produce a high degree of workability, Table 9. In their study, CLSM concrete mixtures were proportioned for compressive strength in the range of 4 to 11 MPa at the 28-day age, Table 10. ASTM Type I cement, obtained from one source, was used for all

mixtures. The mixing water was heated due to cold ambient air temperature during testing. The fine aggregate used was a natural sand meeting ASTM C 33 requirements with a fineness modulus of 2.79. The maximum size of coarse aggregate was 9.5 mm (pea gravel). Mixtures C-1 to C-3 were produced using Class C fly ash, low cement content, and relatively low water content. These mixtures produced a very low slump. The low cementitious Mixture C-1 appeared to be somewhat harsh. All mixtures displayed good workability and could be trowel finished easily. Based on the test results for Mixtures C-1 to C-3, new proportions were developed for Mixtures C-4 to C-7 to produce higher slumps (Table 9). All mixtures showed good workability. Mixtures C-4 to C-7 also had good trowel finishing ability. Mixtures C-1 to C-3 did not flow, while Mixtures C-4 to C-7 displayed good to very good flowability. Compressive strength data on these mixtures is presented in Table 10. Based on the results obtained in this investigation, it was concluded that high-volume fly ash content, flowable, low-strength concrete could be made with ASTM Class C fly ash. Ayers et al. [70] reported additional mixture proportion data on CLSM containing various amounts of Class C fly ash.

FUTURE RESEARCH NEEDS

Class C fly ash is a relatively new material. It has been available in North America since about the early 1980s. Its very long-term performance in concrete is not yet fully established in comparison to Class F fly ash concrete. The effects of Class C fly ash properties, especially physical and mineralogical properties, on concrete need further investigation. This information will be helpful in development of optimum concrete mixtures based on the measured physical and mineralogical properties of fly ash from a given source. Mathematical modeling work is continuing. With the recent trend of increased application of superplasticizer and other chemical additives in production of structural and high-performance concretes, it appears logical to

develop low-cost superplasticizers and to determine their compatibility with various types and sources of cements and fly ashes. Further research is required to quantify the effects of physical and chemical properties of Class C fly ash on air content, stability of entrained air voids, amount of admixture requirement, time of setting, temperature rise, and other rheological properties, especially for high-volume Class C fly ash concrete systems. The long-term hardened concrete properties affected by a given source of Class C fly ash including creep, wetting/drying shrinkage, carbonation resistance, alkali-carbonate reaction, abrasion resistance, salt-scaling resistance, alkali-silica reaction, sulfate resistance, fatigue strength, and other similar long-term properties of concrete incorporating Class C fly ash are not fully understood. Therefore, additional research is required to establish these properties through long-term testing and field evaluations. Such information will be essential in developing optimum mixture proportions for strength and durability requirements for various construction applications. Not much is known about thermal properties of Class C fly ash concretes; and, therefore, additional research is needed to establish thermal conductivity and coefficient of thermal expansion of such fly ash concretes.

Future research efforts should be undertaken for the use of Class C fly ash in pre-blending it with portland cement, dry powder of superplasticizer, and/or activators to create a new generation of blended cements for wide use in high-quality concrete, with minimum (less than 10 %) of portland cement.

Recent investigations have shown that concrete incorporating significant amounts of Class C fly ash can be used in precast/prestressed products. There is also a need for evaluation of long-term strength and durability aspects of such concretes.

In order to promote engineering application of the Class C fly ash in concrete, a data bank on engineering properties of concrete containing Class C needs to be established, especially for concrete containing large amounts of Class C fly ash.

CONCLUDING REMARKS

It is now well established that the use of coal combustion by-products in concrete not only offers economic, and energy & resource conservation benefits, but also improves engineering properties of concrete. Recent investigations have demonstrated that high-strength/high-performance/high-durability concretes can be made with considerable amounts of high-calcium fly ashes. It has been established that concrete can be proportioned to meet high-early strength and required workability for structural grade as well as high-strength/high-performance concretes. Research has indicated that superplasticized high-strength concrete using Class C fly ash can be proportioned for 28-day strength levels of 100 MPa or more.

To-date studies have shown that superplasticized structural as well as high-strength concretes can be manufactured with high volumes of Class C fly ash for cement replacements in excess of 50 %. However, in order to achieve satisfactory durability of fly ash concretes, especially salt-scaling resistance, the amount of cement replacement should be 40 % or less. For precast/prestressed products, to achieve high-early strength, the maximum amount of cement replacement by Class C fly ash has been found to be about 35 % by mass.

In general, elastic modulus, fatigue, drying shrinkage, and creep of concrete are not adversely influenced by the addition of Class C fly ash. Permeability of properly cured Class C fly ash concretes is lower compared to reference concrete without fly ash. Consequently, fly ash concrete are expected to outperform no-fly ash portland cement concrete against freezing and thawing resistance, carbonation, sulfate attack, and other durability properties. At the present

time long-term strength and durability properties of Class C fly ash concrete are insufficiently known, especially for high-volume fly ash concrete systems. These properties are needed for establishing mixture proportions for widespread, everyday applications. Field demonstration projects have been implemented in Wisconsin in the last two decades for future studies and long-term performance evaluation.

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Table 1. Concrete Mixture Proportions and Test Data - 35 MPa Specified 28-Day Strength [17]

Mixture Number*	7	8	9	10	11	12
Cement (kg/m ³)	376	339	320	300	282	263
Fly Ash (kg/m ³)	0	45	68	90	113	135
Water (kg/m ³)	166	151	151	146	144	141
Sand, SSD (kg/m ³)	813	813	813	813	813	813
25 mm Aggregates SSD (kg/m ³)	1068	1068	1068	1068	1068	1068
W/(C+FA)	0.4	0.39	0.39	0.37	0.36	0.35
Slump (mm)	215	210	200	150	190	215
Air Content (°C)	4.9	6.0	7.3	5.8	7.2	7.4
Air Temperature (°C)	22	26	26	22	22	22
Concrete Temperature (°C)	29	30	30	31	31	29
Concrete Density (kg/m ³)	2400	2370	2365	2375	2355	2355

* 2.25 L of WRDA-19 (superplasticizer) added to all mixtures. In addition, all mixtures contained 0.41 L of Daravair (air-entraining agent).

Table 2. Concrete Strength Test Data - 35 MPa Specified 28-Day Strength [17]

Mixture Number	7	8	9	10	11	12
Cement Replacement (%)	0	10	15	20	25	30
Test Age	Compressive Strength (MPa)					
11 hrs	21.9	27.4	23.4	29.7	24.7	24.1
13 hrs	27.1	30.8	35.1	33.4	28.6	26.9
26 hrs	35.7	39.5	43.5	48.6	40.3	40.3
3 days	40.6	49.4	51.6	50.0	47.0	48.8
7 days	44.4	52.8	56.3	56.4	52.7	52.6
14 days	48.4	60.8	61.3	60.9	64.9	62.6
28 days	54.0	66.3	69.1	67.7	65.8	68.2
77 days	61.4	71.7	72.4	69.4	70.2	71.7

Table 3. Mixture Proportions Using Pleasant Prairie Power Plant ASTM Class C (P-4) Fly Ash - 41 MPa Specified Strength [36]

Mixture Number	C-3	P4-2	P4-3	P4-6	P4-7	P4-8
Cement (kg/m ³)	375	259	220	320	179	110
Fly Ash (kg/m ³)	0	139	182	71	226	316
Water (kg/m ³)	135	133	150	129	136	155
Water-cementitious materials ratio	0.36	0.34	0.37	0.33	0.33	0.36
Sand, SSD (kg/m ³)	682	677	659	693	655	607
25 mm aggregates, SSD (kg/m ³)	1182	1172	1153	1180	1139	1145
Slump (mm)	120	160	120	145	115	120
Air Content (%)	6.3	5.2	6.4	6.7	7	6.4
Superplasticizer (L/m ³)	2.9	2.8	2.7	2.8	2.7	2.6
Air-Entraining Agent (mL/m ³)	270	350	515	420	885	1380
Air Temperature (°C)	21	21	21	-	-	-
Concrete Temperature (°C)	23	23	26	21	26	25
Fresh Concrete Density (kg/m ³)	2380	2395	2360	2400	2335	2365
Hardened Concrete Density, SSD (kg/m ³)	2470	2430	2415	2440	2340	2325

Table 4. Modulus of Elasticity Test Data [34]

Age (days)	Modulus of Elasticity (GPa)		
	70 MPa Concrete	75 MPa Concrete	85 MPa Concrete
1	26.0	25.5	25.2
3	28.0	28.3	27.2
7	33.4	35.5	34.5
14	37.2	39.7	39.0
28	37.6	41.4	42.4
35	39.3	41.7	42.0
56	39.7	41.4	40.0

Table 5. Concrete Mixture Proportion and Test Data [47]

Mixture Number	A1	A2	A3	B1	B2	B3	B4	C1	C2	C3
% Class F Fly Ash	40	0	0	0	0	0	0	0	0	0
% Class C Fly Ash	0	50	20	0	10	20	25	37	11	11
% Silica Fume	0	0	0	0	0	0	0	0	8	11
Cement (kg/m ³)	216	176	284	390	390	335	335	356	415	415
Class F Fly Ash (kg/m ³)	145	0	0	0	0	0	0	0	0	0
Class C Fly Ash (kg/m ³)	0	176	66	0	45	71	95	208	59	59
Silica Fume (kg/m ³)	0	0	0	0	0	0	0	0	42	59
Water (kg/m ³)	98	94	96	152	148	150	149	178	142	59
Water-cementitious materials ratio	0.36	0.38	0.35	0.39	0.36	0.37	0.37	0.30	0.29	0.30
Sand (kg/m ³)	915	727	813	718	676	682	688	712	759	742
Coarse Aggregates (kg/m ³)	1094	1080	1143	1038	1038	1038	1038	979	1009	1009
Superplasticizer (L/m ³)	4.6	-	-	2.0	2.1	2.1	2.1	7.6	8.1	9.3
Air-Entraining Agent (mL/m ³)	580	465	270	135	125	125	135	260	510	930
Slump (mm)	65	70	50	160	140	165	150	150	185	265
Air Content (%)	5.5	5.3	5.8	7.6	6.4	7.5	6.5	0.3	1.1	0.3
Air Temperature (°C)	35	28	24	-	-	-	-	20	20	21
Concrete Temperature (°C)	32	31	29	-	-	-	-	22	21	20
Concrete Density (kg/m ³)	2310	2350	2305	2290	2295	2265	2185	2435	2435	2465

Mix A1: 40% Class F Fly Ash Mix B1: Control Mix Mix C1: 37% Class C Fly Ash
 Mix A2: 50% Class C Fly Ash Mix B2: 10% Class C Fly Ash Mix C2: 11% Class C Fly Ash and 8% Silica Fume
 Mix A3: 20% Class C Fly Ash Mix B3: 20% Class C Fly Ash Mix C3: 11% Class C Fly Ash and 11% Silica Fume
 Mix B4: 25% Class C Fly Ash

Table 6. Rapid Chloride-Ion Penetration Test Results for Series 1 at 1-Year Age [47]

Mixture Number	Nominal Fly Ash Content (%)	Test Slice Location	Average Total Charge Passed (Coulombs)	Overall Average Total Charge Passed (Coulombs)	ASTM C 1202 Designation
A1	40 (Class F)	Top	181	188	Very low
		Middle	184		
		Bottom	198		
A2	50 (Class C)	Top	376	391	Very low
		Middle	372		
		Bottom	424		
A3	20 (Class C)	Top	1056	918	Very low
		Middle	798		
		Bottom	900		

Table 7. Rapid Chloride-Ion Penetration Test Results for Series 2 [47]

Mixture Number	Nominal Fly Ash Content (%)	Age (Days)	Actual Total Charge Passed (Coulombs)	ASTM C 1202 Designation
B1	0	28	1,504	Low
		56	1,127	Low
		90	982	Very Low
B2	10 (Class C)	28	1,962	Low
		56	783	Very Low
		90	772	Very Low
B3	20 (Class C)	28	1,508	Low
		56	1,052	Low
		90	964	Very Low
B4	25 (Class C)	28	1,879	Low
		56	1,043	Low
		90	765	Very Low

Table 8. Rapid Chloride Ion Permeability Test Results for Series 3 at 1-Year Age [47]

Mixture Number	Nominal Fly Ash Content (%)	Nominal Silica Fume Content (%)	Test Slice Location	Actual Total Charge Passed (Coulombs)	Average Total Charge Passed (Coulombs)	ASTM C 1202 Designation
C1	37 (Class C)	0	Top	253	259	Very Low
			Upper	302		
			Lower	238		
			Bottom	242		
C2	11 (Class C)	8	Top	238	263	Very Low
			Upper	300		
			Lower	252		
			Bottom	-		
C3	11 (Class C)	11	Top	177	260	Very Low
			Upper	294		
			Lower	283		
			Bottom	284		

Table 9. Mixture Proportions and Field Test Data for High-Fly Ash, Low-Strength Concrete Using Class C Fly Ash [68]

Mixture Number	C-1	C-2	C-3	C-4	C-5	C-6	C-7
Specified Strength at 28-day age (MPa)	3.5	10.3	10.3	3.5	7.0	7.0	7.0
Cement, C (kg/m ³)	44	53	62	42	48	57	57
Fly Ash, FA (kg/m ³)	76	94	112	70	94	116	142
Water, W (kg/m ³)	197	174	168	205	200	200	208
SSD Sand (kg/m ³)	1046	991	955	1025	956	974	916
SSD Pea Gravel (kg/m ³)	1052	1087	1105	1054	1045	1076	1021
Slump (mm)	45	20	30	190	160	165	235
Air Content, percent	3.2	2.7	3	2.1	2.3	2.2	1.0
Air Temperature (°C)	4	7	9	3	4	3	0
Concrete Temperature (°C)	18	17	14	13	16	16	14
Concrete Density (kg/m ³)	2414	2408	2400	2395	2345	2420	2365
W/(C+FA)	1.64	1.19	1	1.84	1.40	1.16	0.95

Table 10. High-Fly Ash, Low-Strength Concrete Test Data [68]

Mixture Number	C-1	C-2	C-3	C-4	C-5	C-6	C-7
Specified Strength (MPa)	3.5	10	10	3.5	7	7	7
Slump (mm)	45	20	30	190	160	165	235
Test Age (days)	Compressive Strength (MPa)						
3	0.8	2.4	2.6	0.8	1.4	1.24	0.8
5	1.5	4.6	4.8	-	-	-	-
6	-	-	-	1.5	3.2	2.9	-
7	1.8	5.8	6.5	-	-	-	2.0
8	-	-	-	1.7	3.5	3.2	-
28	3.5	10.3	11.4	3.4	6.0	6.0	4.5

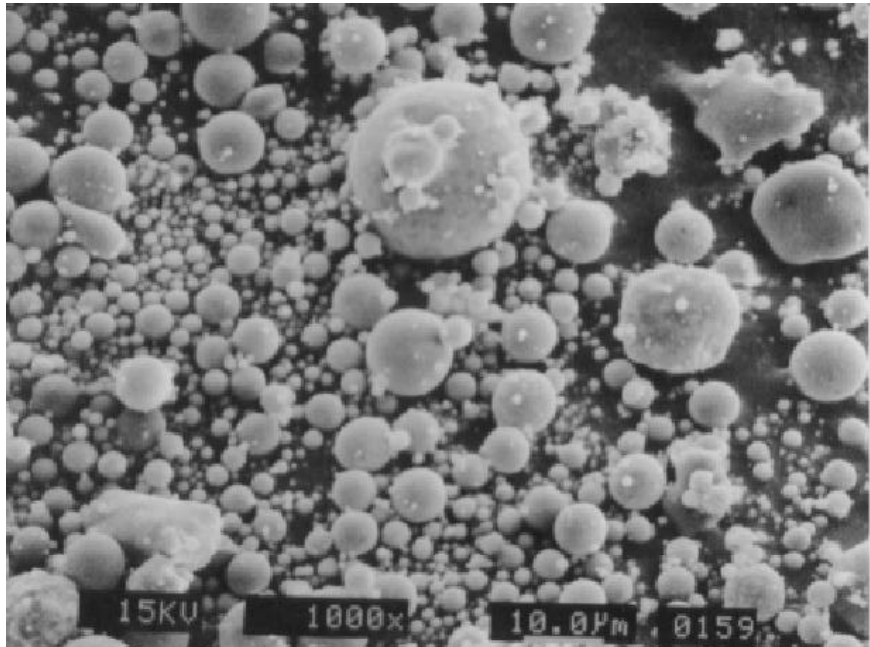


Fig. 1. Fly ash particles (Magnification, 1000 X)