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Report on High-Volume Fly Ash Concrete for Structural Applications

Reported by ACI Committee 232



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Report on High-Volume Fly Ash Concrete for Structural Applications

Reported by ACI Committee 232

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This report presents technical information to support the use of high-volume fly ash concrete for structural applications. The advantages and limitations of high-volume fly ash concrete are discussed, and the characteristics of the fresh and hardened materials and the durability of the material to various aggressive environments are covered. Field applications are presented along with sustainability features.

Keywords: alkali-silica reaction; compressive strength; corrosion of reinforcement; cracking; deicing salts; fly ash; heat of hydration; mixture proportions; modulus of elasticity; shrinkage; sulfate attack; sustainability; tensile strength.

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CHAPTER 1—GENERAL**1.1—Introduction**

High-volume fly ash (HVFA) concrete is a sustainable construction material when proportioned properly and used in appropriate construction applications. This report summarizes published data on the composition and properties of the material, such as workability, strength, and durability. The report affirms the viability of HVFA concrete for structural applications and discusses construction issues.

HVFA concrete is defined as having a large replacement by mass of portland cement with fly ash. [Malhotra \(1986\)](#) defined HVFA concrete as concrete containing 50 percent or more fly ash by mass of total cementitious materials, and [Ramme and Tharaniyil \(2000\)](#) defined it as concrete with 37 percent or more fly ash by mass as total cementitious materials.

[Naik and Ramme \(1985\)](#) tested HVFA concrete using ASTM C618 Class C fly ash mixtures and having water-cementitious material ratios (w/cm) ranging from 0.42 to 0.57, without the use of high-range water-reducing admixtures. In 1986, however, a significant research program was initiated to explore the possibility of HVFA concrete attaining compressive strengths of 7250 psi (50 MPa) or higher for structural applications ([Malhotra 1986](#)). This research used concrete mixtures containing ASTM C618 Class F fly ash, 0.30 w/cm , and high-range water-reducing admixtures. The results of this work showed the potential of HVFA concrete as a sustainable material with workability, strength, and durability exceeding that of conventional port-

land-cement concrete having similar cementitious content. Summaries of the results on HVFA concrete using Class F fly ash are given by [Malhotra \(1992, 2002\)](#), [Bilodeau and Malhotra \(2000\)](#), and [Malhotra and Mehta \(2012\)](#).

Low-strength HVFA concrete mixtures are not covered herein. In this document, HVFA concretes that have minimum specified compressive strengths of 2500 psi (17 MPa) are discussed.

1.2—Significance

This report provides background information and technical data to support the use of HVFA concrete for structural applications. From a sustainability standpoint, HVFA concrete not only significantly reduces consumption of portland cement, but also results in a concrete of superior quality in many aspects when compared with that of conventional concrete in regard to workability, strength, and durability. In addition, this technology is currently available for wide-scale implementation and is backed by more than 25 years of field usage and test results.

1.3—Historical background

In 1937, [Davis et al. \(1937\)](#) experimented with concretes containing fly ash of up to 50 percent replacement by mass of portland cement. They concluded that the use of HVFA in mass concrete has definite advantages, such as lower temperature rise due to heat of hydration and less risk due to thermal cracking. These findings were applied in the first significant use of fly ash in concrete for Hungry Horse Dam in Montana, which was built from 1948-1952. In those early years, concretes using high levels of fly ash were limited to mass concrete structures. The incentive was to reduce the adiabatic temperature rise resulting from heat of hydration of portland cement. Compressive strengths were generally low at early ages with strengths increasing from 1450 to 2900 psi (10 to 20 MPa) at 90 days.

In the late 1970s, the use of fly ash at 60 to 70 percent by mass of cementitious material was found to significantly improve the performance of roller-compacted concrete ([Dunstan 1983](#)). The Upper Stillwater Dam in Utah was constructed using this material in early 1980. During a full-scale trial test of roller-compacted concrete in 1978, a slipformed vertical facing element was constructed using concrete containing approximately 40 percent fly ash by mass ([Dunstan 1983](#)). Subsequently, the first major placement of concrete containing over 50 percent fly ash replacement by mass of portland cement was in 1981, where the concrete was consolidated by immersion vibration for the construction of access roads at the Didcot Power Station in Oxfordshire, UK ([Dunstan 1983](#)). Success in this project led to use of the material in other applications between 1982 and 1984: foundation and retaining walls for an oil tank storage area (51 percent fly ash by mass), marine slipway (52 percent), sewage treatment works (54 percent), and concrete viaducts (35 to 65 percent). Five of these structures were evaluated by visual examination and testing of cores approximately 10 years after construction, and were found to be in excellent condition ([Dunstan et al. 1992](#)).

In the mid-1980s, a number of researchers from different countries embarked on studies of concrete containing 50 percent or more of both Class C and Class F fly ash by mass (Ghosh and Timusk 1981; Munday et al. 1983; Yuan and Cook 1983; Pistilli and Majko 1984; Haque et al. 1986; Joshi et al. 1986; Nasser and Al-Manaseer 1986, 1987; Papayianni 1986; Ravina and Mehta 1986, 1988; Swamy and Mahmud 1986; Tse et al. 1986; Johnston and Malhotra 1987; Naik and Ramme 1987a; Roselle 1987; Sivasundaram et al. 1987). Limited field application of the material resulted from these studies. Two demonstration projects were conducted by Wisconsin Electric in 1984, however, where 70 percent Class C fly ash by mass was used in concrete for pavement and transformer foundations (Naik and Ramme 1987b, 1989). Since that time, Wisconsin Electric has constructed a number of pavements using HVFA concrete with success (Naik et al. 1995).

In 1985, Malhotra and coworkers at CANMET (Malhotra 1986) began work on HVFA concrete. The focus was on concrete having low water content (190 lb/yd³ [115 kg/m³]), low portland cement content (255 lb/yd³ [155 kg/m³]), high Class F fly ash content (55 to 60 percent by mass of cementitious materials), and a HRWRA for workability. Compared to conventional portland-cement concrete, HVFA concrete mixtures achieved moderate early-age and high ultimate strength. In the ensuing years, many significant structures have been built using HVFA concrete based on CANMET's work (Malhotra and Mehta 2012), and today, research data exist from more than 25 years of their field performance.

1.4—Sustainability

Concrete, by volume, is the most common man-made material in the world. It has a relatively low embodied energy coefficient (ranging from 0.95 to 2.0 MJ/kg) depending on geographical location, technology employed in the manufacturing process, and methods of manufacture (Alcorn 2001). Concrete contains approximately 7 to 15 percent portland cement by volume (Kosmatka and Wilson 2011); however, it is energy-intensive—carbon dioxide (CO₂) is generated during its manufacturing process. Producing 1 ton (0.9 tonnes) of portland cement typically requires a 3580 MJ of thermal energy (weighted average) and 108 kWh of electric energy (WBCSD 2012). Therefore, the embodied energy of concrete is a function of the portland cement content of the mixture.

Limestone is the principal raw material used to produce portland cement. The main source of CO₂ emissions from portland cement is due to the decarbonation of the limestone during the manufacturing process. Process emissions, in combination with fossil fuel combustion in the production of portland cement clinker, produce significant amounts of CO₂. Approximately 1890 lb (858 kg) of CO₂ is produced for each metric ton of portland cement clinker, although the level of CO₂ emissions from fuels depends on the portland cement manufacturing process and the fuels used (WBCSD 2012). Indirect CO₂ emissions from electricity, however, are not very large for portland cement and account for approximately 10 percent of total CO₂ emissions in portland cement

manufacture (Schokker 2010). Global CO₂ emissions from portland cement production have been reported in the literature between 4 and 8 percent of the global CO₂ emissions (WBCSD 2011). Variations in the literature exist due to the uncertainty in this figure, which varies between countries from 5 to 10 percent (95 percent confidence interval), with the largest uncertainties for data from countries with fast-changing or emerging economies (Olivier et al. 2012). These variations in the collected CO₂ data arise from the key performance indicators and the portland cement CO₂ and energy protocol employed in the calculations. Globally, portland cement CO₂ addresses all direct and the main indirect sources of CO₂ emissions related to the portland cement manufacturing process and on-site power generation in absolute as well as specific or unit-based terms (WBCSD 2011).

In 2011, global portland cement production was estimated at approximately 3.3 billion tons (3.0 billion tonnes) (International Cement Review 2011) and the current annual world production of fly ash is approximately 990 million tons (900 million tonnes) (Malhotra and Mehta 2012), with both expected to increase. An effective means of decreasing both energy consumption and the production of greenhouse gases is to substitute supplementary cementitious materials (SCMs) such as fly ash for a portion of the portland cement in concrete. HVFA concrete is worthy of focus because of the plentiful supply of fly ash in the world and its beneficial effects on improving the sustainability and durability of concrete.

Fly ash has low embodied energy because it is a by-product of another industrial process. The use of fly ash in concrete production yields a number of environmental and economic benefits, including reductions in CO₂ emissions and energy and water consumption, which have been derived from life cycle inventory data (Bühler 2012; Schokker 2010; Buffenbarger et al. 2012). Moreover, replacing portland cement with fly ash reduces the demand to manufacture portland cement, the environmental impact from processing and extraction of virgin materials, and the pressure on landfills associated with fly ash disposal. Lastly, SCMs enhance the hardened properties of concrete by increasing ultimate compressive strength, decreasing permeability, improving long-term durability, and extending service life, which is the single most important factor in reducing the impact of embodied energy. Increasing durability and service life decreases the need for destruction, removal, and recycling of building materials, which reduces greenhouse gas emissions, fugitive dust emissions, and other environmental concerns associated with demolition.

The reported reduction of greenhouse gas emissions and energy usage in concrete mixtures using HVFA vary in the literature and are summarized in Table 1.4. Sufficient knowledge on the durability and service life of the HVFA concrete is required to calculate the ultimate environmental benefits. The environmental benefit of replacing portland cement with fly ash can be canceled out if the mixture is not durable and requires premature replacement (Van den Heede and De Belie 2010).

The following two examples illustrate sustainability features. The Mitchell Physics Buildings in College Station

Table 1.4—CO₂ and energy reduction estimates corresponding to fly ash replacing portland cement

Study	Fly ash replacement, %	CO ₂ reduction, %	Energy savings, %
Malin (1999)	35	28	Not reported
Glavind and Munch-Petersen (2000)	40	54	Not reported
Sear (2002)	30	17	Not reported
Li et al. (2004)	50	54	Not reported
Lu (2007)	50	20	20

TX, used approximately 4400 yd³ (3360 m³) of HVFA concrete in the foundations and basement walls, which reduced the total portland cement content by approximately 300,000 lb (136,000 kg). This was accomplished without a cost increase or lengthened schedule (Smith and Wendler 2011). A study conducted by Reiner et al. (2006) investigated HVFA concrete products using portland cement replacements from 40 to 70 percent by mass. The products built included an alley panel, curb and gutter sections, a precast manhole and lid, and a twin T prestressed girder. The study reported environmental benefits that included reductions in smog and decreased fossil fuel consumption compared with the same elements built with a 100 percent ordinary portland cement mixture. The economic benefits included capital cost reductions and life-cycle cost reductions when compared with the same element constructed with a 100 percent portland cement mixture.

1.5—Classification of HVFA concrete

For structural applications, HVFA concrete can be classified in two ways: namely, general-use HVFA and high-performance HVFA concrete. This report and most of the research discussed herein focus primarily on high-performance HVFA concrete.

General-use HVFA concrete can be considered for use in applications where strength requirements of 3500 psi (24 MPa) or less would be sufficient. General-use HVFA concrete takes longer to set and gains strength slower than conventional portland-cement concrete. When a conventional concrete specification requires 3500 psi (24 MPa) compressive strength at 28 days, the HVFA specification will call for this strength at 56 or 90 days.

General-use HVFA concrete typically does not contain mid-range or high-range water-reducing admixtures in the mixture. Mixing water provides sufficient workability within the *w/cm* range of 0.35 to 0.50. This report provides examples of mixture designs for general-use HVFA concrete; however, the technical data provided herein are not sufficient because only a few references on this material are found in the published literature. Burke (2012) reported an ongoing study of general-use HVFA concrete used for a floor slab in a biodiesel plant. The mixture contained portland cement at 350 lb/yd³ (208 kg/m³), Class F fly ash at 350 lb/yd³ (208 kg/m³), and 0.45 *w/cm* with a small amount of normal water-

reducing admixture. The compressive strength at 28 days was 3520 psi (24.3 MPa).

High-performance HVFA concrete is applicable for structural members such as beams, walls and columns for multi-story buildings, water storage and transport structures, seawater-exposed structures, post-tensioned structures, and infrastructure applications requiring extended service life. This material can match the setting time and early-age strength properties of conventional concrete. Long-term strength gain is impressive—typically the compressive strength at 1 year is twice the 28-day strength. Besides strength, the durability of high-performance HVFA concrete is better than that of conventional concrete. High resistance to corrosion of reinforcing steel, sulfate attack, and alkali-aggregate reaction are the primary characteristics of this material. To attain these characteristics, HVFA concrete mixtures use low water content resulting in *w/cm* of 0.25 to 0.35. High-range water-reducing admixtures are required in these mixtures. Malhotra and Mehta (2012) provide technical detail on the physical and durability properties of high-performance HVFA concrete.

1.6—Types of fly ash and portland cement

ASTM C618 Class F or Class C fly ash can be used in HVFA concrete; however, a larger portion of the research effort and field applications have been conducted using Class F fly ash.

Burning bituminous or anthracite coal typically produces Class F fly ash, which has a sum of silica, alumina, and iron oxide that must be at least 70 percent by mass. Class C fly ash ordinarily comes from power plants that use lignite or subbituminous coal, and the proportion of silica, alumina, and iron must add up to at least 50 percent. Class C fly ash typically has a higher CaO content than Class F fly ash.

A distinction between the two types of fly ash is that Class C fly ash, when mixed with water, often shows a self-cementing ability, whereas Class F fly ash does not. The use of Class C fly ash can help improve early strengths while also providing long-term improvements in concrete properties by pozzolanic activity when combined with portland cement. Class F fly ash will typically provide slower early concrete strength development, but with a higher silica content than Class C fly ash, it can provide potentially better long-term improvements in concrete material properties when combined with portland cement. Hydrated portland cement produces calcium hydroxide that combines with either Class C and F fly ash in a pozzolanic reaction. The pozzolanic reaction produces calcium silicate hydrate, which leads to improvements in strength and durability properties in HVFA concrete.

During manufacture of portland cement, calcium sulfate is added to perform a dual function in early setting and hardening reactions, that is, it serves as a retarder for tricalcium aluminate and an accelerator for tricalcium silicate (Mehta and Monteiro 2006). Class C fly ash with a high CaO content (more than 20 percent by mass) may contain significant amounts of tricalcium aluminate. As a consequence of the additional aluminate contributed by the Class C fly ash, there may be insufficient sulfate in the system to adequately

control the hydration of tricalcium aluminate. This can lead to initial stiffening due to rapid tricalcium aluminate hydration and possibly even flash setting. If there is insufficient calcium in solution because it has been consumed by the tricalcium aluminate hydration, tricalcium silicate hydration will slow or stop. This can lead to significant retardation of setting (hours or days), a reduction in both early and later age strengths, and can be more pronounced in the presence of chemical admixtures (Malhotra and Mehta 2012; Roberts and Taylor 2007). The addition of calcium sulfate to the mixture, as determined by laboratory tests (ASTM C1679) and trial batches, has been shown to resolve the problem. Therefore, laboratory work and test batches are essential steps with specific material blends to establish an appropriate addition of calcium sulfate to ensure satisfactory performance of HVFA with Class C fly ash.

Blended cement that includes both fly ash and portland cement is common in many parts of the world but less so in North America. Blended cements can be produced by grinding pozzolans with portland cement, or by simply combining them prior to shipping to the concrete production facility. Most of the HVFA concrete research discussed in this report concerns portland cement and fly ash supplied as separate materials and combined at the concrete plant.

Experimental work by Bouzoubaa et al. (2001) showed that HVFA blended cements perform similarly to ready mixed HVFA concrete if an appropriate grinding procedure is followed. With a high-range, water-reducing, low- w/cm mixture, HVFA blended cement concrete yielded good durability, freezing-and-thawing and chloride-ion penetration resistance, adequate early strength, and excellent later strength. The mixture used in Bouzoubaa et al. (2001) study incorporated 50 percent greater high-range water-reducing admixture than the dosage rate used when fly ash was added as a separated constituent to the concrete mixture. This increase in high-range water reducer is likely due to the decrease in the water-reducing effect of the fly ash because grinding breaks up the spherical shape into angular particles.

1.7—Codes and specifications

Currently, North American building codes, including ACI 318, do not prohibit the use of HVFA concrete, except when the concrete is exposed to deicing salts. When the concrete will be exposed to deicing salts, the fly ash content is limited to 25 percent by mass of the total cementitious material. ASTM C1157/C1157M and ASTM C1600/C1600M are performance-based standards, which do not limit pozzolanic replacement in blended cements. However, ASTM C595/C595M does limit the pozzolanic replacement to 40 percent. The European Union's specification EN/197-2002 allows up to 55 percent fly ash by mass in blended cements (Malhotra and Mehta 2012).

1.8—In-place strength

Obla et al. (2008) demonstrated experimentally that large volume structural elements that use HVFA concrete have higher in-place temperatures and early-age in-place strengths (measured by match-cured cylinders and pullout tests)

compared with strength gain by cylinders under standard laboratory conditions. As a result, construction schedules may not have to be extended. Field-cured cylinders underestimated in-place strength development, and standard-cured cylinders must not be used for estimating in-place early-age strengths. Field-cured and standard-cured conditions are discussed in ASTM C31/C31M. The maturity method (ASTM C1074) and the pullout test method (ASTM C900) are applicable to estimate the early-age concrete strength in structures made with HVFA concretes.

CHAPTER 2—DEFINITIONS

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <http://www.concrete.org/Tools/ConcreteTerminology.aspx>

CHAPTER 3—CHARACTERISTICS OF FRESH HVFA CONCRETE

3.1—Materials and mixture proportions

The individual ingredients used in HVFA concrete are the commonly used materials in conventional concrete; only the relative proportions of the ingredients differ. Fly ash used in HVFA concrete is the same material as that used in portland-cement concrete, which contains lesser amounts of fly ash, typically in the range of 15 to 25 percent by mass. Details on fly ash acceptable for use in concrete are given in ACI 232.2R.

Several mixture designs that have been used extensively in the field are provided by Manmohan and Mehta (2002) and Mehta and Manmohan (2006). Table 3.1a gives mixtures for general-use HVFA concrete, where high-range water-reducing admixtures are not required. The fly ash imparts sufficient workability to the concrete at relatively low water content. These mixtures have a slow rate of strength gain at early ages and provide moderate strengths at 28 and 56 days. Table 3.1b gives examples of mixture designs for high-performance HVFA concrete, where high-range water-

Table 3.1a—General-use HVFA concrete mixtures not requiring a high-range water reducer (Mehta and Manmohan 2006)

	Mixture No. 1	Mixture No. 2	Mixture No. 3
Minimum strength, psi (MPa)			
28 days	2760 (19)	3190 (22)	3630 (25)
56 days	3630 (25)	3920 (27)	4060 (28)
90 days	—	5220 (36)	5080 (35)
Portland cement, Type I/II, lb/yd ³ (kg/m ³)	253 (150)	253 (150)	303(180)
Fly ash, Class F, lb/yd ³ (kg/m ³)	253 (150)	270 (160)	303(180)
Water, lb/yd ³ (kg/m ³)	224 (133)	202 (120)	229(136)
w/cm	0.44	0.38	0.38
Coarse aggregate, lb/yd ³ (kg/m ³)	1130 (1905)	1150 (1972)	1160 (1955)
Fine aggregate, lb/yd ³ (kg/m ³)	830 (1399)	830 (1399)	790 (1332)

Table 3.1b—High-performance HVFA concrete mixtures using a high-range water reducer (Manmohan and Mehta 2002)

	Mixture No. 4	Mixture No. 5
Minimum strength, psi (MPa)		
28 days	4660 (32)	5610 (39)
56 days	5610 (39)	5860 (40)
Minimum slump, in. (mm)	4 (100)	5 (130)
Portland cement, Type I/II, lb/yd ³ (kg/m ³)	270 (160)	329 (195)
Fly ash, Class F, lb/yd ³ (kg/m ³)	329 (195)	329 (195)
Water, lb/yd ³ (kg/m ³)	200 (118)	200 (118)
w/cm	0.33	0.30
Coarse aggregate, lb/yd ³ (kg/m ³)	1920 (1139)	1842 (1092)
Fine aggregate, lb/yd ³ (kg/m ³)	1431 (894)	1448 (859)
Water-reducing admixture		
Type A, oz/yd ³ (mL/m ³)	18 (410)	20 (447)
Type F, oz/yd ³ (mL/m ³)	18 to 30 (410 to 680)	26 to 39 (595 to 895)

reducing admixtures are required. Setting times and early-age strengths for these mixtures are equivalent to conventional portland-cement concrete. **Malhotra and Mehta (2012)** provide additional examples of mixture designs.

Laboratory trial batches and field tests are essential because local materials must be tested. In particular, large volumes of local fly ash need to be used in the mixtures to determine strength and workability characteristics. For trial mixture designs, a starting point is using low water content in the range of 200 to 240 lb/yd³ (120 to 145 kg/m³). The lower end applies to mixtures with high-range water-reducing admixtures, and the higher end to mixtures without high-range water-reducing admixtures. Total cementitious materials content ranges from 500 to 675 lb/yd³ (300 to 400 kg/m³). It is desirable for mixtures without high-range water-reducing admixtures that the *w/cm* not exceed 0.45 but, under some circumstances or due to local materials, the *w/cm* may need to be as high as 0.50. ACI 318 limits the *w/cm* of concretes under special exposure conditions (for example, to freezing and thawing conditions, sulfate exposure, and chloride exposure) to values less than 0.50. For mixtures with high-range water-reducing admixtures where early age strengths are desired, a *w/cm* of less than 0.30 is used. Setting times can be adjusted by the use of accelerating admixtures. Chemical compatibility between high-range water-reducing admixtures and other admixtures should be verified to reduce the possibility of undesirable interactions, and use of a single admixture supplier is recommended.

HVFA concrete is susceptible to damage by freezing and thawing like any other concrete. Therefore, to protect concrete from damage by cycles of freezing and thawing, the use of an air-entraining admixture is necessary. Some fly ashes can interact with air-entraining admixtures because of the high amount and nature of the carbon content in the

fly ash, which results in higher dosages of admixture being required. It is important to use fly ash and air-entraining admixtures from consistent sources as it facilitates adjusting the admixture dosage. In general, each additional percentage of air content results in a loss of compressive strength of 4 to 6 percent (Malhotra and Mehta 2012).

3.2—Slump and workability

Substitution of portland cement by fly ash reduces water demand in a concrete mixture. Class F fly ash reduces water demand approximately 4 percent for each additional 10 percent replacement of portland cement by mass (Malhotra and Mehta 2012). A dense, homogeneous microstructure results from the hydration of fine particle fractions of portland cement and fly ash, whereas the coarser particles of fly ash and portland cement may remain unhydrated and may function as microaggregate (**Idorn and Thaulow 1985**).

Manmohan and Mehta (2002) used moderate dosages of mid-range water reducers for their HVFA concrete mixtures at the Barker Hall project in Berkeley, CA, and stated the workability was better than conventional concrete at equivalent slumps. **Bilodeau et al. (2001)** wrote about their experience with HVFA concrete at the Liu Centre in Vancouver, British Columbia, Canada. They found that normal dosages of conventional water-reducing admixtures achieved sufficient workability.

Slump loss is possible with naphthalene- or melamine-based high-range water-reducing admixtures, but new high-range water reducers, based on polycarboxylate, impart longer slump retention to concrete (Malhotra and Mehta 2012).

3.3—Setting time

Typically, the initial set time of HVFA concrete is extended 2 to 3 hours compared with conventional portland-cement concrete (Malhotra and Mehta 2012). Setting times are a crucial issue for construction schedules. Development of mixture designs that employ high-range water-reducing admixtures for mixtures where 50 to 60 percent of portland cement is replaced by Class F fly ash by mass have exhibited promising results in terms of ensuring normal setting times. Also, chemical accelerators can be used to offset delayed setting times. Section 6.4 continues the discussion of strength development of the HVFA concrete and construction schedules. The effects of the use of large amounts of Class C fly ash with portland cement (without the use of high-range water reducers) on time-of-set in concrete is reported by **Naik and Ramme (1990)**.

3.4—Heat of hydration

In general, portland cement produces approximately twice as much heat of hydration as Class F fly ash (**Davis et al. 1937; Mehta and Monteiro 2006**). Hence, HVFA concrete with 50 percent fly ash replacement by mass shows approximately 75 percent of the adiabatic temperature rise when compared with portland-cement concrete. This is significant; portland-cement concrete containing a high portland cement content (675 lb/yd³ [400 kg/m³] or above) can reach peak temperatures exceeding 158°F (70°C). This is potentially