THE EFFECT OF FLY ASH ON TEMPERATURE AND RISE HYDRATION IN PORTLAND CEMENT CONCRETE

by

Hope R. Villanueva
Ramon L. Carrasquillo

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Durability and Performance of Concrete Containing Fly Ash

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PREFACE

This report is one of a series of reports summarizing the durability and performance of concrete containing fly ash. Earlier reports addressed the sulfate resistance of concrete containing fly ash and the temperature rise in cement mortar containing fly ash. This report summarizes the effect of the partial replacement of cement with fly ash on the temperature rise and hydration in concrete. Additional reports in this series will address the topics of freeze-thaw durability and creep and shrinkage at early ages.

This is part of Research Project 3-59-87-481, entitled, "Durability and Performance of Concrete Containing Fly Ash." The study described in this report was jointly conducted by the Center for Transportation Research, Bureau of Engineering Research and the Phil M. Ferguson structural Engineering Laboratory at the University of Texas at Austin. The work was co-sponsored by the Texas State Department of Highways and Public Transportation and The Federal Highway Administration.

The overall study was directed and supervised by Dr. Ramon L. Carrasquillo.

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SUMMARY

greatest problems affecting the concrete industry in Texas is the perfor- xposed to high temperatures. Hot weather and the hydration of cement r concrete temperature rise than if the same concrete were placed at lower temperatures. High concrete temperatures may result in problems in both the fresh and hardened concrete.

The temperature rise in concrete in the field can be lowered through the use of mineral admixtures such as fly ash. This report is the second in a comprehensive study on the effect of fly ash produced in Texas as a Portland cement replacement in reducing the temperature of concrete.

This report presents the results from a research program which consisted of two experimental phases. In the first phase, the internal temperature rise and resulting temperature gradients of full-scale ready mix concrete specimens containing TSDHPT Type A and Type B fly ashes with various curing conditions were monitored. Both 5-sack and 7.5-sack mixes were investigated, as well as fly as replacements by volume of 20 or 25 percent and 30 or 35 percent.

The second experimental phase involved the monitoring of the rate of heat evolution of cement/fly ash pastes subjected to different isothermal temperatures. TSDHPT Type A and B fly ashes were used as partial cement replacement for Type I, Type I-II, and Type III cements in the same replacement levels as used in the ready mix concrete tests. Isothermal temperatures investigated were 40, 60, 80, and 100 degrees F.

The results of this study show that regardless of fly ash type, replacement level, or specimen size, the use of fly ash will result in lower maximum temperature rise in concrete. While the cement content affects the temperature rise of any concrete specimen, the curing method used and the ambient temperature have significant effects only on thinner sections which lose heat easily to the environment. The project engineer is provided with guidelines to produce more durable concrete structures by reducing the internal concrete temperature, thus reducing the potential for thermal cracking.

IMPLEMENTATION

The information in this report constitutes the second step in the development of the information needed to aid resident engineers in the proper selection and use of fly ash to reduce the temperature rise in concrete due to hydration.

The results from this study provide recommendations in the selection of fly ash as a partial replacement for cement, as well as cement content and curing condition, to reduce the potential for thermal cracking in concrete.

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CHAPTER 1
INTRODUCTION

1.1 General

Fly ash has been used in modern day concrete for over 50 years. A comprehensive study of fly ash as a pozzolan in concrete by R. E. Davis et. al. in 1937 was followed by additional research and a subsequent increase in the use of fly ash in concrete [1].

Various fly ash concrete projects have demonstrated the many benefits of the use of fly ash in concrete. These benefits include increased ultimate strength, improved workability, improved durability, lower internal temperature rise, and reduction in cost. Additionally, the use of fly ash is a cost effective alternative to the disposal of a waste by-product.

Fly ash is an inherent component in both mass and high strength concrete. Successful fly ash concrete projects include Hungry Horse Dam, the first major project to use fly ash as a pozzolan, and Water Tower Place in Chicago, the world's tallest reinforced concrete building.

1.2 Justification for Research

One of the greatest problems affecting the concrete industry in Texas is the performance of concrete exposed to high temperatures due to atmospheric conditions. This is referred to as hot weather concreting. Hot weather concreting will result in a higher concrete temperature rise than if the same mixture were placed at a lower temperature, as shown in Figure 1.1. The resulting high concrete temperatures may create problems in both the fresh and the hardened concrete.

Problems which may be seen in fresh concrete include slump loss, additional water required to maintain workability, reduced setting time, and an increased tendency for plastic shrinkage cracking. Plastic shrinkage cracking occurs when the rate of evaporation exceeds the rate at which bleed water rises to the concrete surface.

In hardened concrete, the problems which may arise due to hot weather concreting include decreased ultimate strength, reduced durability, an increased tendency for drying shrinkage, and a greater potential for thermal cracking resulting from temperature gradients. Consequences of thermal cracking may include chemical attack of concrete and/or reinforcing steel, freeze-thaw damage, loss of structural integrity, and increased permeability, as well as an undesirable surface appearance.

Because of the detrimental effects of hot weather concreting and the resulting high concrete temperatures, efforts should be made to keep the concrete temperature as low as possible. Concrete temperature may be lowered by several methods, including

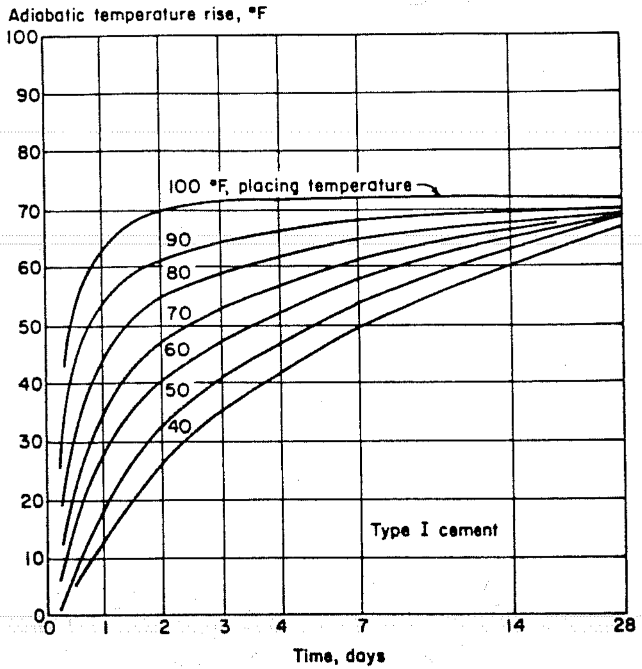


Figure 1.1 The effect of concrete placing temperature on temperature rise in mass concrete (376 lb. cement per cubic yd.) [2].

*precooling of materials and mixing equipment,

*removal of heat through embedded cooling pipes, and

*limiting temperature rise potential of concrete.

The temperature rise potential of concrete may be suppressed through control of the type and the amount of cementitious material. The use of a pozzolan as a partial replacement for portland cement will result in reduced heat generation due to the lower heat of hydration of pozzolans compared to cement.

Fly ash is one such pozzolan which has been used extensively in the concrete in dams because of its lower heat of hydration. It is estimated that the heat of hydration of fly ash may be approximately 25 percent to 50 percent that of cement, an estimate which is dependent upon the particular fly ash used [2]. Most of the fly ash used in dam construction would fall under what the Texas State Department of Highways and Public Transportation (TSDHPT) classifies as Type A (ASTM Class F). Much of the fly ash produced in Texas falls under what TSDHPT classifies as Type B (ASTM Class C). Currently there is little available data on the effect of Texas fly ash on the temperature rise in concrete. Before fly ash is used in concrete for controlling the temperature rise, the effect of variables such as type of cement, mix proportions, physical and chemical properties of the fly ash, and the ambient temperature must be studied and fully understood.

1.3 Research Objectives

This report is the second in a comprehensive study on the effect of fly ash when used as a portland cement replacement in reducing the temperature rise of concrete. The evaluation of fly ash as a partial cement replacement is to be made on the basis of tests conducted to determine the internal temperature rise and resulting temperature gradients, strength, and workability of ready-mix concrete. Also in this study, the effects of fly ash and ambient temperature on the hydration of portland cement were studied through the use of isothermal calorimetry. Guidelines have been developed in this study for the proper selection and use of fly ash for controlling the temperature of fresh concrete to ensure better and more durable concrete.

1.4 Report Format

This report consists of nine chapters. The second chapter provides a brief overview of the chemistry of hydration of cement and discusses variables which may affect cement hydration. Chapter 3 discusses the effects of high concrete temperatures on Portland cement concrete. In Chapter 4 a literature review of the temperature rise, strength, workability, and hydration of concrete containing fly ash is presented. Chapter 5 details the experimental methods and equipment used in this study. Chapters 6, 7, and 8 contain a presentation and discussion of the test results. Summary, conclusions and recommendations for future research are found in Chapter 9.

CHAPTER 2
THE HYDRATION OF PORTLAND CEMENT

2.1 Introduction

Cement may be defined as a finely powdered mixture of inorganic compounds, which, when mixed with water, undergoes a chemical reaction and hardens [3]. The composition of portland cement may be found in Table 2.1. When combined with water, fine aggregate and coarse aggregate, portland cement forms concrete.

Table 2.1 Average Composition of Portland Cement

Oxide	Possible range, percent
Lime (CaO)	60-67
Silica (SiO_2)	17-25
Alumina (Al_2O_3)	3-8
Iron Oxide (Fe_2O_3)	0.5-6
Magnesia (MgO)	0.1-4
Sulphur Trioxide (SO_3)	1-3
Soda and/or Potash ($Na_2O + K_2O$)	0.5-1.3

Cement manufacture involves the burning of a select blend of crushed rock in a kiln to form cement clinker. The crushed rock is a blend of limestones, clays, sands, iron compounds, etc., selected to yield a mixture with the desired chemical composition. After the clinker cools, it is interground with a small amount of gypsum ($CaSO_4 \bullet 2H_2O$), to produce a fine powder. This fine powder is what is known as portland cement.

Portland cement consists of 4 principal compounds. These compounds, their chemical formulas, and abbreviations may be found in Table 2.2. The abbreviations contain notations commonly used among cement chemists, including: CaO=C; SiO_2=$\overline{S}$; Al_2O_4=A; Fe_2O_3=F; SO_3=S; and H_2O=H.

These compounds may be present in varying amounts, thus yielding cements with slightly different properties. Table 2.3 shows typical compound compositions of cements meeting ASTM standards for Type I, II, III, IV, and V cement, respectively.

Table 2.2 Principal Cement Compounds

Compound	Chemical Formula	Abbreviation
Tricalcium Silicate	$3CaO \bullet SiO_2$	C_3S
Dicalcium Silicate	$2CaO \bullet SiO_2$	C_2S
Tricalcium Aluminate	$3CaO \bullet Al_2O_3$	C_3A
Tetracalcium Aluminoferrite	$4CaO \bullet Al_2O_3 \bullet Fe_2O_3$	C_4AF

Table 2.3 Typical Compound Compositions of Portland Cements [38]

Percent by Weight*

Cement Type	ASTM Designation**	C_3S	C_2S	C_3A	C_4AF
Ordinary	I	55	20	12	9
Moderate Heat of Hydration, Moderate Sulfate Resistance	II	45	30	7	12
Rapid Hardening	III	65	10	12	8
Low Heat of Hydration	IV	25	50	5	13
Sulfate Resistant	V	40	35	3	14

* Missing percentages consist of gypsum, and minor components such as MgO, alkali sulfate, etc.

** Designation used in ASTM C150 to identify each type

The hydration of each of these compounds will be discussed in this chapter. Hydration of each compound will be studied individually, although the interactions between compounds may have consequences as well.

Following the study of the hydration of the individual cement compounds will be a discussion of the portland cement hydration process. The kinetics of the process, compound interactions, setting and hardening, and the heat of hydration will all be discussed.

Finally, several factors which may affect the hydration of portland cement will be studied. These factors include temperature, fineness, and water to cement ratio.

2.2 Chemistry of the Hydration of Pure Cement Compounds

2.2.1 Hydration of Calcium Silicates. The most abundant compound in portland cement is tricalcium silicate. Tricalcium silicate makes up 40 to 70 percent by weight of cement. In addition, tricalcium silicate is responsible for controlling the normal setting behavior and early strength gain of portland cement paste, mortar, and concrete.

The hydration reaction of tricalcium silicate may be symbolized as follows:

$$\underset{\substack{\text{TRICALCIUM}\\ \text{SILICATE}}}{2\ C_3S} \quad \underset{\text{WATER}}{+\ 7\ H} \;\rightarrow\; \underset{\substack{\text{CALCIUM}\\ \text{SILICATE}\\ \text{HYDRATE}}}{C_3S_2H_4} \quad \underset{\substack{\text{CALCIUM}\\ \text{HYDROXIDE}}}{+\ 3\ CH} \qquad (2.1)$$

The main product of the reaction, a calcium silicate hydrate, does not maintain the constant composition $C_3S_2H_4$, and is more commonly designated simply as C-S-H. C-S-H is a poorly crystalline material which forms very small (less than $1\mu m$) sized particles [4]. These particles are the primary strength producing compounds in hardened cement paste.

A calorimetric curve offers a convenient method for studying cement reactions. A calorimetric curve shows the rate of heat evolution of a reaction with time. Since the heat flow from a reaction is proportional to the rate of the reaction, a calorimetric curve is easily obtainable. The calorimetric curve for tricalcium silicate may be seen in Figure 2.1. The curve may be broken into five stages, commonly referred to as the initial reaction (or preinduction) stage, the dormant period, the acceleration period, the deceleration period, and the steady state.

Upon first mixing with water, there is a rapid evolution of heat (Stage 1 in Figure 2.1). Calcium and hydroxide ions are given off by the surfaces of the C_3S grains, and the pH of the solution rises to over 12. This first stage lasts around 15 minutes. At this point, the reaction slows (Stage 2). The C_3S remains in a dormant state for 2 to 4 hours. The amount of hydration which has occurred is only a few percent of the final hydration [5].

Once the calcium and hydroxide concentrations reach a critical value, the reaction once again takes off. Initial set usually occurs at the time the C_3S has begun to react again.

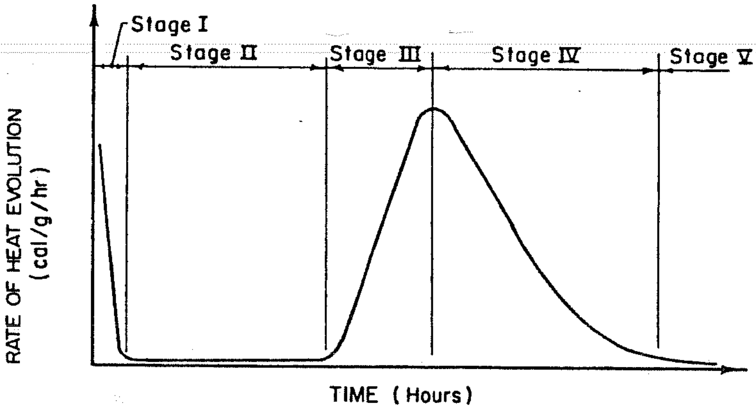


Figure 2.1 Typical calorimetric curve for the hydration of C_3S [4].

The tricalcium silicate will undergo its most rapid hydration during the acceleration and deceleration stages (Stages 3 and 4). The time at which the acceleration stage ends and the deceleration stage begins is arbitrary; the actual change is from a reaction which is controlled by the rate of calcium hydroxide growth to one which is diffusion controlled. As the calcium hydroxide crystallizes in solution during Stage 3, C-S-H develops at the surface of the tricalcium silicate particles and creates a barrier through which water and ions must flow in order to continue hydration. As this diffusion barrier continues to grow, the rate of the reaction slows, and the hydration tends to approach 100 percent completion (Stage 5) [4].

The hydration of dicalcium silicate is similar to that of tricalcium silicate, but the reaction occurs much more slowly due to its lower reactivity. The heat of evolution of C_2S is also less than that of C_3S. A calorimetric curve for C_2S would be expected to be similar to that shown in Figure 2.1 except that the curve for C_2S would exhibit a much smaller second peak [5]. The reaction between C_2S and water may be described symbolically as follows:

$$\begin{array}{cccc} 2\ C_2S & +\ 5H\ \rightarrow & C_3S_2H_4 & +\ CH \\ \text{DICALCIUM} & \text{WATER} & \text{CALCIUM} & \text{CALCIUM} \\ \text{SILICATE} & & \text{SILICATE} & \text{HYDROXIDE} \\ & & \text{HYDRATE} & \end{array} \tag{2.2}$$

2.2.2 Hydration of Tricalcium Aluminate. Tricalcium aluminate is the mineral compound in cement which is the most reactive towards water [5]. Tricalcium aluminate plays an important role in the early hydration of portland cement by accelerating the hydration of C_2S. Additionally, the use of alumina compounds allows the clinkering process to take place at lower temperatures [3].

When there is a generous supply of gypsum present, the initial reaction of C_3A and water yields the hydration product ettringite ($C_6A\overline{S}_3H_{32}$):

$$\begin{array}{cccc} C_3A & +\ 3C\overline{S}\ H_2 & +\ 26\ H & \longrightarrow C_6A\overline{S}\ _3H_{32} \\ \text{TRICALCIUM} & \text{GYPSUM} & \text{WATER} & \text{ETTRINGITE} \\ \text{ALUMINATE} & & & \end{array} \tag{2.3}$$

Ettringite remains a stable hydration product as long as there is a sufficient level of sulfate ions in solution. If ample sulfates are not available, the ettringite becomes unstable and may convert to monosulfoaluminate ($C_4A\overline{S}H_{12}$):

$$\begin{array}{cccc} 2\ C_3A & +\ C_6A\overline{S}\ _3H_{32} & +\ 4\ H & \longrightarrow 3\ C_4A\overline{S}\ H_{12} \\ \text{TRICALCIUM} & \text{ETTRINGITE} & \text{WATER} & \text{MONOSULFO-} \\ \text{ALUMINATE} & & & \text{ALUMINATE} \end{array} \tag{2.4}$$

The formations of both ettringite and monosulfoaluminate are exothermic reactions.

Similar to the diffusion barrier created by C-S-H during the hydration of C_3S, the hydration of C_3A is also slowed by the creation of a diffusion barrier. In the case of C_3A, ettringite forms a coating around the C_3A particles, slowing the diffusion of sulfate, hydroxide, and calcium ions and thus causing an induction period. This diffusion barrier is broken down during the conversion of ettringite to monosulfoaluminate. Once the system becomes deficient in sulfate ions, the ettringite transforms to monosulfoaluminate, and the

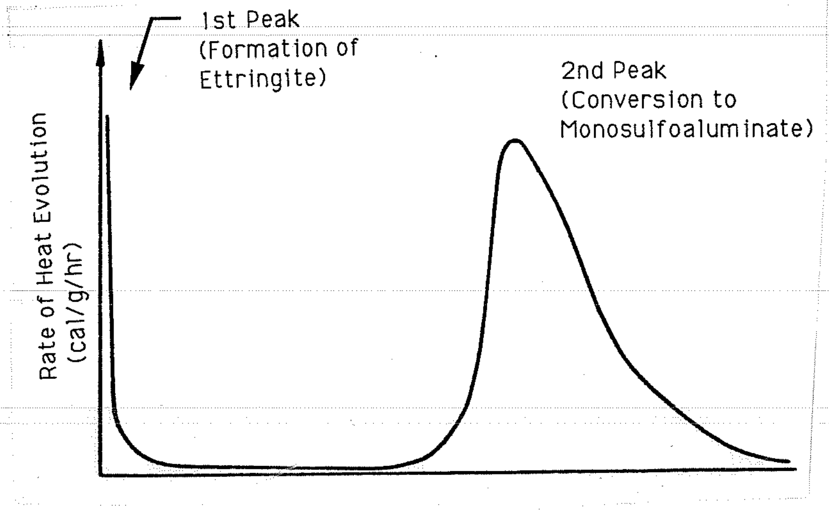


Figure 2.2 Typical calorimetric curve for the hydration of C_3A [3].

hydration of C_3A is allowed to continue at a rapid rate [3]. The more gypsum in the system, the more ettringite formed, and thus the longer the induction period.

Figure 2.2 shows the calorimetric curve for the hydration of C_3A. The curve is qualitatively very similar to the curve for the hydration of C_3S; the difference lies in the actual reactions involved and the amount of heat generated. The heat generated by the hydration of C_3A is much greater than in the hydration of C_3S. The first peak in Figure 2.2 is due to the formation of ettringite and lasts for only 10 to 15 minutes. The second peak occurs during the conversion of ettringite to monosulfoaluminate; the time at which this peak occurs is dependent upon the amount of sulfate (usually supplied by gypsum) there is available. The conversion normally occurs 12 to 36 hours after the initial reaction with water.

When only small amounts of gypsum are present in solution there may be some unreacted C_3A; this C_3A reacts to form a solid solution with a composition somewhere between $C_4A\overline{S}H_{12}$ and C_4AH_{13}.

$$\underset{\substack{\text{MONOSULFO-}\\\text{ALUMINATE}}}{C_4A\overline{S}\,H_{12}} \; + \underset{\substack{\text{TRICALCIUM}\\\text{ALUMINATE}}}{C_3A} \; + \underset{\substack{\text{CALCIUM}\\\text{HYDROXIDE}}}{CH} \; + \underset{\text{WATER}}{12\,H} \longrightarrow 2\,(C_4A(\overline{S},\,H)H_{12}) \tag{2.5}$$

When there is no gypsum present in solution, there may be an extremely fast initial reaction of C_3A and water to form calcium aluminate hydrates. This can lead to a flash set and the liberation of a great deal of heat.

$$\begin{array}{cccc} C_3A & +\ 21\ H & \longrightarrow\ C_4AH_{13} & +\ C_2AH_8 \\ \text{TRICALCIUM} & \text{WATER} & \text{CALCIUM} & \\ \text{ALUMINATE} & & \text{ALUMINATE} & \\ & & \text{HYDRATES} & \end{array} \tag{2.6}$$

The resulting compounds, C_4AH_{13} and C_2AH_8, are unstable and will convert to C_3AH_6, known as hydrogarnet.

$$\begin{array}{cccc} C_4AH_{13} & +\ C_2AH_8 & \longrightarrow\ 2C_3AH_6 & +\ 9\ H \\ & \text{CALCIUM} & \text{HYDROGARNET} & \text{WATER} \\ & \text{ALUMINATE} & & \\ & \text{HYDRATES} & & \end{array} \tag{2.7}$$

2.2.3 Hydration of Ferrites. The hydration of C_4AF is very similar to the hydration of C_3A, except the rate of hydration is much slower. The hydration reaction of C_4AF may be seen in equations 2.8 and 2.9.

$$\begin{array}{ccccc} 3\ C_4AF & +\ 12\ C\overline{S}\ H_2 & +\ 110\ H & \longrightarrow\ 4\ (C_6(A,F)\overline{S}\ _3H_{32}) & +\ 2(A,F)H_3 \\ \text{TETRACALCIUM} & \text{GYPSUM} & \text{WATER} & & \\ \text{ALUMINOFERRITE} & & & & \end{array} \tag{2.8}$$

$$\begin{array}{ccccc} 3\ C_4AF & +\ 2\ (C_6(A,F)\overline{S}\ _3H_{32}) & +\ 14\ H & \longrightarrow\ 6\ (C_4(A,F)\overline{S}\ H_{12}) & +\ 2(A,F)H_3 \\ \text{TETRACALCIUM} & & \text{WATER} & & \\ \text{ALUMINOFERRITE} & & & & \end{array} \tag{2.9}$$

C_4AF is much more sensitive to the addition of gypsum to the solution than is C_3A. In the presence of $Ca(OH)_2$ (lime), the hydration of C_4AF is nearly nonexistent. A

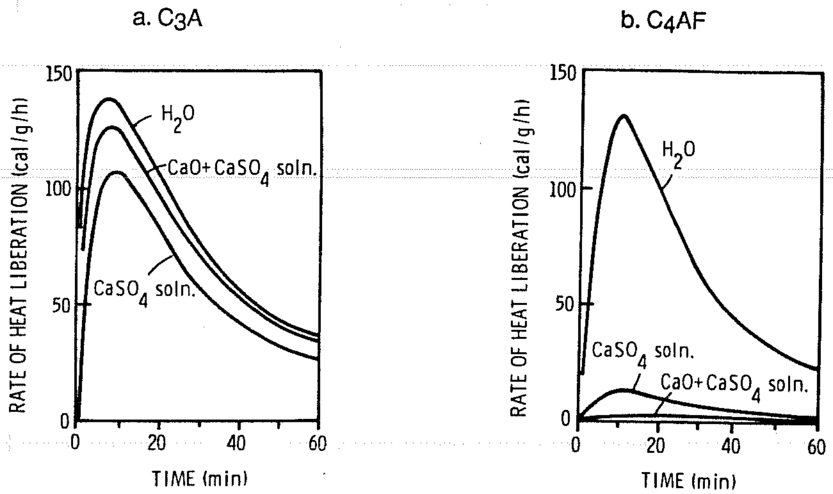


Figure 2.3 Calorimetric curves for (a) C_3A and (b) C_4AF hydrated in water, and in saturated solutions of gypsum and gypsum and lime [5].

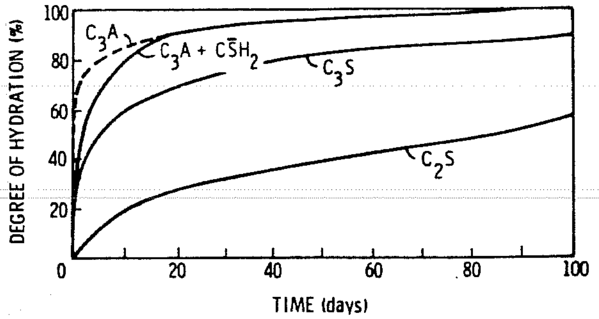
comparison of the effects of gypsum and lime on C_3A and C_4AF initial hydration may be seen in Figure 2.3.

2.3 Portland Cement Hydration Process

2.3.1 Kinetics of the Hydration of Portland Cement. A comparison of the rate of hydration of each of the pure cement compounds during the first few days of hydration finds the greatest rate for C_3A followed by C_3S, C_4AF, and C_2S, in that order. This is illustrated in Figure 2.4. The exact rate of hydration of each compound varies due to crystal size differences and imperfections. Imperfections may result from due varying cooling rates, grinding methods used, and finenesses of cements [5].

The reactivity of each compound is different when found in cement. The difference is mainly due to the presence of impurities. For example, the impure forms of C_3S and C_2S, which are known as alite and belite, respectively, hydrate faster than their pure counterparts. The reactivity of the individual compounds are also influenced to some extent by the fact that other compounds are undergoing hydration at the same time [4].

a. pastes of pure compounds



b. pastes of compounds as found in cement

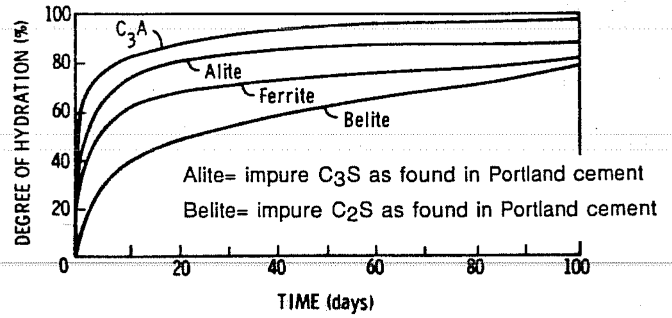


Figure 2.4 Rate of hydration of the principal cement compounds in (a) pastes of pure compounds; (b) cement paste [5].

2.3.2 Compound Interactions. Earlier in this chapter the hydration of each of the cement compounds was studied individually. During the hydration of actual portland cement, the behavior of each compound is affected somewhat by the other compounds. One example of this may be found by looking at the hydration of C_2S. C_2S will hydrate faster in the presence of C_3S due to the changes in concentration of Ca^{+2} and OH^-. Another example of compound interaction involves C_3A and C_4AF. Both compounds will compete for available sulfate ions, with the more reactive C_3A consuming more. The reactivity of C_4AF will thus be increased, since it will form less ettringite than would be expected.

Figure 2.5 depicts a typical calorimetric curve for portland cement. The contributions of C_3S and C_3A may both be distinguished in the curve. It should be noted that

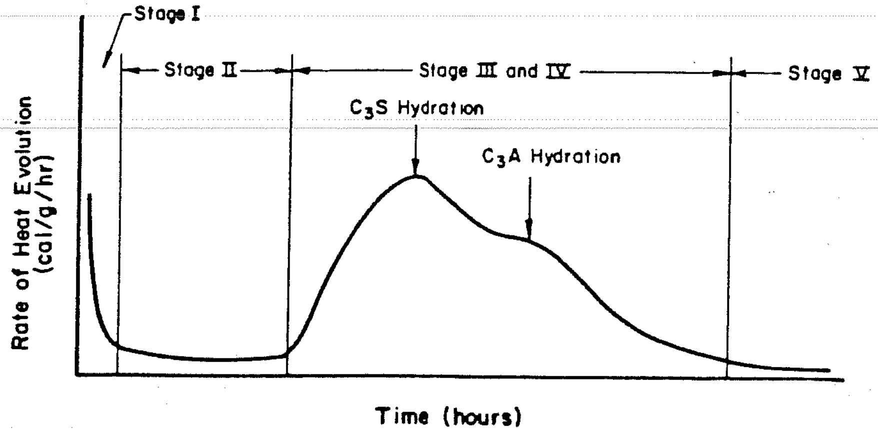


Figure 2.5 Typical calorimetric curve for the hydration of portland cement [3].

the order of occurrence of the peaks may be reversed, and the C_3A peak may be so small as to be indiscernible [6].

2.3.3 Setting and Hardening of Portland Cement. The time of initial set of cement paste corresponds closely to the finish of the induction period in Figure 2.5 [3]. This behavior suggests that setting is controlled by the rate of hydration of C_3S, but it is also theorized that setting relies on the recrystallization of ettringite.

The rate of strength gain is roughly proportional to the area under the curve in Figure 2.5. The final set of cement paste corresponds to the point between the acceleration and deceleration phases of C_3S, which was described earlier as signifying a change from a reaction controlled by calcium hydroxide growth to one which is diffusion controlled. The rate of early hardening of cement paste is dependent upon the degree of hydration of the calcium silicates, especially C_3S. Contributions to strength from the aluminates and ferrites is minimal.

2.3.4 Heat of Hydration. The heat of hydration (or enthalpy) of cement refers to the heat generated during the reaction of cement and water. The quantity, Δ H, represents the residual energy remaining in the system after the redistribution of energy due to the breaking and making of chemical bonds [5]. The heat of hydration may be determined by calculation or may be measured experimentally. Calculations are difficult to perform since it is not easy to determine the extent of hydration, or ΔH, for each reaction.

The compounds in cement which are primarily responsible for heat generation are C_3A and C_3S, as may be seen in Table 2.4. Other factors which may influence the heat of hydration are the water to cement ratio, fineness, and ambient temperature. Generally, an increase in any of these factors leads to an increase in the heat of hydration [3].

Table 2.4 Heats of Hydration of the Cement Compounds In Units of Δ H (Joules/g) for Complete Hydration [3]

Reaction	Pure Compound Calculated	Pure Compound Measured	Clinker* Measured	Cement* Measured
$C_3S \rightarrow$ C-S-H + CH	380	500	570	490
$C_2S \rightarrow$ C-S-H + CH	170	250	260	225
$C_3A \rightarrow C_4AH_{13} + C_2AH_8$	1260	–	–	–
$C_3A \rightarrow C_3AH_6$	900	880	840	–
$C_3A \rightarrow$ monofulfoaluminate	–	–	–	1200
$C_4AF \rightarrow C_3(A,F)H_6$	520	420	335	–
$C_4AF \rightarrow$ monosulfoaluminate	–	–	–	400

* These numbers were determined from regression analyses of the heats of hydration of ground clinker (no added gypsum), or cement.

2.4 Factors Affecting the Hydration of Portland Cement

2.4.1 Temperature. The temperature at which hydration occurs is one of the most important physical variables affecting cement hydration. It is well known that higher temperatures accelerate the early hydration of portland cement [2,7]. This increased hydration at early ages is reversed at later ages, resulting in lower ultimate strength for cements hydrated at higher temperatures.

An explanation for this behavior is given by Verbeck [8]. The more rapid initial reaction which occurs ar high temperatures creates a dense hydration product around the hydrating product. At later ages, this coating retards subsequent hydration and strength gain. Additionally, the rapid early hydration creates nonuniformly distributed products in the paste microstructure, which will later prevent the development of full strength potential.

The hydration of cement is most sensitive to temperature through the acceleration stage, when the reaction is chemically controlled. Once the reaction reaches the deceleration stage, it becomes diffusion controlled, and is much less temperature sensitive [3,4]. This effect may be seen in Figure 2.6, which shows the effects of temperature on the hydration of C_3S.

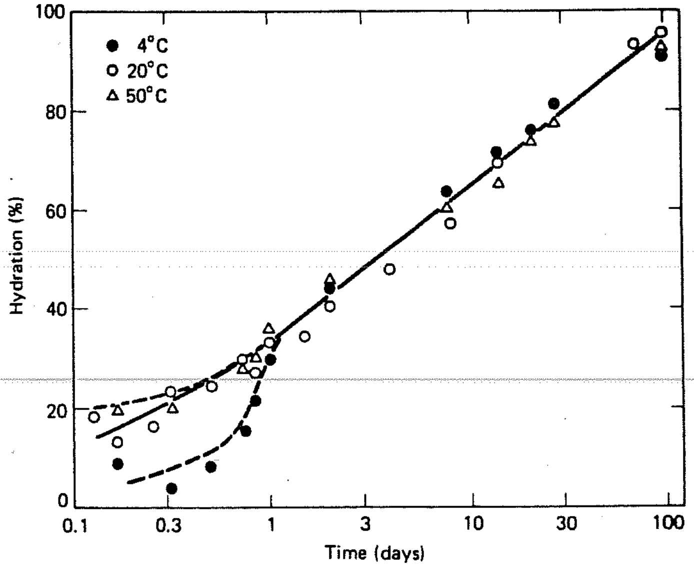


Figure 2.6 The effect of temperature on the early hydration of tricalcium silicate [4].

2.4.2 Fineness. Cement fineness also plays an important role in the hydration of portland cement. The rate of hydration increases with increasing fineness, due to the greater amount of surface area available for reaction with water. The hydration reaction occurs at the cement particle surface; once reaction products are formed, further hydration is hindered, so finer particles have a better chance for more complete hydration. This increased rate of hydration results in both a higher rate of strength gain and a higher heat of hydration [9].

2.4.3 Water to Cement Ratio. The water to cement ratio (w/c) is another factor which affects the hydration of cement. Higher w/c ratios give more space for the dissolving and transporting of calcium and sulfate to the surfaces of aluminates and ferrites. Research by Bensted has found that as the w/c ratio is raised from 0.3 to 0.5, increased quantities of ettringite are formed, while no C-S-H is detected [10]. These results are shown in Figure 2.7.

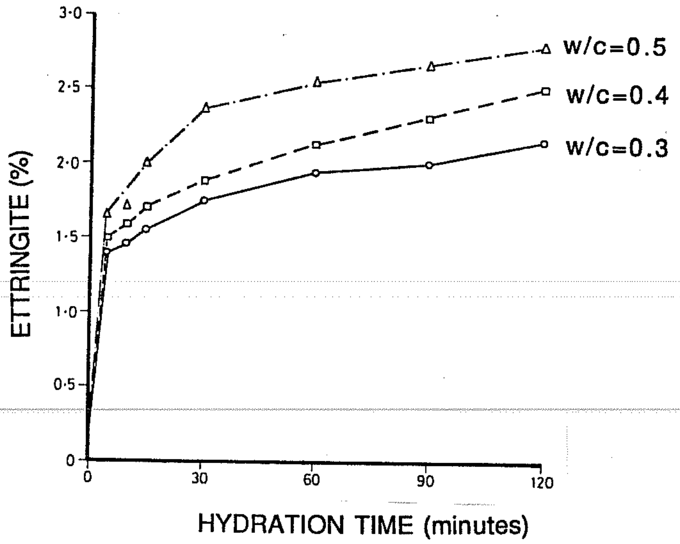


Figure 2.7 The effect of water to cement ratio on the production of ettringite [10].

The formation of ettringite is an exothermic reaction. Therefore, it would be expected that higher w/c ratios would have higher rates of heat evolution due to the increased formation of ettringite at early ages.

This chapter has discussed the hydration of portland cement. Cement is composed of four principle compounds, each of which has its own unique hydration mechanisms, and each of which must interact with the other compounds during the hydration of portland cement. The degree of hydration of portland cement is dependent upon many factors. One of these factors is temperature, which plays an important role in determining the rate of the hydration reaction and in the physical properties of the resulting concrete. The effect of temperature will be discussed in Chapter 3.

CHAPTER 3
EFFECTS OF HIGH CONCRETE TEMPERATURES ON PORTLAND CEMENT CONCRETE PROPERTIES

3.1 Introduction

The placing of concrete in hot weather may result in higher concrete temperatures as well as an accelerated temperature rise. High concrete temperatures may also result from high heat of cement hydration combined with low heat dissipation. This condition if often found in mass concrete. Temperature rises in the range of 75 to 100 degrees F are not uncommon.

High concrete temperatures may create problems for both the fresh and hardened concrete. In this chapter, the effects of high concrete temperatures on the properties of portland cement concrete will be discussed.

3.2 Fresh Concrete

3.2.1 Increased Water Demand. The hydration reaction of portland cement is accelerated at higher temperatures. Since the hydration reaction occurs much more quickly, the rate at which slump is lost also increases. Therefore, in order to maintain a given slump at a given time after batching, more water may be needed during hot weather than would be needed for the same batch in cold weather conditions. A recent paper by Mather stresses that there is not an increased water requirement under hot weather conditions [7]. Mather states that at the time of batching, a given amount of water will produce the same slump regardless of temperature. Only after the initial mixing does the slump become a function of temperature.

3.2.2 Workability. As discussed in the previous section on increased water demand, hot weather conditions will result in accelerated cement hydration.

Figure 3.1 shows the effect of temperature on the hydration and setting time of portland cement. As may be seen in Figure 3.1, cement hydrated at higher temperatures reaches the acceleration stage (final set) much sooner than cement hydrated at lower temperatures. The cements hydrated at higher temperatures therefore see a quicker loss of workability as they lose their plastic state sooner. One important consequence of the loss of workability is an increased potential for the need for the addition of more water to the concrete at the jobsite to restore the slump. This may have detrimental effects on the strength and other properties of the hardened concrete at later ages.

3.2.3 Setting Time. Figure 3.1 shows that cement hydrated at higher temperatures will reach initial and final set sooner. Setting times may be reduced by 2 hours

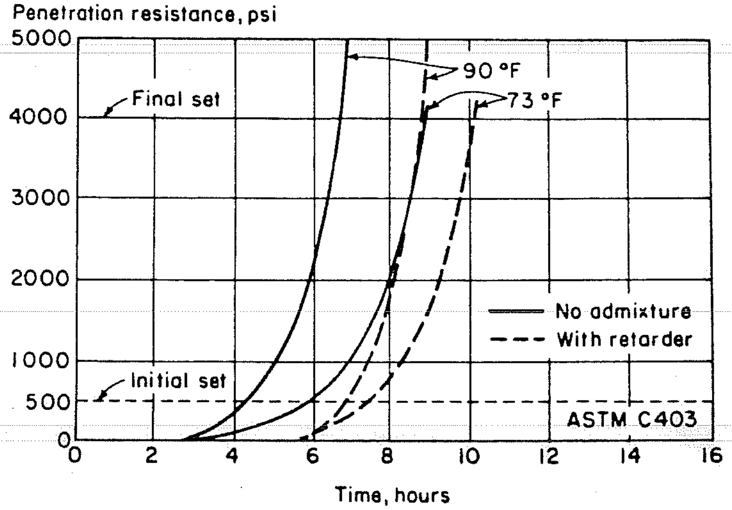


Figure 3.1 The effect of concrete temperature and the use of retarder on the setting time of portland cement [2].

or more with a 20 degree F increase in placing temperature [2]. This aspect of concrete placement may be especially important when placing the concrete in lifts or layers. Concrete needs to remain in a plastic state during subsequent pours to eliminate cold joints or discontinuities.

3.2.4 Plastic Shrinkage Cracking. Plastic shrinkage cracks occur when the rate of evaporation of water from the fresh concrete surface exceeds the rate at which bleedwater rises to the surface. Figure 3.2 shows that humidity, temperature of air and concrete, and the wind velocity all play roles in determining the rate of evaporation of surface moisture. It is apparent from Figure 3.2 that increased concrete temperatures will result in higher rates of evaporation, and therefore greater tendencies for plastic shrinkage cracking.

3.3 Hardened Concrete

3.3.1 Compressive Strength Gain. High initial concrete temperatures will result in higher early compressive strength, but decreased ultimate strength as seen in Figure 3.3 [2]. High early strength is the result of initial reactions occurring more quickly at high

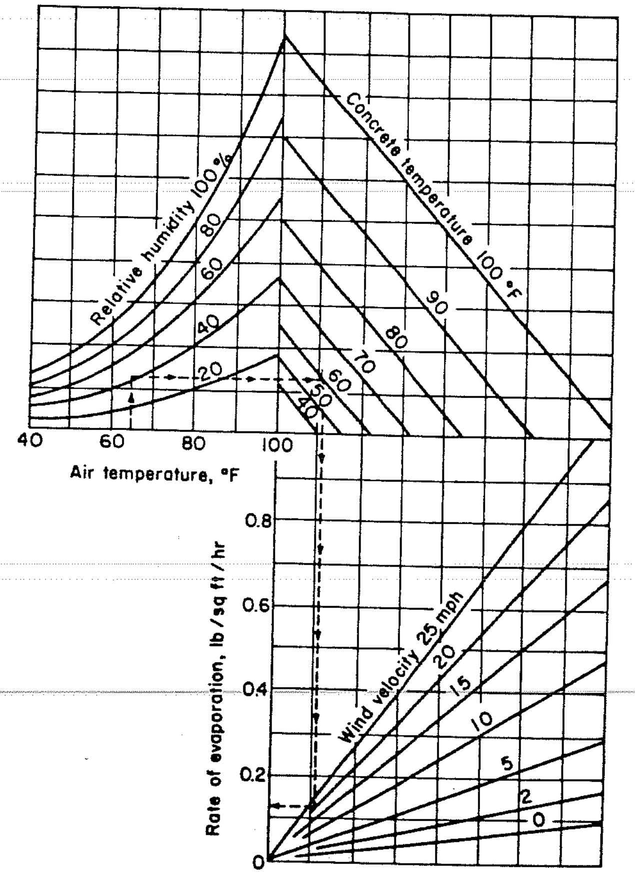


Figure 3.2 The effect of concrete and air temperature, relative humidity, and wind velocity on the rate of evaporation of surface moisture from concrete [2].

temperatures. Hydration products which develop quickly at high temperatures are not as well formed and adequately distributed as those products formed at lower temperatures. At later ages, these non-uniform products will hamper the full development of the paste microstructure and thus the full strength potential of the paste. If any additional water has been added there will be an increase in the water to cement ratio. It is well documented that higher water to cement ratios result in lower compressive strengths.

3.2.2 Drying Shrinkage. Drying shrinkage is directly related to the amount of water per unit volume of concrete [11]. Drying shrinkage increases with increasing water

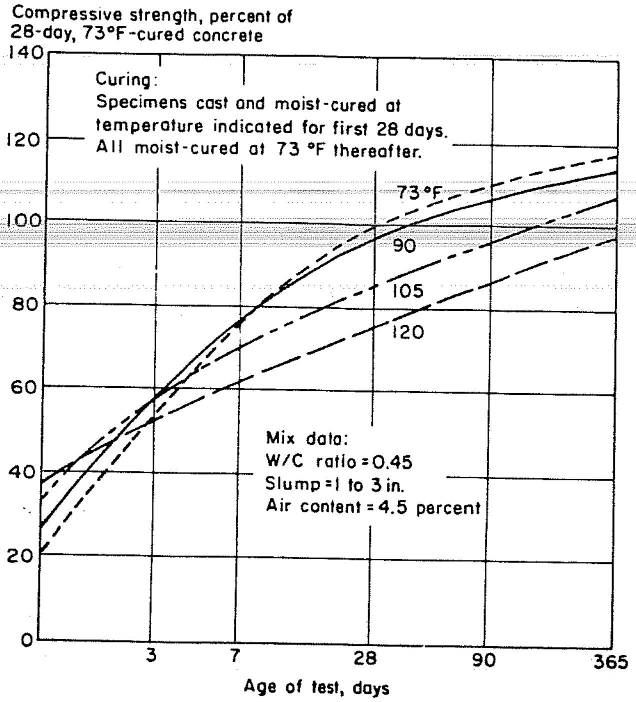


Figure 3.3 The effect of high concrete temperatures on compressive strength at various ages [2].

content. Research has found that a 1 percent increase in mixing water may increase concrete shrinkage by 2 percent [2].

Concrete placed under hot weather conditions is susceptible to increased drying shrinkage because of the increased water demand at higher temperatures. This increased demand and the accompanying rapid slump loss may lead to the addition of extra water at the jobsite, which in turn will increase the drying shrinkage tendencies of the concrete. As the concrete dries, the concrete surface dries and shrinks faster than the inner concrete, which may cause tensile stresses and cracks. These cracks will increase permeability and decrease the durability and appearance of the concrete.

3.3.3 Thermal Cracking.

`3.3.3.1 Cause of Thermal Cracking.` Possibly the greatest potential problem which may result from high concrete temperatures is thermal cracking as a result of severe temperature gradients across a concrete section. It is important to note that high concrete temperatures alone will not cause cracking in concrete. Tensile strains which cause cracking will result when a member is restrained from undergoing length and volume changes induced by temperature rise and subsequent cooling.

Restraint may be external, such as between a concrete structure and its foundation, or internal, such as when the interior temperature of a concrete member is greater than at the surface. When a member is restrained and subjected to a severe enough temperature gradient, the tensile stresses which develop may exceed the tensile strength of the concrete. If this happens, tensile cracks will result in the concrete.

Exactly what constitutes a severe temperature gradient is subject to debate. Various rule of thumb temperature limits for the difference between internal and surface concrete temperatures exist. These values range from 20 F to 60 F [2,12,13,14].

Recent work by Barrow has verified that the shape of the thermal gradient is not linear. Rather, the most severe temperature differentials occur over the first few inches of the cross section [15]. Large changes in temperature across a depth of only a few inches would present more of a threat of thermal cracking than the same temperature drop over a large section, due to the higher stresses which develop. Thus, the often assumed linear temperature gradient is unconservative.

3.3.3.2 Consequences of Thermal Cracking.

Temperature gradients, and the resulting thermal cracks which they may cause are to be avoided because they reduce the durability of the concrete, may create serviceability problems, and are aesthetically undesirable.

The durability of the concrete may be affected in many ways by thermal cracks. The cracks make the concrete more susceptible to freeze-thaw damage and chemical attack of the concrete and/or the reinforcing steel in the section, as well as increasing the permeability of the concrete. Serviceability problems due to thermal cracking may arise, including excessive deflections due to a decreased section, and loss of cover for the steel reinforcement. On an aesthetic level, all cracks are considered unsightly by the general public. Leakage from cracks may stain the concrete and ruin its appearance as well.

3.3.3.3 Concrete Sections Susceptible to Thermal Cracking.

All concrete sections may be subjected to temperature gradients. Thinner sections are able to dissipate developed heat quickly, so problems due to temperature gradients are not common. In massive concrete sections, however, where little heat dissipation occurs and near adiabatic conditions exist, internal temperatures may remain high for weeks. At the same time, surface temperatures will tend toward ambient temperature. Examples of these massive sections include dams, foundation, large retaining walls, bridge piers, and thick structural members [16].

Various parameters should be considered in order to reduce the severity of temperature gradients. One such parameter is the time of formwork removal. A condition known as thermal shock may result if formwork is removed from a still warm concrete section, exposing the surface to a sudden change in temperature and thereby steepening the thermal gradient at the surface.

Also to be considered is when the peak concrete temperature will occur. The temperature gradient in concrete may be somewhat minimized if the time of peak concrete temperature does not occur at the time of low ambient temperature for the day. This is especially important for surfaces which will be cured with the surface exposed to the environment.

One final aspect to consider is the curing technique to be used. Research conducted by Barrow has shown that exposed concrete surfaces undergo more severe temperature gradients than covered surfaces, as illustrated in Figure 3.4. This is because the covered surface is not allowed to dissipate generated heat as readily as the exposed surface.

This chapter has shown the possible problems which may arise when concrete temperatures are high. Placing and finishing of the fresh concrete may be adversely affected, and the hardened concrete faces potential decreased ultimate strength and reduced durability. Thus it is important for the engineer to take steps to limit the temperature rise of concrete, especially during hot weather conditions.

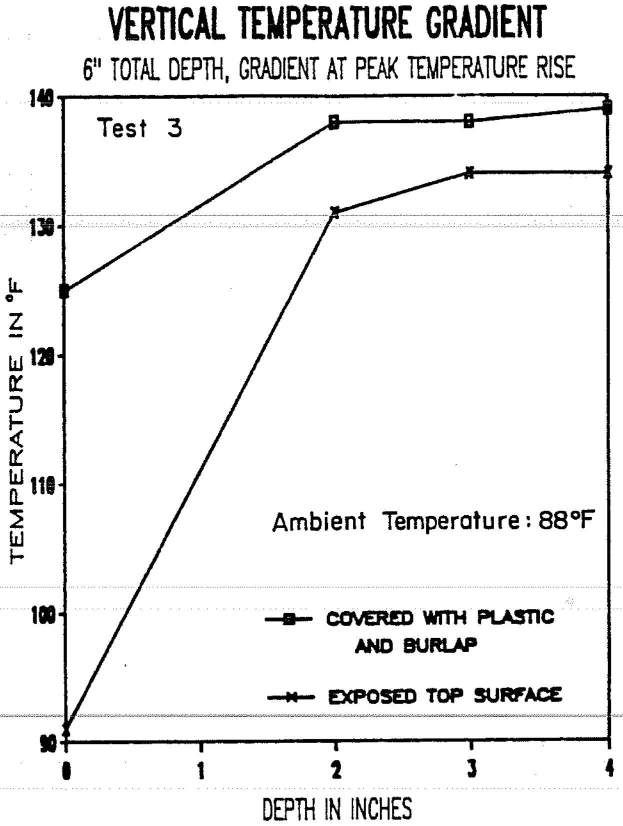


Figure 3.4 Effect of curing method on maximum temperature gradient in an 6-inch beam [15].

CHAPTER 4
THE EFFECTS OF FLY ASH USE IN CONCRETE

4.1 Introduction

In this chapter, a review of published literature is presented to provide a background of other work conducted in the areas pertaining to this study. Areas investigated include the effects of fly ash on the hydration of portland cement and the effects of fly ash on concrete properties. Additionally, definitions and explanations of fly ash and the classification of fly ashes are provided.

4.2 Definition of Fly Ash

Fly ash may be described as a finely divided powder which results from the combustion of pulverized coal in the generation of electricity. During the combustion of coal, many of its mineral impurities (including clay, quartz, and shale) fuse in suspension; upon cooling, this fused material solidifies to form the spherical particles known as fly ash. Instead of being discharged as an atmospheric pollutant, the fly ash may be carried from the combustion chamber by the exhaust gas and then collected by particulate collectors such as electrostatic precipitators, mechanical collectors, or fabric filters.

Fly ashes exhibit pozzolanic activity. A pozzolan is defined as "a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but which will, in finely divided form and in the presence of moisture react with calcium hydroxide to form compounds possessing cementitious properties "[17]. Pozzolans react chemically with the alkalies in the portland cement as well as with the calcium hydroxide or hydrated lime liberated during the hydration of portland cement to form stable strength producing compounds [12]. The cementitious compounds resulting from the reaction of the fly ash with calcium are calcium silicate hydrates which are very similar to those resulting from the hydration of portland cement.

4.3 Definition of Coal

Coal is formed by the decomposition of plant matter, without free access to air, under the influence of moisture, pressure, and temperature. Coal is primarily composed of oxygen, hydrogen, and carbon. The chemical composition of the coal changes with time as lower oxygen and hydrogen contents and higher carbon contents are associated with the coal age [18].

Coals are ranked by degree of coalification (calorific value). From low to high, the ranking consists of peat, brown coal and lignite, subbituminous, bituminous (soft coal), anthracite (hard coal), and graphite. Lignite and brown coal are the lowest ranking fuels commonly referred to as coal. Most bituminous coals were formed 300 to 100 million years ago; examples of these coals may be found in the eastern United States. Coals which show less coalification, such as subbituminous, brown coal, and lignite, were formed more recently. These coals are often found in the western United States. Despite the lower calorific values of the lignite and subbituminous coals, their use has increased as a result of the increased efficiency in the production of electricity from the burning coal, and the need for additional domestic energy supplies.

4.4 Fly Ash Classification

The fly ash resulting from the combustion of coal mainly consists of oxides of silicon, aluminum, iron, and calcium. ASTM C618 groups fly ashes as Class F and Class C, primarily based on the minimum sum of the percentages of silicon, aluminum, and iron oxides [19]. The summation of silicon dioxide, aluminum oxide, and iron oxide must be greater than 70 percent for a Class F fly ash and greater than 50 percent for a Class C fly ash as shown in Table 4.1. Class F fly ashes are normally produced from burning anthracite or bituminous coals (generally eastern coals) and exhibit mostly pozzolanic properties. Class C fly ashes are normally produced from lignite or subbituminous coals (western coals) and exhibit both cementitious properties and pozzolanic properties. The cementitious properties of Class C ashes are primarily due to the higher calcium oxide (lime) content which reacts to form calcium silicate hydrates. ASTM C618 indirectly recognizes the cementitious properties of Class C fly ashes by lowering the minimum amount of silicon, aluminum, and iron oxides which allows for a greater percentage of calcium oxide.

The Texas State Department of Highways and Public Transportation (TSDHPT) classifies fly ashes as Type A or Type B. It can be seen from Table 4.1 that the requirements for a Type A fly ash correspond closely to those of an ASTM Class F fly ash, and the requirements for a Type B fly ash correspond to those of a Class C fly ash. Slight difference do exist between the ASTM fly ash classifications and the TSDHPT fly ash types. The TSDHPT standards provide a more consistent fly ash composition because of the lower allowable limits on moisture content, loss on ignition, and percentage retained on the #325 sieve. Additionally, if the sum of Si, Al, and Fe oxides in the fly ash is greater than 65 percent, that fly ash is designated as a Type A fly ash as per TSDHPT specifications compared to 70 percent for a Class F fly ash as per ASTM C618. The TSDHPT designations will be used in this report.

Table 4.1 Fly Ash Chemical Composition Requirements According to Different Specifications

	ASTM Class F	ASTM Class C	TSDHPT Type A	TSDHPT Type B
Si + Al + Fe minimum percent	70	50	65	50
Ca oxide maximum percent	–	–	*	*
Mg oxide maximum percent	–	–	5.0	5.0
Sulfate maximum percent	5.0	5.0	5.0	5.0
Available Alkalies as Na oxide maximum percent	1.5	1.5	1.5	1.5
Loss on ignition maximum percent	6.0	6.0	3.0	3.0
Moisture maximum percent	3.0	3.0	2.0	2.0
Fineness #325 sieve maximum retained	34	34	75	75
Pozzolanic Activity	75	75	75	75
Shrinkage maximum percent	.03	.03	.03	.03

* 4 percent maximum variation from previous ten samples

4.5 Effect of Fly Ash on Cement Properties

4.5.1 The Pozzolanic Reactions. The most important reaction in a fly ash and cement mixture is between reactive silica and calcium hydroxide from the cement and water reaction to form calcium silicate hydrates [18]. A simplified model for the reaction is as follows:

$$\underset{\text{CALCIUM HYDROXIDE}}{x\text{CH}} \; + \underset{\text{SILCATE}}{y\text{S}} \; + \underset{\text{WATER}}{z\ \text{H}} \; \longrightarrow \underset{\text{CALCIUM SILICATE HYDRATE}}{\text{C}_x\text{S}_y\text{H}_{x+z}} \tag{4.1}$$

Additionally, the alumina available from the fly ash can produce a variety of hydrates, including calcium aluminate hydrate (C_4AH_{19}), gehlenite hydrate (C_2ASH_8), etrringite ($C_3A\bullet\ 3C\overline{S}\bullet\ H_{32}$), and calcium monosulfoaluminate hydrate ($C_3A \bullet C\overline{S}\bullet\ H_{12}$) [18]. In the presence of gypsum, the monosulfoaluminate reaction may be written as

$$\underset{\text{ALUMINATE}}{\text{A}} \; \underset{\text{CALCIUM HYDROXIDE}}{+3\text{CH}} \; \underset{\text{GYPSUM}}{+\text{C}\overline{\text{S}}\text{H}_2} \; \underset{\text{WATER}}{+7\text{H}} \; \underset{\text{MONOSULFO-ALUMINATE}}{\longrightarrow \text{C}_3\text{AC}\overline{\text{S}}\text{H}_{12}} \tag{4.2}$$

Similar equations may be written for the formation of ettringite and calcium aluminate hydrate.

The rates at which the pozzolanic reactions occur are dependent upon the total concentrations of calcium, alkalies, sulfate, silica, and aluminate in the solution from both the fly ash and the cement.

Debate exists as to when the pozzolanic reactions begin. Some research has reported no reaction until 28 days or longer; other research reports reactions at early ages. The discrepancy is likely due to different techniques of measuring reactivity, as well as differences in reactivity. While pozzolanic reactions may occur at early ages, they do not contribute significantly to the strength of concrete until later ages [18].

Work by Maage has found the pozzolanic reactions to be more sensitive to temperature than to the characteristics of the portland cement [20]. Pozzolanic reactions begin earlier at high temperatures and may not significantly occur until 14 days or later at cold temperatures.

4.5.2 Fly Ash-Cement Compound Interactions.

4.5.2.1 C_3S Hydration. Several studies investigating the early hydration of C_3S and fly ash have indicated a retarding effect on the C_3S heat evolution peak, as may be seen in Figure 4.1. Jawed and Skalny theorize that this retardation is due to a chemisorption of Ca ions on the fly ash particle surfaces which reduce the Ca concentration in solution and therefore delay the nucleation of calcium hydroxide, and also a poisoning effect of silicates

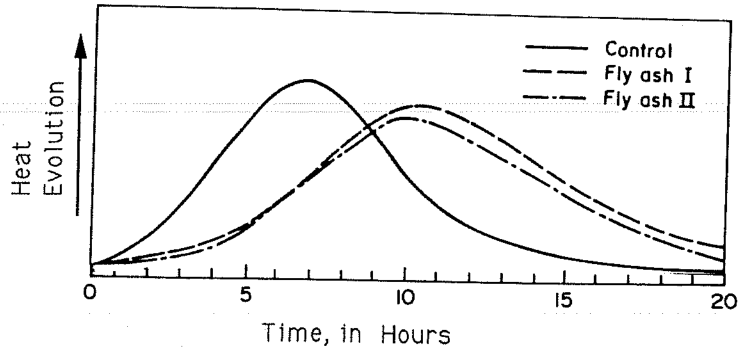


Figure 4.1 Retardation of the hydration of C_3S in the presence of fly ash [18].

and aluminates on the nucleation and crystal growth of calcium hydroxide and calcium silicate hydrate [18].

Recent work conducted by Ogawa et. al., found the early hydration of C_3S to be accelerated by the addition of pozzolans [21]. In other words, the C_3S rate of heat evolution peak was found to increase with the addition of a pozzolan, which acts as additional precipitation sites for hydrates. Also, because the pozzolans absorb Ca ions, the Ca ion concentration is lowered, and the dissolution of the C_3S is then accelerated.

Research by Dalziel and Gutteridge indicates more hydration when fly ash is present. As shown in Figure 4.2, the presence of fly ash increased the percent of C_3S hydrated after just one day [22].

4.5.2.2 C_2S Hydration. The presence of fly ash was found to have no effect on the hydration of C_2S up to about 14 days, after which less hydration occurred when fly ash was present. Figure 4.3 shows the hydration of C_2S as a function of time for cement pastes with and without fly ash present. Apparently the pozzolanic reactions reduce the amount of portlandite available and therefore the amount of C_2S which subsequently hydrates [22].

4.5.2.3 Hydration of C_3A and Ferrites. The amounts of C_3A and C_4AF in portland cement are relatively small, and so there is more uncertainty about their degrees of hydration. Work by Dalziel and Gutteridge found that the hydration of C_3A was little affected by the presence of fly ash, while the hydration of C_4AF was slightly increased [22].

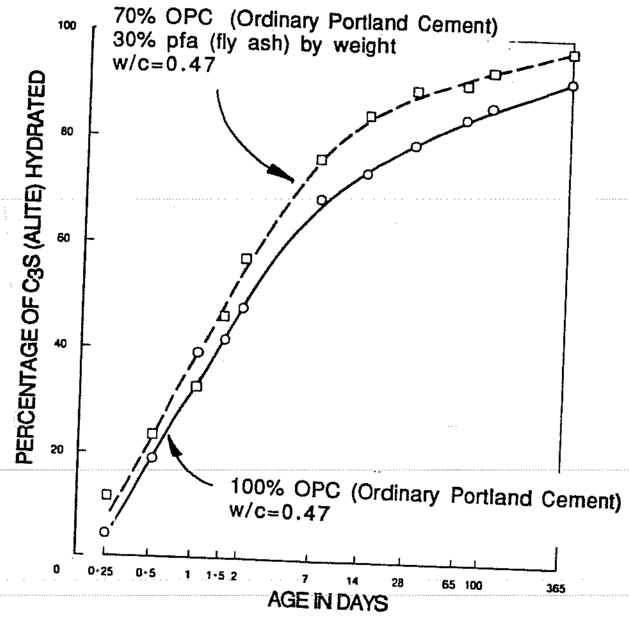


Figure 4.2 Degree of C_3S hydration in the presence of fly ash [22].

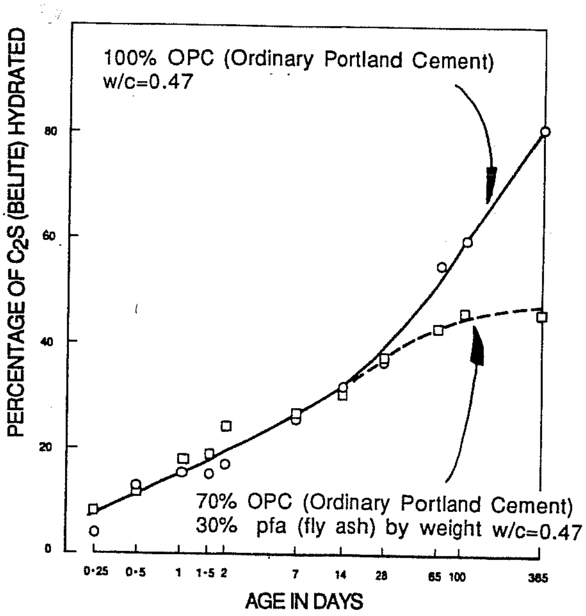


Figure 4.3 Degree of C_2S hydration in the presence of pfa (fly ash) [22].

Cabrera and Plowman have found fly ash to retard the very early hydration of C_3A and C_4AF. It is suggested that the C_3A is retarded by a mechanism similar to that used by gypsum as a retarding agent [23].

4.5.3 Rate of Heat Evolution. Isothermal calorimetry tests performed by Meland [24] have shown that the partial substitution of portland cement with a Class F fly ash results in a reduced rate of heat evolution. This may be seen in the lower second peaks on the curves in Figure 4.4 for pastes with fly ash. When the total heat liberated after 50 hours for the same pastes are studied in Figure 4.5, it may be seen that the normal portland cement displays the greatest heat of hydration and that increased fly ash replacement results in a decrease in total heat of hydration.

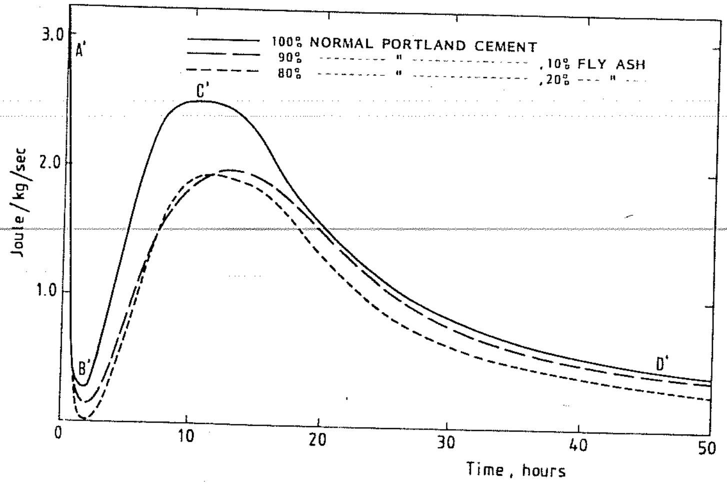


Figure 4.4 Heat evolution curves for normal portland cement and fly ash pastes [24].

4.5.4 Retarding Effects. Various researchers have reported a retardation of the early hydration of fly ash blend cements [18, 23, 24, 25]. Work by Fajun et. al. found that both Class C and Class F fly ashes caused a retardation of C_3S hydration, with the Class C fly ashes causing the most severe retardation. When the fly ash was used in a washed condition, little to no retardation was observed indicating that retardation is due to some characteristic at the fly ash surface [25]. Figure 4.6 shows the rate of heat evolution for pure cement and two fly ash cement blends. It can be seen that the second evolution peak is delayed with increased substitution by fly ash.

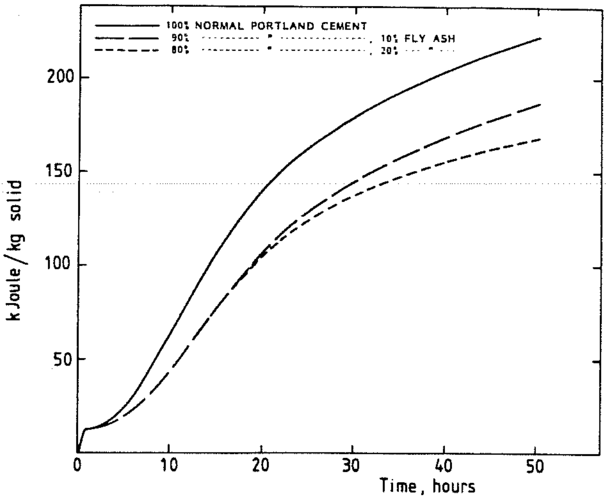


Figure 4.5 Total heat of hydration with respect to time for normal portland cement and fly ash pastes [24].

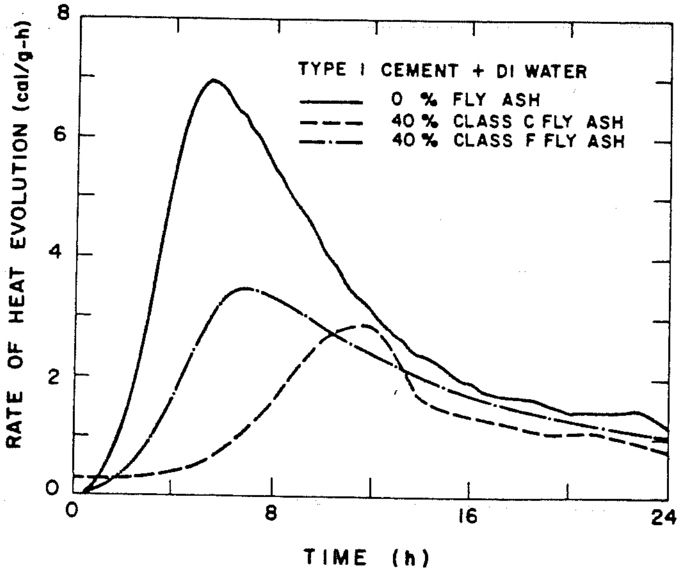


Figure 4.6 Rate of heat evolution of pure cement and fly ash/cement blends [25].

Studies by Ravina and Mehta [26] attribute the delay in setting time to both physical and chemical fly ash properties. Physically, the use of fly ash as a cement replacement reduces the amount of cement in the mixture, and therefore the cement hydration product will be less. If the fly ash is finer than the cement, it may act as nuclei for growth and buildup of cement hydration products. Chemically, sulfates in the fly ash may retard the set in the same way gypsum retards the hydration of C_3A. Alkalies may also affect the concrete setting time. Alkalies will accelerate setting time in general, and very high alkali levels may cause a flash set.

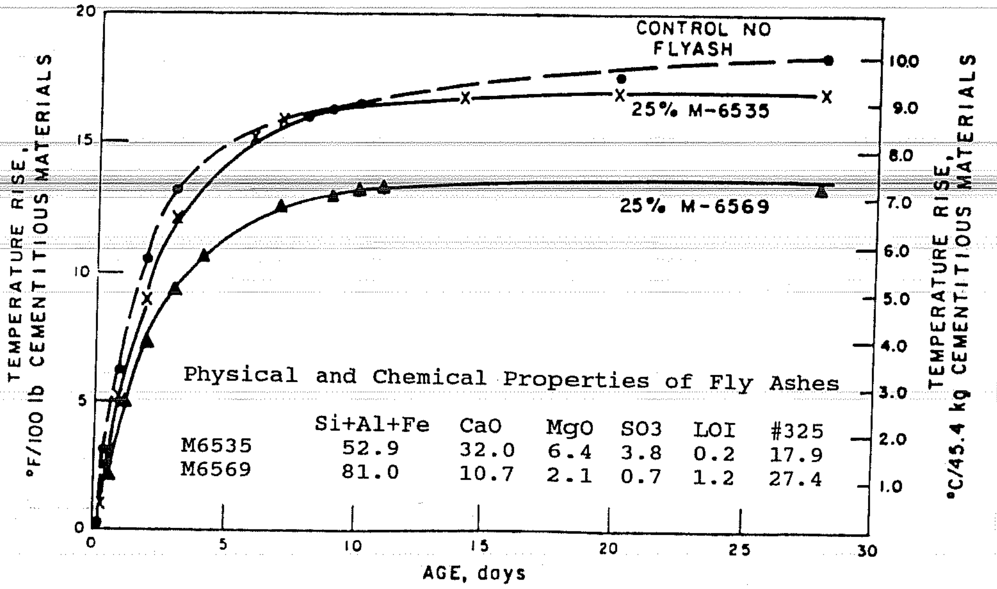
4.6 Effect of Fly Ash on Concrete Properties

4.6.1 Temperature Rise. The temperature rise in concrete may be controlled by limiting the amount of cement in the mix. This is most often done by replacing a portion of the cement with a pozzolan, usually fly ash, because most pozzolans reduce the temperature rise by delaying and reducing the heat evolved due to hydration. Numerous studies have been conducted concerning this heat reduction, but a comparison of these studies is difficult due to the many variables involved which affect the concrete temperature such as cement type, fly ash type, initial concrete temperature, sample size, and sample environment [12].

ACI 211.1-81 suggests a conservative estimate of the pozzolanic contribution to the heat of hydration in the order of 15 to 50 percent that of an equivalent weight of cement [27]. Such estimates may be reasonable for low calcium fly ashes (in general TSDHPT Type A) but may not be accurate for high calcium fly ashes (generally TSDHPT Type B). Early strength is usually proportional to heat generated at early ages and some high calcium fly ashes produce strength and heat at rates similar to cement, as shown in Figures 4.7 and 4.8. Mixture proportions for the concretes in Figure 4.7 may be found in Table 4.2. Earlier work on this project found that partial replacement of the cement with Type B fly ash had no significant effect on the temperature rise of mortar made with cement and fly ash [15].

Research by Bamforth on mass concrete has shown that the effect of fly ash in reducing temperature rise is reduced as the specimen volume increases [29]. As the specimen volume increases and the concrete environment becomes more nearly adiabatic, the total heat generated predominates over the rate of heat generation in determining the peak temperature. In other words, the rate of heat generation predominates as the rate of heat loss increases. This observation indicates that fly ash hydrates at a slower rate than cement but may produce nearly the same amount of heat over a period of days.

As discussed earlier, the presence of fly ash may retard the early hydration of cement. This retardation will allow more time for heat dissipation from a concrete member. While this increase in time for heat dissipation may not significantly influence the temperature rise in a massive section which has a low surface area to volume ratio, it may result in a lower maximum temperature rise in a thinner member, which has a high surface



Physical and Chemical Properties of Fly Ashes

	Si+Al+Fe	CaO	MgO	SO3	LOI	#325
M6535	52.9	32.0	6.4	3.8	0.2	17.9
M6569	81.0	10.7	2.1	0.7	1.2	27.4

Figure 4.7 Adiabatic temperature rise for concretes with and without fly ash [28].

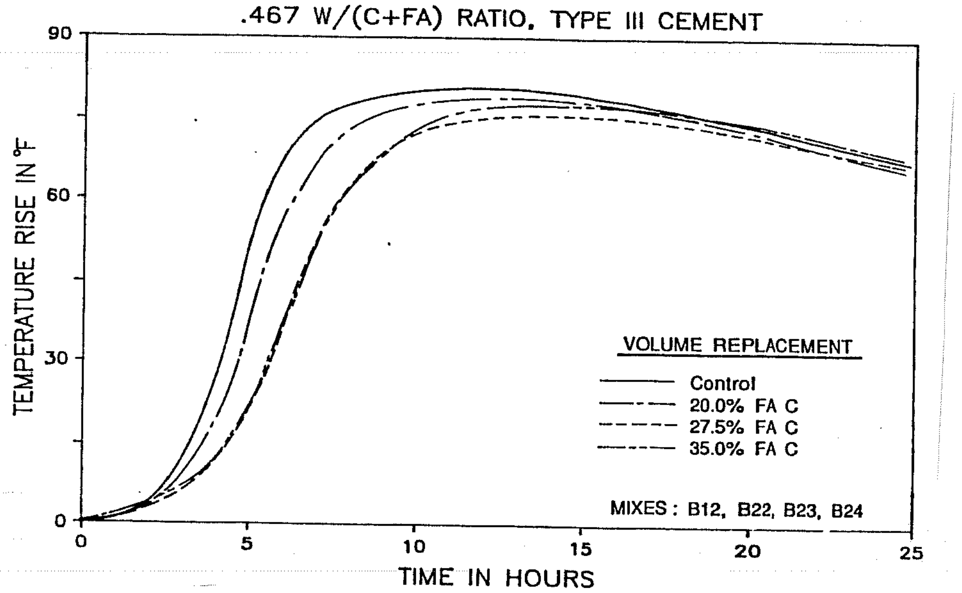


Figure 4.8 Effect of TSDHPT Type B fly ash on the adiabatic temperature rise of cement mortar [15].

Table 4.2 Mixture Proportions for Concretes in Figure 4.7
(Pounds per Cubic Yard)

Mix Description	Cement	Fly Ash	Water	Sand	Coarse Agg.
Control	512	0	226	1059	2211
25 percent M6535	335	112	201	1101	2125
35 percent M6569	349	116	209	1083	2175

to volume ratio, and therefore is able to dissipate heat quickly thereby reducing the risk of thermal cracking.

4.6.2 Workability. The partial replacement of cement by fly ash will generally improve the workability of concretes of equal slump and strength. The improved workability is attributed to the small, smooth, spherical fly ash particles which act as 'ball-bearings' in the fresh concrete. The effect is similar to the increased workability seen when a smooth, round coarse aggregate is used.

Recent work by Helmuth contradicts the ball-bearing analogy [30]. Helmuth hypothesizes that the fly ash acts much like a chemical dispersant such as a superplasticizer (high-range water reducer). The negatively charged fine fly ash particles adhere to the positively charged calcium silicates on the cement particle surfaces. The positive areas of the cement particles will be neutralized if enough of the surface is covered with negative fly ash particle. Then, the resulting negatively charged cement-fly ash particles will repel each other.

Helmuth's hypothesis is supported by several observations. Fly ashes with the highest specific surface areas result in the greatest reductions in mixing water to maintain a given flow. This is contrary to the increased water requirement associated with increased cement fineness. Helmuth also notes that the mixing water requirement does not steadily decrease with increasing fly ash content as would be expected from the ball-bearing analogy [30].

4.6.3 Compressive Strength Gain. A great deal of literature exists concerning the effect of fly ash on compressive strength of concrete [1, 2, 4, 18, 20, 31, 32, 33, 34, 35, 36, 37]. A number of variables influence the compressive strength achieved including the fly ash properties, both chemical and physical, the cement type, the method of fly ash addition, and the mixture proportions. No single fly ash property may be used to predict the potential strength of concrete. Researchers agree that fly ash addition decreases early strength, and that strength development of fly ash concretes is more dependent on curing conditions than ordinary portland cement concretes.

Studies have shown that high calcium fly ashes will produce higher strength concretes and mortars at early ages than low calcium fly ashes due to the additional cementitious properties associated with the higher calcium content fly ash [31, 32, 33]. Further, it has been found that the greater the percent substitution, the greater the retardation of early strength [32]. However, the long term compressive strength of concrete containing fly ash does not necessarily follow the early age trends. Different fly ashes develop strength at different ages, so a fly ash concrete which exhibited low strength at early ages may exhibit higher compressive strengths at later ages in comparison to other fly ash concretes. This may be seen in Figure 4.9, where fly ashes used at 40 percent replacement levels are seen to gain more strength at later ages. Chemical properties of the fly ashes in used in the concretes in Figure 4.9 may be found in Table 4.3, while mixture proportions for the concretes in Figure 4.9 may be found in Table 4.4. This later age strength increase is due to the pore filling characteristic of the pozzolanic reaction.

Table 4.3 Chemical Properties of Fly Ashes Used in Concretes in Figure 4.9
(Weight Percent)

Fly Ash	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Moisture	LOI
Cooper	52.89	29.98	9.70	1.33	1.21	0.30	2.39
Brown	51.90	29.09	11.59	1.10	1.25	0.32	3.30
Spurlock	52.70	28.22	12.85	1.06	0.90	0.17	3.60
Big Sandy	54.18	28.42	8.67	0.94	1.11	0.05	0.95

The strength of fly ash concretes and mortars are more dependent on the curing temperature than mixtures without fly ash [33, 37]. The ultimate compressive strength of fly ash concrete increases with increasing temperature, while non-fly ash concretes exhibit a decrease in compressive strength with temperatures in the range associated with mass or hot weather concreting [37]. Studies by Gebler and Kleiger found that initial moist curing was especially important for the development of long term strength of concretes containing

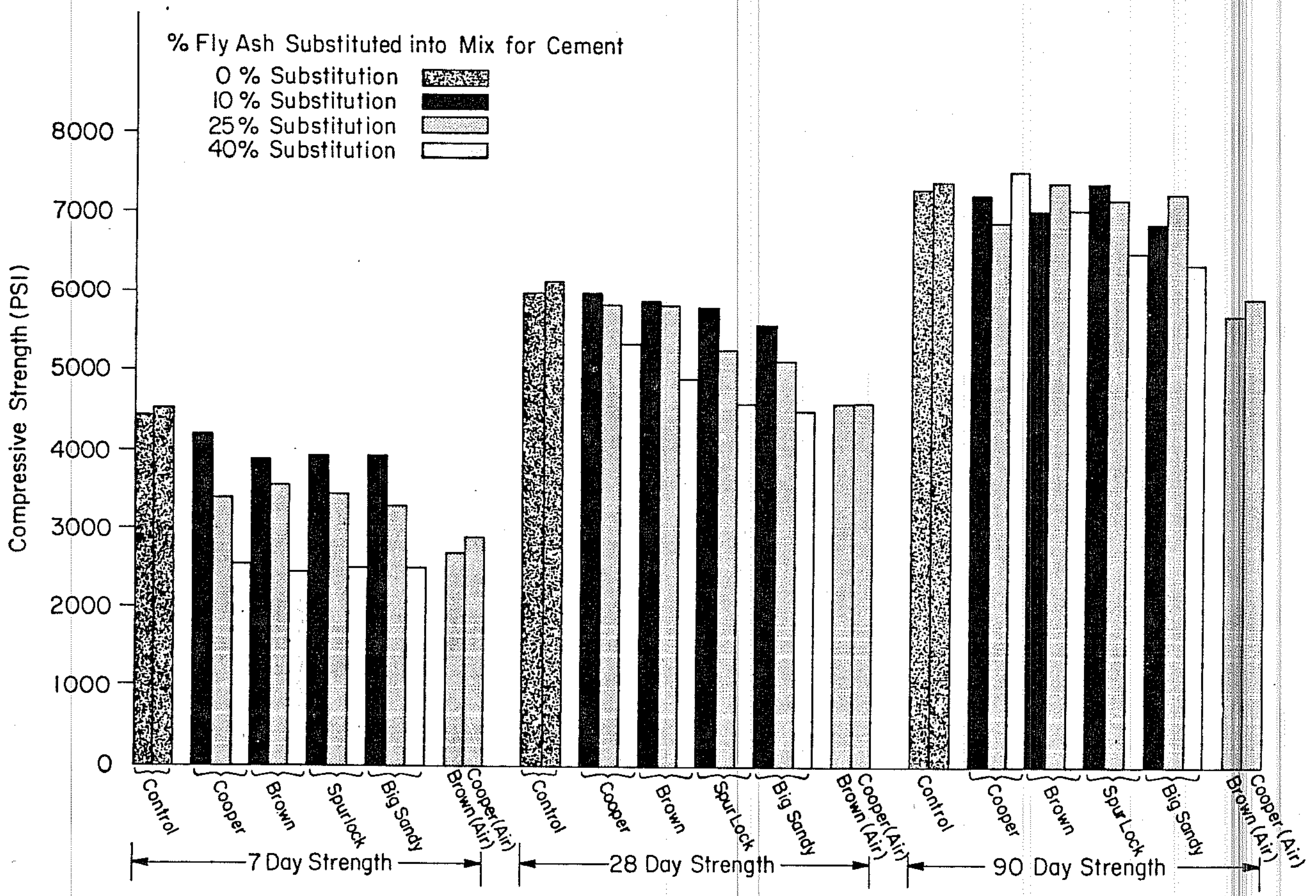


Figure 4.9 Compressive strengths at 7, 28, and 90 days for varied fly ash substitutions.[32]

Table 4.4 Design Mix Weights for Concretes in Figure 4.9
(Pounds per Cubic Yard)

Mix Description	Rock	Sand	Cement	Fly Ash	Water
Control	1850	1400	517	0	296
10 Percent Fly Ash	1850	(1385-1389)*	465	52	296
20 Percent Fly Ash	1850	(1364-1392)*	414	103	296
30 Percent Fly Ash	1850	(1362-1372)*	388	129	296
40 Percent Fly Ash	1850	(1338-1354)*	310	207	296

* Range depending on the specific gravity of individual fly ash

Class F fly ashes. Early age compressive strength of concretes with fly ash were found not to be greatly affected by the availability of moisture, regardless of type of fly ash [33].

CHAPTER 5
EXPERIMENTAL WORK

5.1 Introduction

Experimental work in this study consisted of two phases. One phase involved the monitoring of temperature gradients in full scale ready-mix concrete specimens. Mixtures contained various types and replacement levels of fly ash as well as two different cement contents. Additionally, strength and workability of each concrete mixture was measured.

The purpose of the ready-mix concrete tests was to observe the effectiveness of fly ash as a partial cement replacement in reducing the temperature rise of concrete specimens cast in similar dimensions and with similar mixture designs as the engineer might encounter in actual construction. Thus the engineer will have a basis for the amount of temperature reductions which might be expected when using a similar fly ash and a particular cement content in the field.

The second phase of experimental work involved the use of an isothermal calorimeter to monitor the heat evolution of cement and cement/fly ash pastes at different temperatures. Various types of cements and the same fly ashes used in the ready-mix tests were studied.

Isothermal calorimetry was used in this study for several reasons:

1) The heat evolution of cement paste contributes significantly to the temperature rise in concrete. An isothermal calorimeter is able to continuously monitor the heat evolution rate of a reaction over an extended period of time, and is thus well suited for cement paste study.
2) Isothermal conditions, unlike adiabatic conditions, allow for the study of hydration mechanisms.
3) Several mixes may be studied at the same time.
4) Required sample size is small. Therefore, large supplies of cement and fly ash are not needed.

5.2 Ready-Mix Concrete Temperature Gradient Tests

5.2.1 Test Equipment. Temperature rise in each of the specimens was measured using copper-constantan thermocouples. The thermocouple wire used was supplied by Omega Engineering, and was type T. The wire has a manufacturer's stated accuracy of ±1.76 degrees F or 0.4 percent, whichever is greater, and is good for a range of 32 to 1382 degrees F.

Each thermocouple was connected to a Fluke Helios-I Computer Front End. The computer front end continuously monitored voltage across each thermocouple, and converted this voltage to degrees Fahrenheit. The Helios-I with type T thermocouple wire has a manufacturer's stated accuracy of ±0.63 degrees F.

The Helios-I executed commands from a host computer. After converting the voltages to degrees the temperatures were stored in the host computer's hard drive.

5.2.2 Test Specimens.

5.2.2.1 Formwork. Each of the temperature gradient tests involved the casting of a 4.5-ft cube and two identical 8-foot x 3-foot-10-inch x 10-inch slabs. The formwork consisted of 3/4-inch plywood lined with plastic, as can be seen in Figure 5.1. Formwork remained on all specimens throughout the duration of the test. The only reinforcement in the specimens consisted of four hooked #4 bars in the cube and four #3 bars in the corners of each slab. This reinforcement was used to lift the specimens out of the forms after the testing was completed.

5.2.2.2 Thermocouple Placement. Thermocouples were held in place by attaching them to 80-pound test fishing line. The fishing line was secured to nails at the base of the formwork, and tied around a 2x4 above the surface of the specimen. Thermocouple wire was kept in the same central vertical plane in each specimen, as can be seen in Figure 5.2. A total of 9 thermocouples was used in each cube, while 5 thermocouples were used in each slab. An additional thermocouple was used to monitor the ambient temperature at the casting site. Figures 5.3 and 5.4 show the position of the thermocouples in a typical cast. During the casting of specimens, care was taken not to chute concrete directly into the thermocouples, so each thermocouple displaced little from its original position.

5.2.3 Mix Designs

5.2.3.1 Materials. The fly ashes used in this study are commercially available throughout Texas and provide a basis for comparison of physical and chemical properties of the fly ash in general. It should be noted that other fly ashes may produce different results.

The fly ashes used in this study were all produced in Texas and are approved by the Texas SDHPT. In this study, each of the fly ashes are designated by a letter and number combination, without a reference to their producer. Chemical compositions of each fly ash used in this study may be found in Tables A.3 to A.6 in Appendix A.

The cement used in the thermal gradient tests was that normally used by the ready-mix plant. The cement meets the ASTM C-150 requirements for a Type I cement [38]. The mill results of the cement are presented in Table A.7 of Appendix A.

Figure 5.1 Formwork used in ready-mix concrete tests

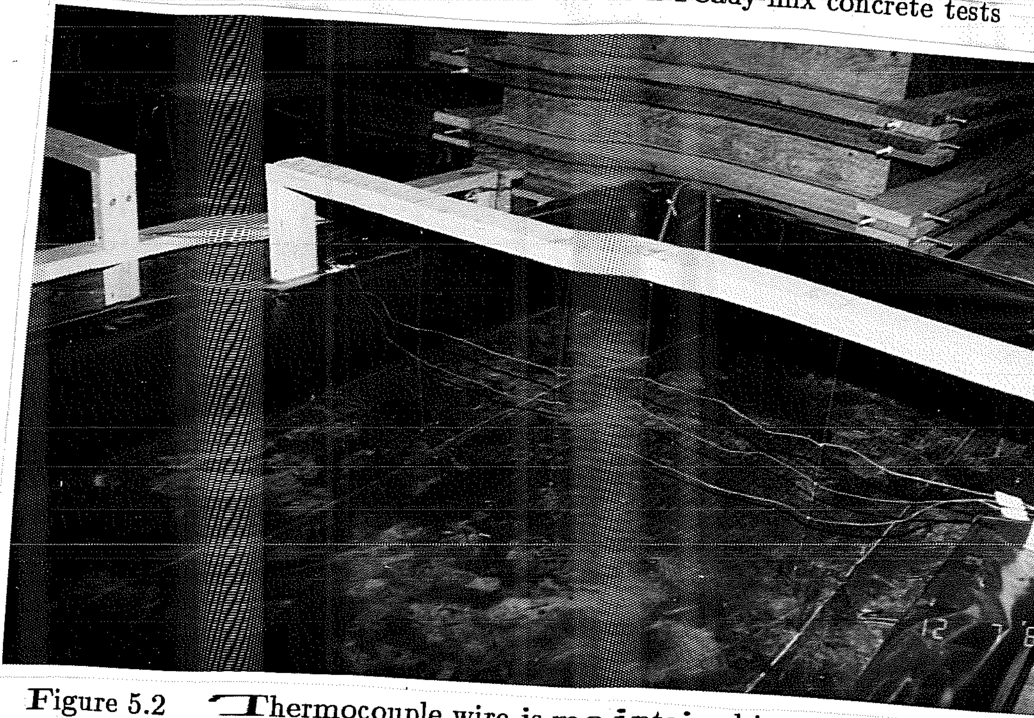
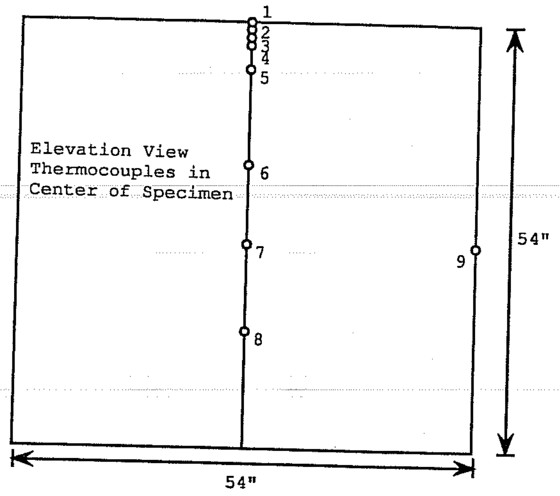


Figure 5.2 Thermocouple wire is maintained in same vertical plane



THERMOCOUPLE NO.	DEPTH BELOW SURFACE
1	0"
2	1"
3	2"
4	3"
5	6"
6	1'-6"
7	2'-3"
8	3'-3"
9	2'-3"

Figure 5.3 Position of thermocouples in 4.5-ft. cube.

River gravel having 3/4-inch maximum size and river sand were used for aggregates. Additionally, since the concrete was cast during the summer months, a lignosulfate based retarder was used. No air entrainment was used in this study.

5.2.3.2 **Mixture Proportions.** Temperature gradient tests were divided into two groups. The first group was based on a 5-sack ready-mix concrete batch with a w/c of 0.53 and 16.5 oz/yd retarder. The second group were based on a 7.5- sack ready-mix concrete batch with a w/c of 0.41 and 22.6 oz/yd retarder. The first test in each group was a control mix containing no fly ash. Subsequent tests contained one of four different fly ashes and one of two different cement replacement ratios.

without any other adjustments necessary. The amount of water,rock, sand, and retarder within each group remained the same. The actual batched mixture proportions for the concretes used are presented in Tables A.1 and A.2 of Appendix A.

5.2.4 Concrete Batching Procedures. All concrete was obtained from the same commercial ready-mix company. With the exception of 7.5-Sack Fly Ash A2 30 percent, all concrete was obtained from the same batching plant as well. For those mixes containing cement replacement by fly ash, the fly ash was added by hand at the batching plant during the batching process. The batching sequence used was as follows:

1) Add all required rock, sand, and cement to ready-mix truck.
2) Add 75 percent of the required mixing water and retarder to the ready-mix truck.
3) Mix contents of drum.
4) Add required fly ash to truck by hand. The procedure may be seen in Figure 5.5.
5) Add remaining 25 percent mixing water to truck. This was sufficient water to wash down the blades as well.
6) Mix contents of drum.

Figure 5.5 Fly ash is added to the ready-mix truck by hand

Drivers were instructed not to make any additions of water to the mixtures after the final 25 percent addition of water was made.

5.2.5 Casting Procedure. All casting was performed during the afternoon in order to subject all specimens to similar temperature cycles. Additionally, all casting was done indoors to avoid differences in weather conditions. All casting was completed between July 12 and September 10, with the exception of 7.5-Sack Control 2 and 7.5-Sack Fly Ash B2 35 percent, which were cast on October 16.

Upon arrival of the truck to the casting site, the concrete was inspected. If additional mixing was needed, this was done. The initial mixture temperature was taken at this time.

The slabs were cast first in each test. Concrete was chuted to either end of the slab, and then mechanically vibrated to the center, where the thermocouples were located. The cubes were cast similarly, using a crane and bucket to place the concrete in four lifts. Figures 5.6 and 5.7 illustrate the placing of the concrete.

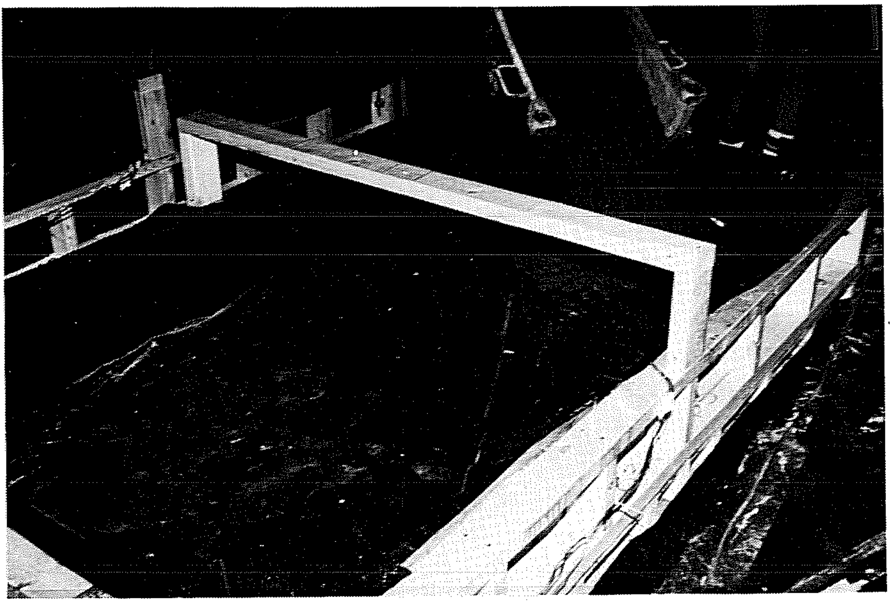
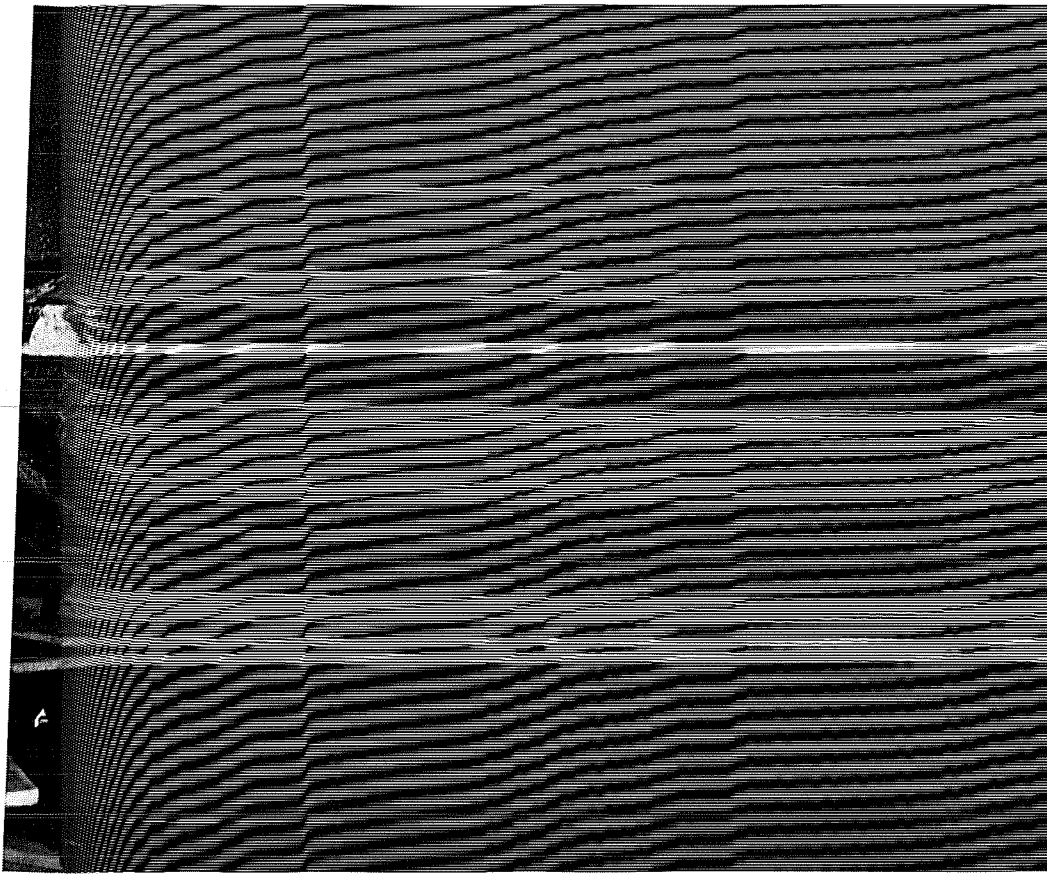


Figure 5.6 Concrete is chuted away from thermocouple wires.



After placing

water. One slab was co

mat soaked with water,

The cube was covered wi

of the test. The appear

5.2.6 Testing

10 minutes, from the ti

stored in the memory of

5.2.6 Ready-

tests were conducted on

were molded, cured and

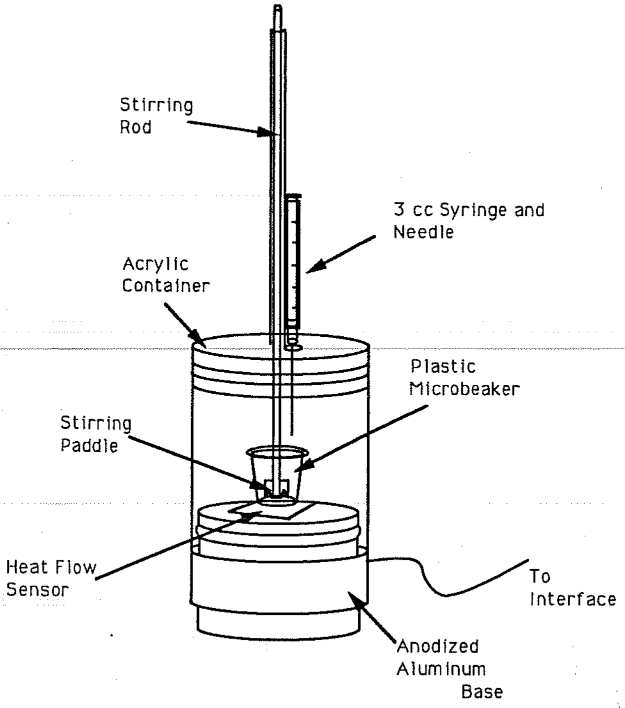


Figure 5.10 Schematic of an individual calorimetric cell

accurate to ± 0.03 degrees Celsius. The pumping capacity of the system is 5 gallons per minute.

The Lauda system was used to circulate the bath liquid in and out of an 8 gallon, 16-inch diameter, circular glass tank. Deionized water was used as the bath liquid. The calorimetry cells were placed in the glass tank. The tank was placed inside 2-inch thick styrofoam insulation to aid in the prevention of heat loss of the water.

5.3.2 *Calibration of Calorimetric Cells.*

5.3.2.1 Theory of Calibration. Each calorimetric cell was individually calibrated before any tests were run. Calibration was performed following a method described by Prosen et. al. [42]. A calorimetric cell is activated with a steady source of power, Wc, until a steady state is reached. This is illustrated in Figure 5.11. According to Prosen et.

computer, an interface box, and up to 15 calorimetric cells. The cells are placed in an isothermal environment, where any generated heat is continuously diffused out of the cells in order to maintain the constant temperature of the system. The calorimetry system monitors the heat given off by reactants within each cell, and stores the data in the host computer memory in units called counts. Each count unit is roughly equivalent to 1 millivolt. During the process, all count readings may be monitored via the computer terminal. The system, which has a manufacturer's stated accuracy of 10 percent, may be seen in Figure 5.9.

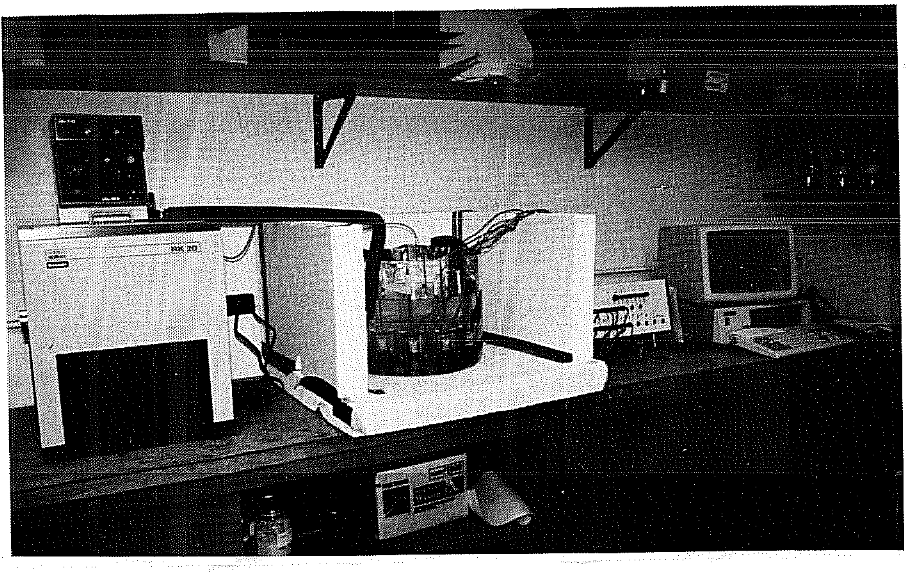
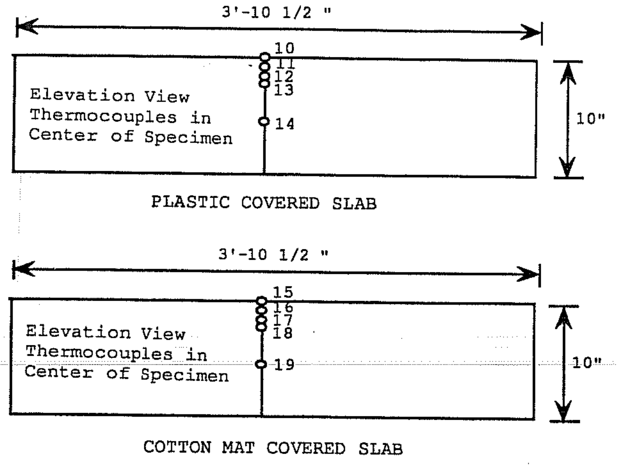


Figure 5.9 Isothermal calorimetry test setup

Each calorimetric cell contains a white heat flow sensor with a voltage output proportional to the heat which flows through it. The sensor is located within an anodized aluminum base. A schematic of an individual calorimetric cell may be seen in Figure 5.10.

Reactants were contained in small plastic microbeakers. Liquid for reaction was added to the beaker through a hypodermic needle and syringe. Stirring was accomplished by the use of metal stirring rods with small plastic paddles cut to fit the microbeakers.

5.3.1.2 Isothermal Water Bath Equipment. A constant temperature environment was maintained through the use of a Lauda refrigerating circulator, model RKS-20D. The circulator has an operating range between -40 to 150 degrees Celsius, and is



THERMOCOUPLE NUMBER	DEPTH BELOW SURFACE
10	0"
11	1"
12	2"
13	3"
14	6"
15	0"
16	1"
17	2"
18	3"
19	6"

Figure 5.4 Position of thermocouples in slab sections

In the case of the 7.5-sack mixtures, an additional control mixture was batched. This was done because the final mixture, 7.5-Sack Fly Ash B2 35 percent was cast approximately 30 days after all previous casts were finished. Consequently, ambient temperatures were about 10 degrees lower than they had been when the other concretes were batched. The second 7.5-sack control mix was cast the same day as the 7.5-Sack Fly Ash B2 35 percent mix in order to observe the effects of casting the same mixture at a lower ambient temperature.

Cement was replaced by fly ash on an equal volume basis. This was done because the specific gravities of the fly ashes used in this study were not the same as the specific gravity of cement. Replacing the cement by volume kept the design volume at one cubic yard

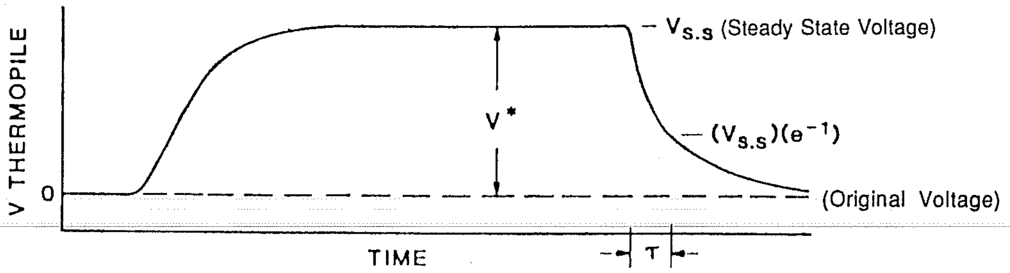


Figure 5.11 Plot of thermocouple voltage versus time for the method of calibration used [42].

al., since the voltage output from each cell is proportional to the power being conducted away from each cell,

$$Wc = F * V^* \qquad where \tag{5.1}$$

Wc = Applied Power

V* = Steady State Voltage - Original Voltage

F = Calibration Constant for Cell

5.3.2.2 Method of Calibration. Power was supplied to the cell through the use of a resistor and a voltage source. The resistor was set in a 10 gram sample of cement paste, in a microbeaker. The paste was allowed to harden and was then placed in the calorimetric cell, directly on the heat sensor. Count readings from the cell were monitored until an equilibrium state was reached. Then the leads of the resistor were attached to 5 Volt supply terminals on the calorimeter interface box. Count readings were monitored until a steady count reading was obtained.

Wattage output of the heater was calculated as

$$Watts = V^2/R \qquad where \tag{5.2}$$

V = Voltage output of interface box, measured by a voltmeter, in Volts

R = Resistance of resistor, in ohms

Using the conversion factor 1 Watt = 860 Calories/Hour, the calibration constant of each cell was computed as follows:

$$Calibration\ Constant = (Watts * 860)/CTS \tag{5.3}$$

where CTS = Steady State Counts - Original Counts

The calibration constant for each cell, in units of calories/hour/count, may be found in Table 5.1.

5.3.3 Materials and Paste Proportions. The same fly ashes used in the temperature gradient tests were used in the calorimetric tests. Cements used included the same Type I cement used in the temperature gradient tests as well as a Type I-II and a Type III cement. The mill reports of these cements may be found in Tables A.8 and A.9 of Appendix A.

Cement was replaced by fly ash on an equal volume basis; the total volume of cementitious material was equal to the volume of 6 grams of cement in all cases, except where noted. For all of the pastes, 3 grams of water was used, except where noted. The Type A fly ashes were used at replacement ratios of 20 and 30 percent, and the Type B fly ashes were used at replacement ratios of 25 and 35 percent.

5.3.4 Test Procedure. The same mixing procedure was used for each test, except where noted. The mixing procedure used was as follows:

1. Fill syringe with required weight of liquid. Allow to float in bath while weighing cements and fly ashes; this helps to bring liquid temperature to equilibrium with the system.
2. Weigh required amounts of cement and/or fly ash into plastic microbeaker.
3. Place microbeaker in calorimeter cell. Secure microbeaker to heat sensor with piece of double-sided tape.
4. Replace acrylic parts of cell, taking care not to upset beaker contents.
5. Remove syringes from water bath, attach to hypodermic needles permanently in place on calorimetric cell.
6. Place calorimeter cell in water bath.

Table 5.1 Calorimetric Cell Calibration Constants
(Calibration Constants in Units of Calories/Hour/Count)

Cell Number	Orig. State Counts	Steady State Counts	Calibration Constant
1	15	477	0.04719
2	2	451	0.04856
3	7	496	0.04486
4	20	474	0.04802
5	14	510	0.04898
6	4	449	0.04899
7	3	465	0.04719
8	14	500	0.04486
9	-15	456	0.04629
10	13	463	0.04845
11	12	472	0.04740
12	16	462	0.04888
13	9	461	0.04824
14	9	404	0.05397
15	6	404	0.05397
16	27	500	0.04609

Notes:
Resistance = 986 Ohms
Voltage = 5.0 Volts
Count Amplification = 128

7. Allow cell to reach equilibrium. Equilibrium of the cell is monitored via the computer terminal. The length of time necessary to reach equilibrium varies, depending on how close the isothermal temperature is to room temperature.
8. Once equilibrium is reached, carefully inject liquid into cell, using care to ensure no liquid is spilled outside the beaker.
9. Immediately 'cut' liquid into the cement, using 5 cuts to evenly distribute water into cement.
10. Following the 5 cuts, turn the stirring paddle 15 times. Again, use care to ensure that no paste leaves the beaker.

11. Touch an engraver to the end of the stirring paddle to help loosen any dry cement and to aid in consolidation of the paste.

Reactions were monitored for 24 hours beginning immediately after the mixing water was added to the reactants in the cell. Three replicates were made for each reaction. Each reaction was repeated at each of four different temperatures: 40, 60, 80, and 100 degrees F. Count readings were taken every 2 minutes for a period of 24 hours and stored in the hard drive of the computer.

CHAPTER 6
TEST RESULTS

6.1 Introduction

Typical results of the experimental work conducted in this study are presented in this chapter. The results of the ready-mix temperature gradient tests are presented in graphical form because of the many data points collected in each test. The values corresponding to the peak temperature and the time to the peak temperature are presented in tabular form in Appendix B.

The compressive strength and workability test results for the ready-mix concrete are presented in graphical form in this chapter, and in tabular form in Appendix B.

The results of the calorimetry tests are presented in graphical form, due to the large amount of data collected in each test. Typical rate of heat evolution plots are shown in this chapter, as well as typical cumulative heat evolution with time profiles, while the values corresponding to the maximum cumulative heat evolution are presented in tabular form in Appendix C.

The test results are presented in this chapter with no discussion of their significance. The test results and their significance will be discussed in Chapters 7 and 8.

6.2 Data Reduction: Temperature Gradient Tests.

6.2.1 Temperature Data. The temperature rise curves shown in Figures 6.1 to 6.4 are not smooth curves fitted to data points, but are a tracing of straight lines connecting data points by a computer and plotter. There are 6 data points per hour, so the straight lines appear as a smooth curve. Each data point represents a single reading.

In order to calculate the temperature rise in each specimens, the temperature at 2 hours after batching at mid-depth was subtracted from subsequent readings at each depth. The temperature at 2 hours was used because not all specimens were placed at the same time after batching. All specimens were placed before 2 hours had elapsed after batching.

6.2.2 Peak Temperature Data. The peak temperature rise at mid-depth was determined by subtracting the mixture temperature at 2 hours after batching from the maximum specimen temperature at mid-depth.

6.2.3 Time to Peak Temperature. In addition to the monitoring of the maximum temperature rise in specimens, the time when this peak occurred was also monitored. The tendency for thermal cracking can be reduced if the time at which the peak temperature

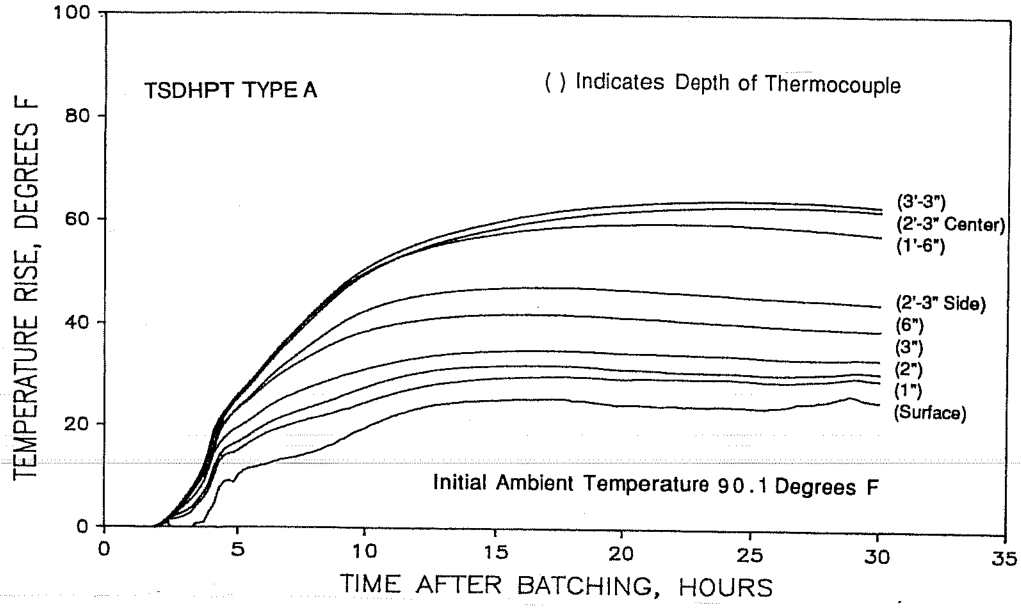


Figure 6.1 Temperature rise profile for 4.5-ft. cube, 5-sack ready mix concrete with 20 percent fly ash A1

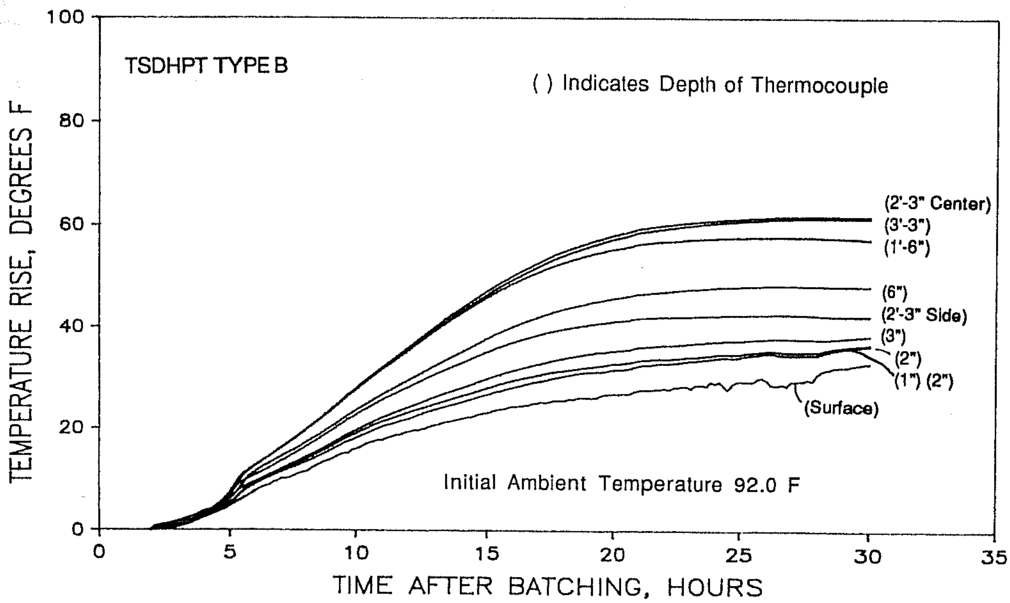


Figure 6.2 Temperature rise profile for 4.5-ft. cube, 5-sack ready mix concrete with 35 percent fly ash B2

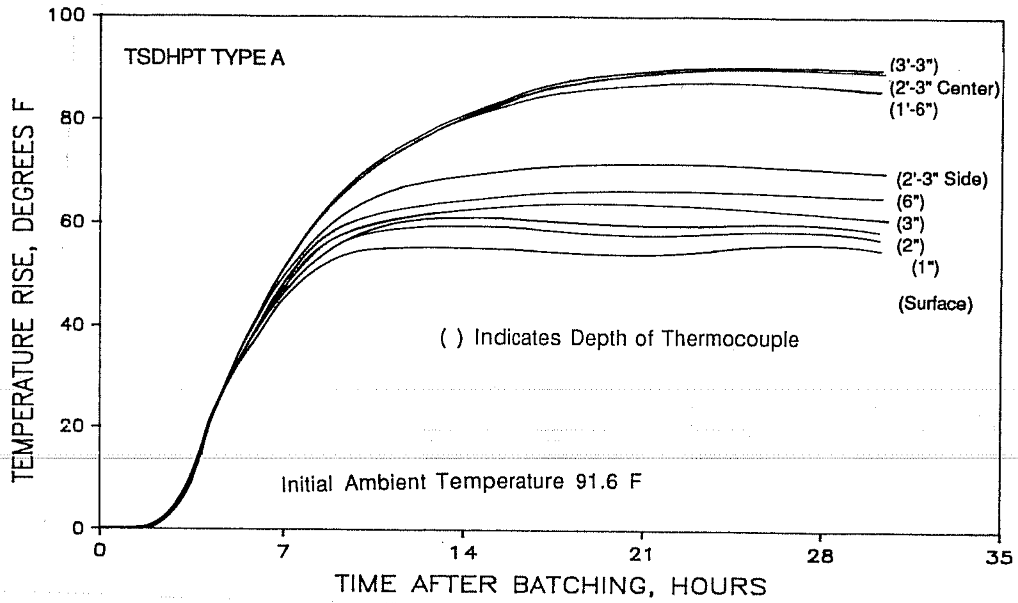


Figure 6.3 Temperature rise profile for 4.5-ft., 5-sack ready mix concrete cube with 30 percent fly ash A2

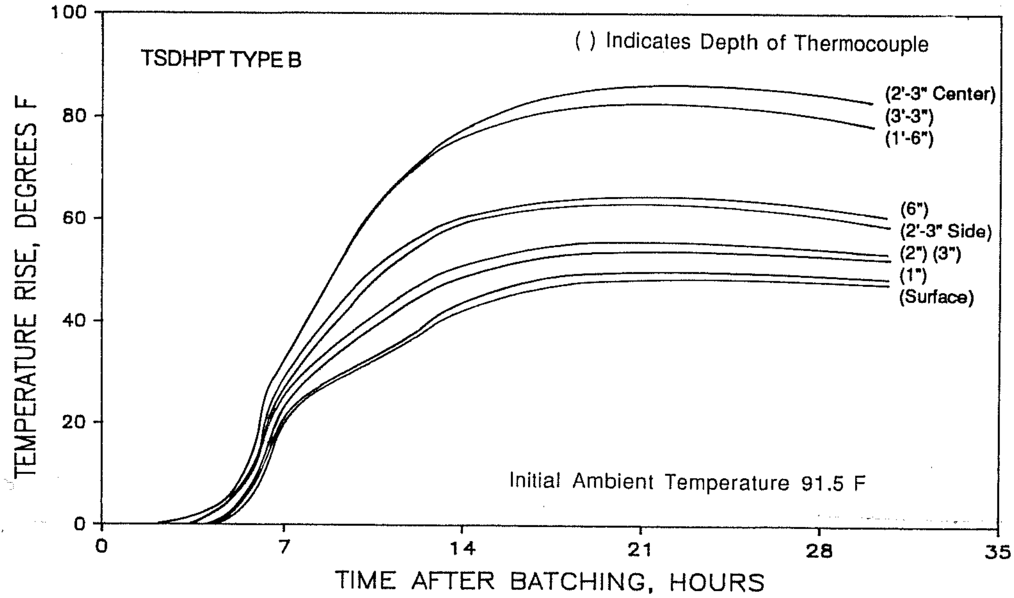


Figure 6.4 Temperature rise profile for 4.5-ft., 5-sack ready mix concrete cube with 35 percent fly ash B1.

will occur is known; casting may be scheduled so that peak temperatures do not coincide with the daily low ambient temperature.

Times to peak temperatures in the cube specimens in this study were determined similarly to those in an earlier study by Barrow [15]. The time to peak does not correspond to the time when the actual maximum temperature was reached. Instead, the time where the curve begins to plateau is designated as the time to peak. The reason for this is that a better comparison between different temperature curves can be made using this determination. Higher temperature curves tend to be rounded at the peak and thus have a defined time of peak. Curves which depict lower temperatures tend to be flatter, and show little change for several hours before and after the maximum temperature is reached. Time elapsed to peak temperature was taken as the time to reach 95 percent of the actual maximum temperature rise; inspection finds this choice to be reasonable.

The time to peak temperature in the slabs was taken as the actual time when maximum temperature occurred. This was done because the temperature profiles in the slabs displayed obvious, rounded peaks, and the time at which maximum temperature occurred was easily noted.

6.2.4 Gradients. The temperature gradient profiles reflect the temperatures across the vertical cross section of the member at the time of maximum temperature difference between the surface and the inside of the member. The inside of the cube was taken as the mid-depth, center thermocouple; the inside of the slab was taken as the thermocouple at 6 inch depth below the surface. The time at which the maximum gradients occur is not necessarily the same time at which maximum peak temperature occurs.

6.3 Typical Temperature Gradient Test Results

6.3.1 Temperature Rise Data. Typical temperature profiles for the 4.5 cubes in the ready-mix concrete tests are shown in Figures 6.1 to 6.4. Typical temperature profiles for polyethylene covered slabs are shown in Figures 6.5 and 6.6. Typical temperature profiles for cotton covered slabs are shown in Figures 6.7 and 6.8.

The peak temperatures for the cubes, polyethylene covered slabs, and cotton mat covered slabs are shown in Tables B.1 to B.3 of Appendix B, respectively.

The time to reach 95 percent of peak temperature in each cube is listed in Table B.1 of Appendix B. The times to reach peak temperature for each curing conditions of slabs is listed in Table B.2 and B.3 of Appendix B.

Ambient temperature profiles for each test may be found in Appendix B.

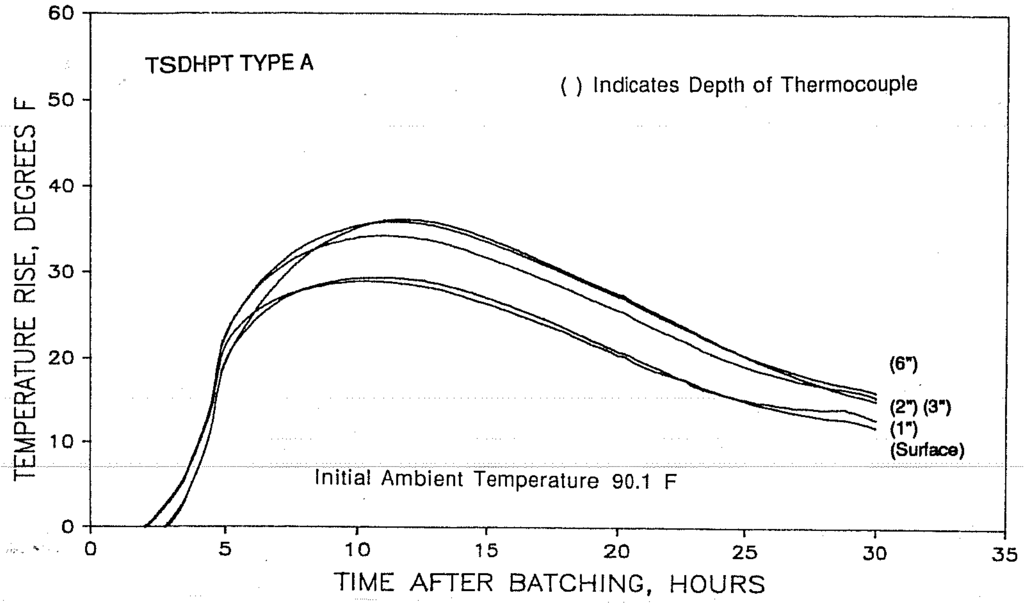


Figure 6.5 Temperature rise profile for plastic covered slab, 5-sack ready-mix concrete with 20 percent fly ash A1

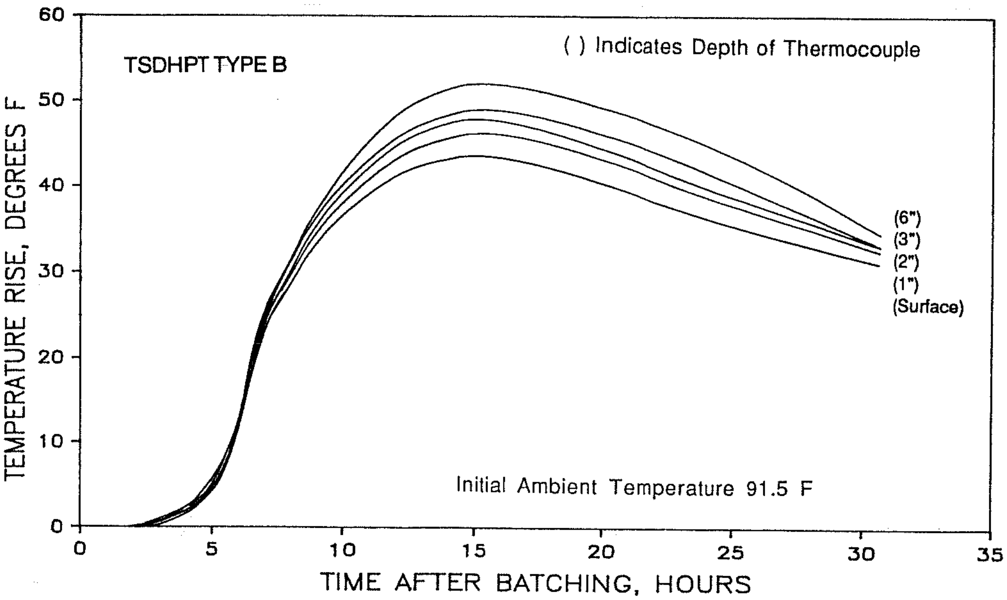


Figure 6.6 Temperature rise profile for plastic covered, 7.5- sack ready mix concrete slab with 35 percent fly ash B1.

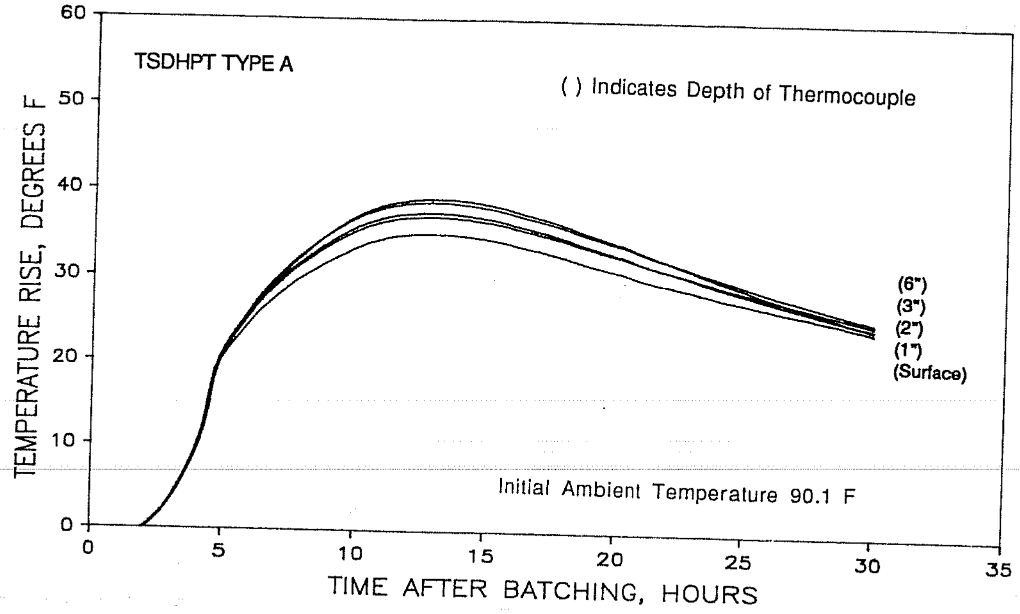


Figure 6.7 Temperature rise profile for cotton mat covered, 5- sack ready-mix concrete slab with 20 percent fly ash A1

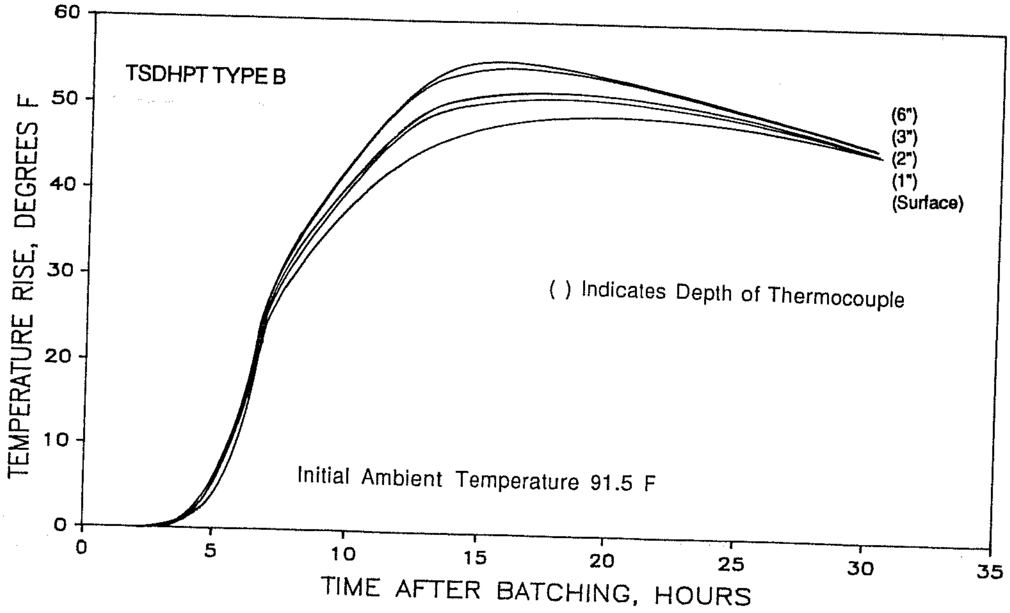


Figure 6.8 Temperature rise profile for cotton mat covered, 7.5-sack ready-mix concrete slab with 35 percent fly ash B1.

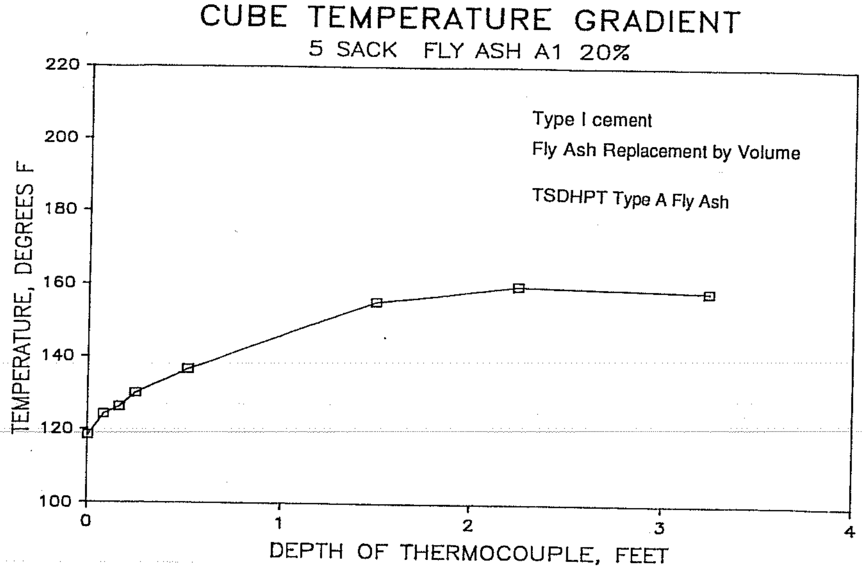


Figure 6.9 Temperature gradient profile for 5-sack ready-mix concrete cube with Type A fly ash.

6.3.2 Temperature Gradients. Typical temperature gradient profiles for the 4.5-foot-cube, polyethylene covered slab, and cotton covered slab are shown in Figures 6.9, 6.10, and 6.11, respectively.

6.3.3 Slump Tests. Slump Tests were conducted on all ready-mix concrete at the time of arrival at the casting site. The results of the slump tests are shown in Figures 6.12 and 6.13. The numerical values of slump measured may be found in Table B.4 of Appendix B.

6.3.4 Compressive Strength Tests. Compressive strength tests were conducted on standard 6" x 12" cylinders. Results for the 5-sack concrete mixtures may be seen in Figure 6.14 while the results for the 7.5-sack concrete mixtures may be seen in Figures 6.15. The results may be found in tabular form in Table B.5 of Appendix B.

6.4 Data Reduction: Calorimetry Tests

6.4.1 Rate of Heat Evolution. The rate of heat evolution curves shown in Figures 6.16 to 6.31, like the earlier presented temperature curves, are a tracing of straight lines connecting data points, as performed by a computer and plotter. These lines appear as smooth curves because there are 30 data points taken per hour. Each data point represents

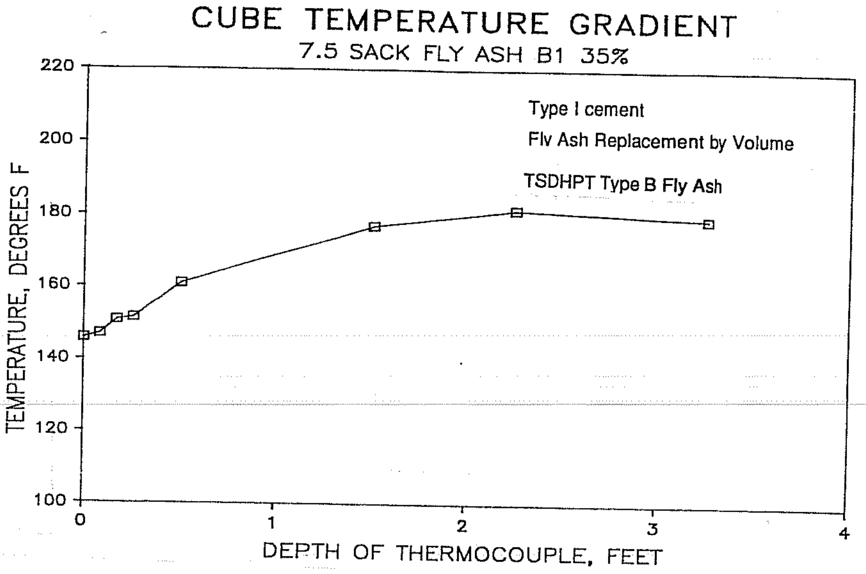


Figure 6.10 Temperature gradient profile for 7.5-sack ready-mix concrete cube with Type B fly ash.

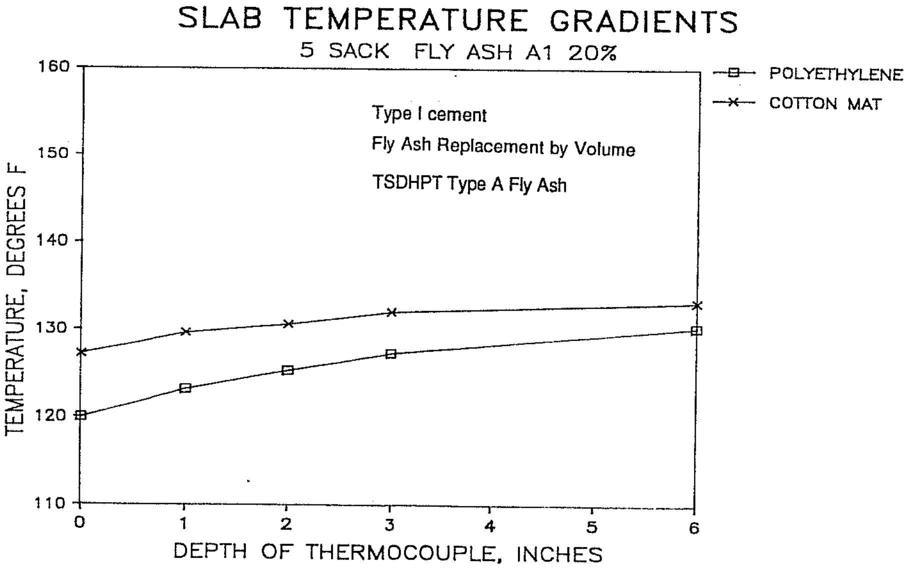


Figure 6.11 Temperature gradient profile for 5-sack ready-mix concrete slab specimens.

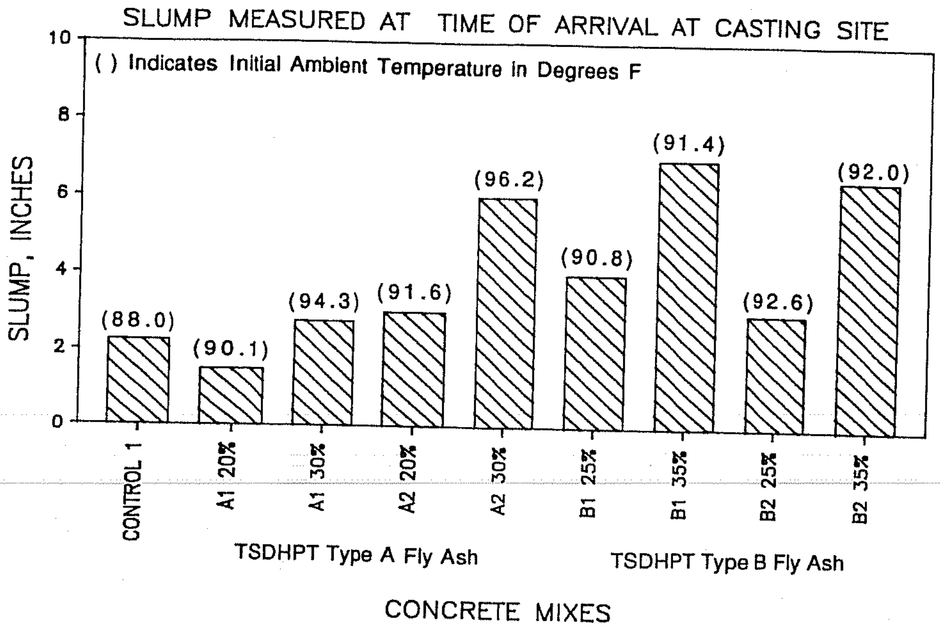


Figure 6.12 Slump test results for 5-sack ready-mix concrete.

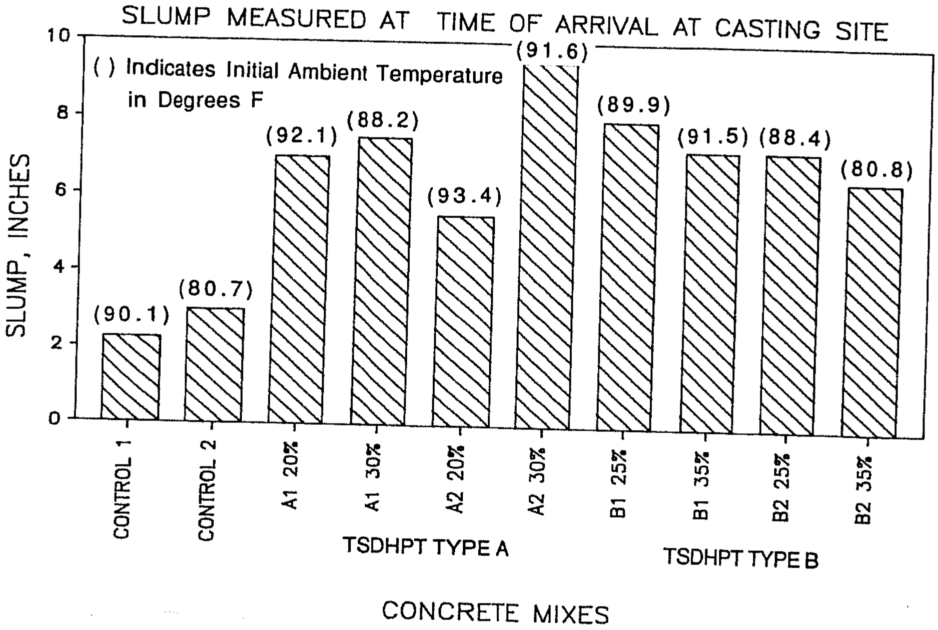


Figure 6.13 Slump test results for 7.5-sack ready-mix concrete.

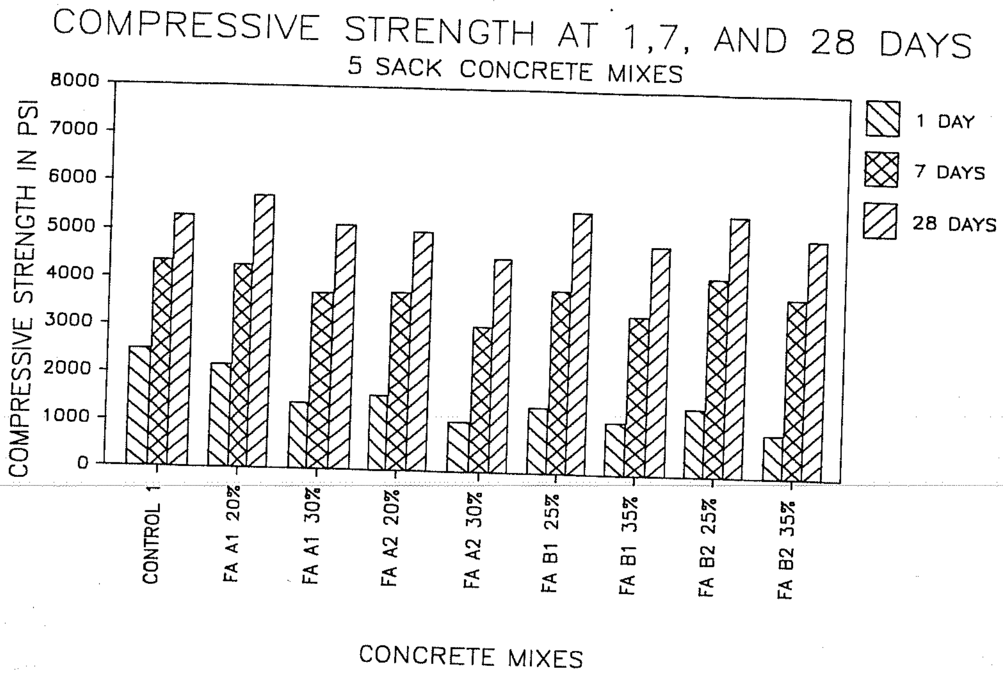


Figure 6.14 Compressive strength test results for 5-sack ready- mix concrete.

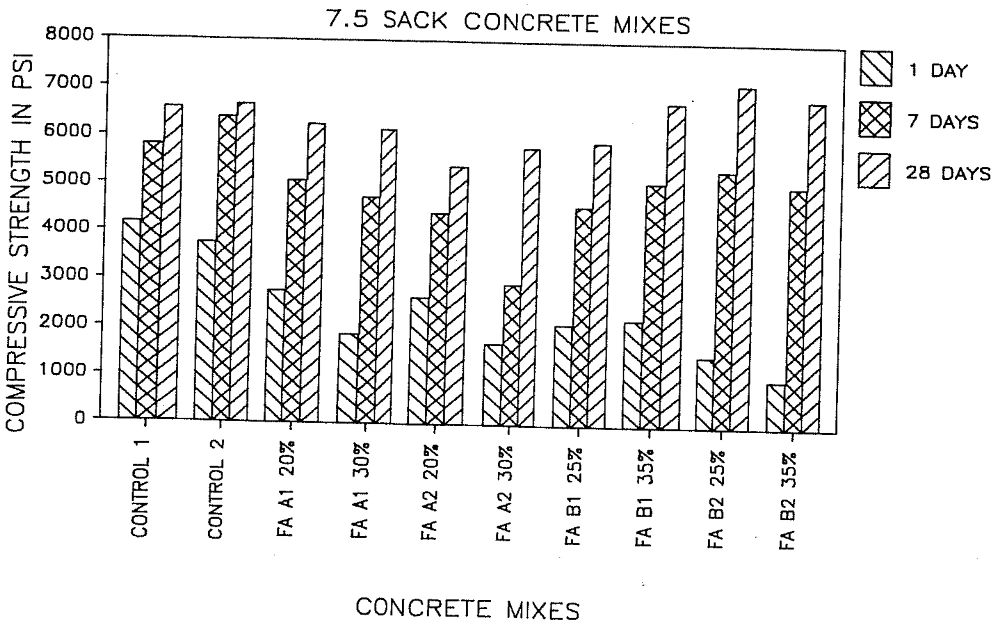


Figure 6.15 Compressive strength test results for 7.5-sack ready-mix concrete.

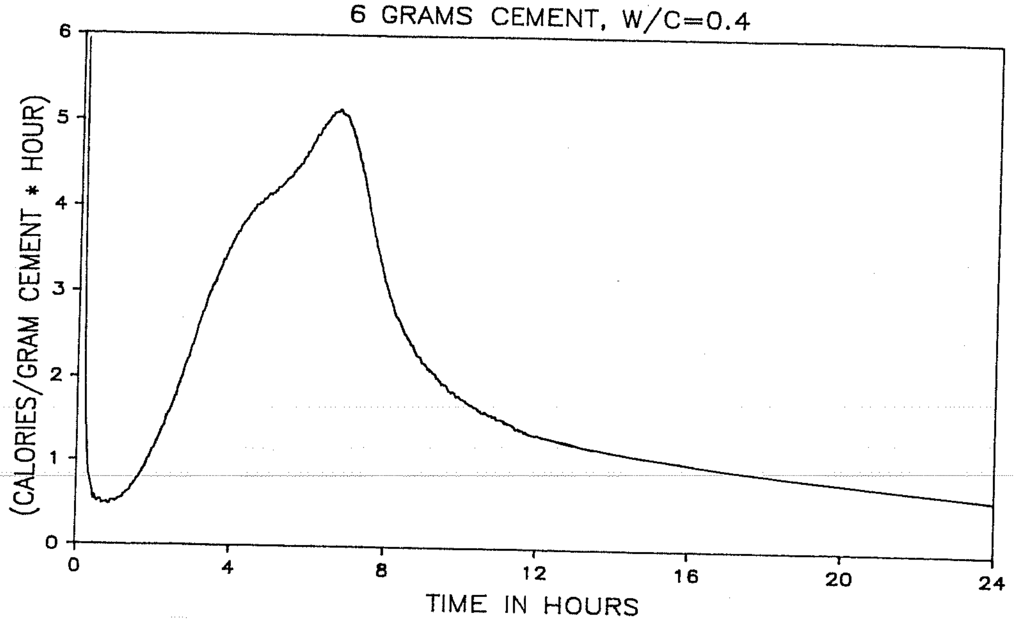


Figure 6.16 Typical rate of heat evolution curve for Type I cement at 100 degrees F.

the average of 3 replicates, unless otherwise noted. The rate of heat evolution data is presented in units of calories/gram cementitious material-hour.

6.4.2 Cumulative Heat Evolution. The cumulative heat evolved during each test was determined using the trapezoidal method to integrate the heat evolution data collected by the calorimetry system. Each cumulative heat evolution curve represents the average of three replicates. Cumulative heat evolution data is presented in units of calories/ gram cementitious material.

6.5 Typical Calorimetry Test Results

6.5.1 Verification of Test Results. A typical rate of heat evolution test result is shown in Figure 6.16. In this test, 6 grams of Type I cement were combined with 2.4 grams of water, for a w/c=0.4. The test was run at 100 degrees F (38 degrees C). An examination of this representative test indicates that the results are comparable to those of similar tests run by other researchers.

A test run by Fajun et. al. [25], on a Type I cement with w/c=0.4 at 100 degrees F was shown in Figure 4.4. It can be seen in Figure 4.4 that the maximum rate of heat evolution approaches 7.0 cal/gram-hour, and that this peak occurs at 5.5 hours. The curve depicted in Figure 6.16 shows similar results: the maximum rate of heat evolution is 5.15 units, and this peak occurs at 6.6 hours.

It should be noted that two different Type I cements were used in the tests under comparison. Therefore, rates of heat evolution will not be identical; they will however, exhibit similar times and magnitudes.

6.5.2 Test Parameters. Before tests were conducted to study the rate of heat evolution in cement pastes, the effects of several important test parameters were studied. Parameters investigated were:

a. Sample Size
b. Number of Cells
c. Raised Cells
d. Number of Paddle Turns
e. Vibration
f. Water to Cementitious Materials Ratio
g. Cement Type

An in-depth review of these parameters was not the purpose of this study, but a brief study was necessary to indicate which parameters have an effect and how sensitive the results in this study are to changes in these parameters. In the actual tests performed to study the rate of heat evolution, an attempt was made to keep all of the above mentioned parameters constant.

6.5.2.1 Effect of Sample Size. A test was run to see if the size of sample used had any effect on the measured rate of heat evolution. Sample sizes of 2, 4, and 6 grams were mixed with enough water to produce a water/cement ratio of 0.50. The same size beaker was used in each test. The tests were conducted at 80 degrees F. The results of the test to study the effect of sample size may be seen in Figure 6.17 The average maximum rate of heat evolution during the acceleration phase for the 2, 4, and 6 gram samples were 3.94, 3.49, and 3.15 calories/gram cement * hour, respectively.

6.5.2.2 Effect of Number of Cells Used. A test was conducted to test the consistency of the results from 9 identical reactants tested simultaneously in 9 different cells under the same conditions. Nine cells containing the same reactants were placed in the bath at 80 degrees F. Each cell also contained 6 grams cement and 3 grams water. The individual cell results may be seen in Figure 6.18.

6.5.2.3 Effect of Cell Rack. A test was run to determine the effect of raising the calorimetric cells off the bottom of the glass water bath tank. Three cells were placed in a plastic rack which allowed the circulation of water to the underside of the cell.

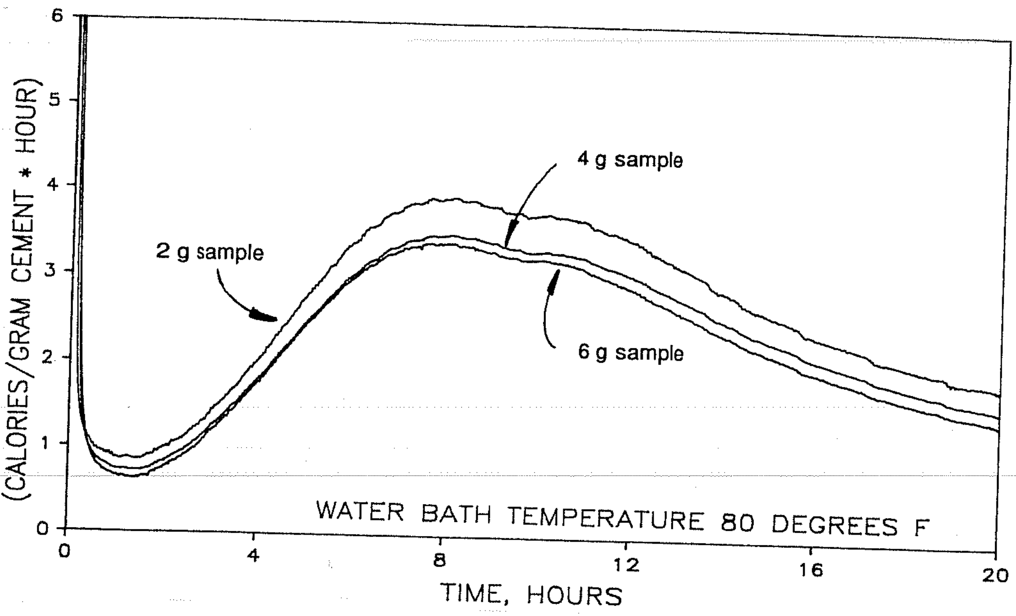


Figure 6.17 Effect of sample size on heat evolution as measured by calorimeter.

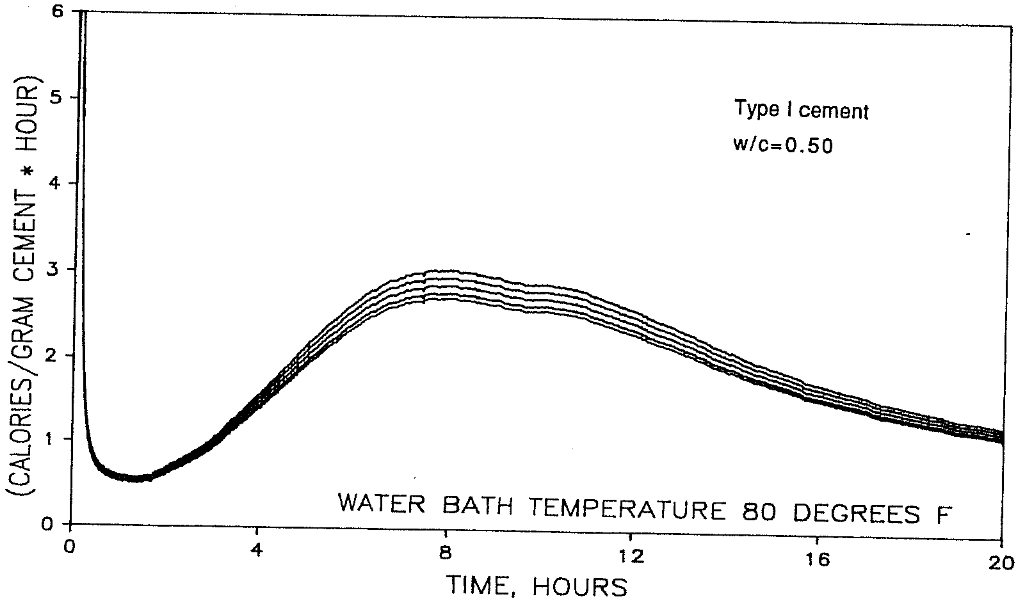


Figure 6.18 Calorimetric curves for 9 calorimetry cells containing identical reactants.

Three cells were placed on the bottom of the glass tank. Each cell contained 6 grams cement and 3 grams water; the water bath temperature was 80 degrees F. Individual cell results may be seen in Figure 6.19.

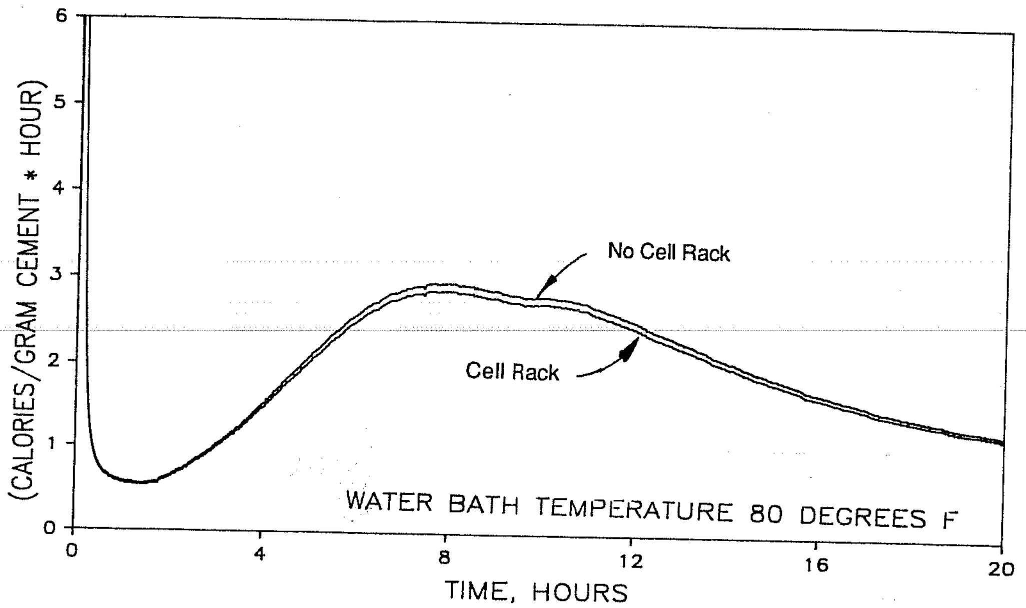


Figure 6.19 Effect of raising cell off bottom of water bath tank.

6.5.2.4 **Effect of Number of Paddle Turns.** The effect of varying the number of paddle turns used to mix the paste may be seen in Figure 6.20. Each calorimetric cell used in the test contained 6 grams Type I cement, and was injected with 3 grams water. After injection with water, five cuts were used to help distribute water throughout the cement. Three cells were then given five complete paddle turns, another three cells were given ten complete paddle turns, and the final three cells were given fifteen paddle turns. The maximum rates of heat evolution in the acceleration phase for 5, 10, and 15 paddle turns were 2.76, 2.88, and 2.96 calories/gram cement*hour, respectively.

6.5.2.5 **Effect of Vibration.** A test was conducted to determine the effect of using vibration to aid in consolidation of the cement paste. Six cells were placed in the bath at 80 degrees F; each cell contained 6 grams Type I cement and 3 grams water. After injection with water, all cells were cut five times and given fifteen paddle turns. In addition, three of the cells had a vibrator held to their paddles for five seconds. The individual cell results may be seen in Figure 6.21. The average maximum rates of heat evolution for unvibrated and vibrated cells were 2.87, and 3.01 calories/gram cement * hour, respectively.

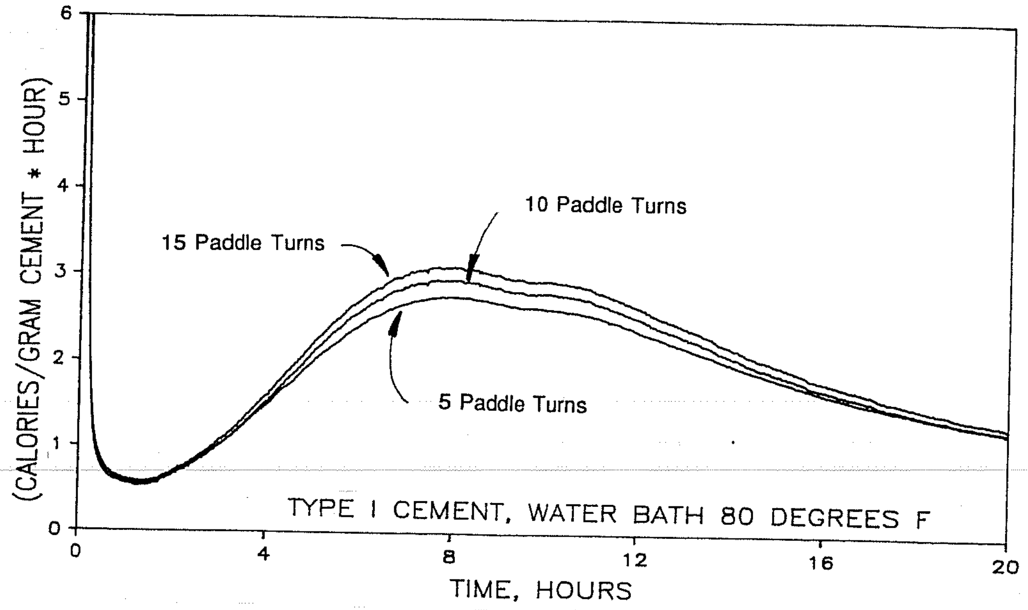


Figure 6.20 Effect of number of paddle turns on the heat evolution of Type I cement paste.

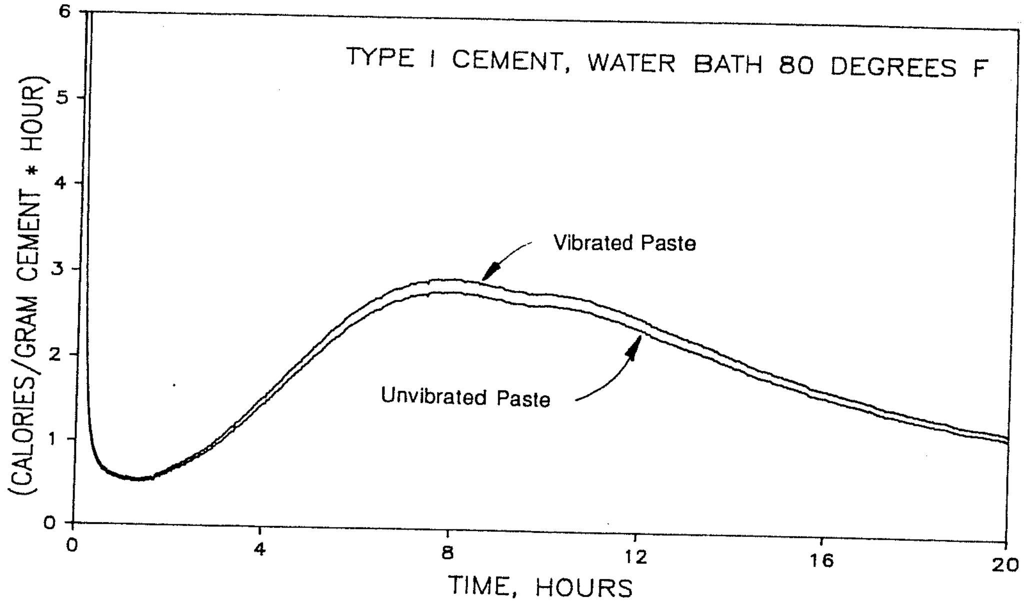


Figure 6.21 Effect of vibration on the heat evolution of Type I cement.

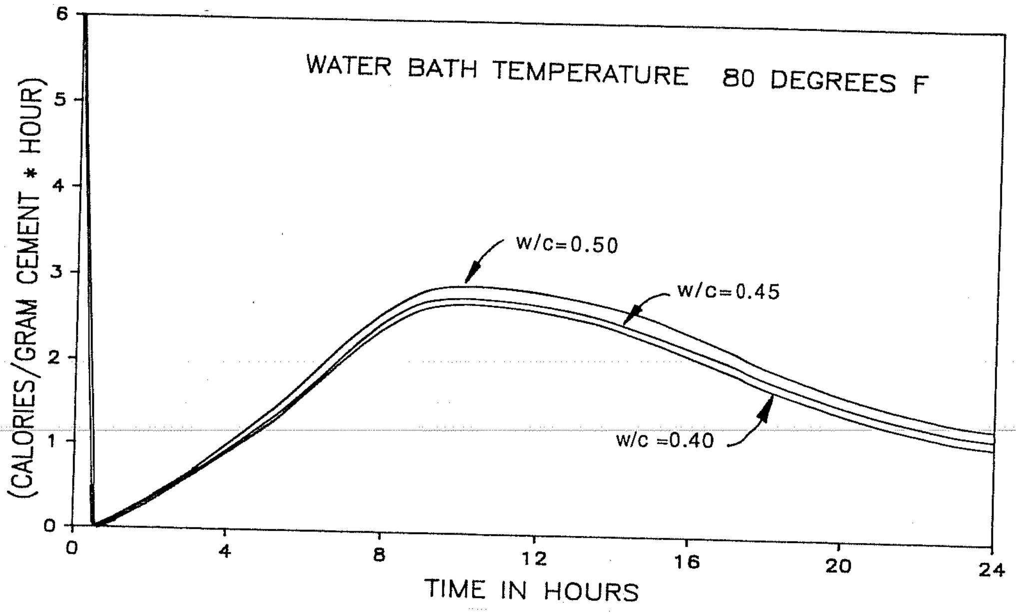


Figure 6.22 Effect of water to cement ratio on heat evolution of Type I cement.

6.5.2.6 Effect of Water to Cementitious Materials Ratio. The effect of water to cementitious materials ratio by weight was monitored for Type I cement. Three sets of three cells contained 6 grams Type I cement; sets were injected with 2.4,2.7,and 3.0 grams of water. All tests were run at 80 degrees F. Results may be seen in Figure 6.22. Average maximum rates of heat evolution for w/c of 0.40, 0.45, and 0.50 were 2.73, 2.82, and 2.96, respectively.

6.5.2.7 Effect of Cement Type. The effect of cement type on the rate of heat evolution is shown in Figure 6.23. Cement types investigated were Type I, Type I-II, and Type III. Each paste had a w/c=0.50. Maximum rate of heat evolution for the Type I, Type I-II, and Type III cement at 80 degrees F were 2.77, 2.76, and 3.82, respectively.

6.5.3 Hydration Profiles.

6.5.3.1 Rate of Heat Evolution. The hydration of cement and cement/fly ash paste subjected to different isothermal temperatures was studied through the use of an isothermal calorimetry system. Typical results of the calorimetry tests to measure the rate of heat evolution for each of the four temperatures are shown in Figures 6.24 to 6.31 . In these tests, fly ash type, percent replacement, and water bath temperature were varied. The (W/C+FA) ratio varied since the amount of water remained constant and the cement was replaced by fly ash on a volume basis. The remaining rate of heat evolution profiles

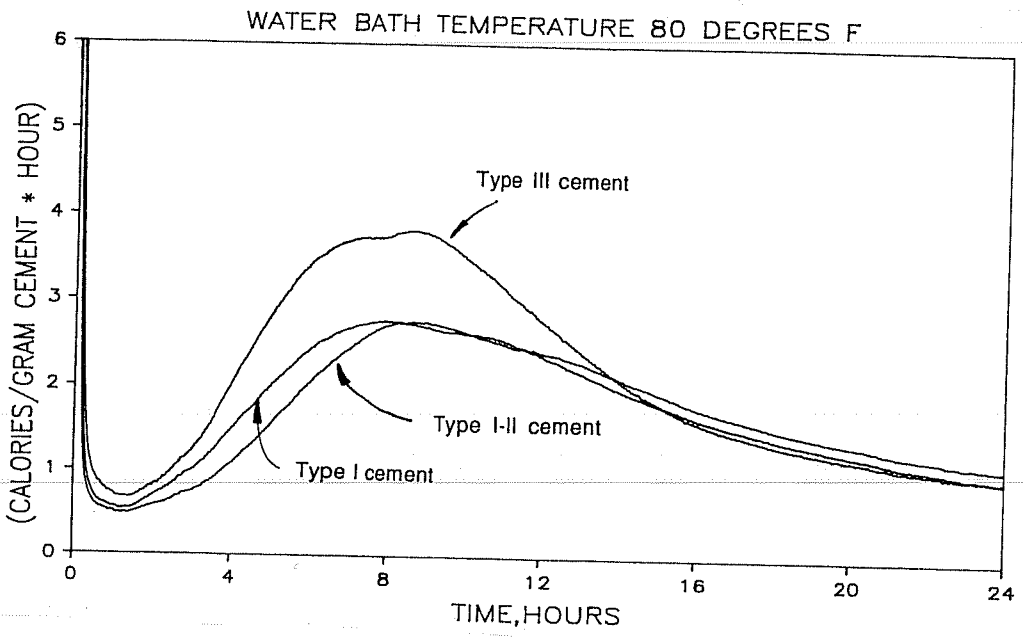


Figure 6.23 Heat evolution curves for Type I, Type I-II, and Type III cements at 80 degrees F.

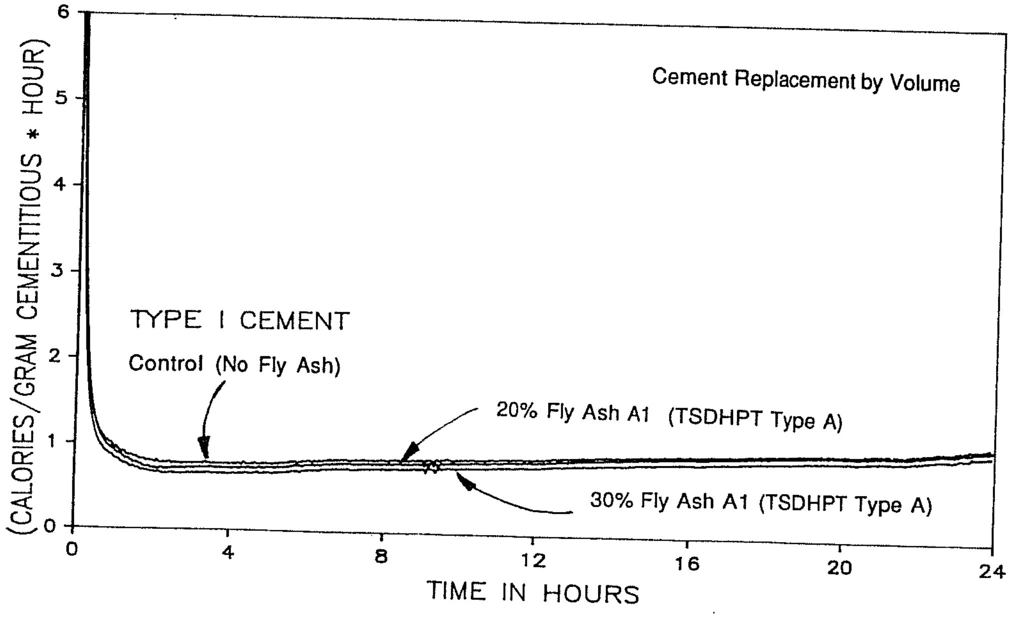


Figure 6.24 Rate of heat evolution for Type I cement with Type A fly ash at 40 degrees F.

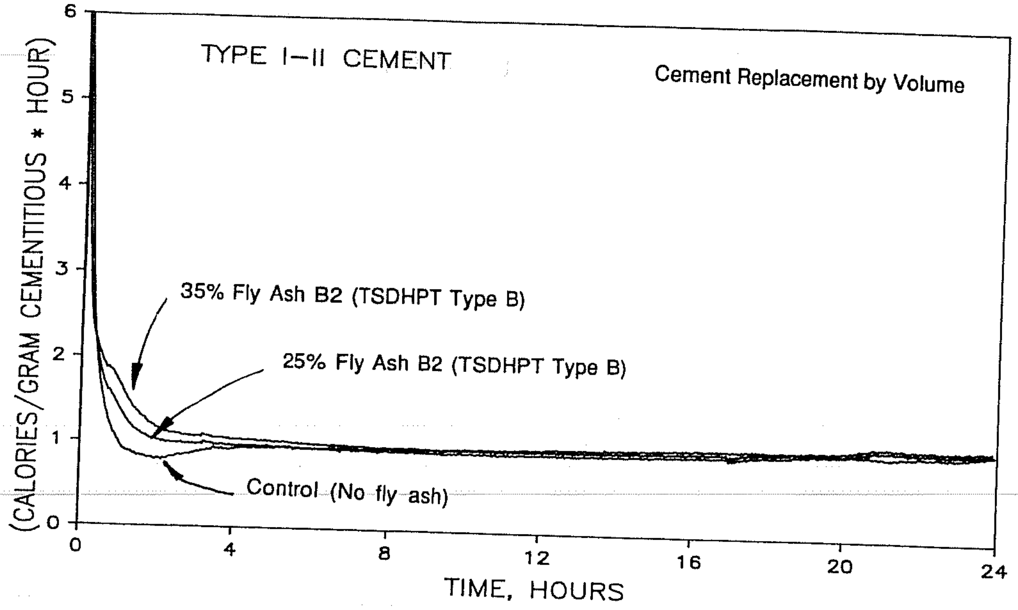


Figure 6.25 Rate of heat evolution for Type I-II cement with Type B fly ash at 40 degrees F.

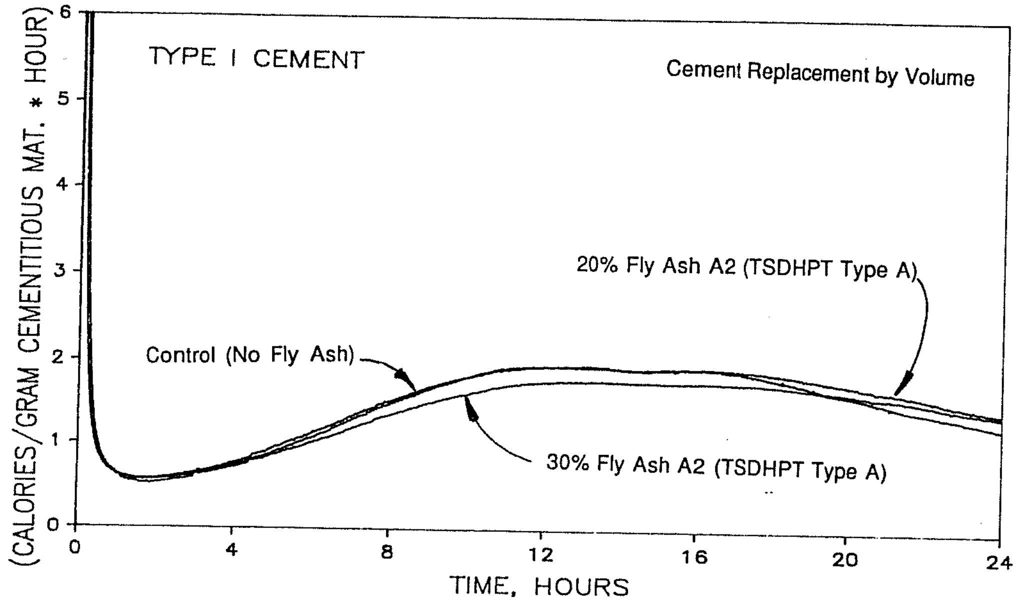


Figure 6.26 Rate of heat evolution for Type I cement with Type A fly ash at 60 degrees F.

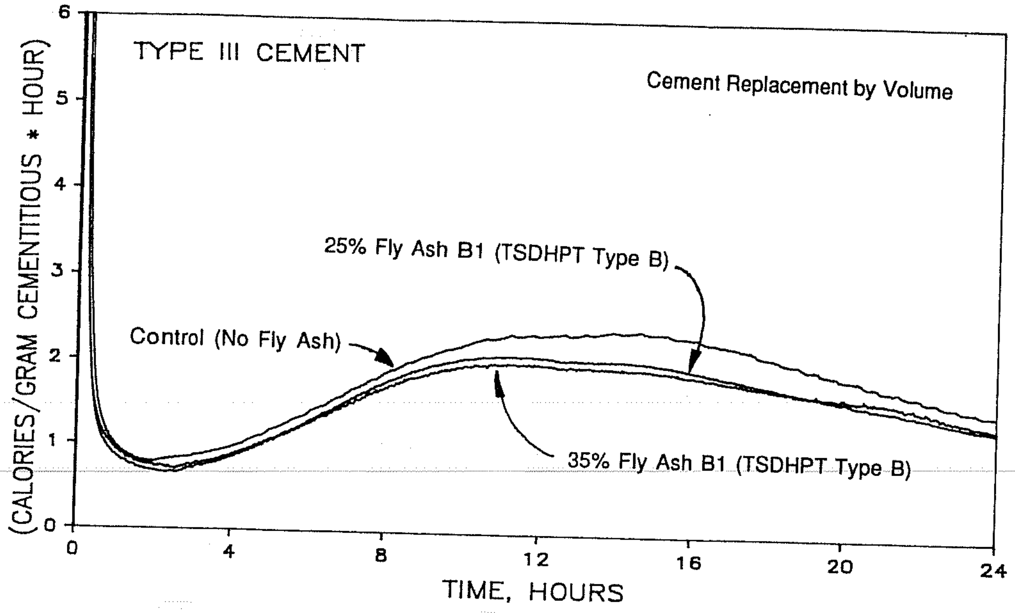


Figure 6.27 Rate of heat evolution for Type III cement with Type B fly ash at 60 degrees F.

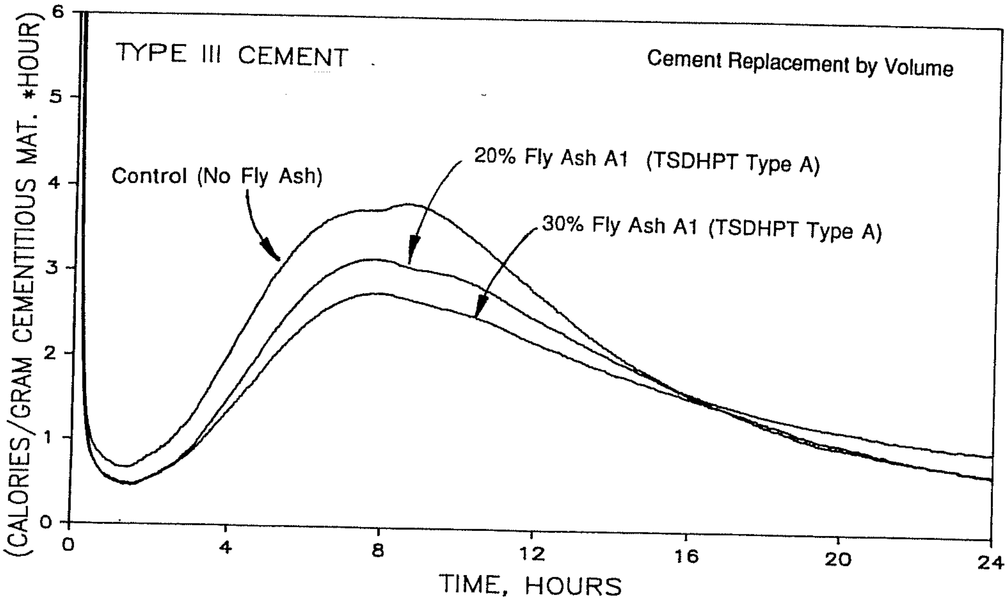


Figure 6.28 Rate of heat evolution for Type III cement with Type A fly ash at 80 degrees F.

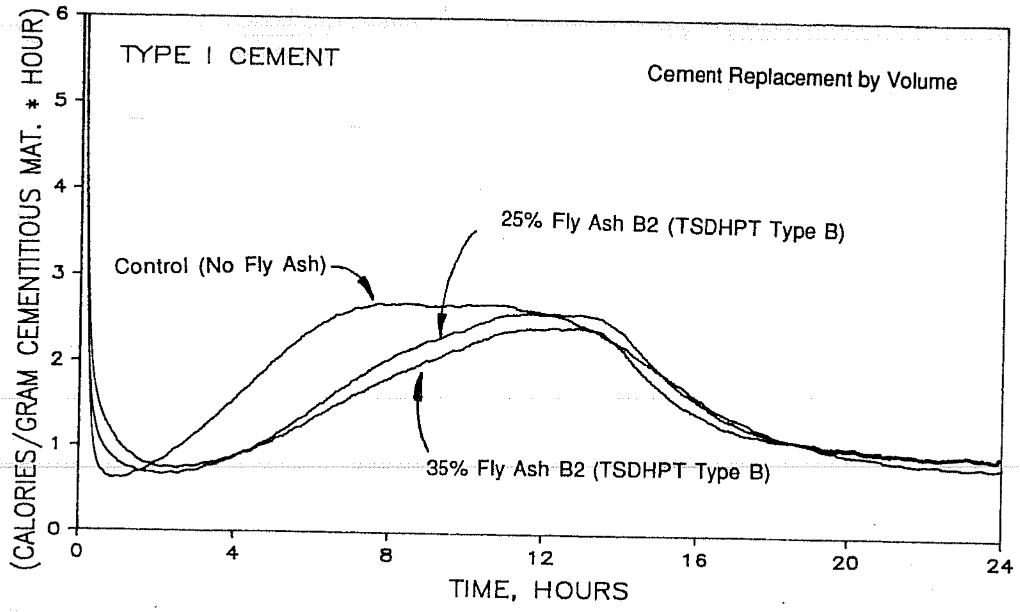


Figure 6.29 Rate of heat evolution for Type I cement with Type B fly ash at 80 degrees F.

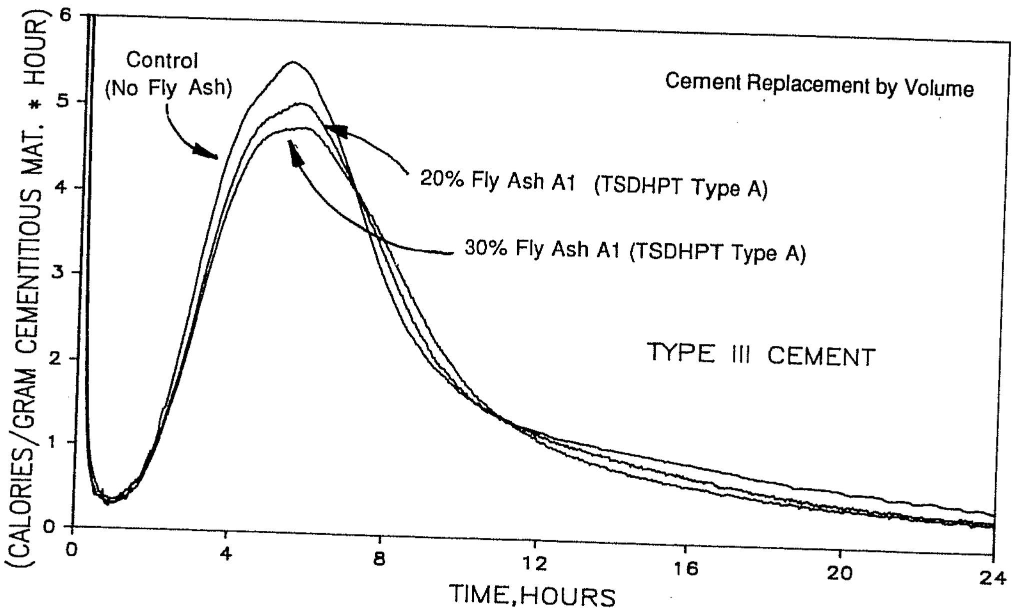


Figure 6.30 Rate of heat evolution for Type III cement with Type A fly ash at 100 degrees F.

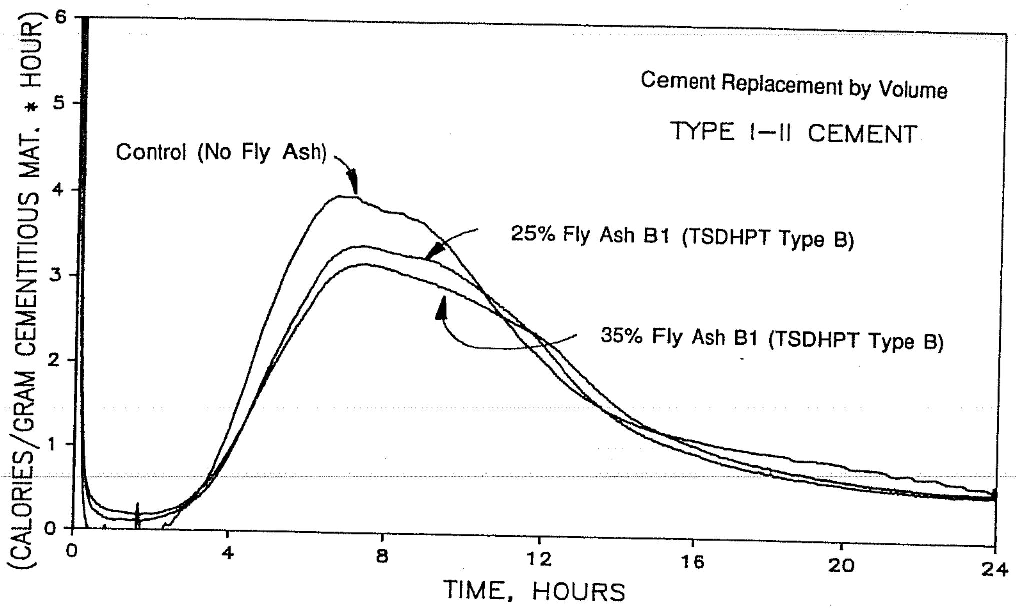


Figure 6.31 Rate of heat evolution for Type I-II cement with Type B fly ash at 100 degrees F.

may be found in Appendix C. The rate of heat evolution profiles are arranged by water bath temperature and cement type.

6.5.3.2 **Cumulative Heat of Evolution.** Typical cumulative heat of evolution results for each of the four temperatures investigated are shown in Figures 6.32 to 6.35. The maximum cumulative heat of evolution results for all tests may be found in tabular form in Appendix C.

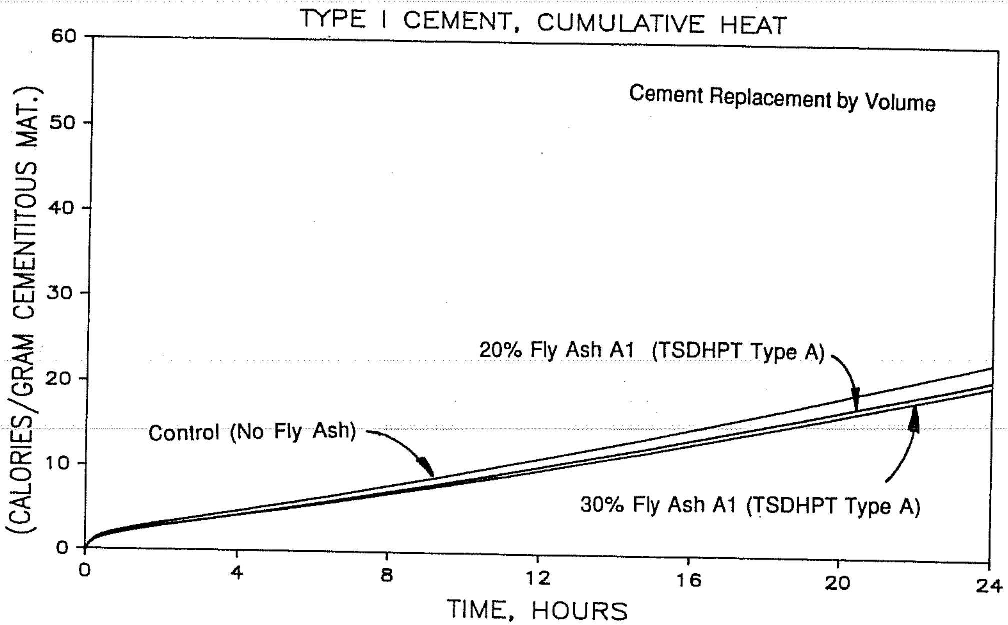


Figure 6.32 Cumulative heat evolution for Type I cement with Type A fly ash at 40 degrees F.

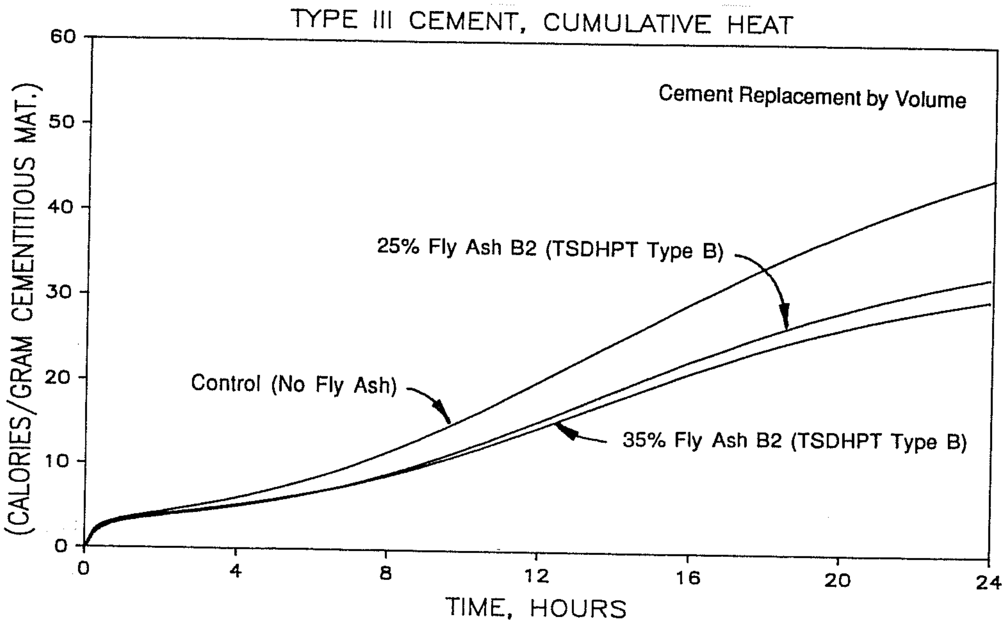


Figure 6.33 Cumulative heat evolution for Type III cement with Type B fly ash at 60 degrees F.

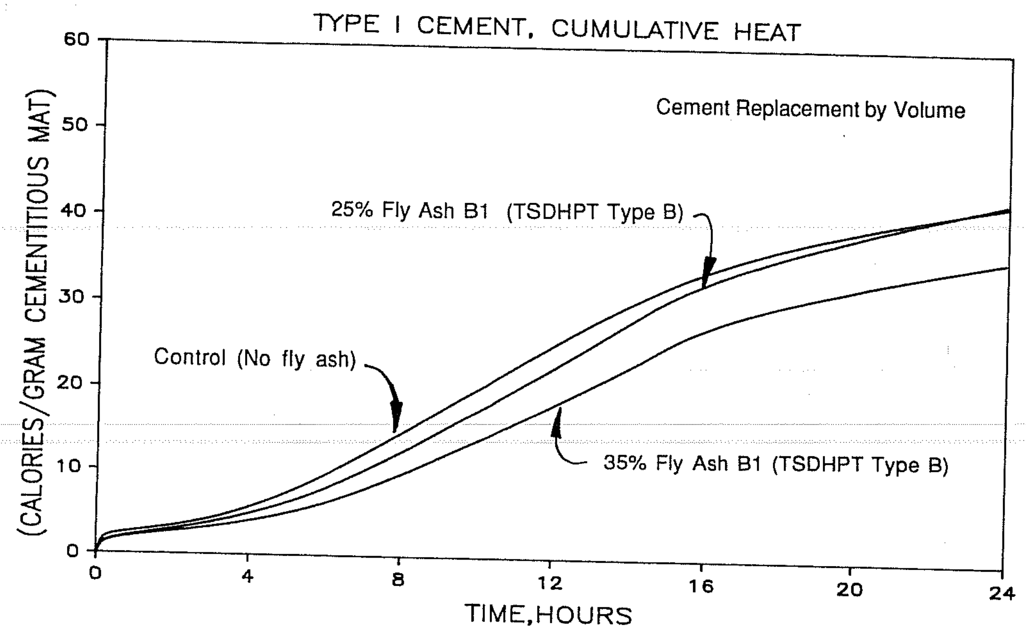


Figure 6.34 Cumulative heat evolution for Type I cement with Type B fly ash at 80 degrees F.

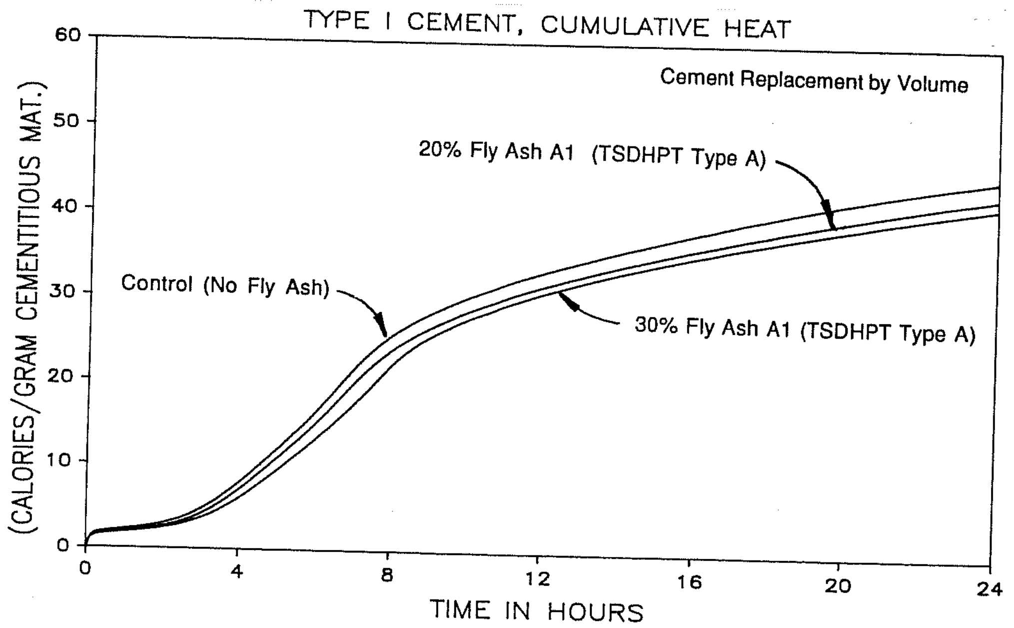


Figure 6.35 Cumulative heat evolution for Type I cement with Type A fly ash at 100 degrees F.

CHAPTER 7
DISCUSSION OF READY-MIX CONCRETE TEST RESULTS

7.1 Introduction

In this chapter, the ready-mix concrete experimental test results are discussed. The cements, fly ashes, and admixtures used in this study are commercially available throughout Texas and provide a basis for comparison of physical and chemical properties for cements, fly ashes, and admixtures in general. It should be noted that other cements, fly ashes, and chemical admixtures may produce different results; however, the trends are believed to be similar to those shown in this section. Thus, for different materials it is recommended to prepare trial batches before construction.

7.2 Effect of Fly Ash on Temperature Rise of Mass Concrete

7.2.1 Maximum Temperature Rise. The temperature rise per 100 pounds of cement was computed for all three control mixtures, and may be found in Table 7.1. In each case, the contribution was found to be 16.2 degrees F per 100 pounds of cement, regardless of the total weight of cement in the mixture.

The temperature rises per 100 pounds of cement plus fly ash for the remaining mixtures were computed assuming the cement contribution was that found for the control mixtures, 16.2 degrees F per 100 pounds of cement. The contribution due to fly ash was then computed by dividing the temperature rise not attributed to cement by the number of 100 pounds of fly ash in the mixture. Results may be seen in Table 7.1. It can be seen that the temperature rise in concrete attributed to fly ash ranged from 10 to 60 percent of that of the same weight of cement.

The effectiveness of fly ash in reducing the temperature rise is somehow dependent upon the cement content. Contributions attributed to fly ash were in general greater for the 7.5-sack cement mixtures. It appears that the increased cement content and corresponding higher adiabatic surrounding temperatures cause the fly ash to contribute more to temperature rise. Because pozzolanic reactions are more temperature sensitive than cement, the additional temperature rise seen in the higher cement content mixtures may be due in part to pozzolanic reactions occurring much sooner than in the lower cement content mixtures, due to the greater adiabatic temperatures. In Figure 7.1, it may be seen that after 5 hours, a maximum internal temperature rise of about 26 degrees F has been reached in the 5-sack concrete mixture, while a maximum internal temperature rise of about 46 degrees has been reached after the same amount of time in the 7.5-sack concrete mixture.

Figures 7.2 and 7.3 show the maximum temperature rise for the 5-sack and 7.5-sack concrete mixtures, respectively. It should be noted that the two 7.5-sack control

Table 7.1 Contributions of Cement and Fly Ash to Temperature Rise

Mix Description Sacks Cement/Yd	TSDHPT Type Fly Ash	Fly Ash	Replacement Ratio	Degrees F per 100 Lb.Cement	Degrees F per 100 Lb.Fly Ash
5 SACK MIXES	N.A. Control mix	N.A.	N.A.	16.2	N.A.
	A	A1	20%	16.2*	3.0
			30%	16.2*	2.5
		A2	20%	16.2*	2.0
			30%	16.2*	0.9
	B	B1	25%	16.2*	5.6
			35%	16.2*	4.0
		B2	25%	16.2*	9.3
			35%	16.2*	8.3
7.5 SACK MIXES	N.A. Control Mixes	N.A.	N.A.	16.2	N.A.
		N.A.	N.A.	16.2	N.A.
	A	A1	20%	16.2*	6.8
			30%	16.2*	6.7
		A2	20%	16.2*	3.9
			30%	16.2*	3.3
	B	B1	25%	16.2*	5.8
			35%	16.2*	8.5
		B2	25%	16.2*	7.1
			35%	16.2*	5.9

* For mixtures containing fly ash, the contribution of the cement was assumed to be the same as that measured for the companion mixture containing no fly ash.

mixtures showed nearly the same temperature rise despite the fact that there was a difference in initial fresh concrete temperature of 9.4 degrees F. This is the result of the 4.5-ft. cube offering a nearly adiabatic condition for the internal concrete, and so no heat is lost to the environment. Therefore, a direct comparison of the maximum temperature rise of the 7.5-sack 35 percent fly ash B2 mixture cast at 80.7 degrees F with the other 7.5-sack mixtures cast at temperatures in the 90 degree range is valid.

In all cases, the use of fly ash resulted in a lower maximum temperature rise as compared to the control mixtures. The use of increased amounts of fly ash resulted in greater decreases in maximum temperature rise.

In general, the use of Type A fly ashes resulted in lower temperature rises than Type B fly ashes. This lower temperature rise displayed by the Type A fly ashes appears

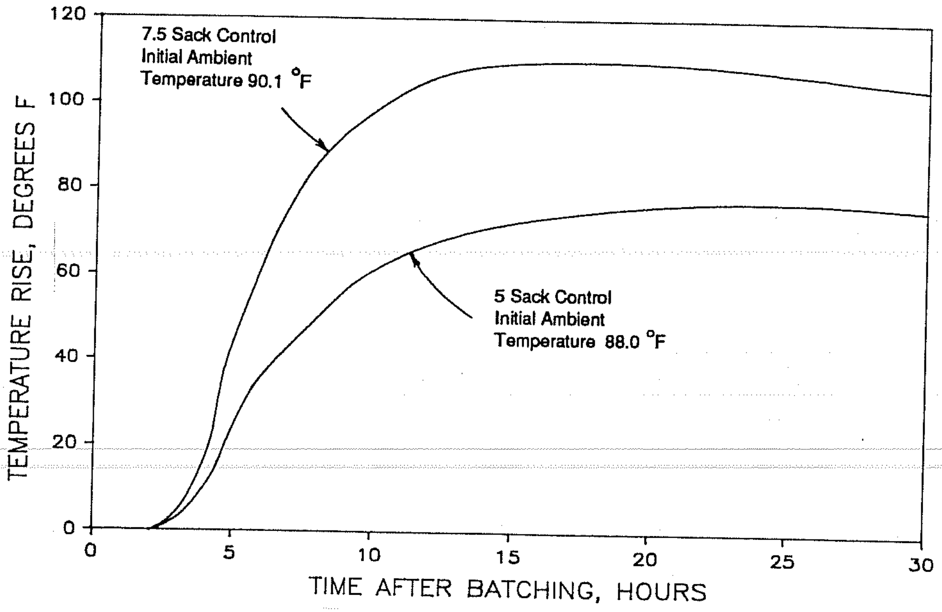


Figure 7.1 Maximum temperature rise profiles for 5 and 7.5-sack control mixtures cast at similar ambient temperatures.

to be due to the replacement of cement by a material which is fairly unreactive at early ages and having little to no cementitious properties. The effectiveness of Type A fly ashes over Type B fly ashes is not as apparent for the higher cement content mixtures. This may again be due to the activation of the pozzolanic reactions at an earlier age under the influence of higher internal concrete temperatures.

It is generally believed that high calcium fly ashes will generate more heat during reaction than low calcium fly ashes. While this may be true, the CaO content alone cannot explain the temperature rise which is attributed to fly ash. Fly ash A1 has a CaO content of 9.55 percent as opposed to a CaO content of 9.60 percent for fly ash A2, but the maximum temperatures for fly ash A1 mixtures are generally higher than those for fly ash A2.

7.2.2 Time to Peak Temperature. Under adiabatic conditions, the time required to reach the maximum temperature rise does not have an effect on the peak temperature because no heat is lost to the environment. This may be seen in Figure 7.4, which compares temperature rise profiles for the two identical 7.5-sack control mixtures cast at different ambient temperatures. While the mixture cast at the lower temperature is several hours behind the mixture cast at the higher temperature in reaching the peak temperature, the maximum temperature rise which is reached by each mixture is very nearly the same, 112.3 versus 111.8 degrees F.

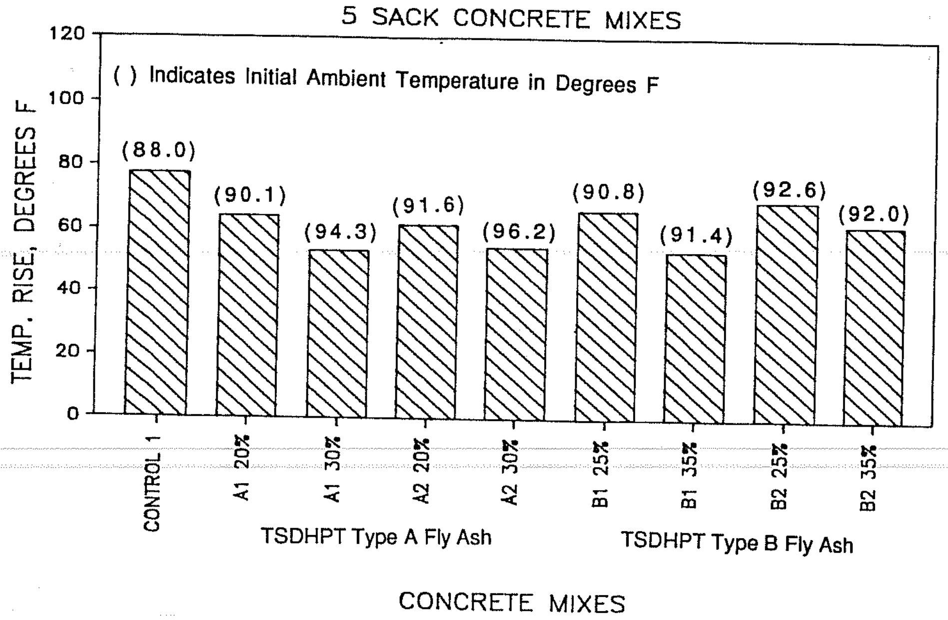


Figure 7.2 Maximum temperature rise values for 4.5-ft. cubes, 5-sack concrete mixtures.

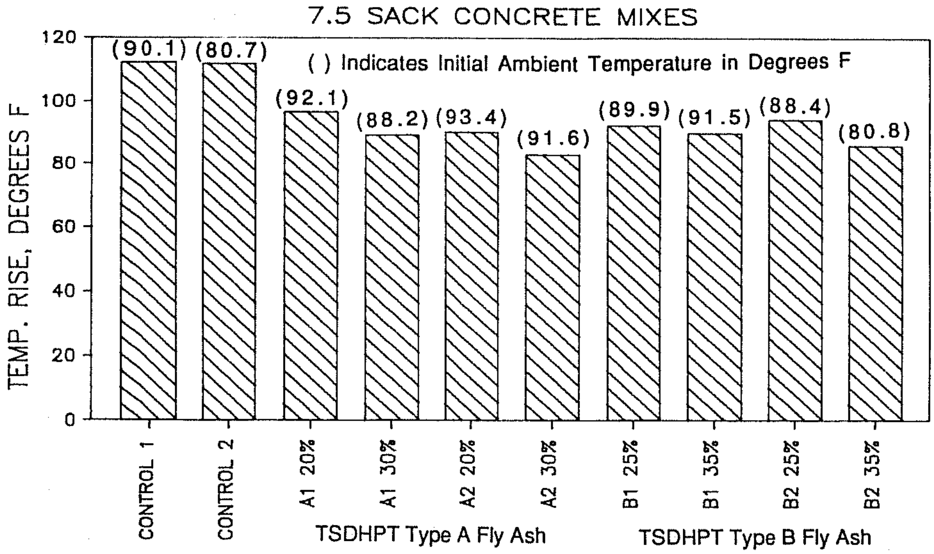


Figure 7.3 Maximum temperature rise values for 4.5-ft. cubes, 7.5-sack concrete mixtures.

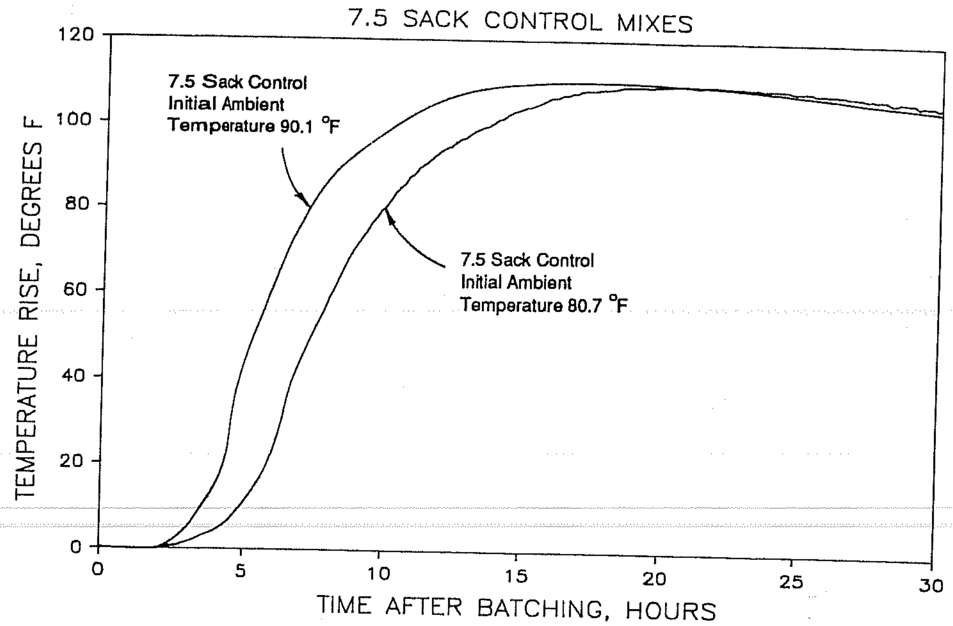


Figure 7.4 Maximum temperature rise for 7.5-sack control mixtures cast at different ambient temperatures.

In concrete members where heat loss is significant, such as a slab section, the time to peak temperature influences the peak temperature because a longer time to peak allows more heat to dissipate. The longer time to peak thus results in a lower internal temperature rise in concrete.

The time to reach 95 percent peak temperature rise for the 5 and 7.5-sack concrete cubes are shown in Figures 7.5 and 7.6, respectively. The time to reach 95 percent peak temperature is dependent on the ambient temperature, the cement content, and the fly ash type.

The influence of ambient temperature on the time to peak temperature is illustrated in Figure 7.6. The time to peak temperature for the two 7.5-sack control mixtures is not the same, even though the maximum temperature rise was the same for both mixtures, as was illustrated in Figure 7.1. Control mixture 1, which was cast at an initial ambient temperature of 90.1 degrees F required about 10.6 hours to reach 95 percent of peak temperature rise, while Control mixture 2, which was cast at 80.7 degrees F initial temperature, took over 15 hours to reach 95 percent maximum temperature. The concrete placed at a higher temperature required a shorter time to reach maximum temperature rise because cement hydration occurs more rapidly at higher temperatures. Therefore, a comparison of the time to peak temperature for the 7.5-sack mixture with 35 percent fly ash B2 to the other 7.5-sack mixtures cast at higher temperatures is not completely valid. The time to

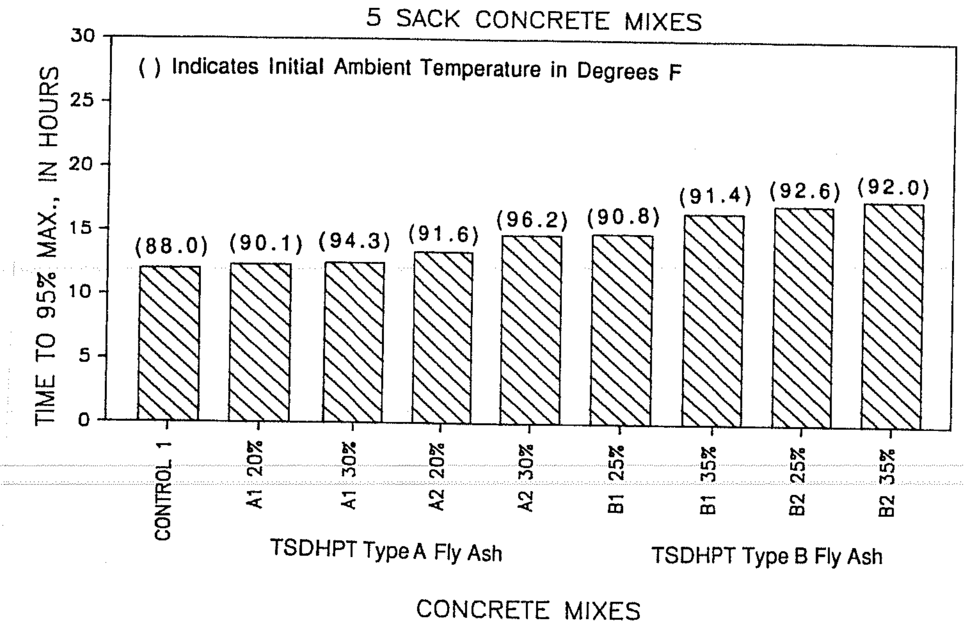


Figure 7.5 Time to reach 95 percent peak temperature in 4.5-ft. cubes, 5-sack concrete mixtures.

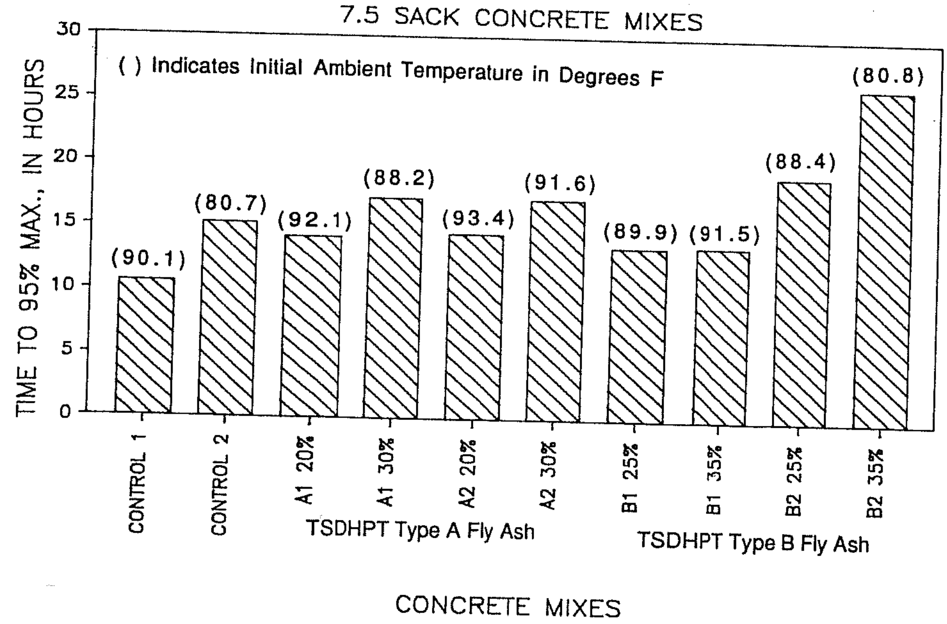


Figure 7.6 Time to reach 95 percent peak temperature in 4.5-ft. cubes, 7.5-sack concrete mixtures.

peak for the 7.5-sack 35 percent fly ash B2 mixture is probably longer than it would have been if cast at the same temperature as the other 7.5-sack mixtures with fly ash.

A comparison of the control mixtures which were cast at similar temperatures shows that the 5-sack control mixture required a greater time to reach peak temperature than the 7.5-sack Control 1. The accelerated hydration of the cement due to the higher adiabatic temperatures at early ages is most probably the cause of this behavior. A comparison of the 5 and 7.5-sack mixtures with fly ash does not find the same trend. The 7.5-sack mixtures with fly ash required longer times to reach maximum temperature than their respective 5- sack mixtures, except in the case of fly ash B1. The retarding effects of the fly ashes were more apparent when used in mixtures with higher cement contents, which exhibit higher and more accelerated temperature rise.

No fly ash mixtures reached the peak temperature earlier than the control mixtures containing no fly ash. In general, the Type A fly ash mixtures reached the peak temperature earlier than did the Type B fly ash mixtures. The time to peak temperature increased with increased fly ash replacement, regardless of the fly ash type. The longer time to peak temperature found when fly ash is used is therefore not due simply to the replacement of cement by a nonreactive material, but to some characteristic of the fly ash, because the effect increases with greater fly ash replacement. As was explained in Chapter 4, researchers have not come to a consensus on what chemical or physical characteristics of the fly ashes cause the retardation to occur.

The longer time to peak temperature displayed when fly ash was used as a partial cement replacement may indicate that, although the peak temperature may not be greatly reduced under nearly adiabatic conditions, under conditions where the rate of heat loss is significant, the longer time to peak may result in a lower temperature rise in concrete in service. As the temperature is reaching its peak, more time is allowed for heat to dissipate, thereby reducing the peak temperature reached.

7.3 Effect of Fly Ash on Temperature Rise of Slab Specimens

7.3.1 Maximum Temperature Rise. The method of curing used plays an important role in determining the actual temperature rise of concrete. Covering a section with a thick, moistened cotton mat will provide more nearly adiabatic conditions, while covering a section with polyethylene sheeting allows for easier dissipation of heat from the concrete. Figures 7.7 and 7.8 show that in general, the use of a cotton mat as a curing method will result in a similar or greater temperature rise than the use of polyethylene sheeting.

This result is not as apparent for the 5-sack concrete mixtures as compared to the 7.5-sack concrete mixtures.

When higher cement content mixtures are used, greater rates of temperature rise are seen. The effect of the curing condition used is more pronounced under these conditions; since each curing condition will only allow a certain rate of heat dissipation, when there is a greater rate of heat generation, temperature buildups in the section will be greater. The cotton mat allows less heat dissipation than the polyethylene sheeting allows, so greater temperature rises would be expected when it is used. At lower temperatures and lower rates of temperature rise, the rate of heat generation may be small or may not even exceed the rate of heat dissipation allowed by either curing condition, and so differences in temperature rise in sections cast of the same concrete but subjected to different curing conditions may not be evident.

The results shown in Figures 7.7 and 7.8 for slab specimens show that the use of fly ash results in reductions in the maximum temperature rise of concrete regardless of the curing method used. In all cases, the use of fly ash resulted in reduced peak temperatures in comparison to the control mixtures. The effectiveness of fly ash in reducing the maximum temperature rise was generally greater for the 7.5-sack concrete mixtures.

The 7.5-sack control mixtures cast at different temperatures did not exhibit the same maximum temperature rise. The slabs covered with polyethylene showed maximum temperature rises of 84.5 degrees F for the slab cast at 90.1 degrees F, and 69.9 degrees F for the slab cast at 80.7 degrees F. The slabs covered with cotton mats showed maximum temperature rises of 81.9 degrees F for the slab cast at 90.1 degrees F, and 75.4 degrees F for the slab cast at 80.7 degrees F.

The difference in these results is the result of the higher heat dissipation that occurs at lower rates of temperature rise. Since the rate of temperature rise is lower at lower ambient temperatures, there is more time allowed for heat dissipation, and thus lower maximum temperatures will be reached.

The results also confirm the higher rate of heat dissipation allowed by the polyethylene as compared to the cotton mat. At lower temperatures and their corresponding lower rates of temperature rise, the rate of heat generation may not exceed the amount of heat dissipation allowed either curing condition, so differences between the cotton mat and polyethylene curing methods may not be seen. However, at higher ambient temperatures, the rate of temperature rise will be greater, and may exceed the rate of heat dissipation of the curing conditions. The polyethylene allowed more heat dissipation and thus resulted in a lower maximum temperature rise as compared to the cotton mat, 69.9 degrees F versus 75.4 degrees F for the 7.5-sack control mixes.

In general, polyethylene covered slabs with Type B fly ashes showed greater or similar temperature rise reductions in comparison to Type A fly ashes. Increased fly ash

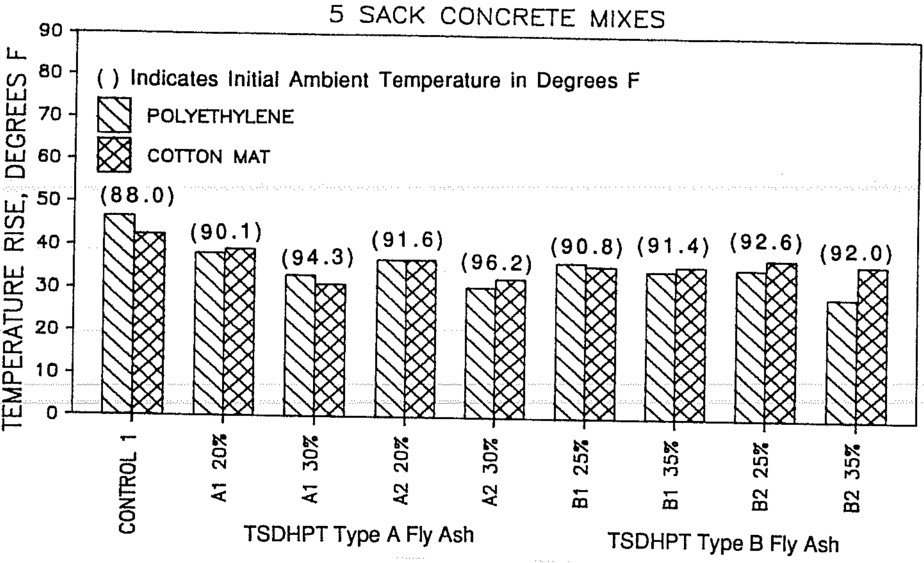


Figure 7.7 Maximum temperature rise values for 5-sack concrete slab specimens.

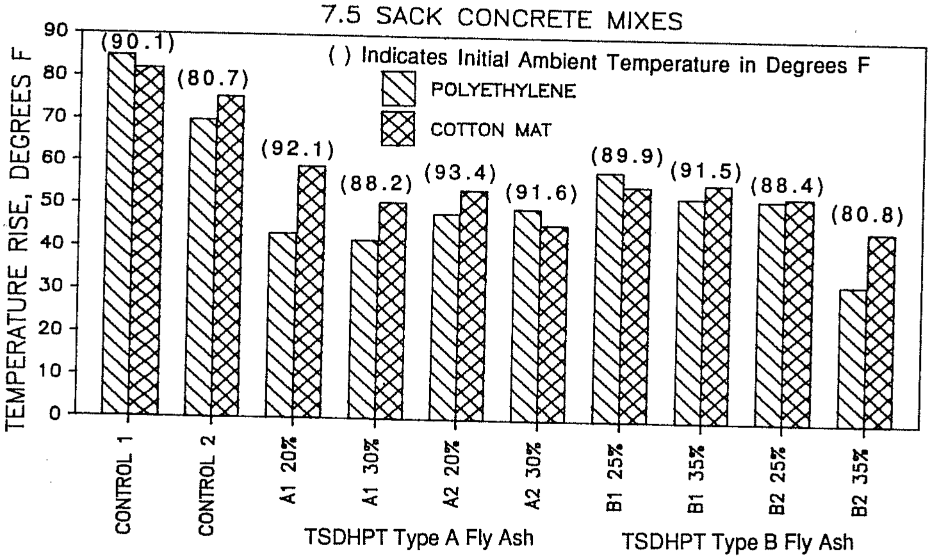


Figure 7.8 Maximum temperature rise values for 7.5-sack concrete slab specimens.

replacement generally resulted in greater decreases in temperature rise regardless of fly ash type.

For cotton mat covered slabs, temperature rises for Type B fly ashes were generally greater than those exhibited by Type A fly ashes. Increasing levels of Type A fly ash replacement resulted in decreased temperature rise for both 5 and 7.5-sack mixes for slabs covered with cotton mats. Increased replacement with Type B fly ashes did not result in an additional decrease in temperature rise, except for the 7.5-sack 35 percent fly ash B2 mixture. This mix was cast at a lower temperature, so the decreased temperature observed is to be expected.

7.3.2 Time to Peak Temperature in Slabs. The method of curing used has an effect on the time to reach maximum temperature. As seen in Figures 7.9 and 7.10, the use of a cotton mat resulted in longer times to peak temperature than the use of polyethylene sheeting in almost all cases. The cotton mat serves as an insulator, and does not allow heat to dissipate away from the section as quickly as the polyethylene sheeting.

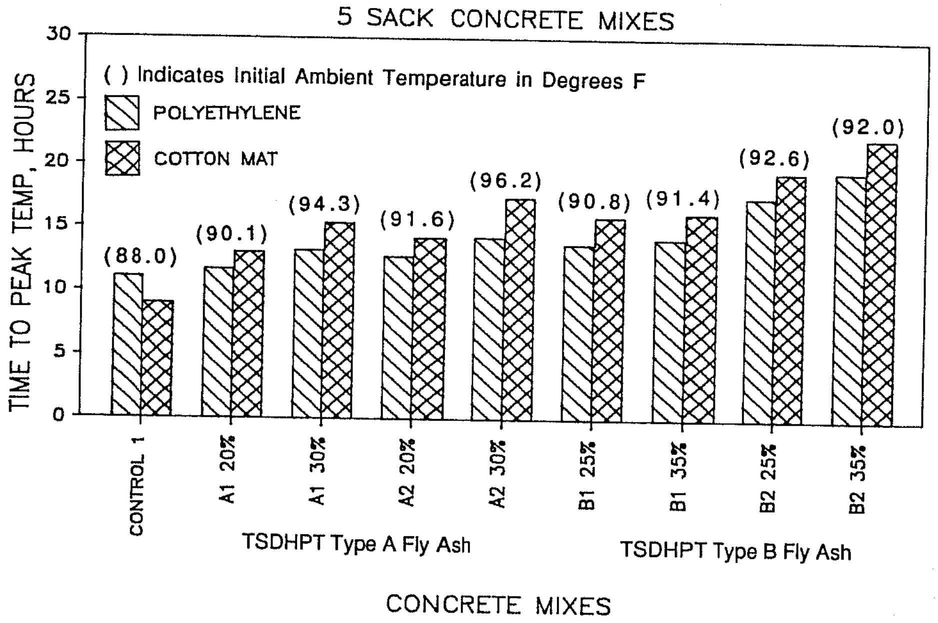


Figure 7.9 Time to reach peak temperature in 5-sack concrete mix slab specimens.

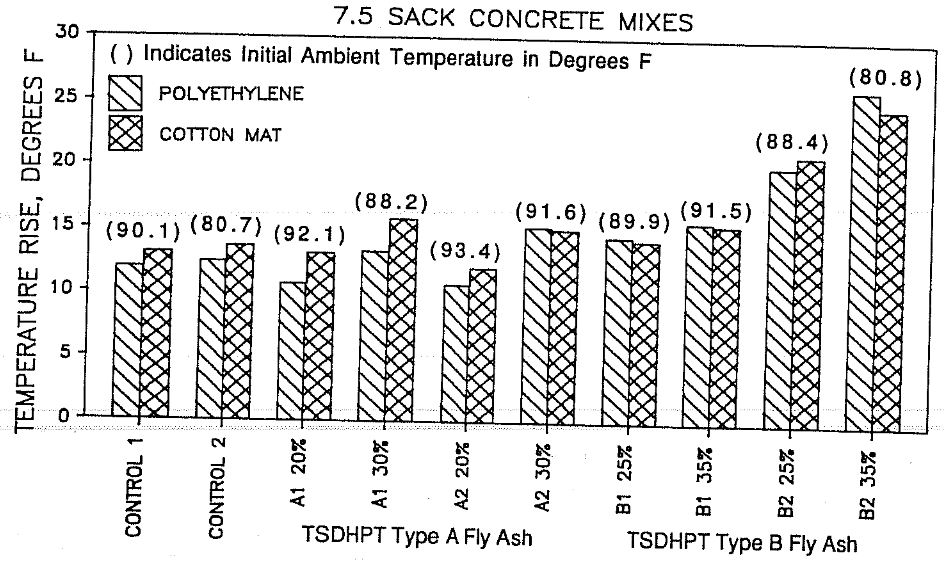


Figure 7.10 Time to reach peak temperature in 7.5-sack concrete mix slab specimens.

The use of fly ash resulted in increased time to peak temperature rise in all cases. In general, Type A fly ashes were found to reach the maximum temperature earlier than Type B fly ashes. Regardless of fly ash type, the use of increased levels of fly ash replacement resulted in increased time to peak temperature.

The role of the time to peak temperature in determining the maximum temperature rise of the slab sections may be seen in comparing the two 7.5-sack control mixtures cast at different temperatures. Both control slabs cast at an initial ambient temperature of 90.1 degrees F displayed greater temperature rises than the control slabs cast at an initial ambient temperature of 80.7 degrees F. Further, the polyethylene covered slab and the cotton mat covered slab cast at 90.1 degrees F also reached their peak temperatures slightly earlier than the similarly cured control slabs cast at 80.7 degrees F. Thus, the slabs cast at lower temperatures underwent hydration at a slower rate, allowing more time for the heat generated in the section to dissipate, resulting in lower temperature rises.

The importance of the time to peak temperature was also observed for the polyethylene covered slabs containing fly ash. The use of fly ash resulted in increases in the time to peak temperature, and also in reductions in the maximum temperature rise of all sections. The times to peak temperatures for Type B fly ashes were generally longer than those for Type A fly ashes. Maximum temperature rises for Type B fly ashes were generally comparable to or less than those for Type A fly ashes. The longer time to peak temperature allows Type B fly ash mixes to see the greater temperature reductions usually attributed to Type A fly ashes because the section is allowed more time to dissipate generated heat.

The advantage of the longer time to peak temperature is not as apparent when the cotton mat curing is used. Temperature rises for slabs containing Type B fly ashes were generally greater than those for slabs with Type A fly ashes, despite the longer time to peak temperature of the Type B fly ashes. Additionally, the use of increasing levels of Type B fly ash did not result in significant changes in the maximum temperature rise. Apparently the advantage of the longer time to peak temperature of Type B fly ashes must compete with the insulating effect of the cotton mat.

The use of fly ash in the 7.5-sack concrete mixtures resulted in temperature rises in both polyethylene and cotton mat cured slabs which were comparable to or just slightly higher than the temperature found in the 5-sack concrete mixture slabs without fly ash. The longer time to peak temperature associated with the use of fly ash allows more time for heat dissipation and thus lower temperatures.

7.4 Effect of Specimen Size and Curing Conditions on the Temperature Rise of Concrete

A comparison of the maximum temperature rise and time to peak temperature rise results for the 4.5-ft. cubes and the slab sections show several interesting similarities and differences:

1) For all specimens in this study, the use of fly ash resulted in reductions in the maximum temperature rise, regardless of fly ash type or the curing condition used. Temperature rises were greater for the 7.5-sack concrete mixtures than for the 5-sack concrete mixtures.

2) The maximum temperature rise for the two 7.5-sack control mixtures cast at different temperatures was the same for the two 4.5-ft. cubes, but was not the same for the two polyethylene covered slabs or the two cotton mat covered slabs. The time to peak temperature was greater for the 7.5-sack control mixture cast at an initial ambient temperature of 80.7 degrees F. This longer time to peak temperature did not have an effect on the temperature rise of the mass concrete because an adiabatic condition existed and no heat was being lost to the environment. However, for the slab conditions where heat loss to the environment is possible, the increase in time to peak temperature, and therefore more time for heat to leave the section, resulted in lower temperature rises for the control mixture cast at lower temperatures.

3) Polyethylene covered slabs showed greater or similar temperature reductions for Type B fly ashes in comparison to Type A fly ashes. Increased fly ash replacement resulted in greater decreases in temperature rise regardless of fly ash type. Mass concrete specimens showed different results: Type A fly ashes resulted in lower maximum temperature rises than Type B fly ashes. The longer time to peak temperature associated with Type B fly ashes allowed more heat dissipation in the slab sections, and therefore more temperature reduction than was seen in the mass sections.

4) In general, the temperature rise results of the slabs covered with the cotton mat mirrored those of the 4.5-ft. cubes, except the temperature ranges for the two specimens were different. Temperature rise was generally greater for Type B fly ashes in comparison to Type A fly ashes for both specimens and both cement contents. Thus, the cotton mat provides an environment in some way similar to that seen by concrete in an adiabatic condition.

5) The use of fly ash enabled 7.5-sack mixture slabs with fly ash to achieve temperature rises comparable to those seen by the 5-sack control mixture with no fly ash, regardless of curing method. In the 4.5-ft. cubes, the temperature rises of 7.5-sack mixtures with fly ash were greater than the temperature rise of the 5-sack control mixture. The 4.5-ft. cube does not allow the dissipation of heat, so the advantages of the increased time to peak temperature associated with fly ash use are not found.

7.5 Effect of Fly Ash on Temperature Gradients

7.5.1 Mass Concrete. Temperature gradients across the cross section of a member may result in thermal cracking, especially if large temperature changes occur over just a few inches. Immediately upon the removal of formwork, the internal temperatures would remain nearly the same due to the insulating effect of the surrounding concrete. However, at or near the surface, concrete would tend toward the ambient temperature. As a result, great changes in temperature could be expected over the first few inches of depth of the section. Temperature gradient plots for this study were all made while the formwork was still in place. The mass concrete plots show the following trends:

1) Temperature gradients for higher cement content mixtures involve greater temperatures, and therefore possess greater potential for thermal cracking upon removal of formwork. Figure 7.11 shows a comparison of temperature gradients for the 5 and 7.5-sack control mixtures. At the time this gradient was measured, the cubes were covered with wet burlap and polyethylene sheeting. The shape of the gradients are similar, and temperature changes across a given depth are similar.

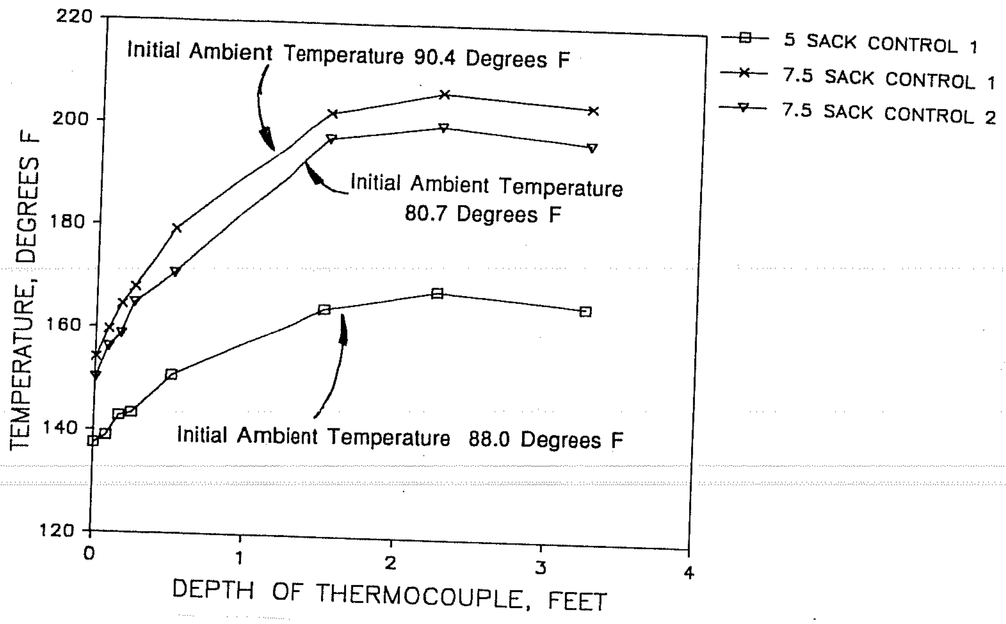


Figure 7.11 Comparison of temperature gradients for control mixtures at time of maximum difference between internal and surface temperature.

However, once the formwork is removed from the section, this situation would change.

Figure 7.12 shows the possible result if formwork had been removed from the 4.5-ft. cubes cast from the 5-sack control mixture and 7.5-sack control mixture 1. The temperatures at 6-inch depth would remain nearly constant, due to the insulating effect of the outer concrete. This temperature would be 179 degrees F for the 7.5-sack mixture, while for the 5-sack mixture this temperature would be 151 degrees F. Surface temperatures for both specimens would tend toward ambient temperature, which for the purpose of example will be taken as 90 degrees F. The change across the first 6 inches of depth for the 5-sack mixture would therefore be about 61 degrees F while for the 7.5-sack mixture, it would be almost 90 degrees F. The potential for thermal cracking is higher for the 7.5-sack mixture because of the greater temperature change. As the change in temperature increases, the stresses in the concrete increase, and if great enough, will exceed the tensile strength of the concrete. The use of high cement content concrete has a higher potential for thermal cracking.

2) The use of fly ash reduced the potential for thermal cracking in all mixtures because of the lower maximum temperature rise. Temperature gradients for fly

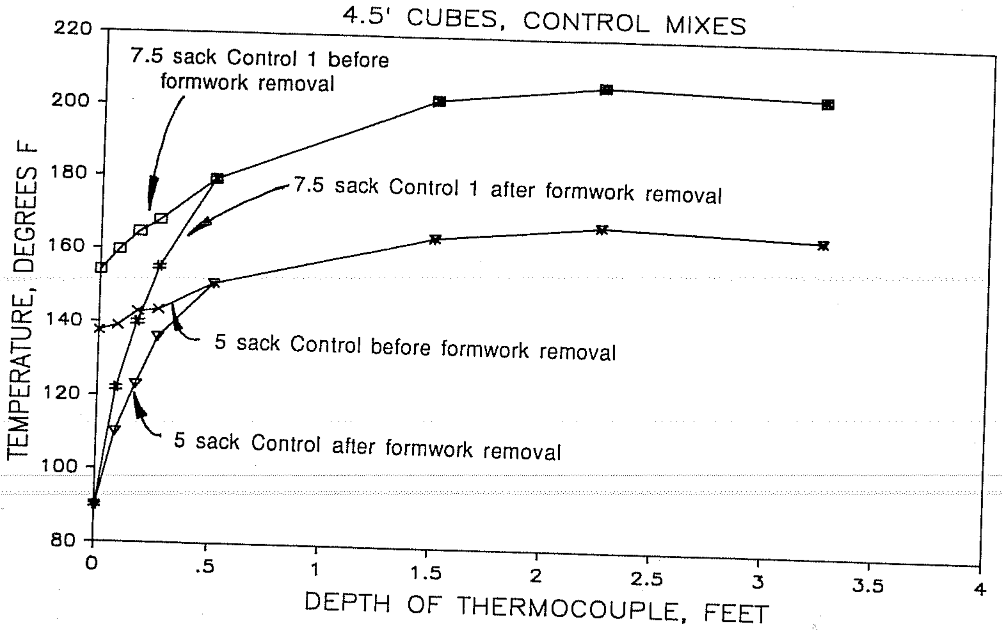


Figure 7.12 Depiction of possible effects of formwork removal from control specimens at time of maximum temperature gradient.

ash mixtures occurred at lower temperatures than their respective control mixtures, as illustrated in Figures 7.13 and 7.14. Therefore, at the time of formwork removal, there will be a smaller change in temperature across the initial inches of depth for the fly ash mixtures. The use of fly ash reduces the potential for thermal cracking.

7.5.2 Slab Specimens. In comparison to the temperature gradients for the 4.5-ft. cube specimens, the temperature gradients for the slab specimens were smaller in all cases. The following trends were observed for the slab specimens:

1) Specimens cast with higher cement content concrete exhibited greater temperatures and thus possess greater potential for thermal cracking, regardless of the curing condition used. Figure 7.15 shows a comparison of temperature gradients in slabs cast of 5-sack and 7.5-sack concrete mixtures with fly ash. The temperature gradient for the 7.5-sack mixture occurs at a higher range of temperatures than the gradient for the 5-sack mixture. The internal temperature of the concrete will remain insulated from the outside temperatures and so will remain somewhat constant, but the surface temperature of the concrete will vary with the ambient temperature. Thus, higher cement content mixtures possess greater risk of thermal cracking because there is more potential for significant differences between surface and internal concrete temperatures.

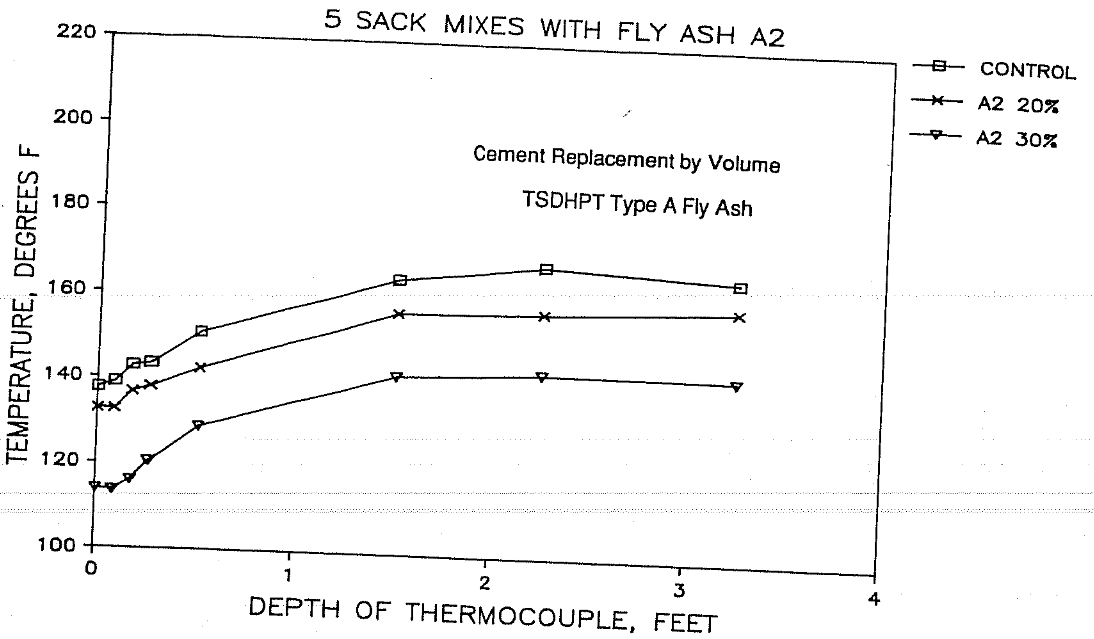


Figure 7.13 Temperature gradient profiles in 4.5-ft. cube for 5-sack mixtures with Type A fly ash.

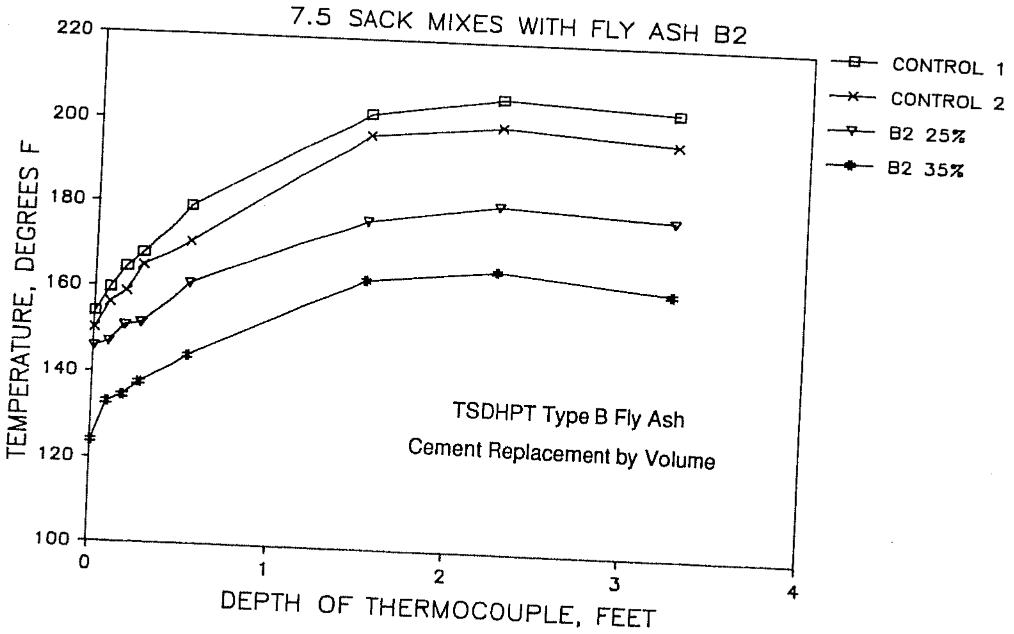


Figure 7.14 Temperature gradient profiles in 4.5-ft. cube for 7.5-sack mixtures with Type B fly ash.

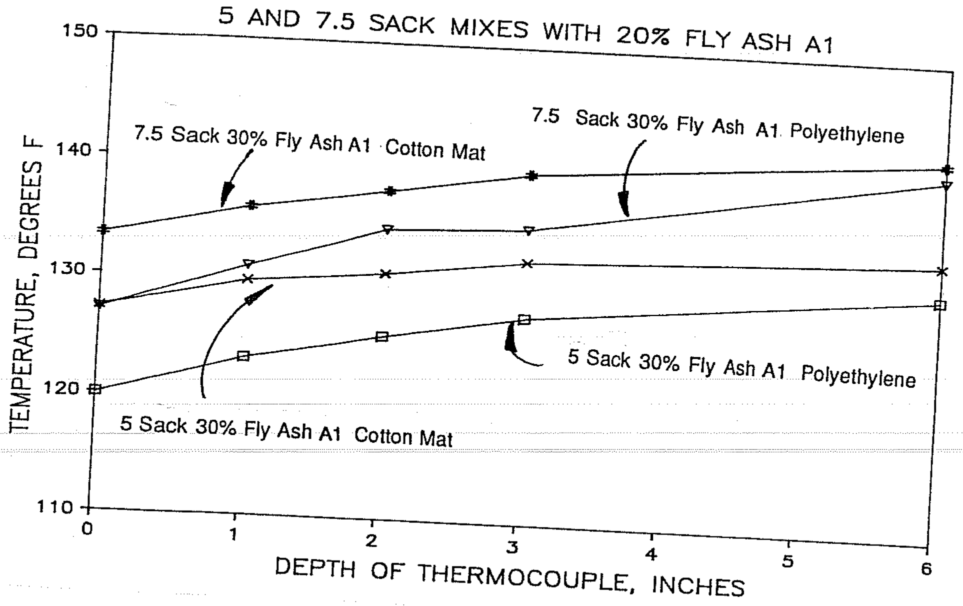


Figure 7.15 Effect of cement content on temperature gradients in polyethylene and cotton covered slabs.

2) Slab specimens cast at higher ambient temperatures will see greater temperatures, regardless of curing condition, and thus possess greater chances for thermal cracking. Figures 7.16 and 7.17 compare the two 7.5-sack control mixtures cast at different temperatures. The control mixture cast at 90.4 degrees F has a maximum gradient which occurs at higher temperatures than the same mixture cast at 80.7 degrees F, and thus the mixture cast at the higher temperature presents more of a potential risk of thermal cracking.

3) Temperature differentials for cotton mat covered slabs were generally more constant than those for polyethylene covered slabs, although the gradients for the cotton mat covered slabs occurred at higher temperatures. Figures 7.18 and 7.19 show comparisons of the temperature gradients for the two curing conditions. Greater changes in temperature across a given depth of section are seen for the polyethylene covered slabs because of heat dissipation, but the gradients are small in all cases.

4) The use of fly ash caused gradients to occur at lower temperatures. Figures 7.20 and 7.21 show temperature gradient profiles for polyethylene and cotton mat covered slabs cast of concrete containing fly ash.

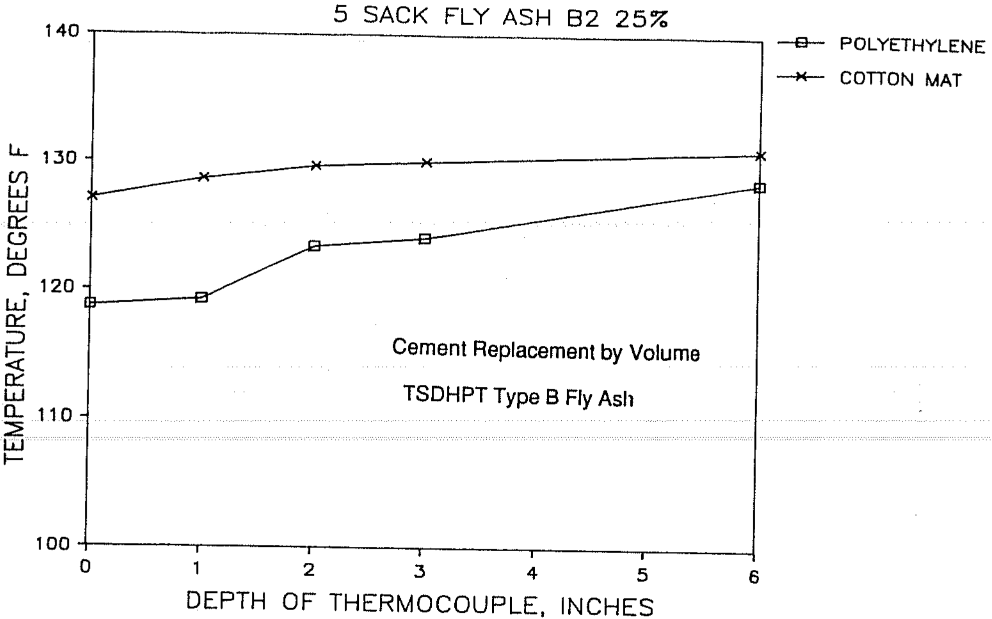


Figure 7.18 Temperature gradient profiles for 5-sack concrete mixture slabs with Type B fly ash.

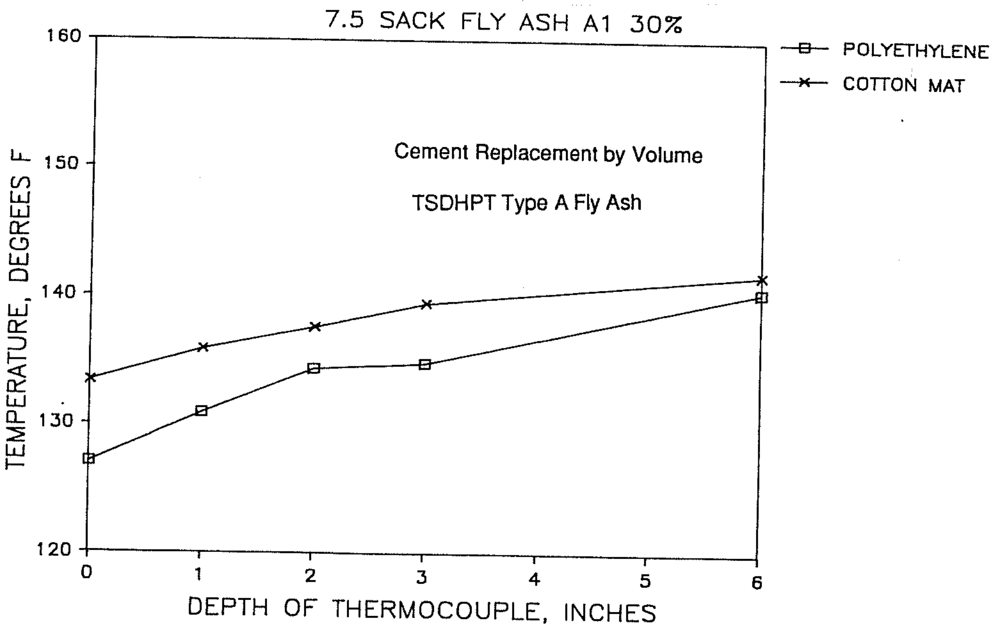


Figure 7.19 Temperature gradient profiles for 7.5-sack concrete mixture slabs with Type A fly ash.

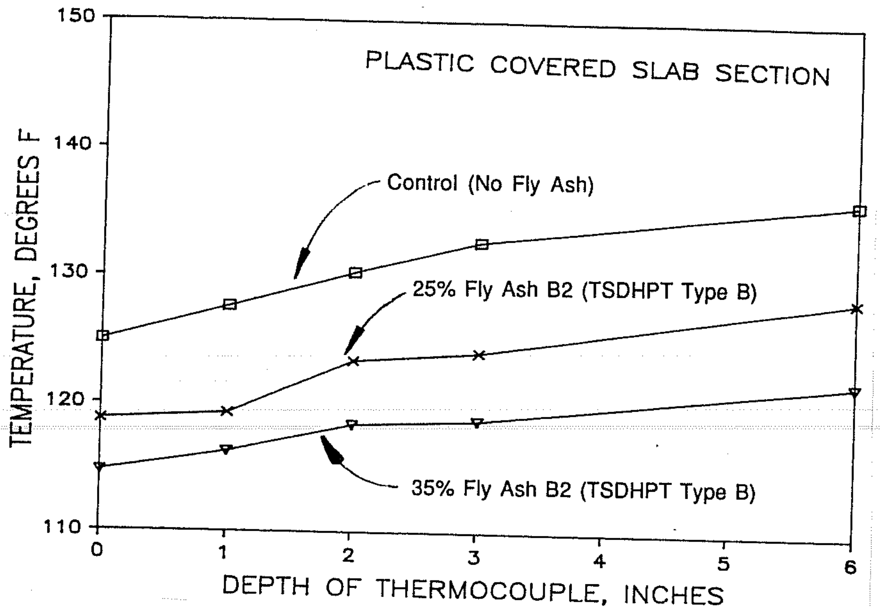


Figure 7.20 Comparison of temperature gradients in 5-sack polyethylene covered slabs with Type B fly ash.

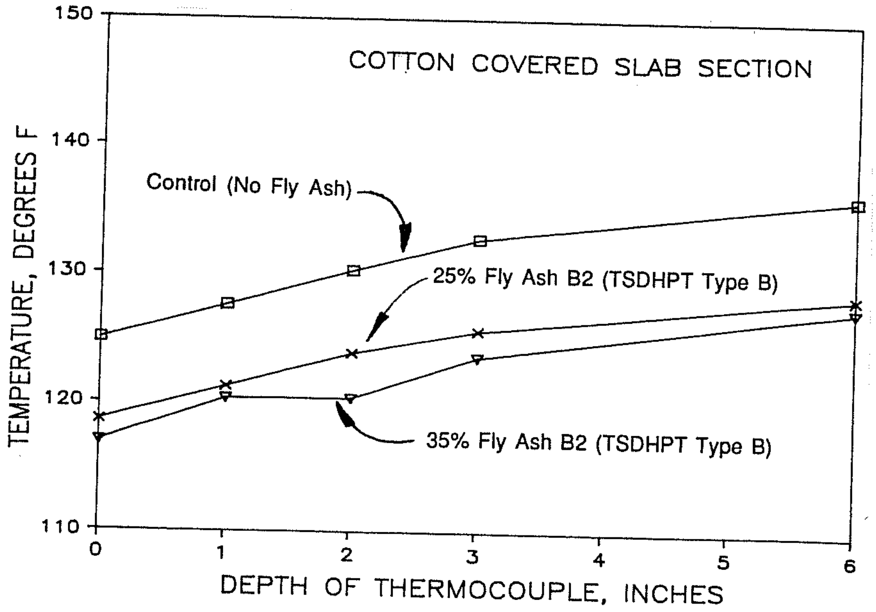


Figure 7.21 Comparison of temperature gradients in 5-sack cotton mat covered slabs with Type B fly ash.

In these figures, it can be seen that the use of fly ash resulted in gradients which occurred at lower temperatures. The use of increased amounts of fly ash resulted in a greater reductions in the temperatures at which the maximum gradients occurred. Thus, the use of fly ash will reduce the potential for thermal cracking by lowering the temperatures at which the maximum gradients will occur.

7.6 Slump Test Results

A comparison of slump results for the control mixtures reveals that the slump of the 5-sack control at 2.25 inches and the slumps of the 7.5-sack controls at 2.25 inches and 3.0 inches. The replacement of cement with fly ash resulted in increased slump for all mixtures with the exception of the 5-sack 20 percent A1 mixture. The slump measurements for the 7.5-sack mixtures were generally higher than those for the 5-sack mixtures.

The increased level of fly ash addition did not always result in an increase in slump, as shown in Figures 6.12 and 6.13. The use of increased amounts of Type A fly ash in the 7.5-sack mixtures resulted in increases in slump, but this trend was not seen for Type B fly ashes. The Type B fly ashes were finer than the cement used, so the increased surface area associated with the finer particles combined with the same amount of water in each mixture caused a decrease in the slump of the mixture after a certain level of fly ash content was in the mixture.

7.7 Compressive Strength Results

The strength gain of the cylinders tested in this study tended to agree with the research findings reported in Chapter 4. All of the strength tests conducted in this study were based on a constant weight of mixing water, without any water reduction to offset the increase in slump associated with the replacement of cement by fly ash.

The use of fly ash resulted in lower early strength in comparison to the control mixtures in all cases, regardless of cement content, fly ash type or replacement level. The use of increased amounts of fly ash resulted in greater decreases in early strength for all fly ashes used in this study.

Figures 7.22 and 7.23 show the compressive strength gain of 5-sack concrete mixtures expressed as a percentage of the 28 day compressive strength. At 1 day, the 5-sack control mixture had gained nearly half of its 28 day compressive strength, while Type A fly ash mixtures had attained between 25 percent and 50 percent of 28 day compressive strength, and Type B fly ashes had attained less than 25 percent of 28 day compressive strength.

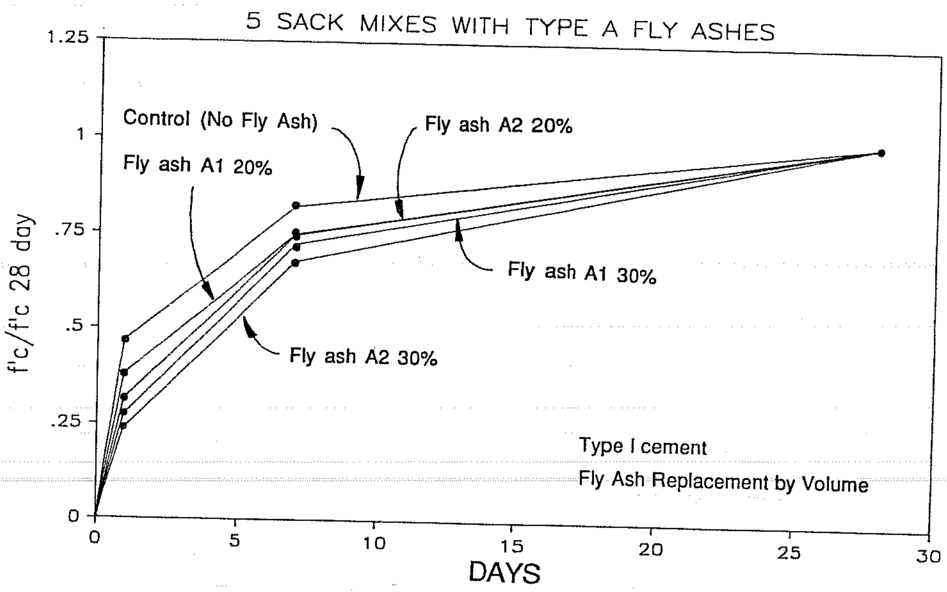


Figure 7.22 Compressive strength gain for 5-sack ready-mix concretes with Type A fly ash.

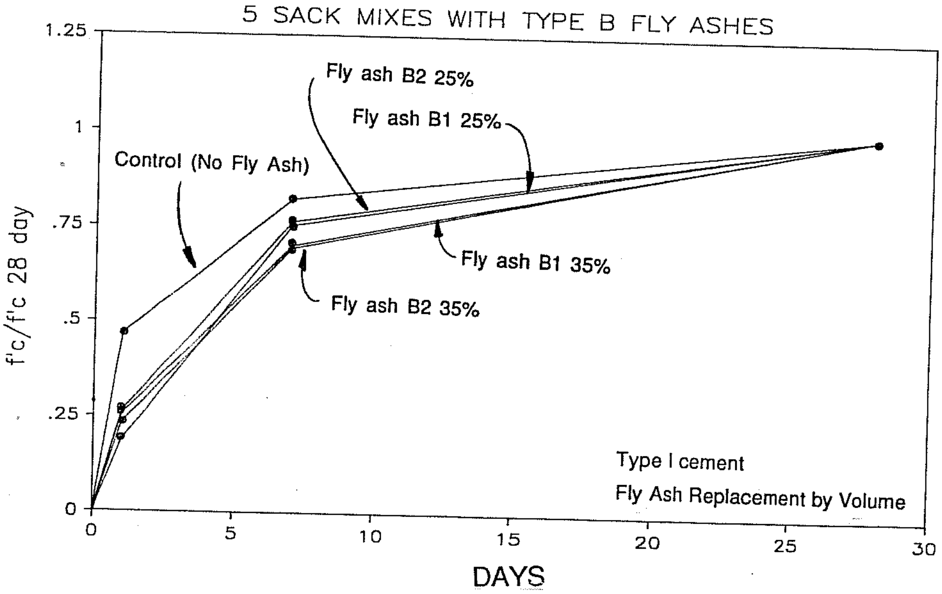


Figure 7.23 Compressive strength gain for 5-sack ready-mix concretes with Type B fly ash.

Figures 7.24 and 7.25 show the compressive strength gain of 7.5-sack concrete mixtures in terms of fraction of 28 day compressive strength. At 1 day, the control mixtures had reached over 50 percent of their 28-day compressive strength. Type A fly ashes had achieved between 25 percent and 50 percent of 28-day compressive strength, while Type B fly ashes had achieved between 10 percent and 35 percent of 28-day compressive strengths.

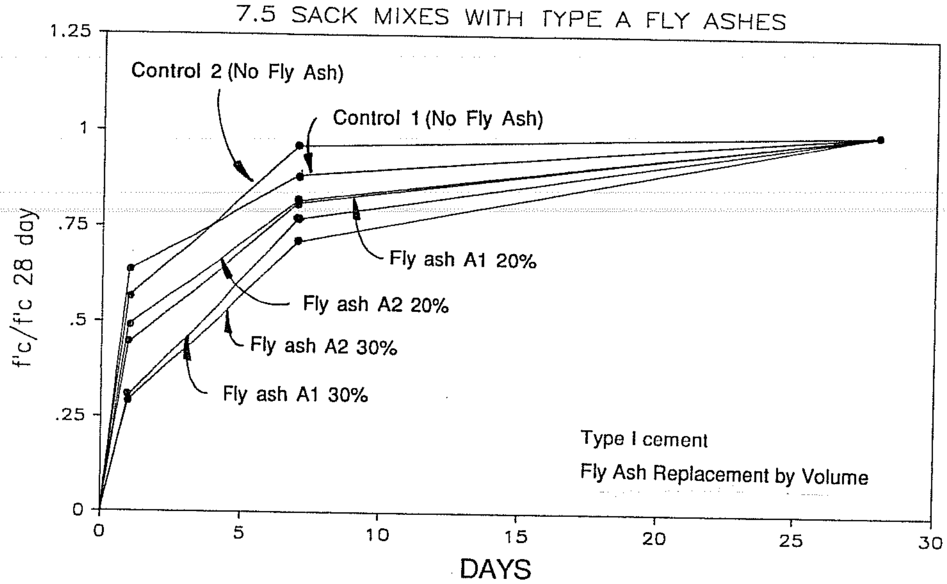


Figure 7.24 Compressive strength gain for 7.5-sack ready-mix concretes with Type A fly ash.

The effect of curing temperature on the compressive strength of concrete may be seen in a comparison of the 1 day compressive strengths of the two 7.5-sack control mixtures cast and cured at different ambient temperatures. The 1 day compressive strength of the mixture cast at 90.4 degrees F was 4170 psi versus 3760 psi for the same control mixture cast at 80.7 degrees F. This behavior matches with the known hydration behavior of cement at higher temperatures. The hydration is accelerated when cured at high temperatures, and thus greater compressive strength is achieved in the cylinders cured under higher temperatures.

In all cases, the 7-day compressive strengths of concrete mixtures with fly ash were less than the compressive strengths of the control mixtures. The fly ash mixture concretes showed greater rates of strength gain than the control mixtures did between 1 and 7 days, regardless of fly ash type or replacement level, as illustrated in Figures 7.22 to 7.26. For example, the 5-sack concrete mixtures containing Type B fly ashes showed a gain

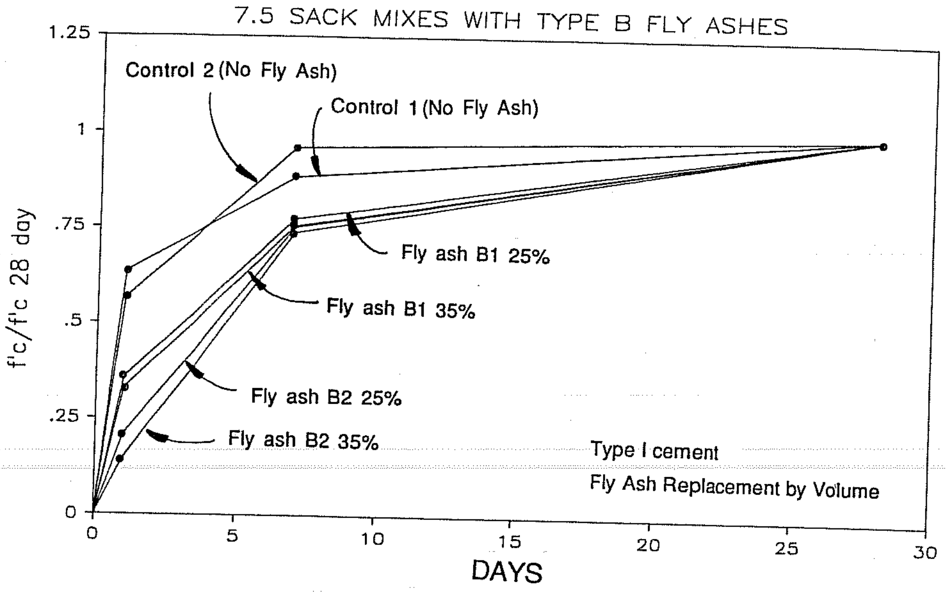


Figure 7.25 Compressive strength gain for 7.5-sack ready-mix concretes with Type B fly ash.

of 50 percent of the 28-day compressive strength between 1 and 7 days, while the 5-sack control mixture showed a gain of only 30 percent. The same behavior was observed for the 7.5-sack concrete mixtures.

In general, the strength gain between 1 and 7 days were greater for Type B fly ashes than for Type A fly ashes. This may be partly due to the fact that the Type B fly ashes were used in greater replacement ratios than the Type A fly ashes. The 1-day strength would be expected to be lower due to the smaller amount of cement in the mixture, and the fact that the amount of water in each mixture remained constant. The gains made between 1 and 7 days may be due to the additional cementitious properties associated with the higher calcium content of Type B fly ashes.

Strength gain between 7 and 28 days was seen to be greater for fly ash concretes than for the control mixtures. The differences in strength gain associated with the varying levels of fly ash replacement were not as apparent at 7 and 28 days for any of the fly ash mixtures in this study.

The 28-day compressive strength results for all mixtures, which are found in tabular form in Appendix B, revealed that in some cases the compressive strength of fly ash concretes were greater than the strengths of the control mixtures. There was no apparent trend in this behavior in regards to type of fly ash, replacement level, or cement content.

In mass or hot weather concreting applications, where the concrete is continuously subjected to high temperatures, a substantial increase in early strength may result in any concrete, regardless of whether or not fly ash is used. The ultimate strength of fly ash concrete generally increases with curing temperatures in the range of hot weather conditions, while the ultimate strength of plain concrete under the same temperature conditions decreases.

CHAPTER 8
DISCUSSION OF ISOTHERMAL CALORIMETRY TESTS

8.1 Introduction

In this chapter, the isothermal calorimetry test results are discussed. Again, it is important to note that the results provide a basis for comparison of physical and chemical properties for cements and fly ashes in general. Other cements and fly ashes than those used in the tests may produce different results.

8.2 Discussion of Test Parameters

8.2.1 Effect of Sample Size. Results of a test conducted to study the effect of sample size on the rate of heat evolution measured by the calorimetry system used in this study were shown in Figure 6.17. As the sample size was decreased, the rate of heat evolution per gram of sample increased. Since the same size beaker was used in each test, a greater percentage of the 2 gram sample volume was directly against the heat sensor of the calorimetric cell. Reactions occurring in the smaller sample would be concentrated closer to the heat sensor of the cell. Therefore, it would be expected that the results for smaller size samples would be somewhat greater than for larger samples. All tests in this study were conducted with the same volume of dry sample.

8.2.2 Effect of Number of Cells Used. The test run to check the consistency of 9 identical reactions conducted at the same time and under the same conditions was illustrated in Figure 6.18. Several cells yielded identical results, and all cells recorded similarly shaped curves. Maximum rate of heat evolution values varied from a low of 2.52 calories/gram cement*hour to 3.08 calories/gram cement*hour. At no time were more than 9 cells tested simultaneously in this study.

8.2.3 Effect of Cell Rack. Results of the test run to determine the effect of raising the cells off the bottom of the water bath tank and allowing bath water to circulate around the cell completely found no significant difference in the rate of heat evolution measured by the calorimetry system. In this study, the cell rack was not used.

8.2.4 Effect of Number of Paddle Turns. The test conducted to observe the effects of the number of paddle turns used to mix the paste samples found that the greater the number of paddle turns, the higher the maximum rate of heat evolution. This is believed to be due to the fact that a greater number of paddle turns results in a more thorough mixing of the paste, and better allows the cement to interact with the water and undergo hydration. In order to ensure complete mixing, 15 paddle turns were used in this study, as described in the mixing procedure in Chapter 5.

8.2.5 Effect of Vibration. The use of vibration was seen to increase the rate of heat evolution in Figure 6.21. Once again, this increase is believed to be due to the better mixing achieved when the vibrating technique is used. The cement particles are better able to come in contact with the available water, and thus greater hydration is seen. Because of the more complete mixing achieved with vibration, the engraver was used in all tests in this study.

8.2.6 Effect of Water to Cementitious Materials Ratio. The results of a test conducted to determine the effects of water to cementitious materials ratio on the heat evolution of cement paste found that pastes with higher water to cementitious materials ratios had greater maximum rates of heat evolution. The greater water to cementitious materials ratio allows for better and more thorough mixing of the paste, and thus more hydration. The amount of water in each paste sample was kept constant at 3 grams.

8.2.7 Effect of Cement Type. A test run to observe the differences in hydration behavior of three different types of cements found that Type III cement produces the greatest maximum rate of heat evolution. Type I and Type I-II cements produce similar maximum rates of heat evolution but Type I cements begin the deceleration phase before Type I-II cements. Figure 8.1 shows a comparison of the cumulative heat evolution for the same pastes. It can be seen that the Type III cement at all times generates more heat than Type I or Type I-II cements.

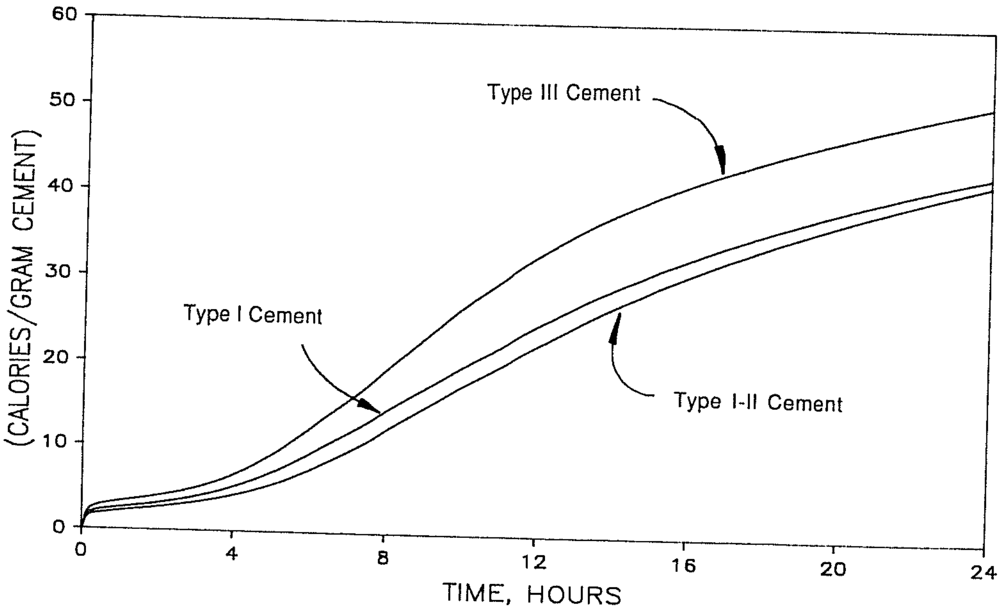


Figure 8.1 Comparison of cumulative heat evolution for Type I, Type I-II, and Type III cements at 80 degrees F.

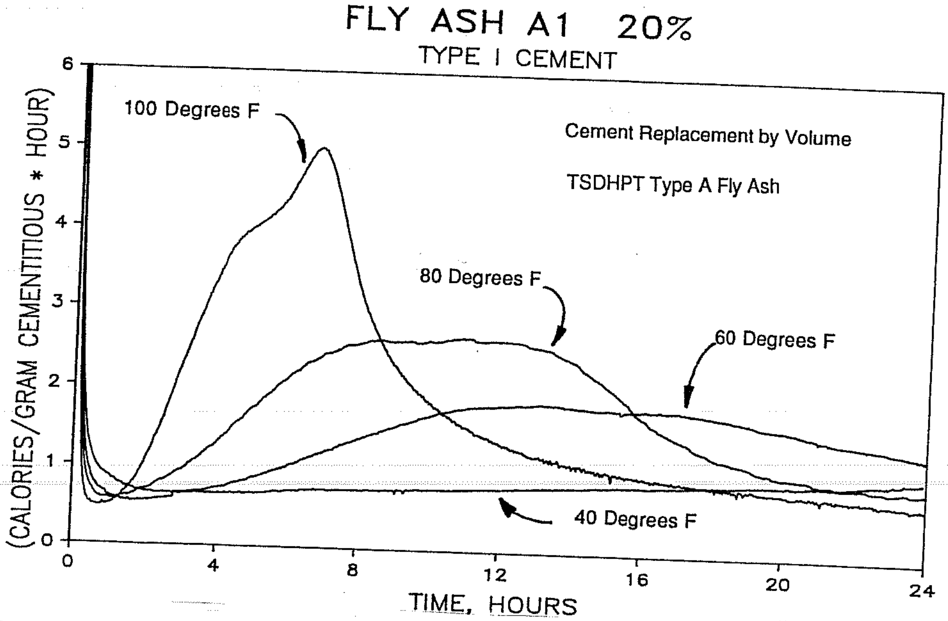


Figure 8.2 Rate of heat evolution for Type I cement paste with Type A fly at different temperatures.

8.3 The Effects of Fly Ash and Ambient Temperature on the Hydration of Portland Cement

8.3.1 The Effect of Temperature on Cement/Fly Ash Paste Hydration. Changes in temperature were found to have similar effects on the hydration behavior of all three cements studied, regardless of whether or not fly ash was used. Figure 8.2 shows a comparison of the rate of hydration of Type I cement with 20 percent Fly ash A1 at the four different temperatures studied. At 40 degrees F, the hydration curve is nearly flat. As the ambient temperature is increased, it may be seen that the acceleration phase begins to take shape and also occurs earlier. At 100 degrees F, the C_3A and C_3S peaks may both be observed. Similar behavior was seen for both the Type I-II and Type III cements used in this study. The hydration of cement is accelerated at higher temperatures.

Figure 8.3 shows a comparison of the cumulative heats with time for the pastes illustrated in Figure 8.2. The cement hydrated at 100 degrees F develops much of its heat early on and then experiences a much slower development of heat. This corresponds with Figure 8.2, which showed the paste hydrated at 100 degrees F having the lowest rate of heat evolution at 24 hours. In contrast, the cements hydrated at 40 and 60 degrees F tend to develop heat and hydrate at slower, more steady rates.

While the cements hydrated at higher temperatures show more heat generation early after mixing with water, the cements hydrated at lower temperatures appear to show

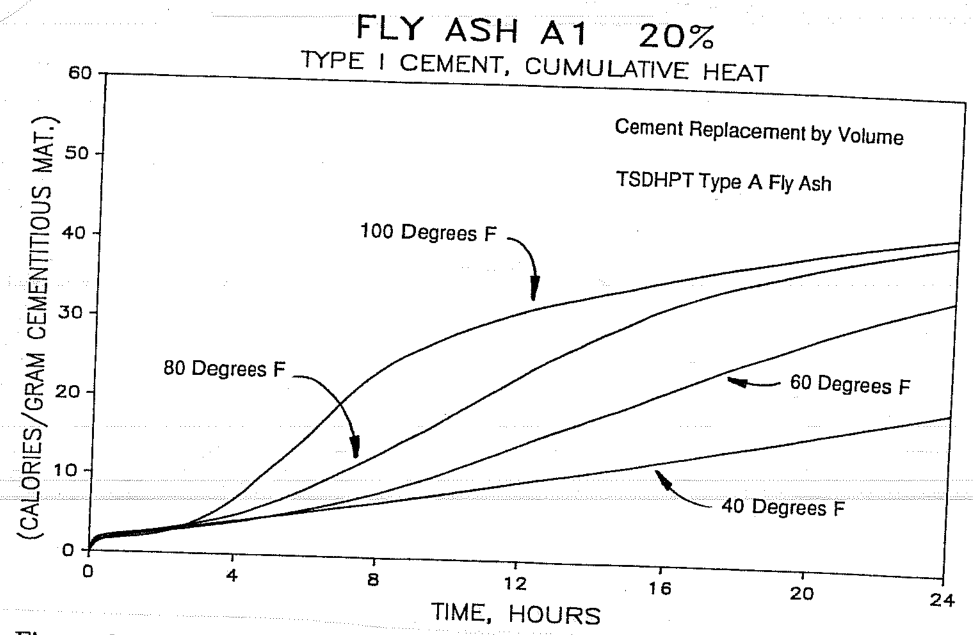


Figure 8.3 Cumulative heat evolution for Type I cement paste with Type A fly ash at different temperatures.

more steady heat generation. In Figure 8.3 it can be seen that this steady rate of heat evolution results in a steady slope of the cumulative heat curve for the entire 24 hour period studied. This behavior is similar to that observed in the strength gain of concrete. Concrete subjected to high temperatures may have high strength at early ages, but at later ages it will not see as much strength gain as concrete subjected to lower temperatures because most of its strength gain happened during the first few hours of hydration.

8.3.2 Effect of Fly Ash Type and Replacement Level on Heat Evolution. The temperature rise in concrete is related to the heat evolution of the cement paste. Higher rates of heat evolution translate into greater rates of temperature rise in concrete, and likewise, reductions in the rate of heat evolution of a paste will mean lower rates of temperature rise due to the hydration of cement in concrete.

The use of either Type A or Type B fly ash at a temperature of 40 degrees F resulted in little change in the maximum rate of heat evolution and the cumulative heat evolution for all three cements in this study, as illustrated in Figures 8.4 and 8.5. The use of increasing amounts of fly ash also did not result in significant changes in the rate of heat evolution or the cumulative heat of evolution, as was seen in Figures 6.24, 6.25, and 6.32. At this lower temperature, the effects of the use of fly ash were not as apparent as they were at higher temperatures. This is probably not due to the fly ash being more reactive at lower temperatures, but more likely to the fact that there is little cement hydration

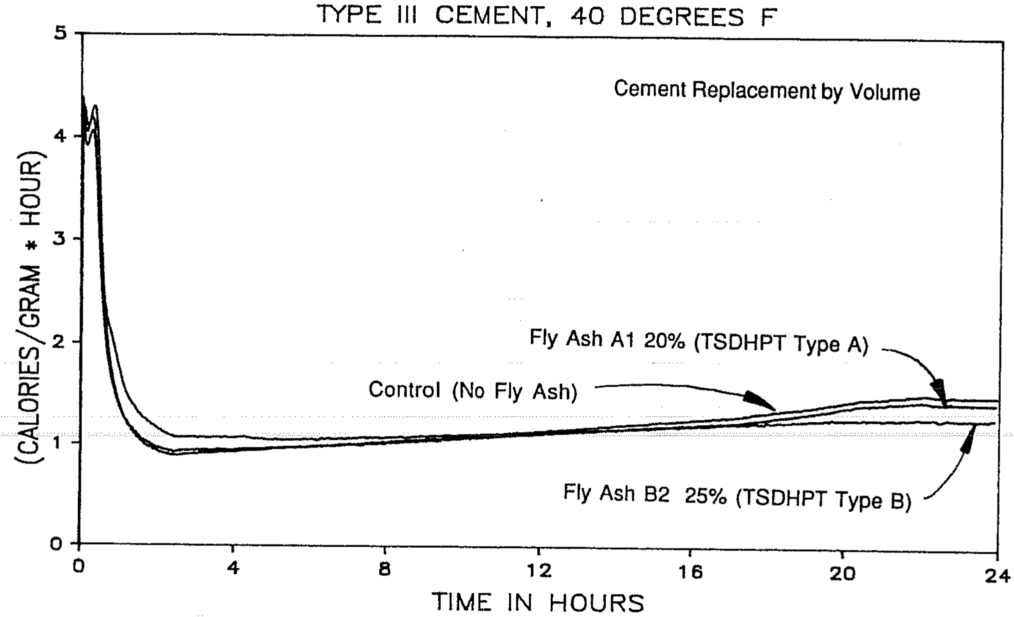


Figure 8.4 Rate of heat evolution for pastes with Type A and Type B fly ash at 40 degrees F.

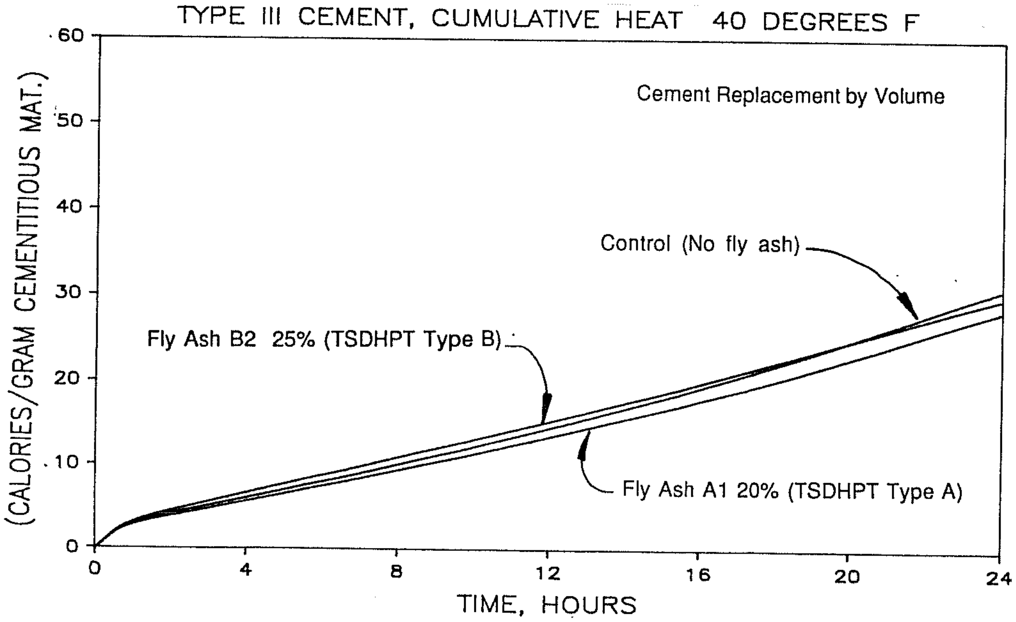


Figure 8.5 Cumulative heat evolution for pastes with Type A and Type B fly ash at 40 degrees F.

occurring at these lower temperatures, so the partial replacement of the cement will not result in great changes in heat evolution.

The use of either Type A or Type B fly ash at 60 degrees F resulted in reductions in the maximum rate of heat evolution and generally resulted in decreased cumulative heat evolution, as may be seen in Figures 8.6 and 8.7. The use of increasing levels of fly ash resulted in slightly reduced values of the rate of heat generation and cumulative heat, as was shown in Figures 6.26, 6.27, and 6.33.

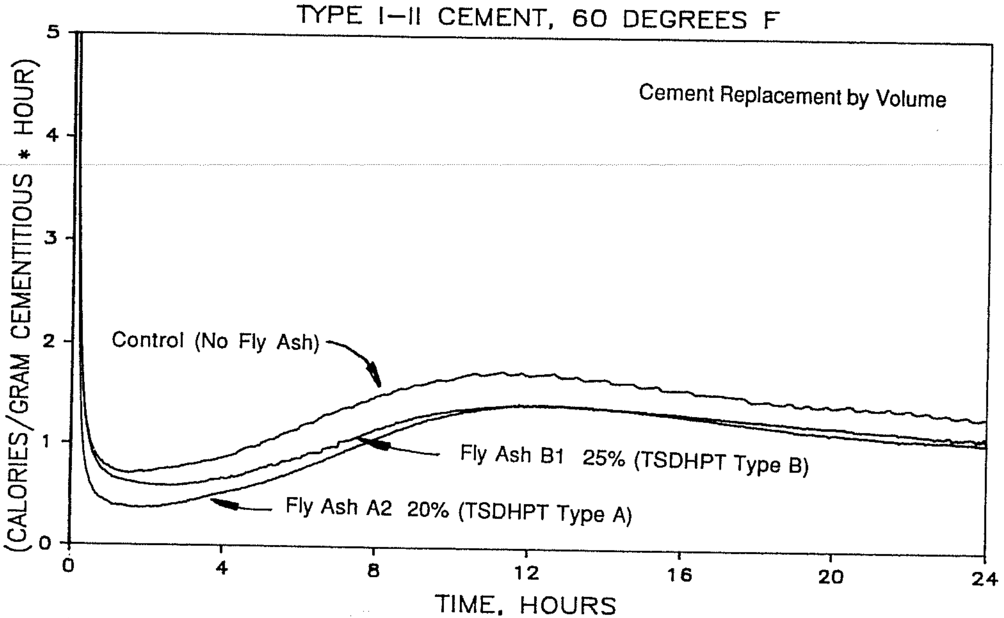


Figure 8.6 Rate of heat evolution for pastes with Type A and Type B fly ash at 60 degrees F.

The use of Type A fly ash at 80 and 100 degrees F generally resulted in a reduction of the maximum rate of heat evolution as well as the cumulative heat evolution for all three cements in this study, as was shown in Figures 6.28 to 6.31, 6.34 and 6.35. In general, the use of Type A fly ashes tended to simply reduce the maximum value of the acceleration phase peak, without affecting the shape of the hydration curve to any extent, as shown in Figure 8.8. This indicates that Type A fly ashes are contributing little to the hydration of the paste in terms of heat generation during the initial 24 hours at temperatures in the range of 80 to 100 degrees F.

There is not a direct relationship between the amount of cement replaced by Type A fly ash and the cumulative heat generation. The 30 percent replacement level of Type A fly ash resulted in lower cumulative heat generation than the 20 percent replacement level, but not necessarily in an amount proportionate to the reduction seen at the 20 percent

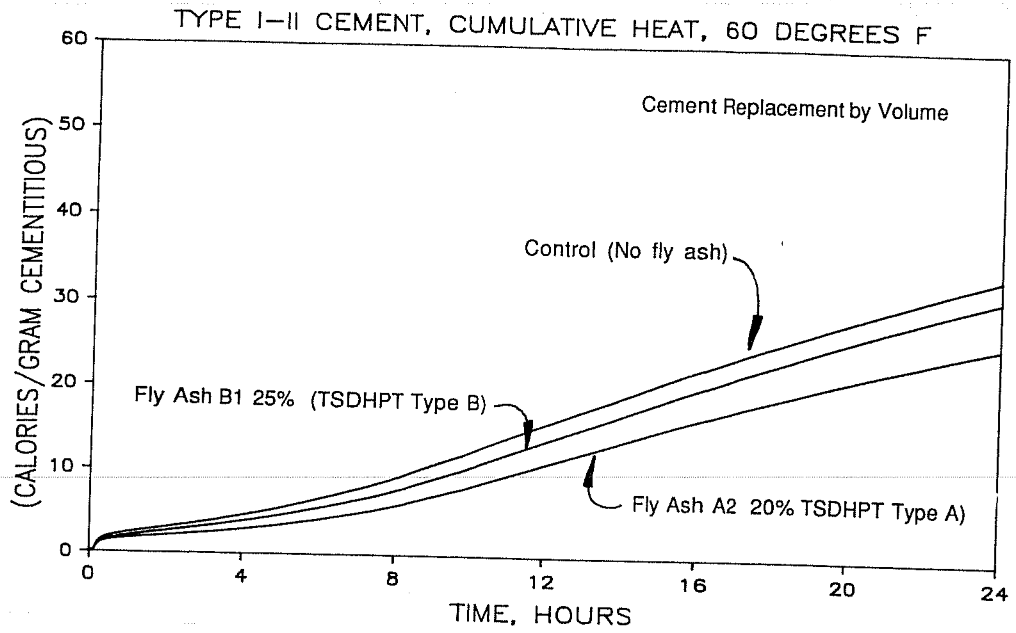


Figure 8.7 Cumulative heat evolution for pastes with Type A and Type B fly ash at 60 degrees F.

replacement level. For example, Figure 6.28 showed the cumulative heat evolution for Type I cement with fly ash A1 at 80 degrees F. Cumulative heat values at 24 hours for the control paste and the 20 percent and 30 percent replacement fly ash replacements were 50.99, 42.21, and 39.27 calories/gram cementitious material, respectively. If a proportionate drop in cumulative heat was to be found, the reduction in cumulative heat for the 30 percent replacement level would be 1.5 times the drop for the 20 percent replacement level, or 13.17 calories/gram cementitious material. However, the drop for the 30 percent replacement level in this case was lower, only 11.72 calories/gram cementitious material. Thus, the Type A fly ashes play a role in increasing the hydration of the cement, even if they do not generate heat themselves. This role may include increasing workability and the degree of hydration as well as providing additional sites for hydrate growth.

Figures 8.9 and 8.10 compare typical behavior of Type A and Type B fly ashes at 80 and 100 degrees F. In these figures, it can be seen that the use of Type B fly ashes may result in dramatic changes in the paste hydration curves. These changes include increased heat evolution immediately following mixing with water, increased maximum rates of heat evolution, and retardation of C_3S hydration.

In many cases, both Type B fly ashes, and particularly fly ash B2, show increased rates of heat generation in comparison to plain cement immediately following the rapid heat evolution associated with the initial reaction with water, as illustrated in Region A of Figure

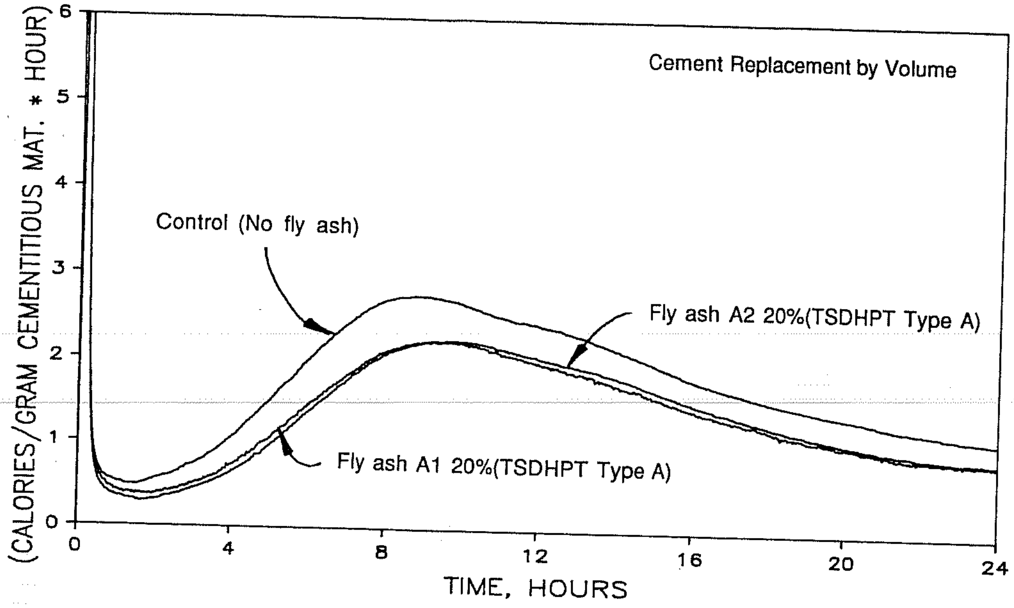


Figure 8.8 Effect of Type A fly ash on rate of heat evolution of Type I-II cement at 80 degrees F.

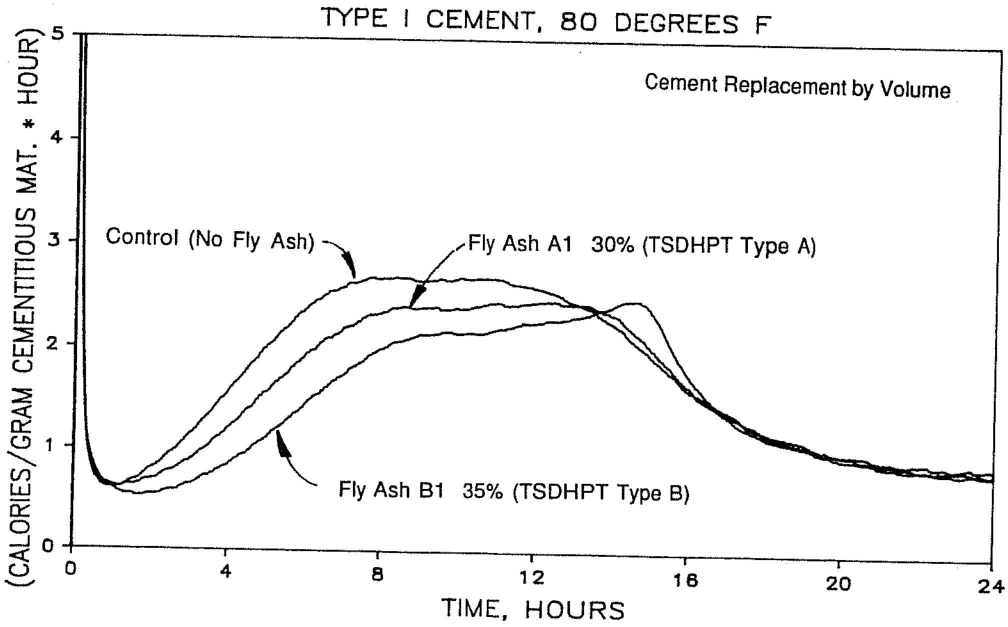


Figure 8.9 Rate of heat evolution for pastes with Type A and Type B fly ash at 80 degrees F.

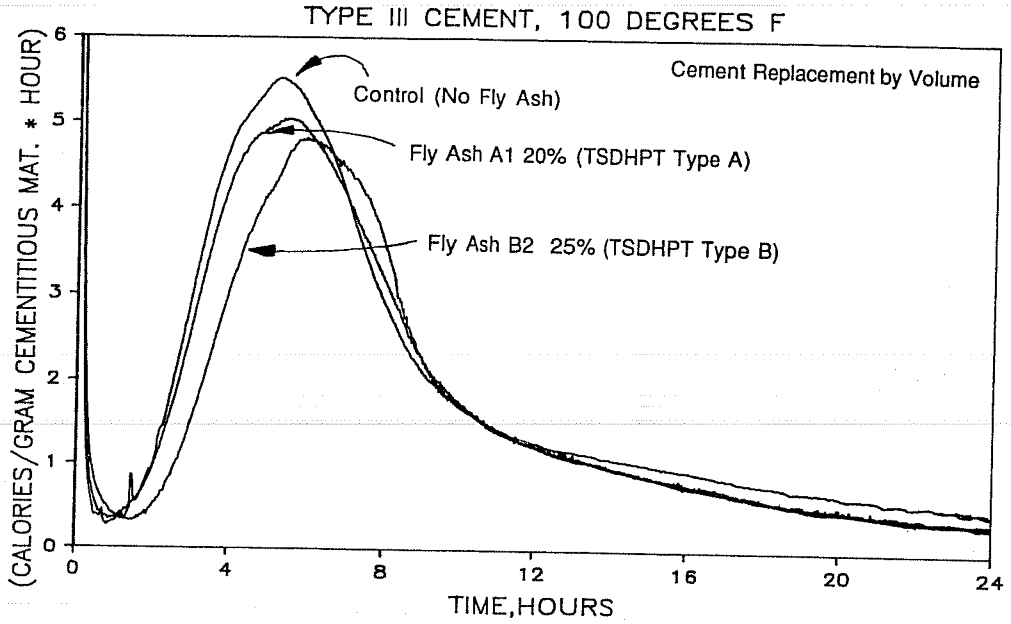


Figure 8.10 Rate of heat evolution for pastes with Type A and Type B fly ash at 100 degrees F.

8.11. This may be due to the higher levels of Ca present, the greater levels of glassy material in Type B fly ashes, and insufficient sulfate levels in the available cement to completely retard the hydration of the additional C_3A due to the fly ash.

Both Type B fly ashes used in this study were seen to affect the C_3S hydration peak of all three cements in this study in some way, either reducing the peak, retarding the time of onset of the peak, or both. Possible explanations for this behavior will be discussed in section 8.3.3.

The use of Type B fly ash at a 25 percent replacement level resulted in increased rates of heat evolution for some cements and replacement levels at 80 degrees F. This behavior was not always seen in the same cements and replacement levels at 100 degrees F, as may be seen in Regions B and C of Figures 8.12 and 8.13. In Figure 8.12, Type I cement replaced with 25 percent fly ash B1 at 80 degrees F resulted in a greater maximum rate of heat evolution than plain Type I cement; the same trend was found for 25 percent fly ash B1 at 100 degrees F with Type I cement, as can be seen in Figure 8.13. However, this trend does not hold true for 25 percent fly ash B2 with Type I cement. While maximum rates of heat evolution similar to those of to plain cement are found at 80 degrees F, the use of 25 percent fly ash B2 at 100 degrees F resulted in decreased maximum rate of heat evolution.

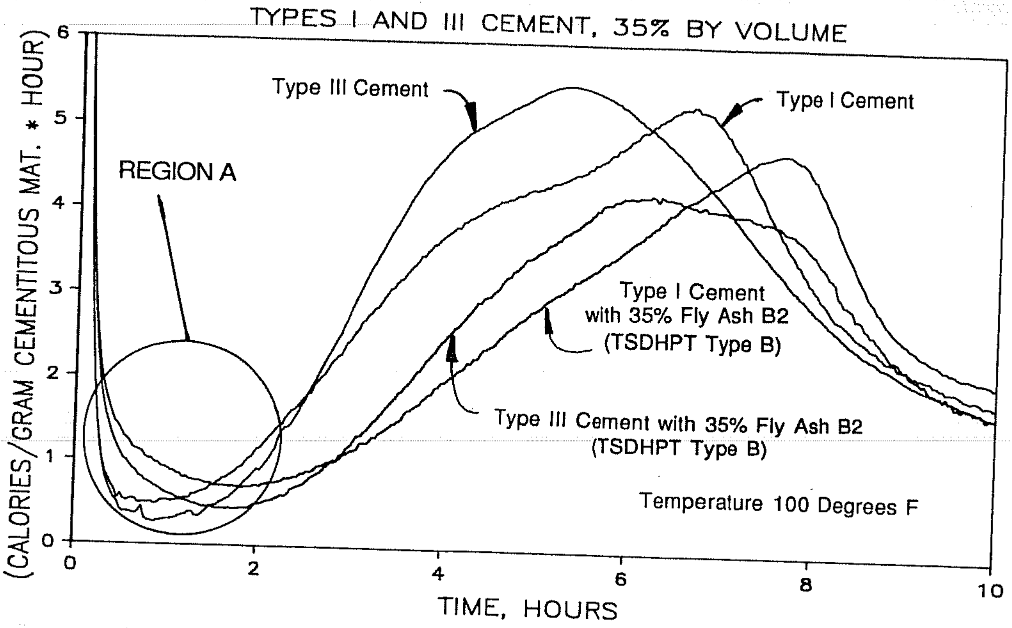


Figure 8.11 Early hydration of cement Types I and III with replacement by Type B fly ash.

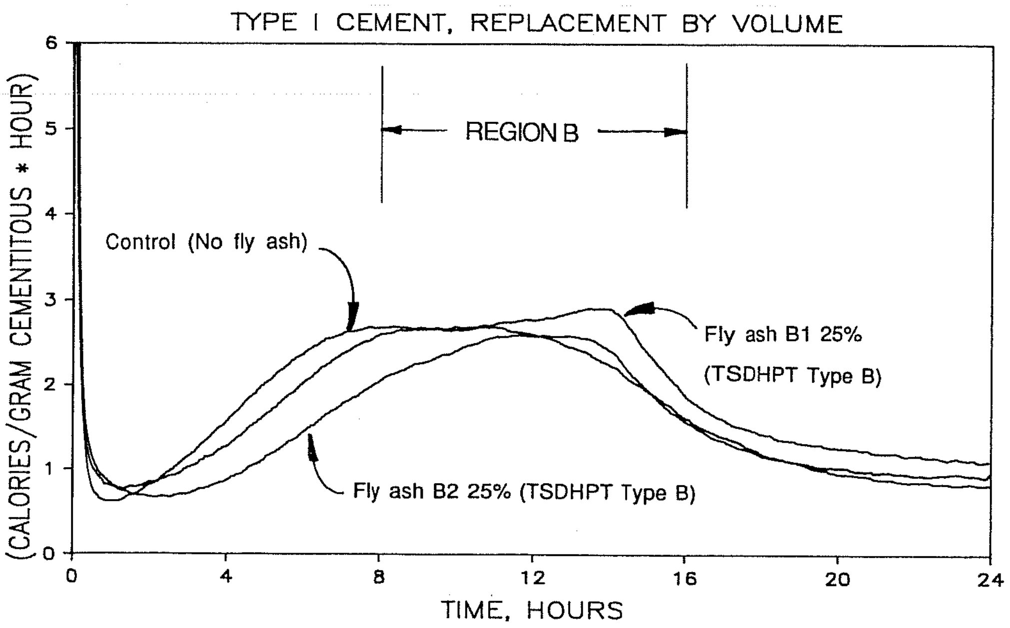


Figure 8.12 Effect of replacement of Type I cement by Type B fly ash on rate of heat evolution at 80 degrees F.

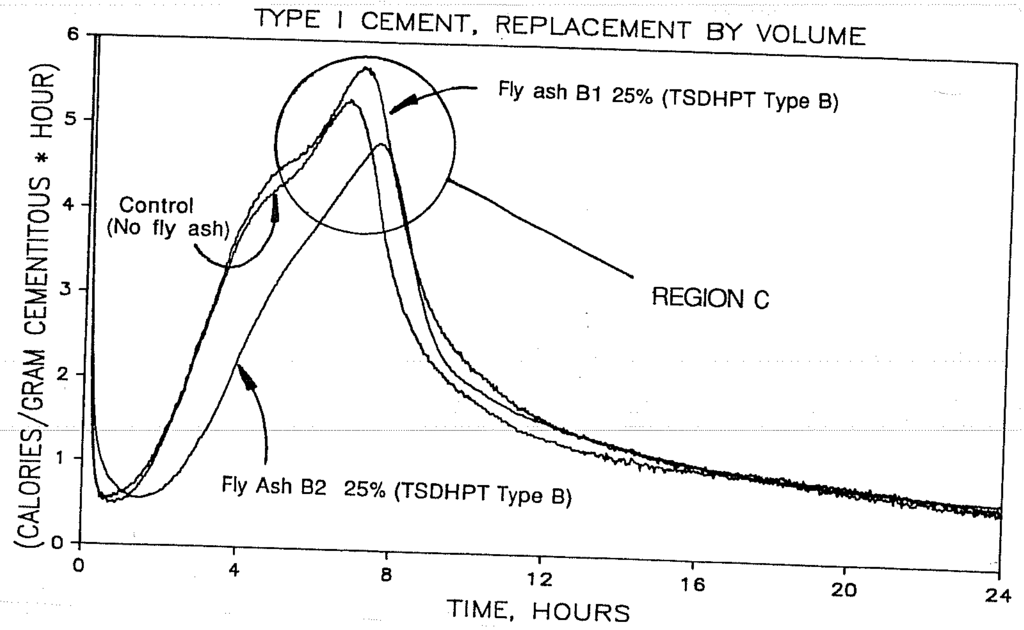


Figure 8.13 Effect of replacement of Type I cement by Type B fly ash on heat evolution at 100 degrees F.

The increased maximum rate of heat evolution which was found to occur with the replacement of cement by 25 percent Type B fly ash at higher temperatures in some cases resulted in greater heat cumulative heat generation than plain cement paste, as illustrated in Figures 8.14 and 8.15. The greater rate of heat evolution results in a steeper slope of the cumulative heat curve and thus greater gains in total heat generation.

The 35 percent replacement level of both Type B fly ashes resulted in reductions in the maximum rate of heat evolution and the cumulative heat evolution for all three cements in this study as compared to plain cement. This behavior was observed even in the cases where the use of Type B fly ashes at a replacement level of 25 percent resulted in greater maximum rates of heat evolution than plain cement. Thus the increased rate of heat evolution sometimes observed with the use of Type B fly ash at 80 and 100 degrees F is not due to just the fly ash, since the presence of more fly ash does not increase the behavior. More likely, it is due to an interaction between the cement and the fly ash.

8.3.3 Retarding Effects of Fly Ash on the Hydration of Cement. The retarding effects of fly ash can be beneficial to the engineer placing concrete under hot weather conditions. When the hydration of cement is delayed, the concrete remains in a plastic state longer, and thus more time for the placing and finishing of concrete is allowed. More important, as the time to reach maximum rate of heat evolution is increased, the time to reach peak temperature in the concrete will be increased. As previously discussed, a longer

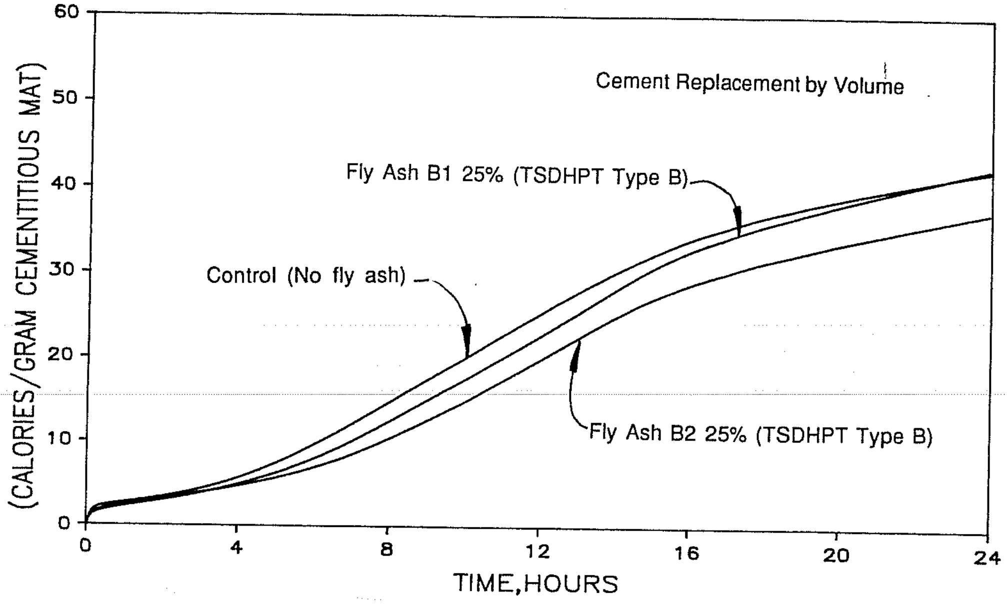


Figure 8.14 Effect of replacement of Type I cement by Type B fly ash on cumulative heat evolution at 80 degrees F.

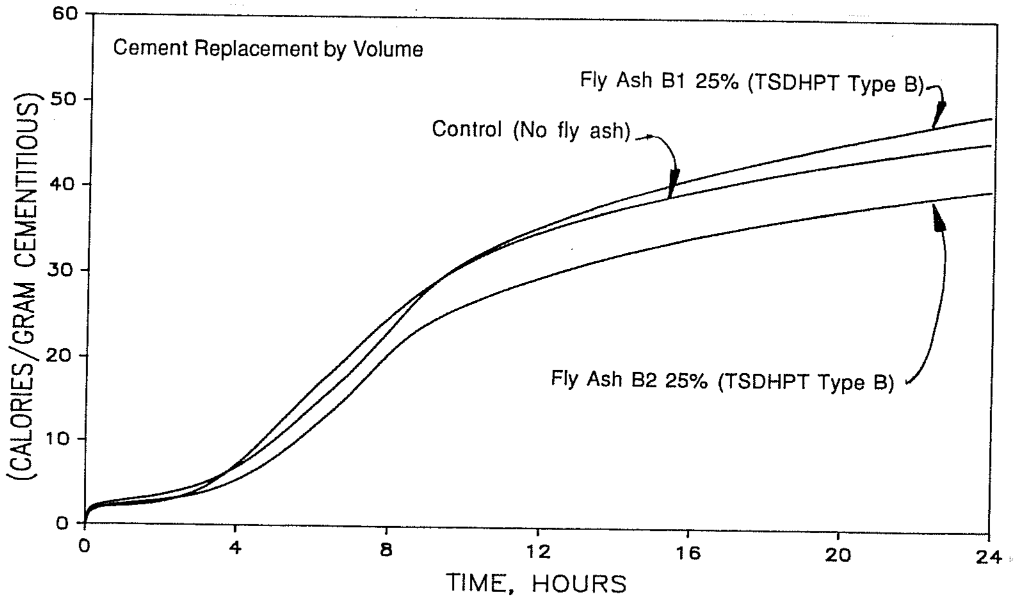


Figure 8.15 Effect of replacement of Type I cement by Type B fly ash on cumulative heat evolution at 100 degrees F.

time to peak temperature will allow more time for dissipation of heat to the environment and thus may result in lower temperature in sections which lose heat to the environment.

The use of Type A fly ash as a partial replacement for the three cements in this study generally did not retard the acceleration stage of cement hydration at 40 degrees F. Again, since there was little cement hydration occurring at this low temperature, any retardation could not be very significant.

The use of Type A fly ashes at 60 degrees F generally did not affect the onset of the acceleration stage. Additionally the use of greater levels of Type A fly ashes did not affect the time at which the acceleration stage began.

At 80 and 100 degrees F, the use of Type A fly ash caused slight retardation of the cement hydration. The use of increasing levels of Type A fly ash replacement did not always increase the retarding effects of fly ash use.

A typical comparison of the retarding effects of the two Type A fly ashes used in this study may be seen in Figures 8.16. It can be seen that fly ash A2 displays more retarding effects on the cement hydration than fly ash A1 does. Fly ash A1 has a higher level of sulfates, 0.90 percent, than does fly ash A2, which has 0.52 percent, so the additional retardation seen with fly ash A2 is not due to the retardation of the C_3A hydration by sulfate. A comparison of the chemical properties of the fly ashes does not indicate any reason for the difference, so the retarding effects of the Type A fly ashes may be due to physical characteristics of the individual fly ashes. Fly ash A2 is finer than fly ash A1, so fineness may play a role in the retardation observed. The finer fly ash may provide additional sites for the growth of hydrates, thus tying up reactions and causing the acceleration stage to occur later.

The use of Type B fly ashes at 40 degrees F as partial cement replacements also did not always result in significant retardation of hydration. The onset of the acceleration stage at 60 degrees F was somewhat delayed by the addition of Type B fly ashes. This effect was greater with the higher level of Type B fly ash replacement (35 percent). At 80 and 100 degrees F, the use of Type B fly ashes generally caused significant delays in the start of the acceleration stage. This delay was further increased by the addition of greater levels of Type B fly ash, as illustrated in Figure 8.17.

Retardation due to fly ash B2 was generally greater than that attributed to fly ash B1, as shown in Figure 8.18. A comparison of some of the physical and chemical properties of the two fly ashes finds that fly ash B2 is finer, has more sulfate, and less alkali than fly ash B1, all properties which were discussed in Chapter 4 as possible causes of delay in hydration.

The degree of retardation or acceleration of the hydration of cement in the presence of fly ash is apparently to some degree dependent upon the relative finenesses of the

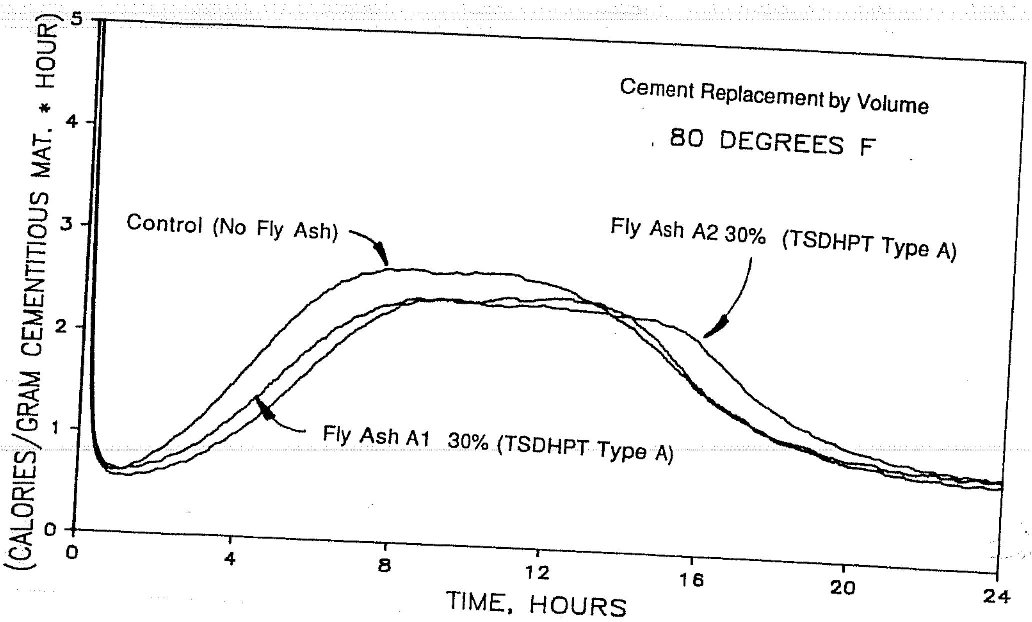


Figure 8.16 Comparison of the retarding effects of two different Type A fly ashes on the heat evolution of Type I cement paste.

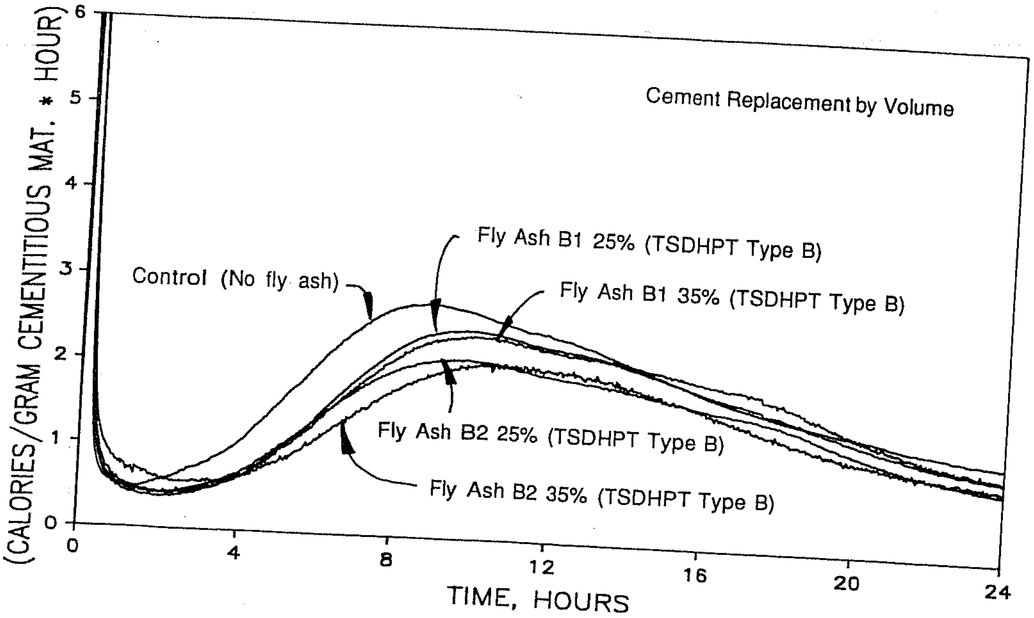


Figure 8.17 Effect of increasing level of Type B fly ash on the heat evolution of Type I-II cement paste.

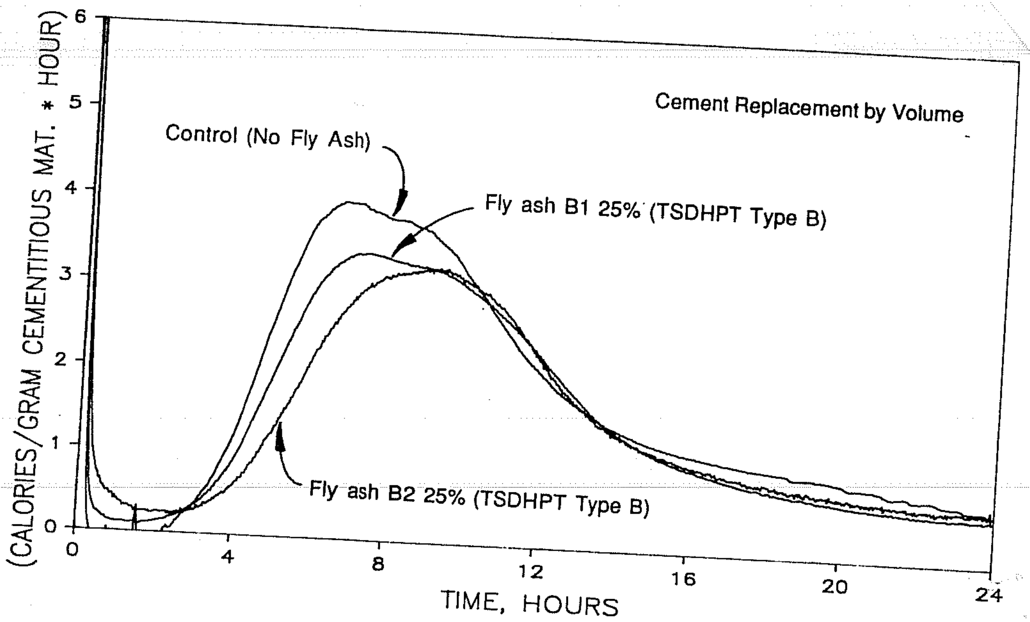


Figure 8.18 Comparison of the retarding effects of two different Type B fly ashes on the heat evolution of Type I-II cement paste at 100 degrees F.

cements and fly ashes used. The retarding effects of the two Type B fly ashes were more apparent with the Type I and Type I-II cements than they were for the Type III cement. Additionally, at 60 degrees F the use of Type A fly ash with Type III cement was seen to accelerate the onset of the acceleration stage. This behavior was not seen with the Type I or Type I-II cement.

A comparison of the finenesses of the fly ashes and cements reveals that Type I and Type I-II cements as well as the two Type B fly ashes exhibit similar fineness. The two Type A fly ashes are somewhat coarser, while the Type III cement shows a greater fineness. The replacement of the Type III cement with a slightly coarser material (Type B fly ash) has little effect on the onset of hydration, as may be seen in Figure 8.19. Similar behavior is observed when the Type I and Type I-II cements are replaced with the coarser Type A fly ashes.

In contrast, when the Type I and Type I-II cements are replaced with the finer Type B fly ashes, retardation is seen in almost all cases, which may be seen in Figure 8.20. When the very fine Type III cement is replaced by much coarser fly ashes, slight accelerations in hydration may even be seen. This case is shown in Figure 8.21.

The observed differences in behavior between the different cements obviously cannot be explained in terms of fineness of materials alone. Chemical interactions as well as the ambient temperature have some degree of effect on the hydration of a particular cement in the presence of a particular fly ash. The results of this study do suggest, however, that

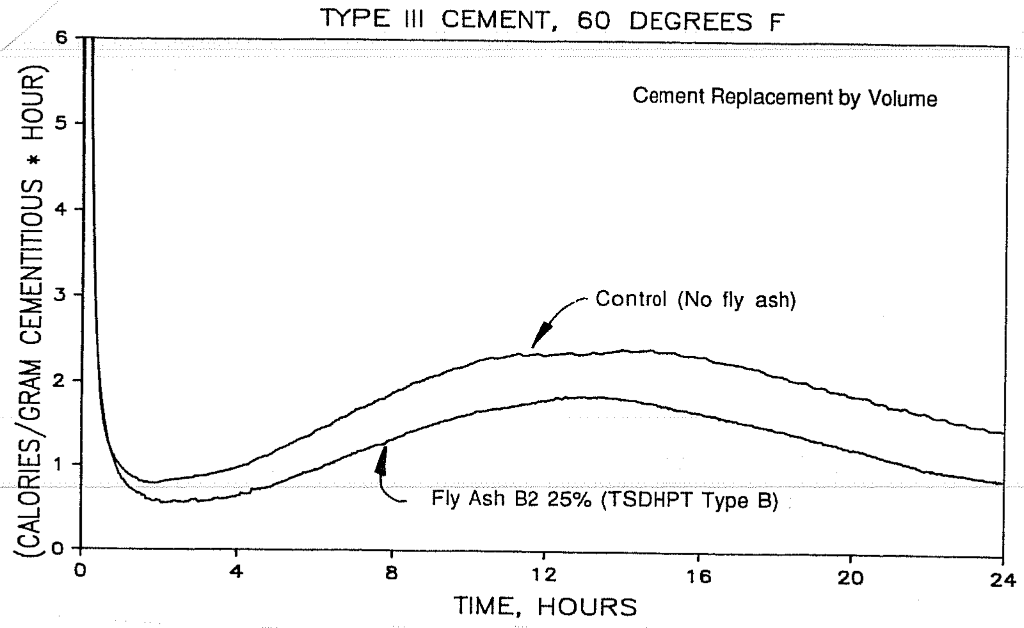


Figure 8.19 Effect of replacement of Type III cement with a slightly coarser fly ash.

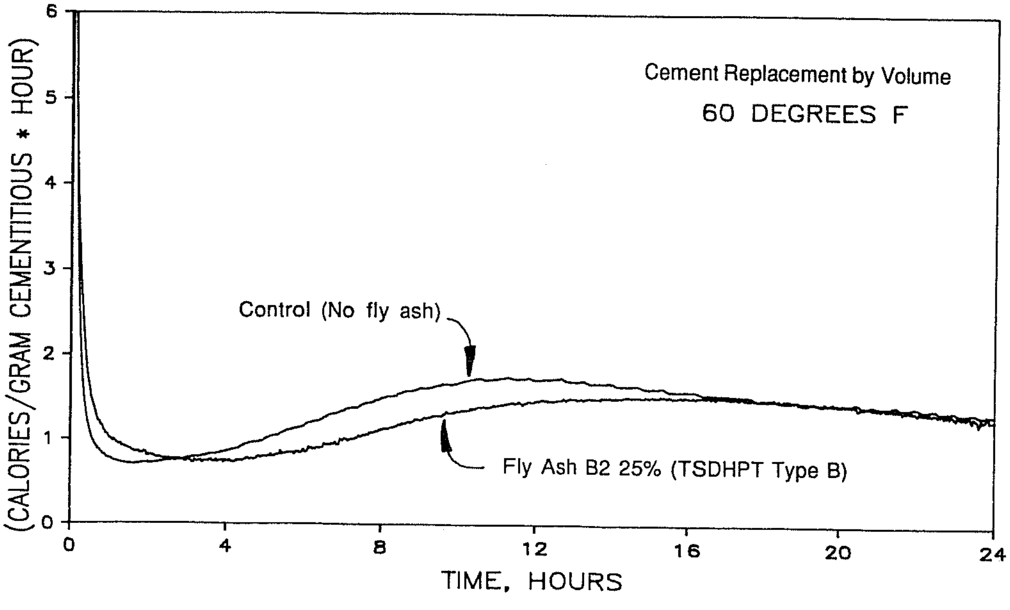


Figure 8.20 Effect of replacement of Type I-II cement with a finer fly ash.

the replacement of cement with a finer material may retard the cement hydration, while the replacement of a cement with a less fine material may accelerate the hydration at some temperatures. Finer materials may provide additional sites for the nucleation and growth

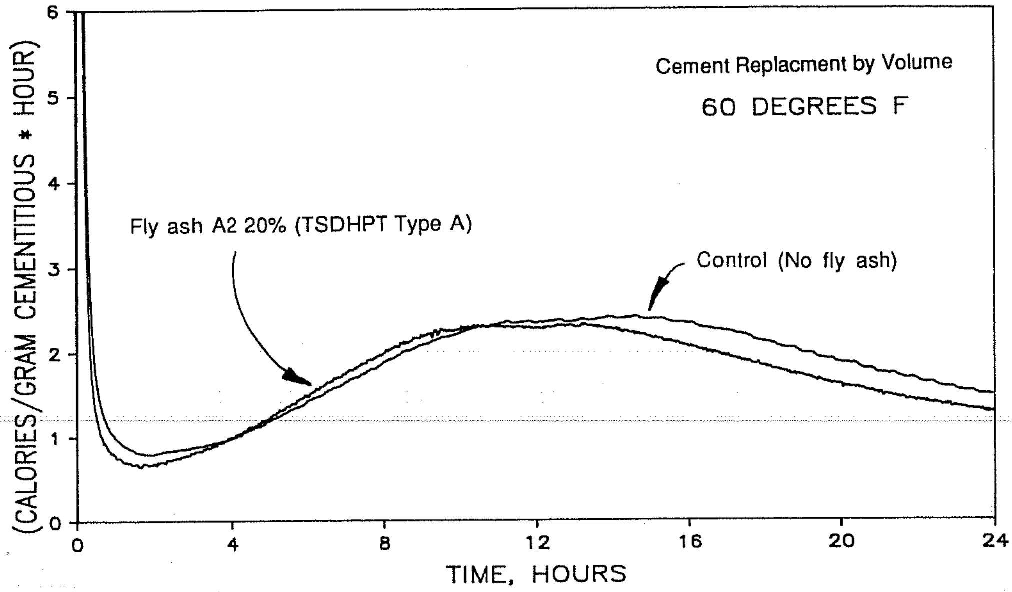


Figure 8.21 Effect of replacement of Type III cement with a much coarser fly ash.

of hydration products and thus prolong the induction period. Less fine materials provide fewer of these nucleation sites and thus hydration will be little affected or may even begin earlier.

8.4 Comparison of Results of Ready-Mix Concrete and Isothermal Calorimetry Tests

A direct comparison of the results of isothermal calorimetry tests and the temperature rise of actual concrete is not possible because the paste and concrete are subjected to different ambient conditions. Isothermal calorimetry tests involve the maintaining of a constant temperature environment in order to observe the kinetics and mechanisms of the hydration reaction. On the other hand, the concrete in actual structures is subjected to constantly changing temperatures due to the environment and the heat generated by the hydration of the cement in the concrete itself. Still, isothermal calorimetry tests may offer useful information in terms of predicting possible trends and behavior patterns in the temperature rise of actual concrete.

With regards to temperature, both series of tests indicate that the hydration of cement occurs at faster rates when subjected to higher temperatures. Additionally, the isothermal tests show that at higher temperatures, a substantially greater percentage of the 24 hour cumulative heat is obtained just a few hours after mixing with water.

However, by 24 hours, the cumulative heat evolved from the same pastes subjected to lower temperatures approaches that of pastes subjected to higher temperatures, as was shown in Figure 8.3. A similar result was seen in Figure 7.4 which showed the same ready-mix concrete mixture subjected to two different initial ambient temperatures. The early hydration of mass concrete cast at the higher temperature proceeds faster than the mass concrete cast at the lower temperature. At later ages, the two mixtures reach similar maximum temperatures.

Both series of tests show that the use of fly ash as a partial cement replacement may reduce the heat generation of the resulting paste or concrete.

However, the use of fly ash did not always result in less cumulative heat generation in the isothermal tests, while the use of fly ash did reduce the temperature rise in all of the ready-mix concrete tests. For both series of tests, it may generally be said the use of increased levels of fly ash resulted in greater reduction in heat generation, although each series had its exceptions.

Type B fly ashes were found in both test series to cause more significant retardations of the hydration of cement than Type A fly ashes. The retardations found in the ready-mix concrete tests were somewhat more dramatic than that observed in the isothermal calorimetry tests. This is probably partially due to the different temperature environments inherent in each test series.

CHAPTER 9
SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

9.1 SUMMARY

This study was conducted in order to develop guidelines to aid the engineer in designing more durable concrete with respect to temperature effects through the use of partial cement replacement with fly ash. The cements, fly ashes, and admixtures used in this study are commercially available throughout Texas and provide a basis for comparison of physical and chemical properties of cements, fly ashes, and admixtures in general.

The primary purpose of this study was to investigate the effect of fly ash produced in Texas on the temperature rise and hydration in concrete. The study consisted of two experimental phases: full-scale ready-mix concrete tests and isothermal calorimetry tests.

The first experimental phase involved the measuring of temperature rise in full scale specimens cast of ready-mix concrete. For each mix, a 4.5 ft. cube was cast, as well as two 8-ft x 3-ft-10-in. x 10-in. slabs. The two slabs were subjected to two different curing conditions: one was covered with polyethylene sheeting and the other was covered with a thick cotton mat.

The following materials and proportions were investigated:

1) Cement Content
    a) 5-sack mixture
    b) 7.5-sack mixture
2) Fly Ash Type
    a) Type A
    b) Type B
3) Percent Replacement of Cement by Volume
    a) 0 percent
    b) 20 percent or 25 percent
    c) 30 percent or 35 percent

Slump and compressive strength tests were conducted on all concrete mixtures. These tests provide a basis for comparison between mixtures with or without fly ash based on the properties of placeability and strength, which generally are the controlling criteria for concrete mixture design.

The second experimental phase involved the monitoring of the rate of heat evolution of cement/fly ash pastes subjected to different isothermal temperatures. The following materials and proportions were investigated:

1) Cement Type
   a) Type I
   b) Type I-II
   c) Type III
2) Fly Ash Type
   a) Type A
   b) Type B
3) Percent Replacement of Cement by Volume
   a) 0 percent
   b) 20 percent or 25 percent
   c) 30 percent or 35 percent
4) Isothermal Temperature
   a) 40 degrees F
   b) 60 degrees F
   c) 80 degrees F
   d) 100 degrees F

9.2 Conclusions

9.2.1 Ready-Mix Concrete Tests.

9.2.1.1 Temperature Rise. The purpose of this report is to aid the engineer in designing more durable concrete by providing guidelines which will reduce the tendency for thermal cracking. The conclusions of the ready-mix concrete tests pertaining to internal concrete temperature rise are as follows:

1) In all cases, regardless of cement content, specimen size, curing condition, or type of fly ash, the use of fly ash as a partial cement replacement resulted in a lower maximum temperature rise in comparison to the control mixtures.
2) Temperature rises were greater for the 7.5-sack concrete mixtures as compared to the 5-sack concrete mixtures.

3) In all cases, regardless of cement content, specimen size, curing condition, or type of fly ash, the use of fly ash as a partial cement replacement resulted in an increase in the time to reach peak temperature as compared to the control mixtures. In general, Type A fly ash mixtures reached peak temperature earlier than did Type B fly ash mixtures. Regardless of fly ash type, the time to peak temperature in all cases increased with increased fly ash replacement.

4) In general, lower maximum temperatures were seen in mass concrete containing Type A fly ashes as compared to mass concrete containing Type B fly ashes. The use of increased fly ash replacement levels resulted in a greater decrease in the maximum temperature rise. The effectiveness of Type A fly ashes over Type B fly ashes was not as apparent in the 7.5-sack mixtures. Thus, the effectiveness of a particular fly ash in reducing the maximum temperature rise in mass concrete is dependent upon the cement content.

5) In general, temperature rise results of the cotton mat covered slabs were similar to those of the mass concrete, except that the temperature ranges for the two different size specimens were different. Temperature rise was generally greater in the cotton mat covered slabs for Type B fly ashes in comparison to Type A fly ashes for both cement contents. The cotton mat provides an environment in some way similar to that seen by concrete in an adiabatic condition.

6) Polyethylene covered slabs did not follow the trends of the mass concrete and cotton mat covered slabs. The use of Type B fly ashes was seen to result in greater or similar temperature reductions in comparison to Type A fly ashes. The longer time to peak temperature associated with Type B fly ashes allowed more heat dissipation in the polyethylene slab sections, and therefore more temperature reduction than was seen in the mass sections.

7) The time to reach peak temperature did not play an important role in determining the temperature rise of the mass concrete, but did play a role in determining the temperature rise of the slab sections. The same mixture cast at two different initial ambient temperatures still reached nearly the same maximum temperature rise in the mass concrete even though the mixture cast at the lower temperature took a longer time to reach peak temperature. However, in the polyethylene and cotton mat covered slabs, the temperature rise was lower for the mixture which was cast at the lower temperature. The longer time to peak temperature allowed more time for heat dissipation from the thin slab sections. The time to peak temperature is not an important factor for mass concrete, but can be an important factor in thinner sections which dissipate heat easily.

8) The use of the cotton mat as a curing method generally resulted in greater temperature rises than the use of polyethylene sheeting. Differences in the temperature

rises of the two slab curing methods were more apparent in the higher cement content mixtures. Thus the method of curing used is more critical in higher cement content mixtures.

9) The use of fly ash in the higher cement content mixtures resulted in temperature rises in slabs of both curing conditions comparable to those found in the lower cement content mixtures without fly ash.

9.2.1.2 Temperature Gradients. The conclusions of the ready-mix concrete tests concerning temperature gradients in concrete are:

1) Specimens cast of higher cement content mixtures reached greater temperatures and thus possess greater potential for thermal cracking, regardless of specimen size or the curing condition used.

2) The use of fly ash caused reductions in the maximum temperature rise and thus caused temperature gradients to occur at lower temperatures. The use of fly ash will reduce the tendency for thermal cracking by lowering the temperatures at which the maximum gradients will occur.

3) The temperature gradients in mass concrete cast at different hot weather temperatures were little affected by the different ambient temperatures.

4) Temperature gradients in both slab sections were affected by the initial ambient temperature. The same mixture cast at a higher temperature reached higher maximum temperatures in both slab curing conditions. The temperature at the time of casting is more critical for thin concrete sections which will lose heat to the environment easily. Concrete cast at higher temperatures will reach greater maximum temperatures in thin sections and thus will increase the potential for thermal cracking.

9.2.1.3 Slump. The conclusions of the slump tests of the ready-mix concrete are:

1) In general, for a given mixing water content, the slump of ready- mix concrete is increased with the replacement of cement by fly ash. This effect was more pronounced in the 7.5-sack mixtures as compared to the 5-sack mixtures.

2) The use of increased levels of fly ash with no adjustments in the amount of water in the mixture did not always result in an increase in the slump of the mixture. The increased surface area associated with greater fineness of some fly ash particles in comparison to cement resulted in a decrease in slump of the mixture after a certain level of fly ash was in the mixture.

9.2.1.4 Compressive Strength. The conclusions from the testing of compressive strength are:

1) The use of fly ash as a partial replacement for cement with no adjustments in the amount of water in the mixture resulted in lower early strength in comparison to the control mixtures in all cases. The use of increased amounts of fly ash resulted in greater decreases in early strength for all fly ashes in this study.

2) In all cases, the 7-day compressive strengths of the concrete mixtures with fly ash were less than the compressive strengths of the control mixtures.

3) The fly ash concrete mixtures showed greater rates of strength gain than the control mixtures did between 1 and 7 days, regardless of fly ash type or replacement level.

4) Strength gain between 1 and 7 days was generally greater for Type B fly ashes than for Type A fly ashes. This gain is due to the additional cementitious properties associated with the higher calcium content of Type B fly ashes.

5) Compressive strength gain between 7 and 28 days was seen to be greater for fly ash concretes than for the control mixtures. At 28 days, some fly ash concretes exhibited greater compressive strength than the control mixtures. There was no apparent trend in this behavior in regards to type of fly ash, replacement level, or cement content.

9.2.2 Isothermal Calorimetry Tests. The conclusions of the isothermal calorimetry tests are as follows:

1) Changes in isothermal temperature were found to have similar effects on the hydration behavior of all three cements studied, regardless of whether or not fly ash was used. The hydration of cement is sensitive to temperatures in the range of hot weather concreting. The hydration of cement is accelerated at higher temperatures.

2) The use of fly ash at 40 degrees F resulted in little change in the heat evolution of the three cements in this study. The use of increasing amounts of fly ash did not result in significant changes in the heat evolution.

3) The use of fly ash at 60 degrees F resulted in reductions in the heat evolution of the cements studied. The use of increased levels of fly ash replacement resulted in slight decreases in the heat evolution.

4) The use of Type A fly ashes at 80 and 100 degrees F generally resulted in reductions in the maximum rate of heat evolution and the cumulative heat evolution. Type A fly ashes generally contributed little to heat generation, but did aid in increasing the hydration of the cement.

5) The use of Type B fly ashes at 80 and 100 degrees F resulted in changes in the hydration curves of the cements studied. The use of Type B fly ashes in some cases increased the rate of heat evolution and the cumulative heat evolution.

6) The use of Type A fly ashes generally did not have significant effects on the time of onset of the acceleration stage for the three cements studied at any of the four isothermal temperatures, although some delay was noticed in most cases. Increasing levels of Type A fly ash did not always result in additional increases in the retarding effects.

7) The use of Type B fly ashes resulted in delays in the time of onset of the acceleration period. The time of delay was increased with increasing isothermal temperature and with increasing level of fly ash replacement.

8) The degree of retardation or acceleration of the hydration of cement in the presence of fly ash is to some degree dependent upon the relative finenesses of the cements and fly ashes.

9.3 Guidelines

Based on the test results presented in this study, the following guidelines for the partial replacement of cement with fly ash to reduce the temperature rise in concrete and the tendency for thermal cracking have been developed:

1) Regardless of fly ash type, the use of fly ash will reduce the potential for thermal cracking in any concrete section by lowering the maximum temperature rise.

2) Higher cement content mixtures will reach higher temperatures and thus possess greater potential for thermal cracking in any concrete section.

3) Regardless of fly ash type, the use of fly ash in higher cement content mixtures may reduce the temperature rise in thin sections to levels comparable to those seen by lower cement content mixtures without fly ash.

4) The method of curing used will not have a significant effect on the temperature rise of mass concrete. The method of curing used will have an effect on the temperature rise of thinner concrete sections, especially when high cement content mixtures are used. Polyethylene sheeting will allow more dissipation of heat to the environment and thus will generally result in lower temperature rises than the cotton mat curing.

5) The time to peak temperature is not a significant factor in determining the temperature rise of mass concrete. The time to peak temperature plays an important role in determining the time to peak temperature of thinner sections, especially if polyethylene is used for curing. The use of fly ash will result in greater times

to peak temperature and thus will allow more time for heat dissipation. The use of Type B fly ashes will result in greater times to peak temperature than Type A fly ashes, and so temperature rises comparable to those seen by Type A fly ashes may be achieved when using Type B fly ashes, if the section allows the dissipation of heat.

6) The temperature rise of mass concrete is not greatly influenced by the ambient temperature at temperatures associated with hot weather concreting because a nearly adiabatic condition exists, and no heat is lost to the environment. The temperature rise of thinner sections is influenced by the ambient temperature; thin concrete sections placed at higher temperatures will see a greater temperature rise due to the increased rate of hydration and the reduced amounts of heat which may be dissipated from the section, depending on its curing condition. At lower temperatures, the heat generated by the hydration of cement can be dissipated more easily and so lower temperature rises are seen.

7) The relative finenesses of the cements and fly ashes used in concrete will have an effect on the time to peak temperature. Finer fly ashes tend to delay the time to peak temperature more than do less coarser fly ashes. Replacing a cement with a coarser material may accelerate the hydration to some degree, while the replacement with a finer material may delay the time to peak temperature.

9.4 Recommendations for Future Research

This report addressed the important question of whether the partial replacement of fly ash will reduce the temperature rise in concrete. The results of this study suggest some other possible areas of research which might provide additional information on the temperature rise in concrete. Recommended areas for future research are:

1) Monitor the temperature rise of full scale ready-mix concrete tests under cold weather conditions to see if similar trends are found concerning maximum temperature rise and the influence of the time to peak temperature as were found under hot weather conditions.

2) Subject concrete to curing and atmospheric conditions conducive to thermal cracking in order to measure the detrimental effects of thermal cracking, possibly through flexural tests of the exposed surface.

3) Develop a failure theory for concrete subjected to a thermal strain gradient.

4) Conduct calorimetric tests on cement/fly ash pastes in the presence of chemical admixtures such as retarders and superplasticizers to study reaction mechanisms and predict possible reductions in the rate of heat generation when such admixtures are used with particular fly ashes and cements.

5) Conduct calorimetric tests on other Type A and Type B fly ashes to see if the trends observed in this study pertain to all fly ashes.

APPENDIX A
MATERIALS AND MIX PROPORTIONS FOR READY MIX CONCRETE TESTS

Table A.1 Ready Mixed Concrete Proportions, 5 Sack Mixes
(One Yard Weights)

Mix Description:	Type I Cement (lb.)	Fly Ash (lb.)	3/4" Coarse Agg.(lb.)	Fine Agg.(lb.)	Water (lb.)	Retarder (oz/yd)
Control	472	0	1913	1360	228	16.6
FA A1: 20%	378	72.5	1960	1361	247	16.5
FA A1: 30%	327	109	1907	1363	247	16.5
FA A2: 20%	380	64.5	1886	1381	251	16.4
FA A2: 30%	333	97	1907	1361	249	16.6
FA B1: 25%	353	96	1880	1373	248	16.3
FA B1: 35%	305	135	1867	1362	249	16.4
FA B2: 25%	359	102	1893	1371	249	16.5
FA B2: 35%	306	143	1913	1376	248	16.6

Table A.2 Ready Mixed Concrete Proportions, 7.5 Sack Mixes
(One Yard Weights)

Mix Description:	Type I Cement (lb.)	Fly Ash (lb.)	3/4" Coarse Agg.(lb.)	Fine Agg.(lb.)	Water (lb.)	Retarder (oz/yd)
Control A	703	0	1707	1227	289	26.1
Control B	710	0	1720	1230	290	26.1
FA A1: 20%	562	109	1733	1222	290	26.0
FA A1: 30%	493	163	1700	1242	294	26.0
FA A2: 20%	569	98	1700	1223	292	26.1
FA A2: 30%	491	146	1733	1236	290	26.1
FA B1: 25%	527	144	1727	1226	291	26.0
FA B1: 35%	457	202	1713	1229	290	26.1
FA B2: 25%	535	153	1727	1242	291	26.1
FA B2: 35%	455	214	1727	1243	291	26.0

Table A.3 Chemical and Physical Properties of Fly Ash A1

	Fly Ash A1	TSDHPT* Type A	TSDHPT* Type B
Si+Al+Fe Oxides (%)	79.77	65	50
Si Oxide (%)	52.90	-	-
Al Oxide (%)	17.89	-	-
Ca Oxide (%)	9.55	**	**
Mg Oxide (%)	1.66	5.0	5.0
Sulfate (%)	0.90	5.0	5.0
Available Alkalies (%)	0.57	1.5	1.5
Loss on Ignition (%)	0.19	3.0	3.0
Moisture Content (%)	0.03	2.0	2.0
Shrinkage (%)	0.01	0.03	0.03
Pozzolanic Activity	90.90	75	75
Specific Gravity	2.43	-	-
Blaine Fineness (cm^2/gm)	2560	-	-
Percent Retained on #325 Sieve	23.81	30	30

* Maximum values except for sum of oxides and pozzolanic activity

** 4% maximum variation from previous ten samples

Table A.4 Chemical and Physical Properties of Fly Ash A2

	Fly Ash A2	TSDHPT* Type A	TSDHPT* Type B
Si+Al+Fe Oxides (%)	88.10	65	50
Si Oxide (%)	57.90	-	-
Al Oxide (%)	26.30	-	-
Ca Oxide (%)	9.60	**	**
Mg Oxide (%)	2.10	5.0	5.0
Sulfate (%)	0.52	5.0	5.0
Available Alkalies (%)	0.30	1.5	1.5
Loss on Ignition (%)	0.17	3.0	3.0
Moisture Content (%)	0.09	2.0	2.0
Shrinkage (%)	0.001	0.03	0.03
Pozzolanic Activity	89.51	75	75
Specific Gravity	2.16	-	-
Blaine Fineness (cm^2/gm)	NA	-	-
Percent Retained on #325 Sieve	22.60	30	30

* Maximum values except for sum of oxides and pozzolanic activity

** 4% maximum variation from previous ten samples

Table A.5 Chemical and Physical Properties of Fly Ash B1

	Fly Ash B1	TSDHPT* Type A	TSDHPT* Type B
Si+Al+Fe Oxides (%)	62.97	65	50
Si Oxide (%)	35.59	-	-
Al Oxide (%)	22.41	-	-
Ca Oxide (%)	23.13	**	**
Mg Oxide (%)	4.25	5.0	5.0
Sulfate (%)	2.10	5.0	5.0
Available Alkalies (%)	2.04	1.5	1.5
Loss on Ignition (%)	0.52	3.0	3.0
Moisture Content (%)	0.02	2.0	2.0
Shrinkage (%)	-0.006	0.03	0.03
Pozzolanic Activity	102.13	75	75
Specific Gravity	2.58	-	-
Blaine Fineness (cm^2/gm)	3820	-	-
Percent Retained on #325 Sieve	22.00	30	30

* Maximum values except for sum of oxides and pozzolanic activity
** 4% maximum variation from previous ten samples

Table A.6 Chemical and Physical Properties of Fly Ash B2

	Fly Ash B2	TSDHPT* Type A	TSDHPT* Type B
Si+Al+Fe Oxides (%)	57.4	65	50
Si Oxide (%)	30.80	-	-
Al Oxide (%)	21.94	-	-
Ca Oxide (%)	31.34	**	**
Mg Oxide (%)	6.14	5.0	5.0
Sulfate (%)	1.97	5.0	5.0
Available Alkalies (%)	1.67	1.5	1.5
Loss on Ignition (%)	0.17	3.0	3.0
Moisture Content (%)	0.06	2.0	2.0
Shrinkage (%)	-0.013	0.03	0.03
Pozzolanic Activity	105.40	75	75
Specific Gravity	2.73	-	-
Blaine Fineness (cm^2/gm)	3935	-	-
Percent Retained on #325 Sieve	15.7	30	30

* Maximum values except for sum of oxides and pozzolanic activity
** 4% maximum variation from previous ten samples

Table A.7 Chemical and Physical Properties of Type I Portland Cement

Chemical Composition	Percent
Silicon Dioxide (SiO_2)	20.16
Aluminum Dioxide (Al_2O_3)	5.73
Ferric Oxide $(Fe_2)O_3$	1.97
Calcium Oxide (CaO)	65.67
Magnesium Oxide (MgO)	1.24
Sulfur Trioxide (SO_3)	3.00
Loss on Ignition	1.48
Insoluble Residue	0.25
Tricalcium Silicate (C_3S)	64.26
Tricalcium Aluminate (C_3A)	11.85
Alkali Total	0.54

Physical Properties			
Time of Setting:	Gilmore		Vicat
Initial	180 min.		110 min.
Final	360 min.		210 min.
Specific Surface:			
Blaine		3630 cm^2/gm	
Wagner		1896 cm^2/gm	
Compressive Strength:			
1-day		N.A.	
3-day		4065 psi	

Table A.8 Chemical and Physical Properties of Type I-II Portland Cement

Chemical Composition	**Percent**
Silicon Dioxide (SiO_2)	21.8
Aluminum Dioxide (Al_2O_3)	4.2
Ferric Oxide ($(Fe_2)O_3$)	3.2
Calcium Oxide (CaO)	64.7
Magnesium Oxide (MgO)	0.6
Sulfur Trioxide (SO_3)	3.00
Loss on Ignition	0.9
Insoluble Residue	0.3
Tricalcium Silicate (C_3S)	54.0
Tricalcium Aluminate (C_3A)	6.0
Alkali Total	0.63

Physical Properties			
Time of Setting:	Gilmore		Vicat
Initial	125 min.		88 min.
Final	225 min.		201 min.
Specific Surface:			
Blaine		3350 cm^2/gm	
Wagner		1880 cm^2/gm	
Compressive Strength:			
1-day		1970 psi	
3-day		3550 psi	

Table A.9 Chemical and Physical Properties of Type III Portland Cement

Chemical Composition	Percent
Silicon Dioxide (SiO_2)	20.6
Aluminum Dioxide (Al_2O_3)	5.4
Ferric Oxide $(Fe_2)O_3$	2.6
Calcium Oxide (CaO)	64.4
Magnesium Oxide (MgO)	1.1
Sulfur Trioxide (SO_3)	3.7
Loss on Ignition	1.6
Insoluble Residue	0.22
Tricalcium Silicate (C_3S)	55.0
Tricalcium Aluminate (C_3A)	10.0
Alkali Total	0.75

Physical Properties			
Time of Setting:	Gilmore		Vicat
Initial	100 min.		-
Final	195 min.		-
Specific Surface:			
Blaine		5990 cm^2/gm	
Wagner		2840 cm^2/gm	
Compressive Strength:			
1-day		3760 psi	
3-day		5100 psi	

APPENDIX B
RESULTS OF READY MIX CONCRETE TESTS

Table B.1 Temperature Rise Results for 4.5' Cubes

Mix Description	Peak Temperature Rise Degrees F	Time to 95% Peak Temperature Hours	Initial Ambient Temperature Degrees F
5 Sack Control 1	77.5	12.0	88.0
5 Sack FA A1 20%	64.2	12.3	90.1
5 Sack FA A1 30%	53.3	12.5	94.3
5 Sack FA A2 20%	61.6	13.4	91.6
5 Sack FA A2 30%	54.5	14.8	96.2
5 Sack FA B1 25%	66.3	14.9	90.8
5 Sack FA B1 35%	53.4	16.5	91.4
5 Sack FA B2 25%	68.4	17.2	92.6
5 Sack FA B2 35%	62.0	17.6	92.0
7.5 Sack Control 1	112.3	10.6	90.1
7.5 Sack Control 2	111.9	15.2	80.7
7.5 Sack FA A1 20%	96.7	14.2	92.1
7.5 Sack FA A1 30%	89.3	17.3	88.2
7.5 Sack FA A2 20%	90.3	14.5	93.4
7.5 Sack FA A2 30%	83.0	17.3	91.6
7.5 Sack FA B1 25%	92.5	13.6	89.9
7.5 Sack FA B1 35%	90.0	13.7	91.5
7.5 Sack FA B2 25%	94.4	19.2	88.4
7.5 Sack FA B2 35%	86.0	26.2	80.8

Table B.2 **Temperature Rise Results for Polyethylene Covered Slabs**

Mix Description	Peak Temperature Rise Degrees F	Time to Peak Temperature Hours	Initial Ambient Temperature Degrees F
5 Sack Control 1	46.6	11.0	88.0
5 Sack FA A1 20%	38.1	11.7	90.1
5 Sack FA A1 30%	33.2	13.2	94.3
5 Sack FA A2 20%	36.9	12.7	91.6
5 Sack FA A2 30%	30.7	14.3	96.2
5 Sack FA B1 25%	36.6	13.7	90.8
5 Sack FA B1 35%	34.8	14.2	91.4
5 Sack FA B2 25%	35.5	17.5	92.6
5 Sack FA B2 35%	28.9	19.6	92.0
7.5 Sack Control 1	84.5	11.9	90.1
7.5 Sack Control 2	69.9	12.4	80.7
7.5 Sack FA A1 20%	43.3	10.7	92.1
7.5 Sack FA A1 30%	41.8	13.3	88.2
7.5 Sack FA A2 20%	48.3	10.7	93.4
7.5 Sack FA A2 30%	49.6	15.3	91.6
7.5 Sack FA B1 25%	58.7	14.6	89.9
7.5 Sack FA B1 35%	52.6	15.7	91.5
7.5 Sack FA B2 25%	52.3	20.1	88.4
7.5 Sack FA B2 35%	32.6	26.2	80.8

Table B.3 Temperature Rise Results for Cotton Mat Covered Slabs

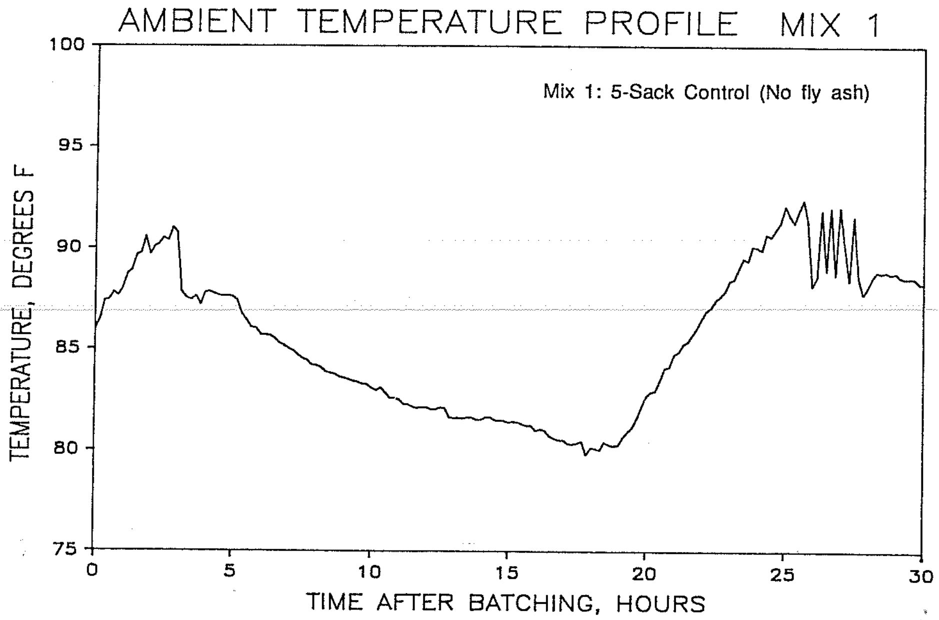
Mix Description	Peak Temperature Rise Degrees F	Time to Peak Temperature Hours	Initial Ambient Temperature Degrees F
5 Sack Control 1	42.5	9.0	88.0
5 Sack FA A1 20%	39.1	13.0	90.1
5 Sack FA A1 30%	31.2	15.3	94.3
5 Sack FA A2 20%	37.0	14.2	91.6
5 Sack FA A2 30%	32.7	17.4	96.2
5 Sack FA B1 25%	35.9	15.9	90.8
5 Sack FA B1 35%	36.0	16.2	91.4
5 Sack FA B2 25%	37.7	19.5	92.6
5 Sack FA B2 35%	36.6	22.3	92.0
7.5 Sack Control 1	81.9	13.0	90.1
7.5 Sack Control 2	75.4	13.6	80.7
7.5 Sack FA A1 20%	59.0	13.1	92.1
7.5 Sack FA A1 30%	50.7	15.8	88.2
7.5 Sack FA A2 20%	53.9	12.0	93.4
7.5 Sack FA A2 30%	46.1	15.1	91.6
7.5 Sack FA B1 25%	55.2	14.3	89.9
7.5 Sack FA B1 35%	55.9	15.5	91.5
7.5 Sack FA B2 25%	53.0	21.0	88.4
7.5 Sack FA B2 35%	45.2	24.8	80.8

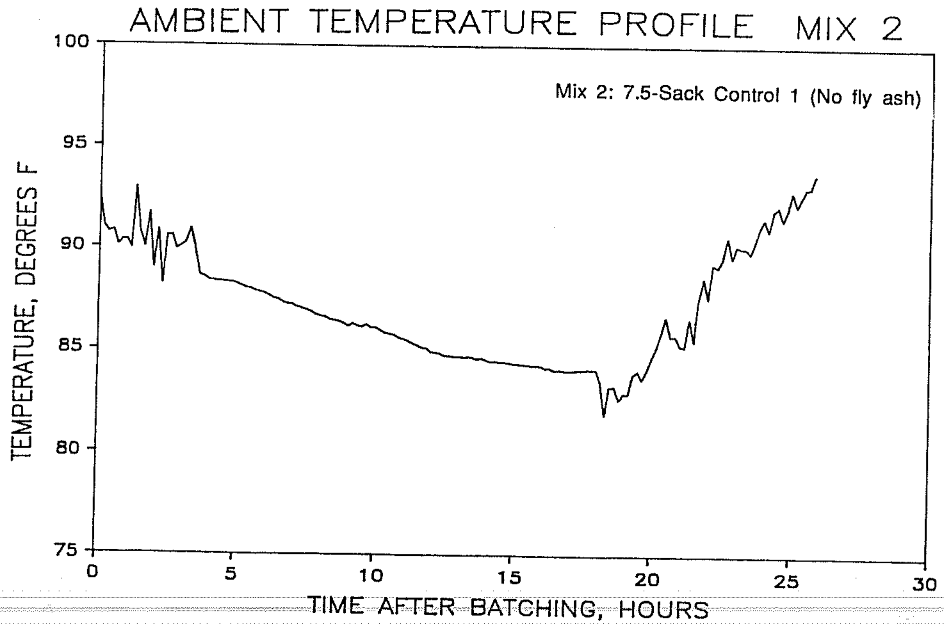
Table B.4 Slump Test Results for Ready Mix Concrete

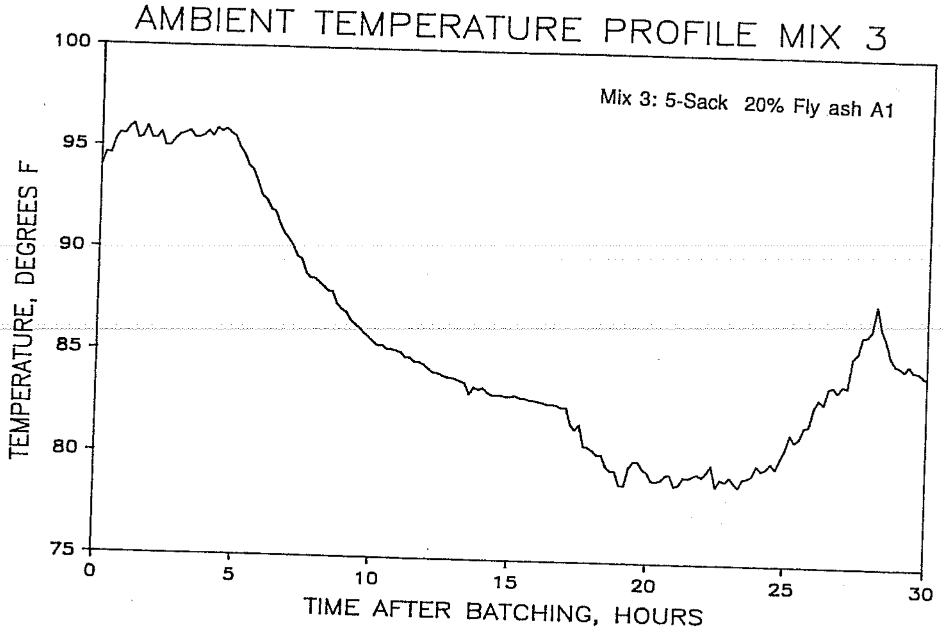
Mix Description	Slump Inches	Initial Ambient Temperature Degrees F
5 Sack Control 1	2.25	88.0
5 Sack FA A1 20%	1.5	90.1
5 Sack FA A1 30%	2.75	94.3
5 Sack FA A2 20%	3.0	91.6
5 Sack FA A2 30%	6.0	96.2
5 Sack FA B1 25%	4.0	90.8
5 Sack FA B1 35%	7.0	91.4
5 Sack FA B2 25%	3.0	92.6
5 Sack FA B2 35%	6.5	92.0
7.5 Sack Control 1	2.25	90.1
7.5 Sack Control 2	3.0	80.7
7.5 Sack FA A1 20%	7.0	92.1
7.5 Sack FA A1 30%	7.5	88.2
7.5 Sack FA A2 20%	5.5	93.4
7.5 Sack FA A2 30%	9.5	91.6
7.5 Sack FA B1 25%	8.0	89.9
7.5 Sack FA B1 35%	7.25	91.5
7.5 Sack FA B2 25%	7.25	88.4
7.5 Sack FA B2 35%	6.5	80.8

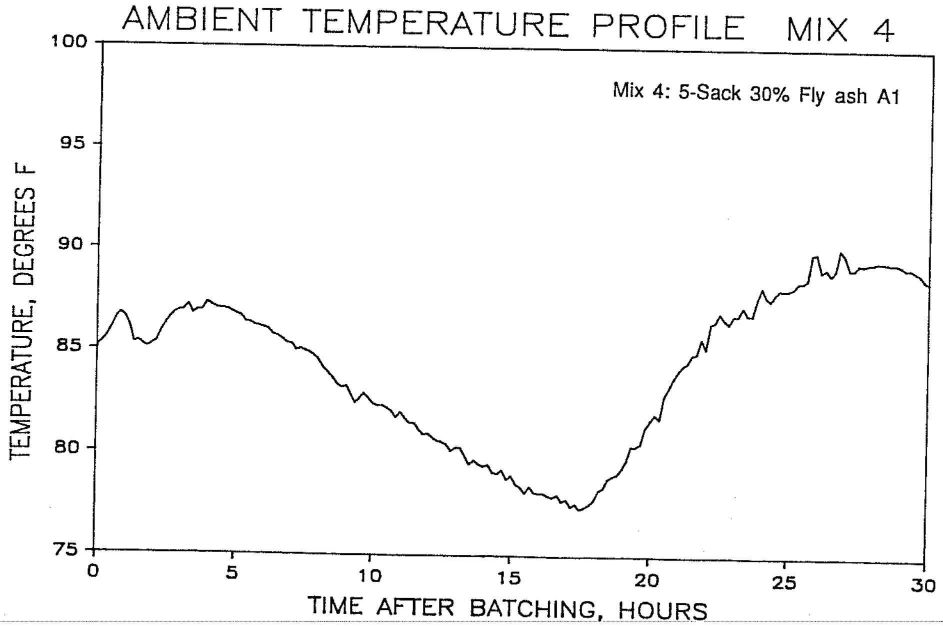
Table B.5 Compressive Strength of Ready Mix Concrete

Mix Description	1-Day Strength (psi)	7-Day Strength (psi)	28-Day Strength (psi)
5 Sack Control 1	2480	4360	5300
5 Sack FA A1 20%	2170	4280	5710
5 Sack FA A1 30%	1410	3720	5140
5 Sack FA A2 20%	1590	3750	5030
5 Sack FA A2 30%	1070	3060	4510
5 Sack FA B1 25%	1405	3860	5500
5 Sack FA B1 35%	1130	3350	4830
5 Sack FA B2 25%	1440	4190	5480
5 Sack FA B2 35%	930	3780	5010
7.5 Sack Control 1	4170	5810	6570
7.5 Sack Control 2	3760	6380	6640
7.5 Sack FA A1 20%	2770	5070	6250
7.5 Sack FA A1 30%	1870	4730	6150
7.5 Sack FA A2 20%	2650	4420	5400
7.5 Sack FA A2 30%	1700	4120	5800
7.5 Sack FA B1 25%	2120	4580	5920
7.5 Sack FA B1 35%	2220	5100	6750
7.5 Sack FA B2 25%	1480	5370	7140
7.5 Sack FA B2 35%	1000	5050	6840


AMBIENT TEMPERATURE PROFILE MIX 1
Mix 1: 5-Sack Control (No fly ash)
TEMPERATURE, DEGREES F
100
95
90
85
80
75
0
5
10
15
20
25
30
TIME AFTER BATCHING, HOURS


AMBIENT TEMPERATURE PROFILE MIX 2
Mix 2: 7.5-Sack Control 1 (No fly ash)
TEMPERATURE, DEGREES F
100
95
90
85
80
75
0
5
10
15
20
25
30
TIME AFTER BATCHING, HOURS


AMBIENT TEMPERATURE PROFILE MIX 3
Mix 3: 5-Sack 20% Fly ash A1
TEMPERATURE, DEGREES F
100
95
90
85
80
75
0
5
10
15
20
25
30
TIME AFTER BATCHING, HOURS


AMBIENT TEMPERATURE PROFILE MIX 4
Mix 4: 5-Sack 30% Fly ash A1
TEMPERATURE, DEGREES F
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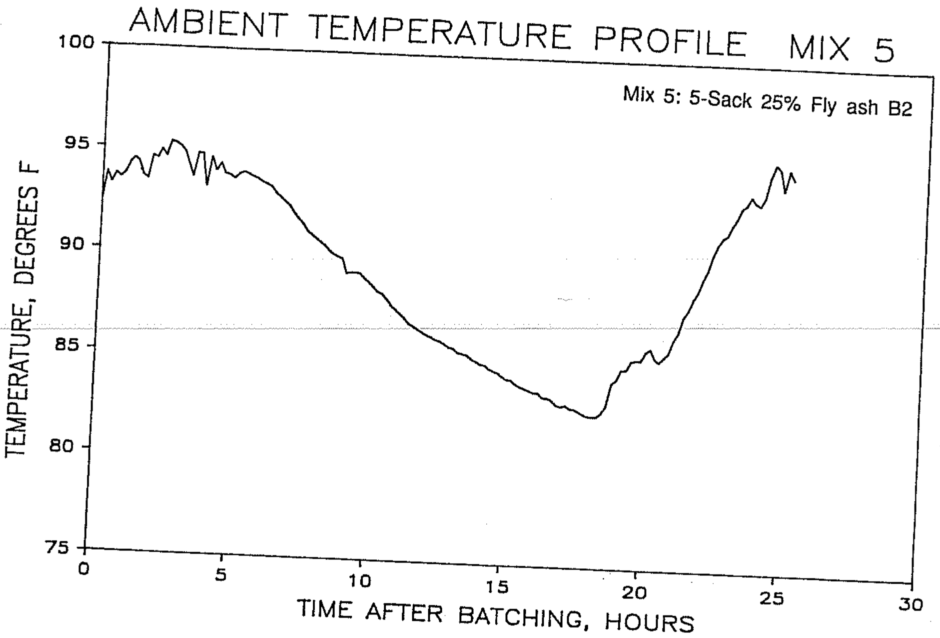
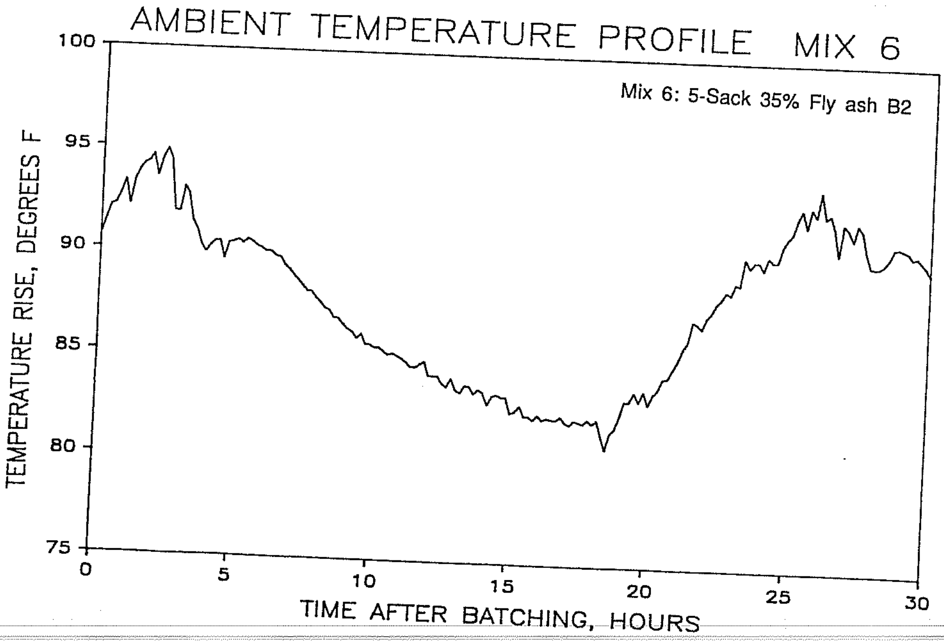
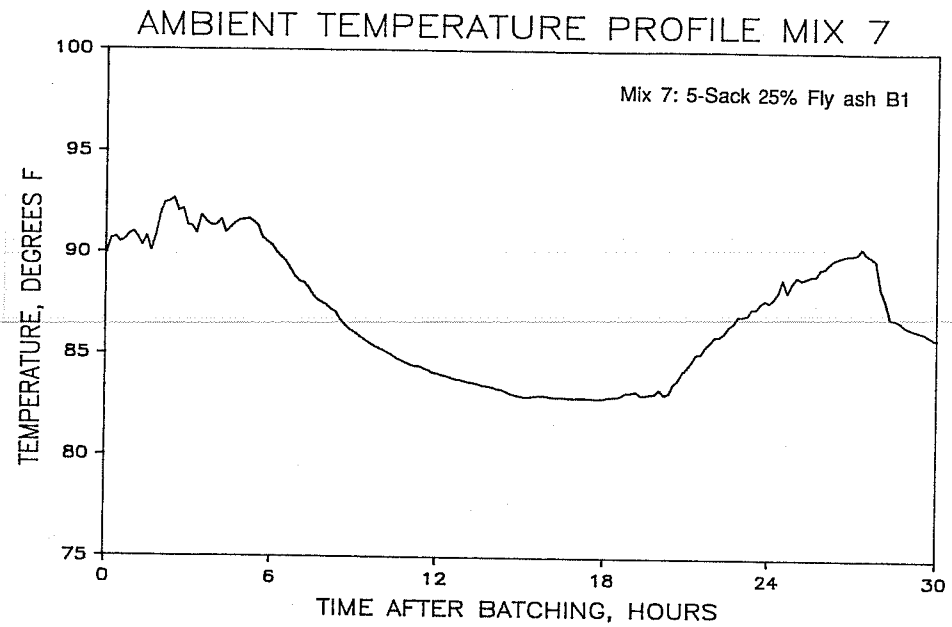
95
90
85
80
75
0
5
10
15
20
25
30
TIME AFTER BATCHING, HOURS


AMBIENT TEMPERATURE PROFILE MIX 5
Mix 5: 5-Sack 25% Fly ash B2
TEMPERATURE, DEGREES F
100
95
90
85
80
75
0
5
10
15
20
25
30
TIME AFTER BATCHING, HOURS


AMBIENT TEMPERATURE PROFILE MIX 6
Mix 6: 5-Sack 35% Fly ash B2
TEMPERATURE RISE, DEGREES F
100
95
90
85
80
75
0
5
10
15
20
25
30
TIME AFTER BATCHING, HOURS


AMBIENT TEMPERATURE PROFILE MIX 7
Mix 7: 5-Sack 25% Fly ash B1
TEMPERATURE, DEGREES F
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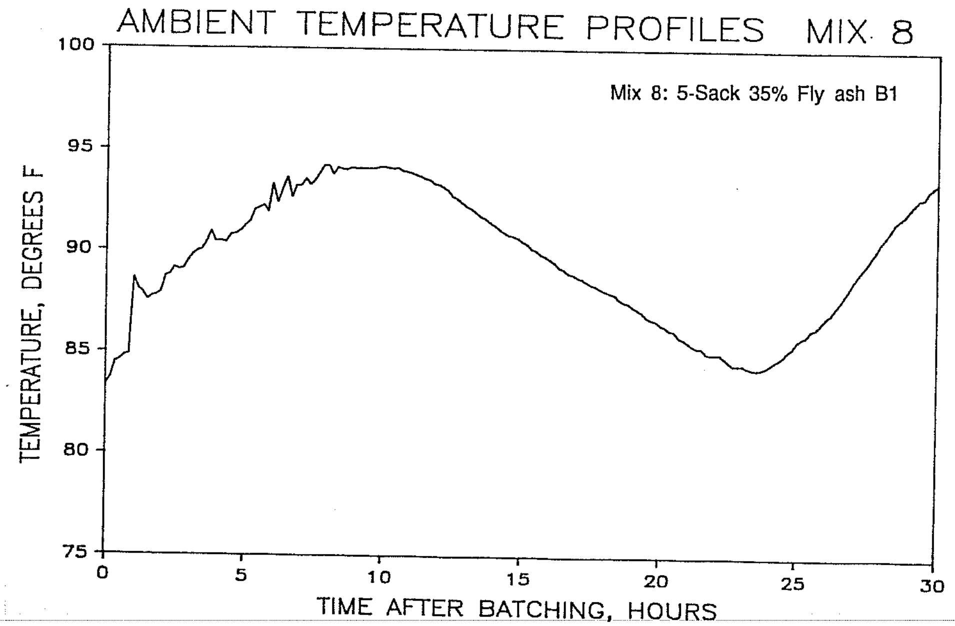
95
90
85
80
75
0
6
12
18
24
30
TIME AFTER BATCHING, HOURS


AMBIENT TEMPERATURE PROFILES MIX 8
Mix 8: 5-Sack 35% Fly ash B1
TEMPERATURE, DEGREES F
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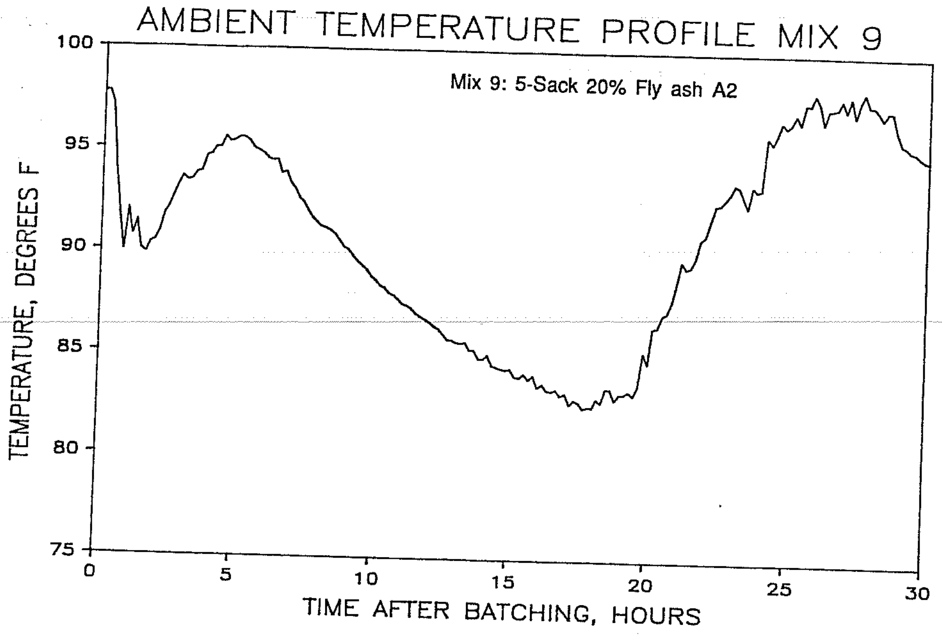
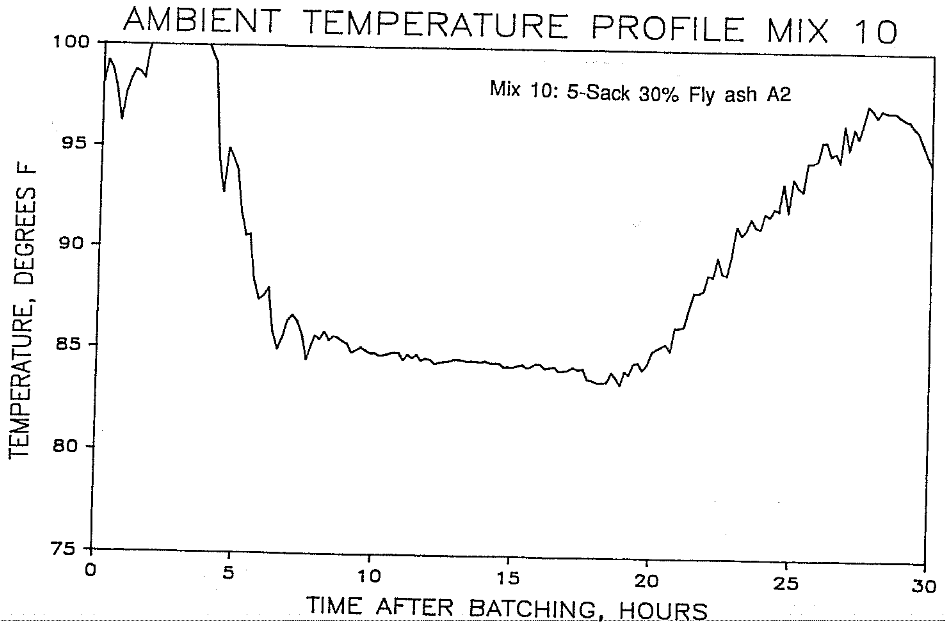
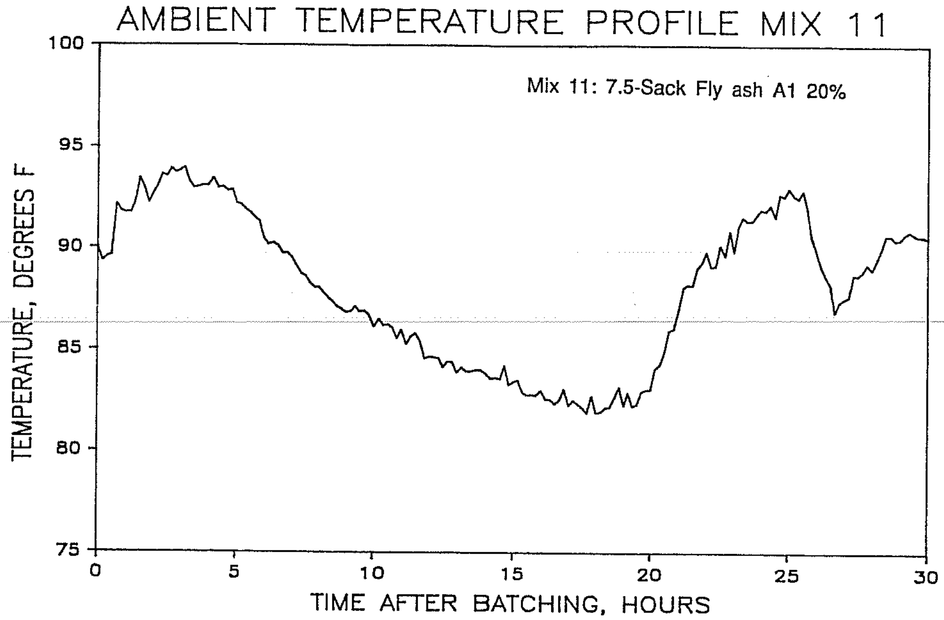
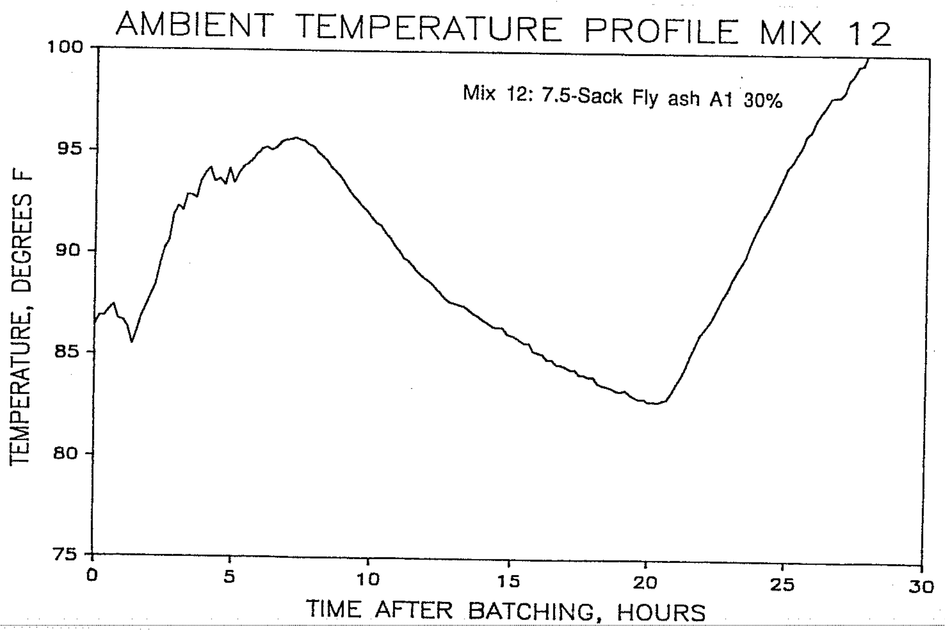
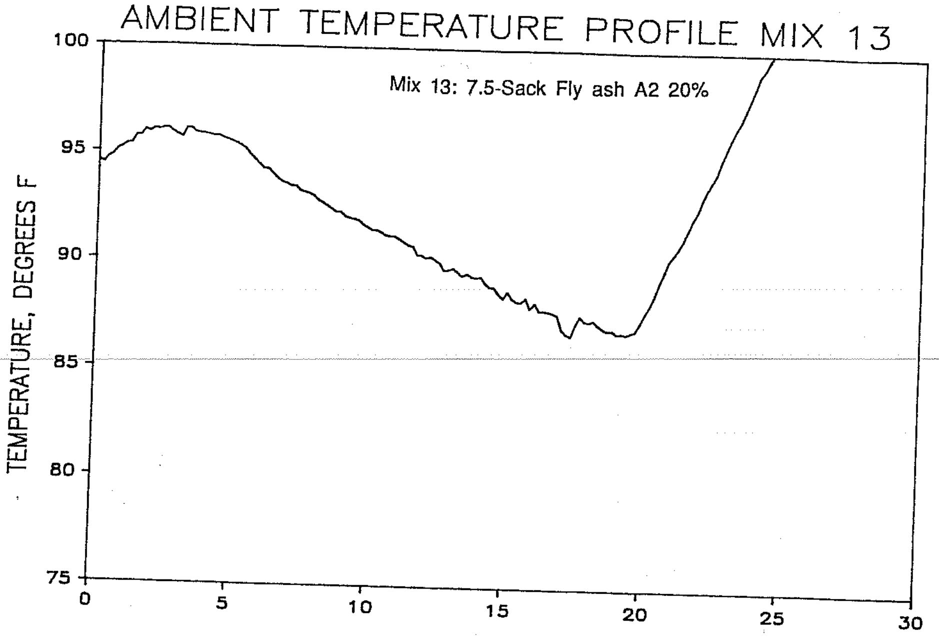
90
85
80
75
0
5
10
15
20
25
30
TIME AFTER BATCHING, HOURS

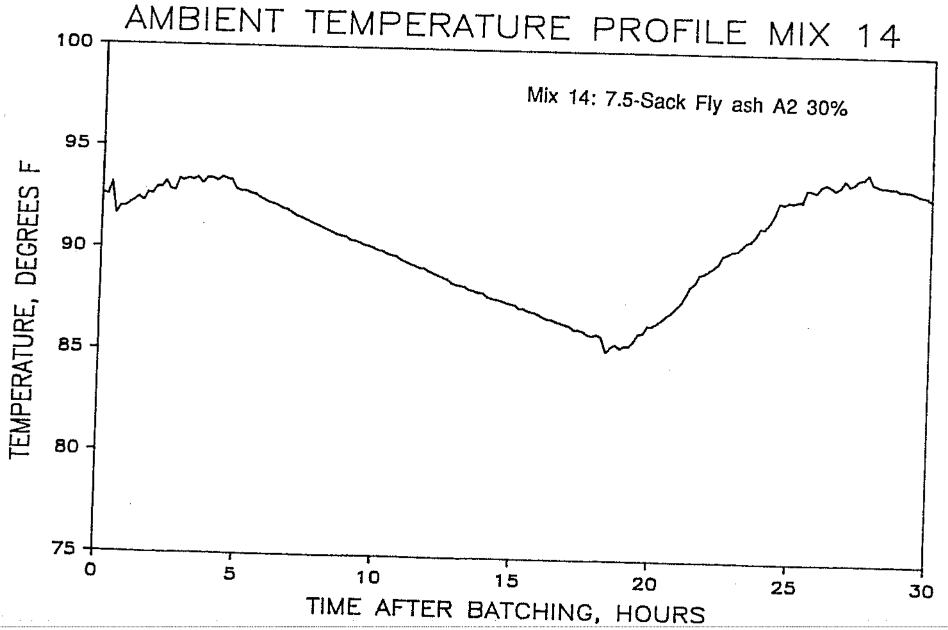

AMBIENT TEMPERATURE PROFILE MIX 9
Mix 9: 5-Sack 20% Fly ash A2
TEMPERATURE, DEGREES F
100
95
90
85
80
75
0
5
10
15
20
25
30
TIME AFTER BATCHING, HOURS

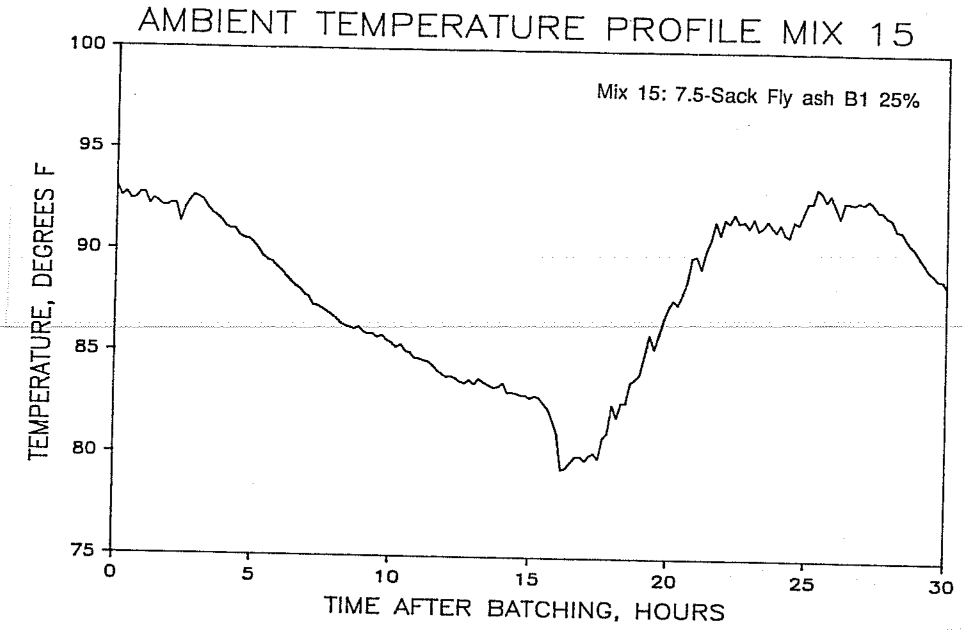

AMBIENT TEMPERATURE PROFILE MIX 10
Mix 10: 5-Sack 30% Fly ash A2
TEMPERATURE, DEGREES F
100
95
90
85
80
75
0
5
10
15
20
25
30
TIME AFTER BATCHING, HOURS

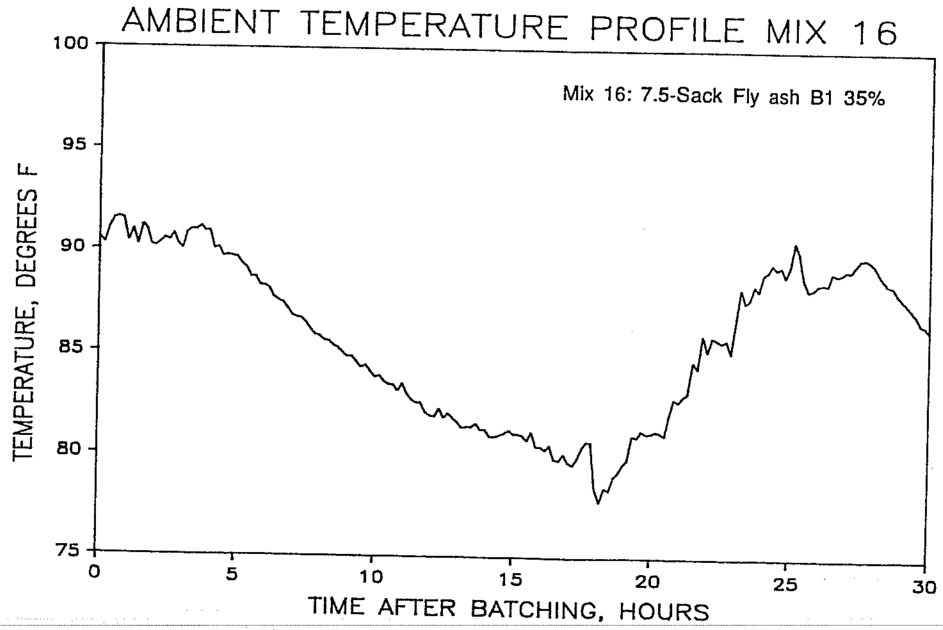

AMBIENT TEMPERATURE PROFILE MIX 11
Mix 11: 7.5-Sack Fly ash A1 20%
TEMPERATURE, DEGREES F
100
95
90
85
80
75
0
5
10
15
20
25
30
TIME AFTER BATCHING, HOURS

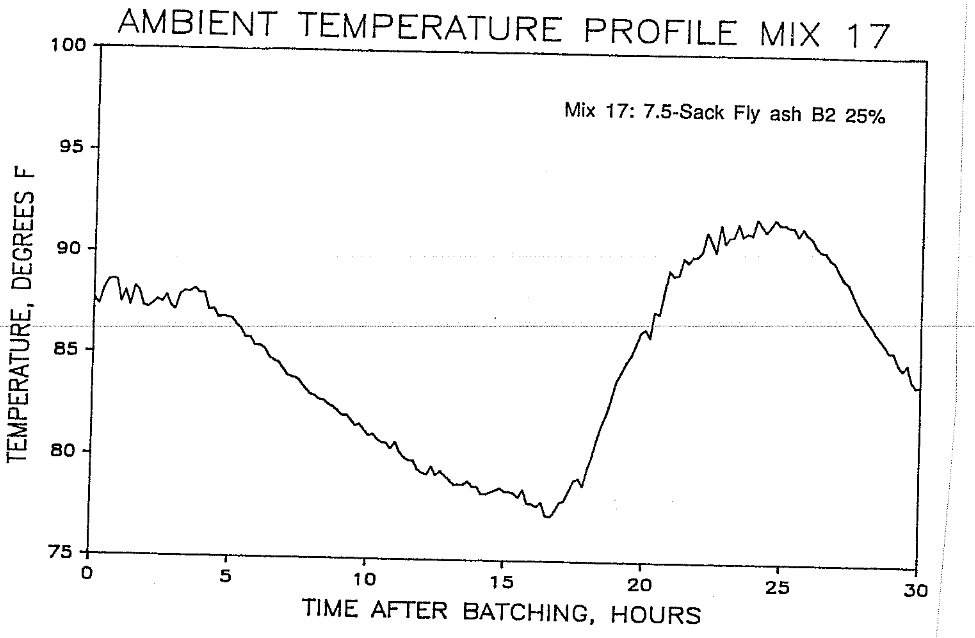

AMBIENT TEMPERATURE PROFILE MIX 12
Mix 12: 7.5-Sack Fly ash A1 30%
TEMPERATURE, DEGREES F
100
95
90
85
80
75
0
5
10
15
20
25
30
TIME AFTER BATCHING, HOURS

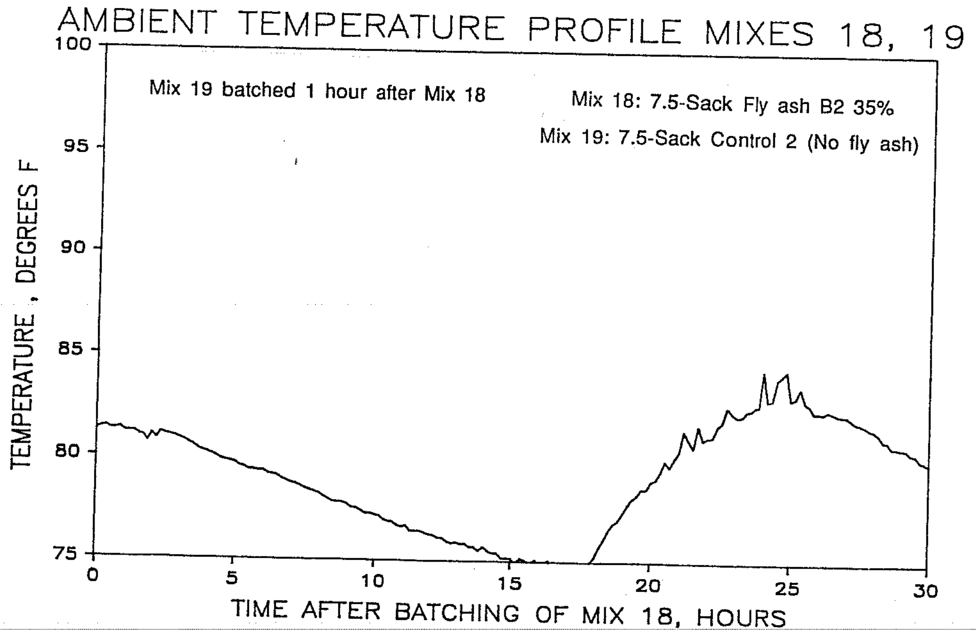

AMBIENT TEMPERATURE PROFILE MIX 13
Mix 13: 7.5-Sack Fly ash A2 20%
TEMPERATURE, DEGREES F
100
95
90
85
80
75
0
5
10
15
20
25
30


AMBIENT TEMPERATURE PROFILE MIX 14
Mix 14: 7.5-Sack Fly ash A2 30%
TEMPERATURE, DEGREES F
100
95
90
85
80
75
0
5
10
15
20
25
30
TIME AFTER BATCHING, HOURS


AMBIENT TEMPERATURE PROFILE MIX 15
Mix 15: 7.5-Sack Fly ash B1 25%
TEMPERATURE, DEGREES F
100
95
90
85
80
75
0
5
10
15
20
25
30
TIME AFTER BATCHING, HOURS


AMBIENT TEMPERATURE PROFILE MIX 16
Mix 16: 7.5-Sack Fly ash B1 35%
TEMPERATURE, DEGREES F
100
95
90
85
80
75
0
5
10
15
20
25
30
TIME AFTER BATCHING, HOURS


AMBIENT TEMPERATURE PROFILE MIX 17
Mix 17: 7.5-Sack Fly ash B2 25%
TEMPERATURE, DEGREES F
100
95
90
85
80
75
0
5
10
15
20
25
30
TIME AFTER BATCHING, HOURS


AMBIENT TEMPERATURE PROFILE MIXES 18, 19
Mix 19 batched 1 hour after Mix 18
Mix 18: 7.5-Sack Fly ash B2 35%
Mix 19: 7.5-Sack Control 2 (No fly ash)
TEMPERATURE , DEGREES F
100
95
90
85
80
75
0
5
10
15
20
25
30
TIME AFTER BATCHING OF MIX 18, HOURS

APPENDIX C
RESULTS OF ISOTHERMAL CALORIMETRY TESTS

Table C.1 24 Hour Cumulative Heat Evolution for Type I Cement Pastes
(Cumulative Heat in Calories/Gram Cementitious Material)

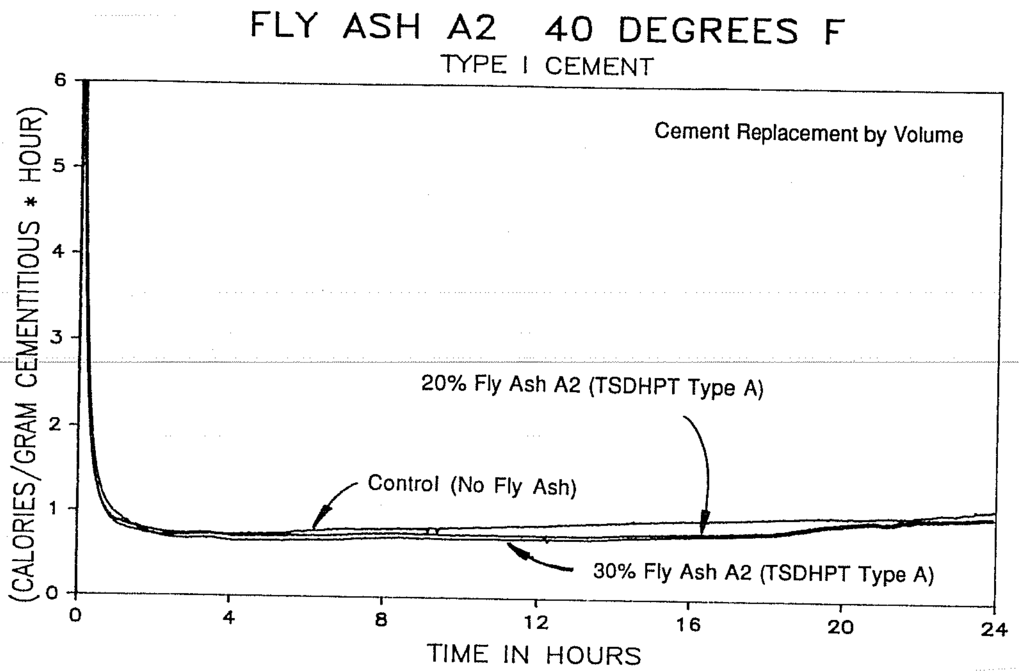
Paste Description	40 F	60 F	80 F	100 F
Plain Type I	22.231	34.709	42.189	44.582
Fly ash A1 20%	21.916	34.526	41.443	42.524
Fly ash A1 30%	19.916	32.602	38.934	41.397
Fly ash A2 20%	19.995	36.638	41.490	45.459
Fly ash A2 30%	18.881	34.599	38.888	44.429
Fly ash B1 25%	19.842	38.549	42.467	48.865
Fly ash B1 35%	21.302	27.672	35.692	39.150
Fly ash B2 25%	19.671	28.473	37.286	40.170
Fly ash B2 35%	18.700	26.508	35.999	42.569

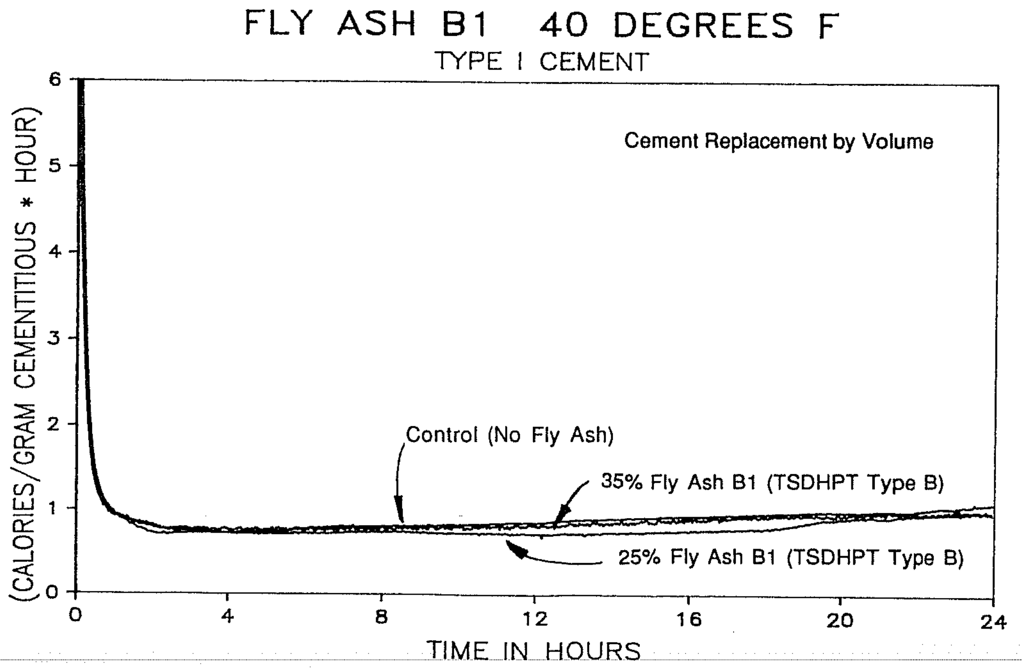
Table C.2 24 Hour Cumulative Heat Evolution for Type I-II Cement Pastes
(Cumulative Heat in Calories/Gram Cementitious Material)

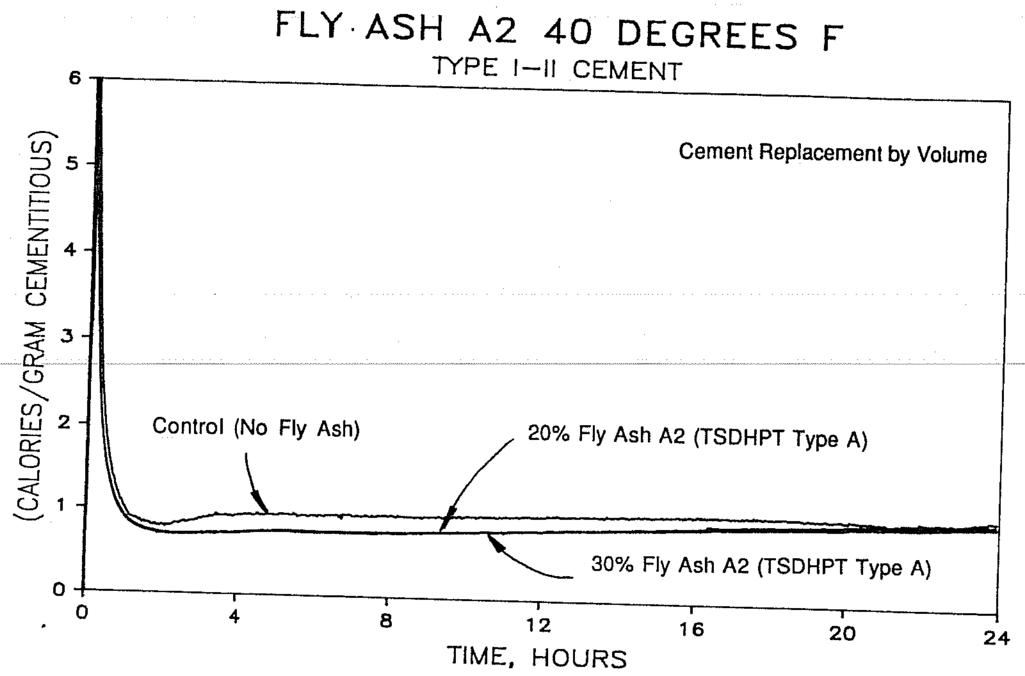
Paste Description	40 F	60 F	80 F	100 F
Plain Type I-II	24.254	33.683	41.799	39.862
Fly ash A1 20%	26.198	23.110	32.931	35.199
Fly ash A1 30%	25.447	24.506	28.542	33.519
Fly ash A2 20%	22.000	25.572	33.083	36.336
Fly ash A2 30%	21.463	26.197	29.686	31.582
Fly ash B1 25%	24.786	31.122	37.432	36.703
Fly ash B1 35%	26.336	27.023	38.551	36.160
Fly ash B2 25%	24.856	30.198	31.831	36.068
Fly ash B2 35%	25.777	24.515	31.367	35.425

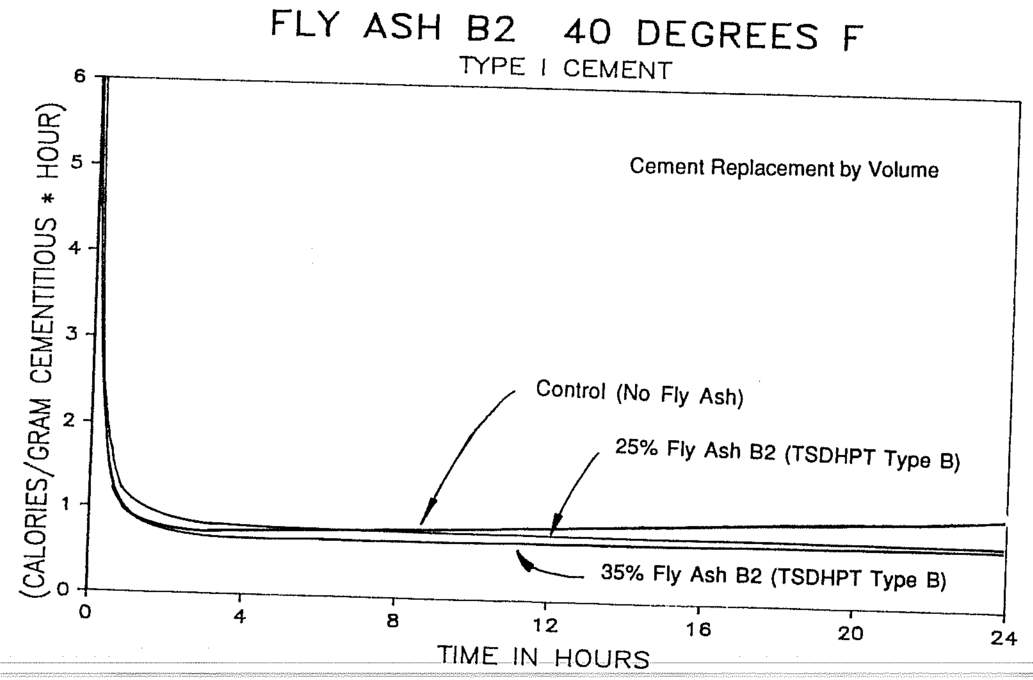
Table C.3 24 Hour Cumulative Heat Evolution for Type III Cement Pastes
(Cumulative Heat in Calories/Gram Cementitious Material)

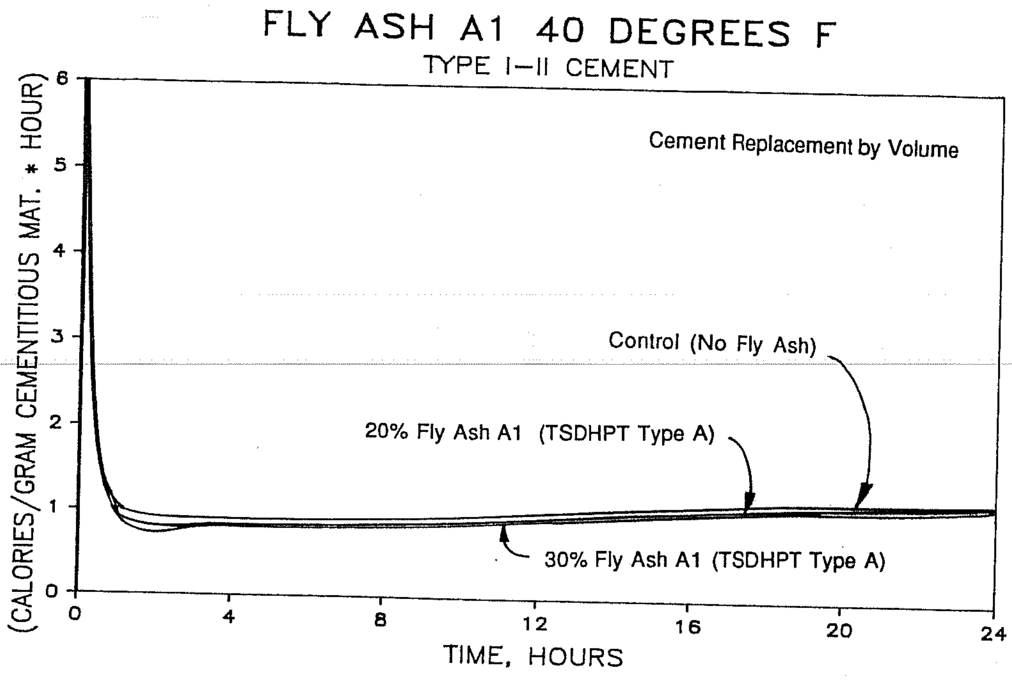
Paste Description	40 F	60 F	80 F	100 F
Plain Type III	30.796	44.305	50.986	44.202
Fly ash A1 20%	28.294	38.345	42.205	41.095
Fly ash A1 30%	28.639	36.203	39.274	39.490
Fly ash A2 20%	30.138	41.363	43.945	49.246
Fly ash A2 30%	29.618	40.535	39.953	41.210
Fly ash B1 25%	29.075	33.403	42.237	41.251
Fly ash B1 35%	28.752	32.060	40.572	37.820
Fly ash B2 25%	29.772	32.798	37.757	38.019
Fly ash B2 35%	28.087	30.180	36.043	36.240


FLY ASH A2 40 DEGREES F
TYPE I CEMENT
(CALORIES/GRAM CEMENTITIOUS * HOUR)
0
1
2
3
4
5
6
TIME IN HOURS
0
4
8
12
16
20
24
Cement Replacement by Volume
20% Fly Ash A2 (TSDHPT Type A)
Control (No Fly Ash)
30% Fly Ash A2 (TSDHPT Type A)


FLY ASH B1 40 DEGREES F
TYPE I CEMENT
(CALORIES/GRAM CEMENTITIOUS * HOUR)
0
1
2
3
4
5
6
TIME IN HOURS
0
4
8
12
16
20
24
Cement Replacement by Volume
Control (No Fly Ash)
35% Fly Ash B1 (TSDHPT Type B)
25% Fly Ash B1 (TSDHPT Type B)

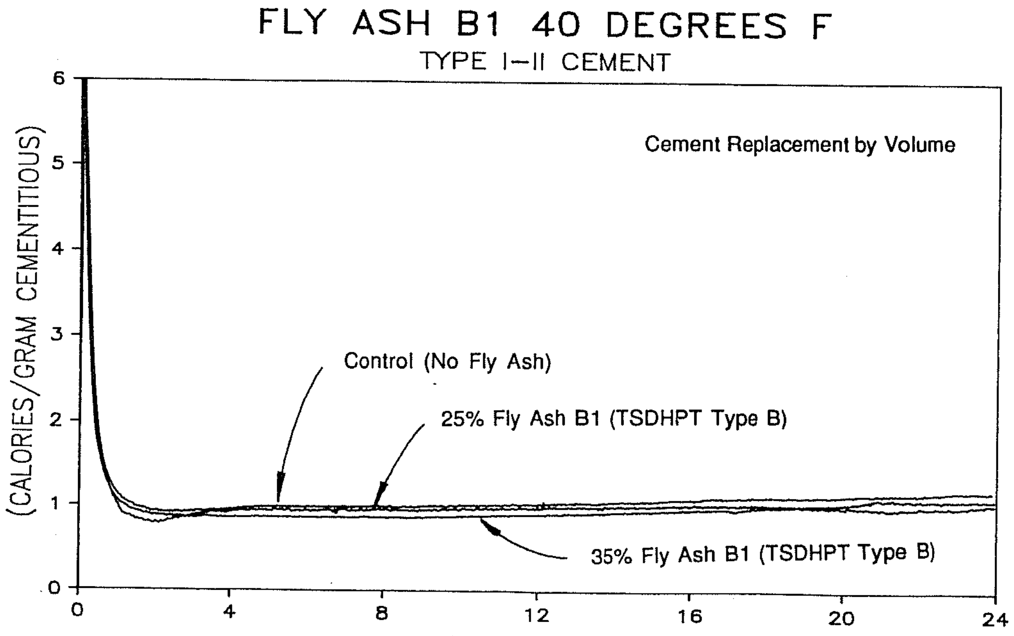

FLY ASH A2 40 DEGREES F
TYPE I–II CEMENT
Cement Replacement by Volume
(CALORIES/GRAM CEMENTITIOUS)
0
1
2
3
4
5
6
Control (No Fly Ash)
20% Fly Ash A2 (TSDHPT Type A)
30% Fly Ash A2 (TSDHPT Type A)
0
4
8
12
16
20
24
TIME, HOURS


FLY ASH B2 40 DEGREES F
TYPE I CEMENT
Cement Replacement by Volume
(CALORIES/GRAM CEMENTITIOUS * HOUR)
0
1
2
3
4
5
6
Control (No Fly Ash)
25% Fly Ash B2 (TSDHPT Type B)
35% Fly Ash B2 (TSDHPT Type B)
0
4
8
12
16
20
24
TIME IN HOURS



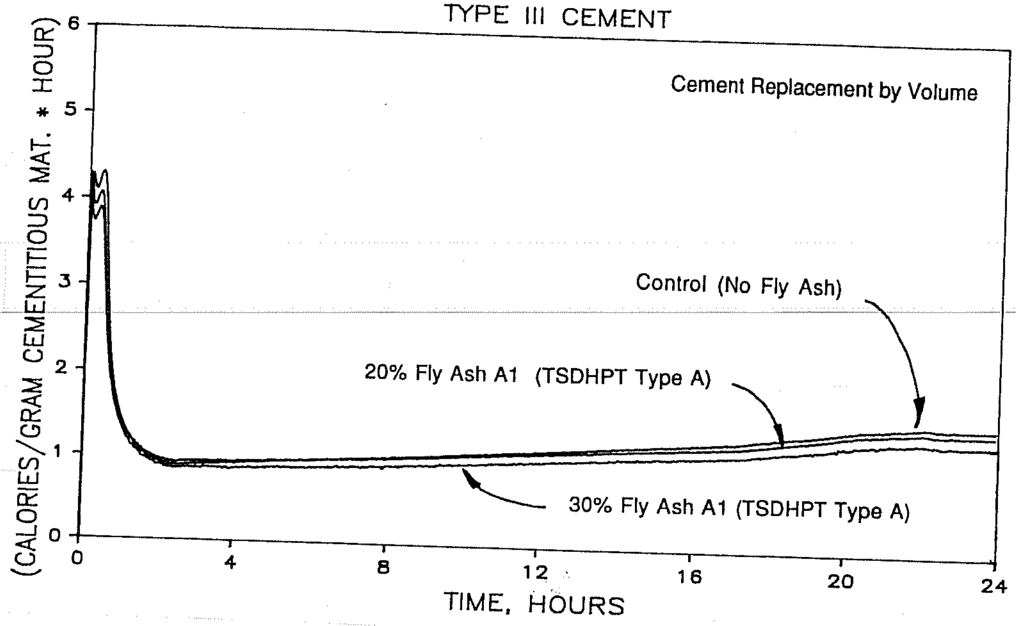
FLY ASH A1 40 DEGREES F

TYPE I–II CEMENT

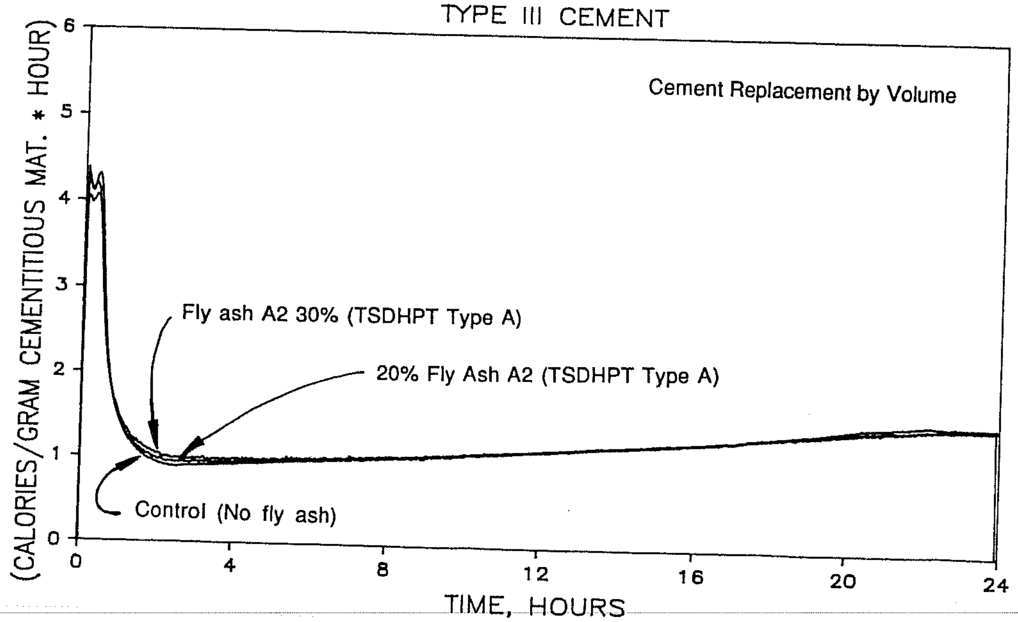


FLY ASH B1 40 DEGREES F

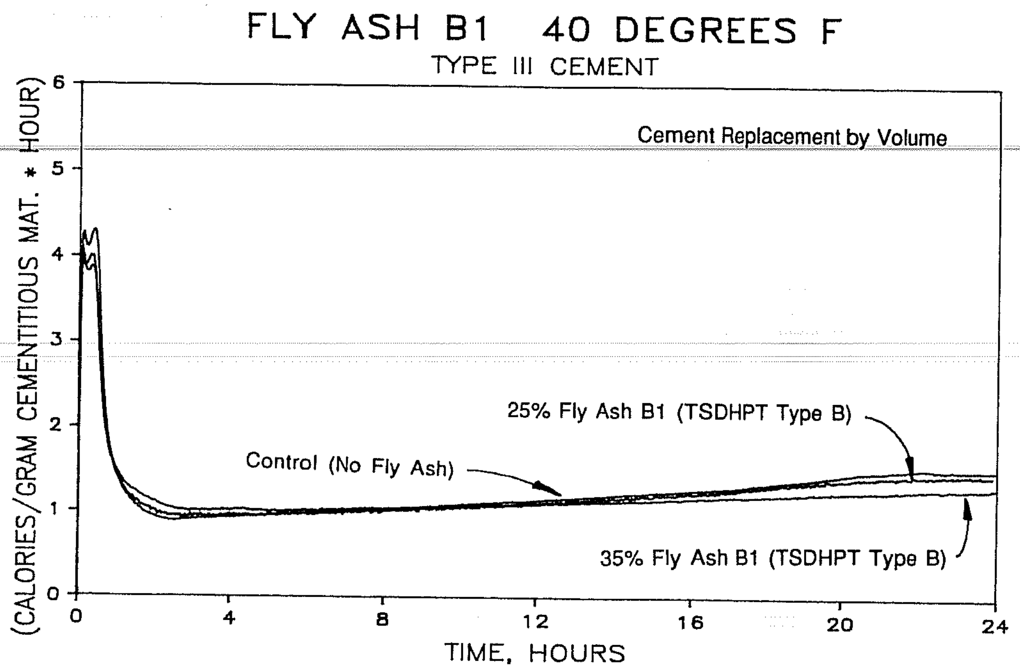
TYPE I–II CEMENT

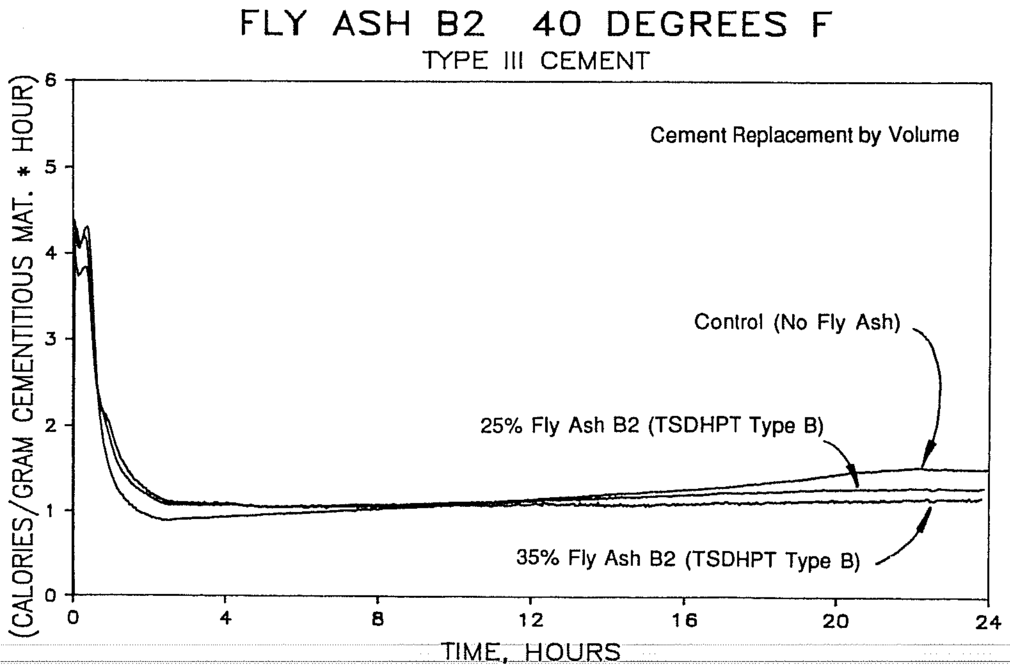


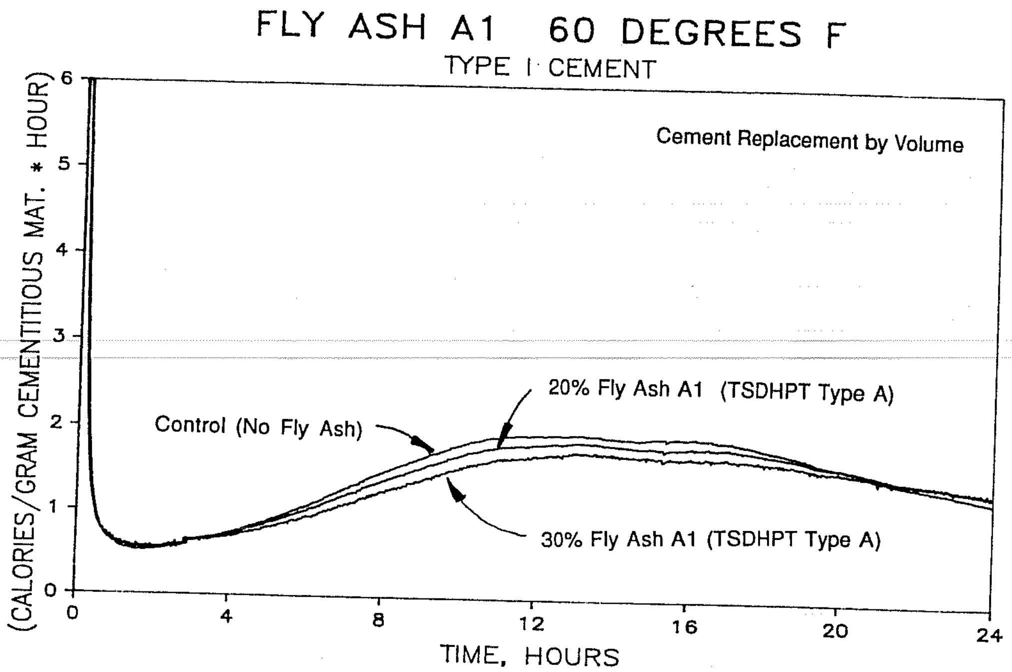
FLY ASH A1 40 DEGREES F
TYPE III CEMENT

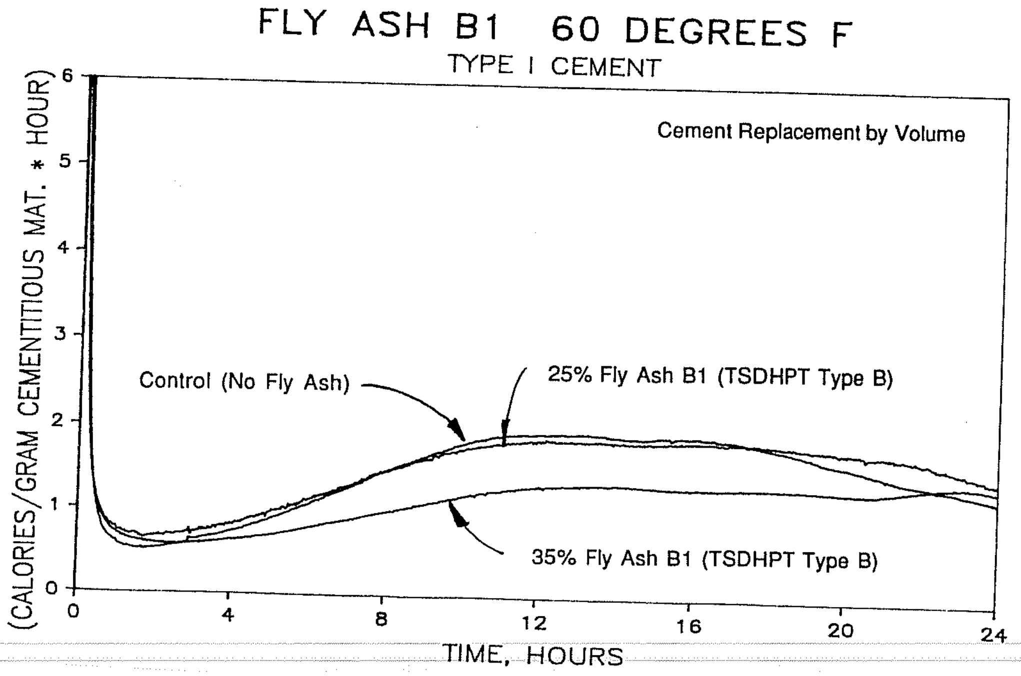


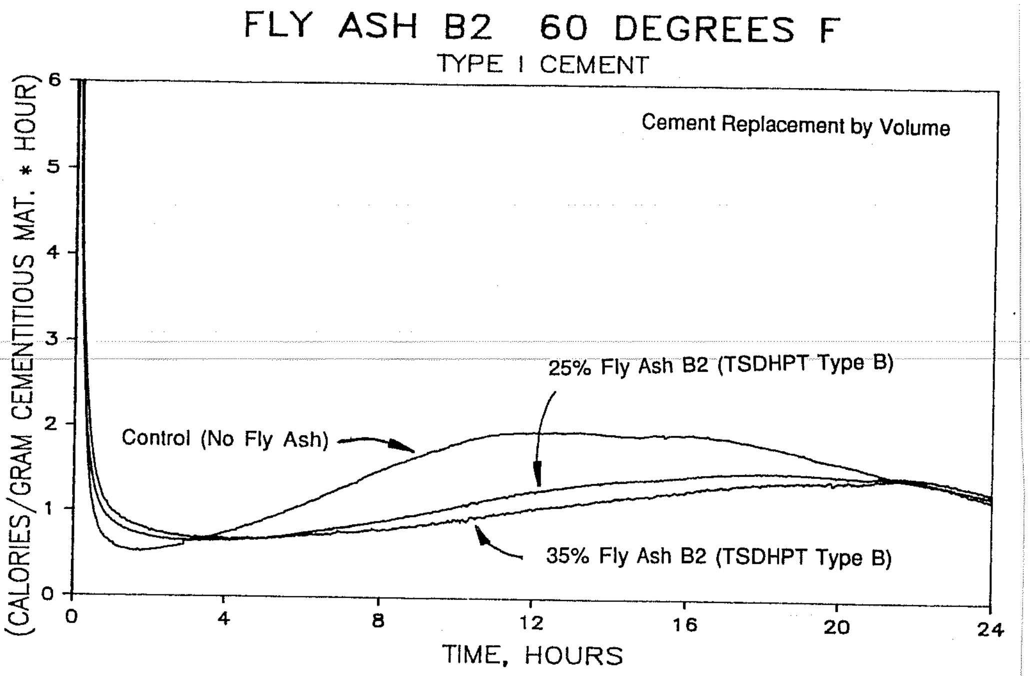
FLY ASH A2 40 DEGREES F
TYPE III CEMENT

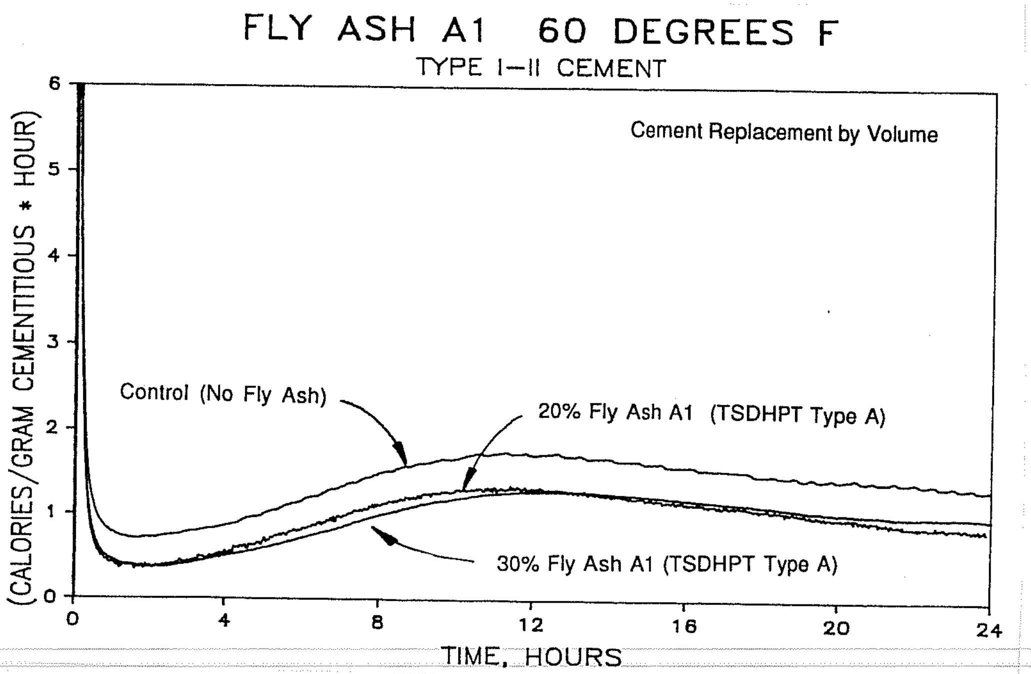

FLY ASH B1 40 DEGREES F
TYPE III CEMENT
Cement Replacement by Volume
25% Fly Ash B1 (TSDHPT Type B)
Control (No Fly Ash)
35% Fly Ash B1 (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
0
4
8
12
16
20
24
TIME, HOURS

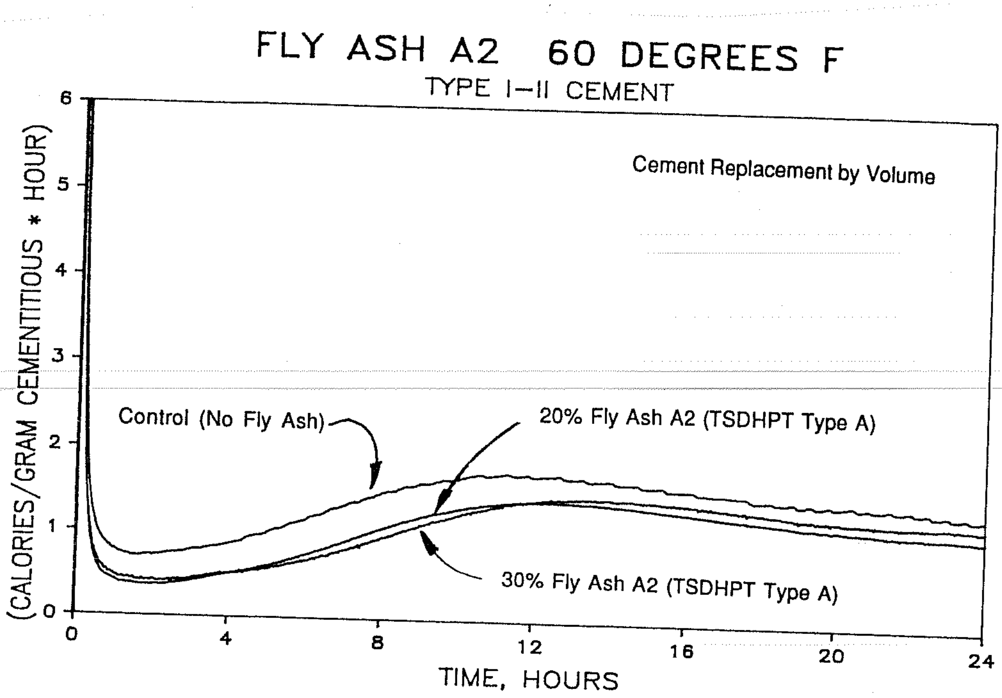

FLY ASH B2 40 DEGREES F
TYPE III CEMENT
Cement Replacement by Volume
Control (No Fly Ash)
25% Fly Ash B2 (TSDHPT Type B)
35% Fly Ash B2 (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
0
4
8
12
16
20
24
TIME, HOURS

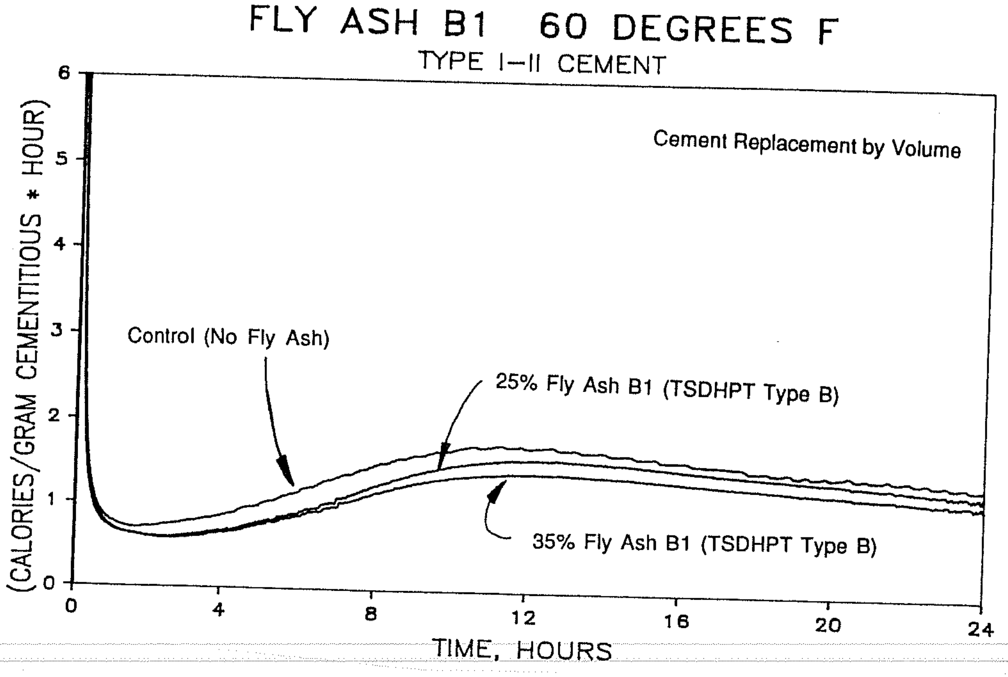

FLY ASH A1 60 DEGREES F
TYPE I CEMENT
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
TIME, HOURS
0
4
8
12
16
20
24
Cement Replacement by Volume
Control (No Fly Ash)
20% Fly Ash A1 (TSDHPT Type A)
30% Fly Ash A1 (TSDHPT Type A)

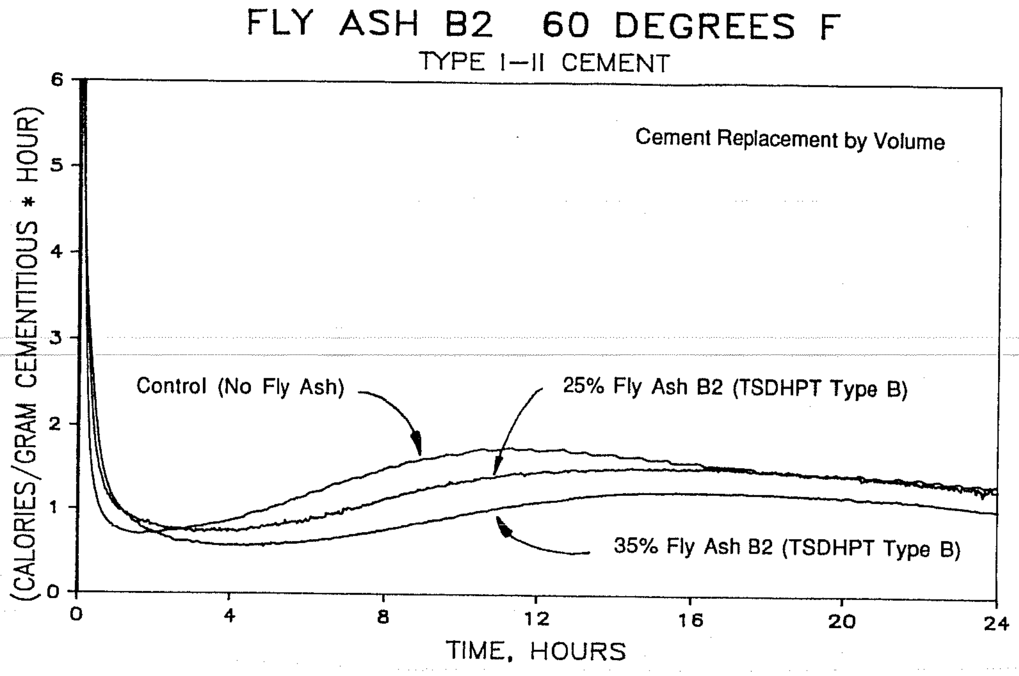

FLY ASH B1 60 DEGREES F
TYPE I CEMENT
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
TIME, HOURS
0
4
8
12
16
20
24
Cement Replacement by Volume
Control (No Fly Ash)
25% Fly Ash B1 (TSDHPT Type B)
35% Fly Ash B1 (TSDHPT Type B)


FLY ASH B2 60 DEGREES F
TYPE I CEMENT
Cement Replacement by Volume
25% Fly Ash B2 (TSDHPT Type B)
Control (No Fly Ash)
35% Fly Ash B2 (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
0
4
8
12
16
20
24
TIME, HOURS


FLY ASH A1 60 DEGREES F
TYPE I–II CEMENT
Cement Replacement by Volume
Control (No Fly Ash)
20% Fly Ash A1 (TSDHPT Type A)
30% Fly Ash A1 (TSDHPT Type A)
(CALORIES/GRAM CEMENTITIOUS * HOUR)
0
1
2
3
4
5
6
0
4
8
12
16
20
24
TIME, HOURS

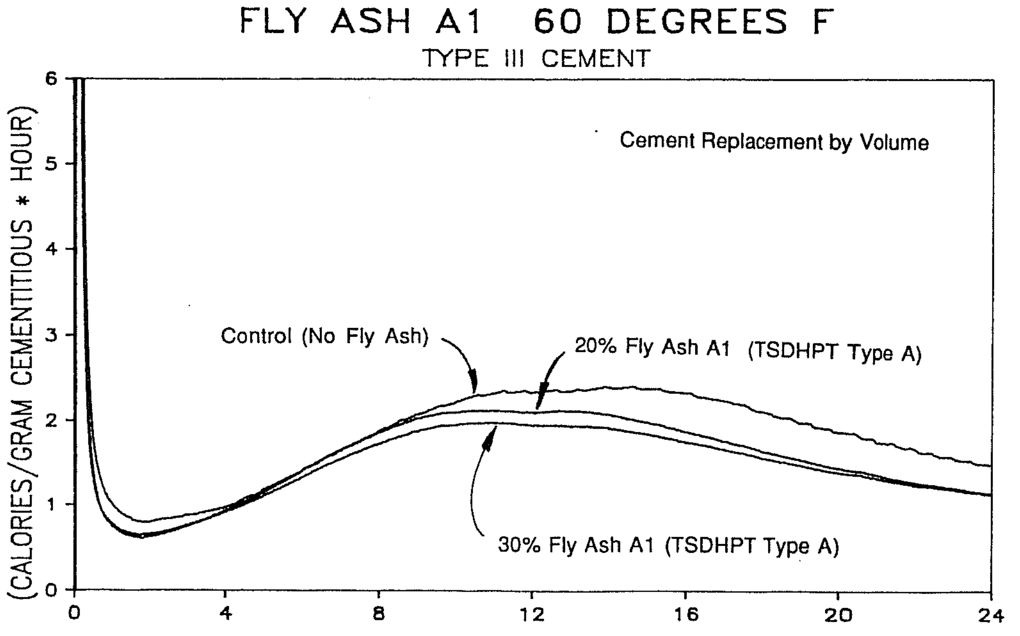

FLY ASH A2 60 DEGREES F
TYPE I–II CEMENT
Cement Replacement by Volume
(CALORIES/GRAM CEMENTITIOUS * HOUR)
0
1
2
3
4
5
6
Control (No Fly Ash)
20% Fly Ash A2 (TSDHPT Type A)
30% Fly Ash A2 (TSDHPT Type A)
0
4
8
12
16
20
24
TIME, HOURS


FLY ASH B1 60 DEGREES F
TYPE I–II CEMENT
Cement Replacement by Volume
(CALORIES/GRAM CEMENTITIOUS * HOUR)
0
1
2
3
4
5
6
Control (No Fly Ash)
25% Fly Ash B1 (TSDHPT Type B)
35% Fly Ash B1 (TSDHPT Type B)
0
4
8
12
16
20
24
TIME, HOURS



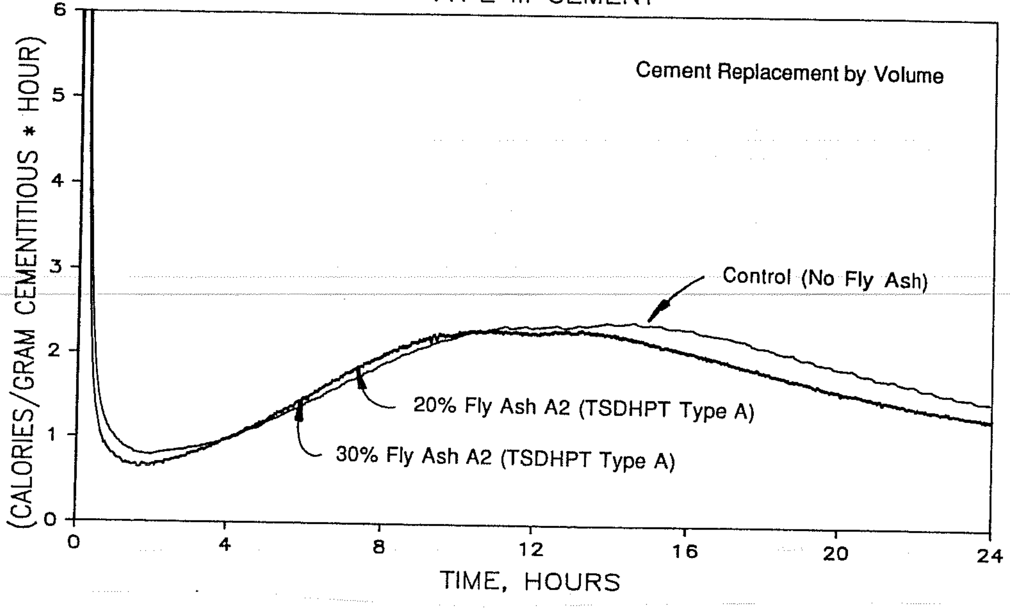
FLY ASH B2 60 DEGREES F

TYPE I–II CEMENT



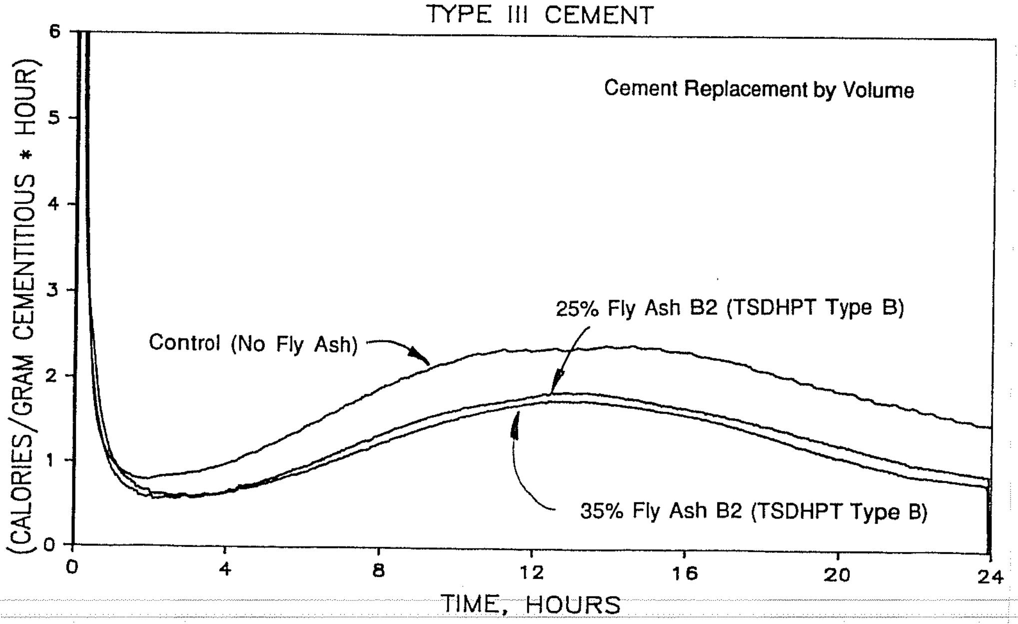
FLY ASH A1 60 DEGREES F

TYPE III CEMENT



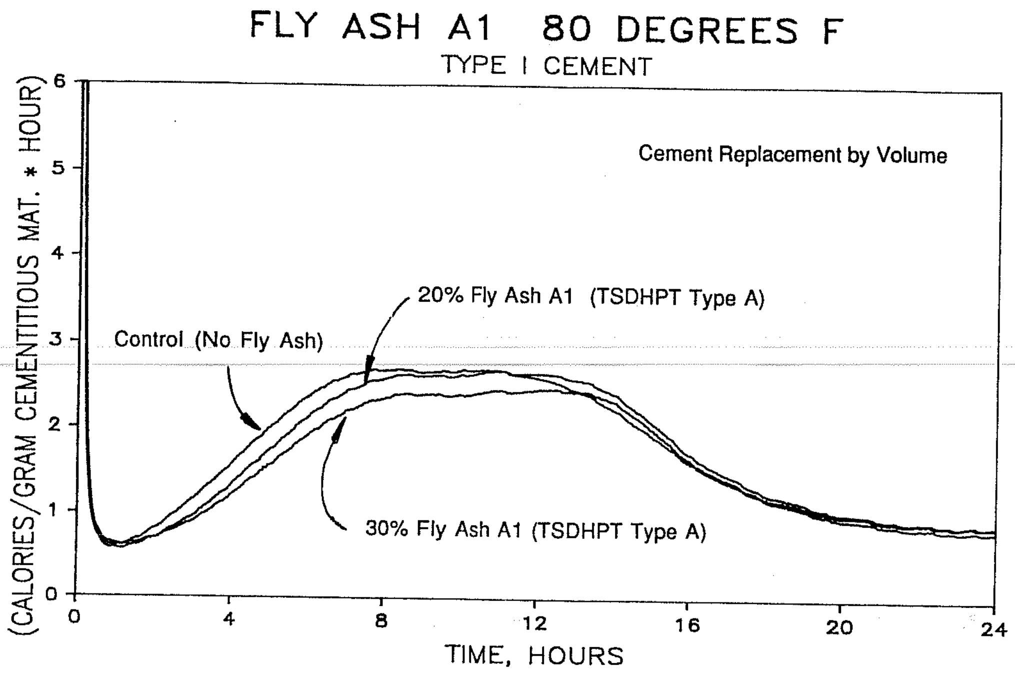
FLY ASH A2 60 DEGREES F

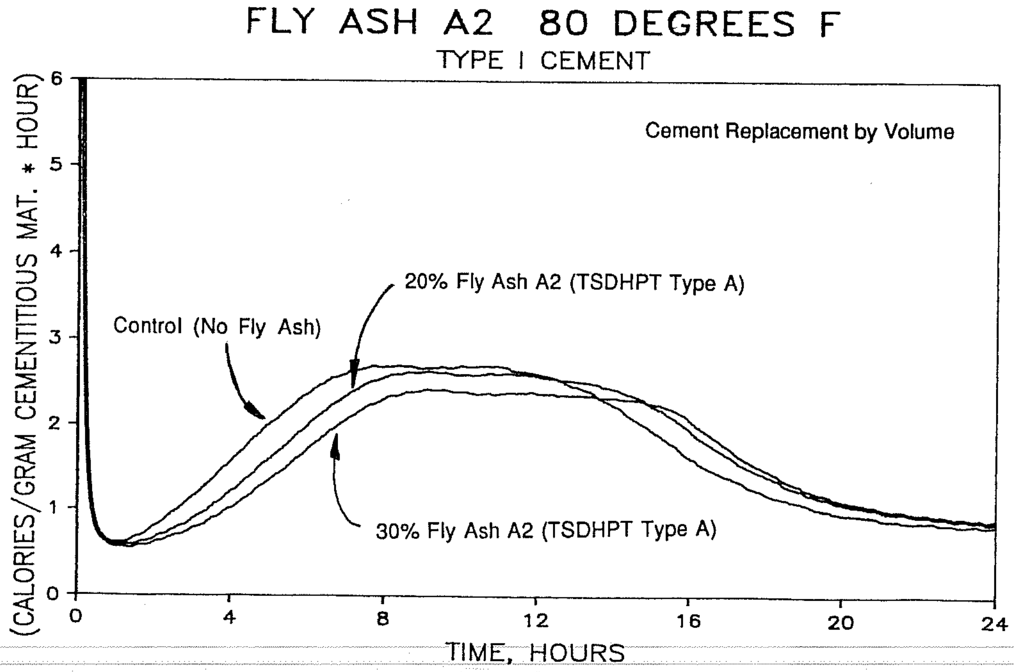
TYPE III CEMENT

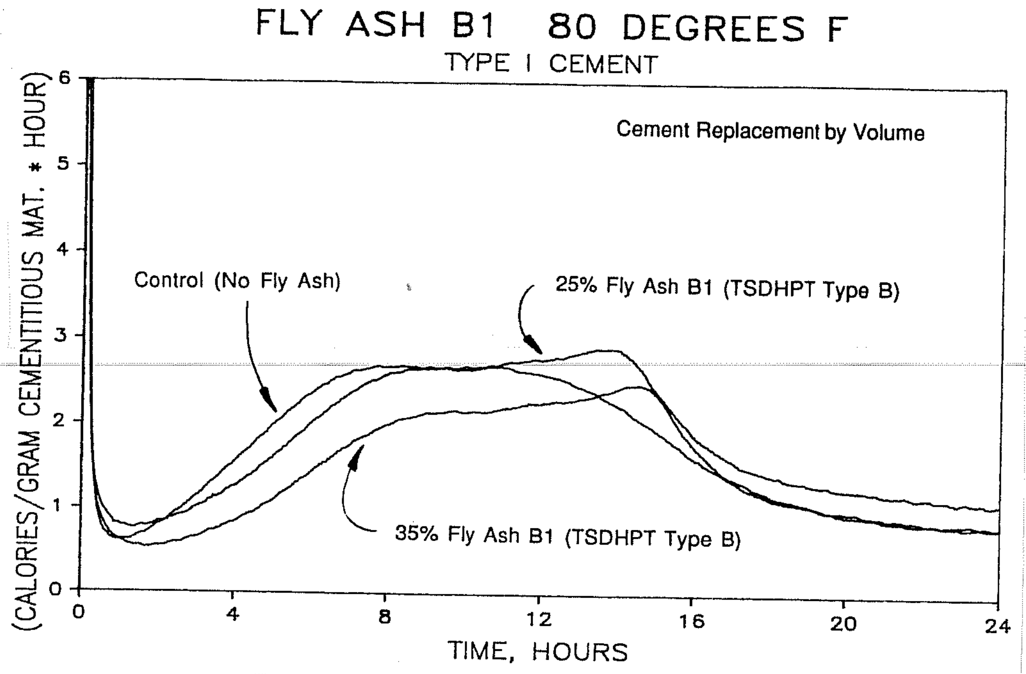


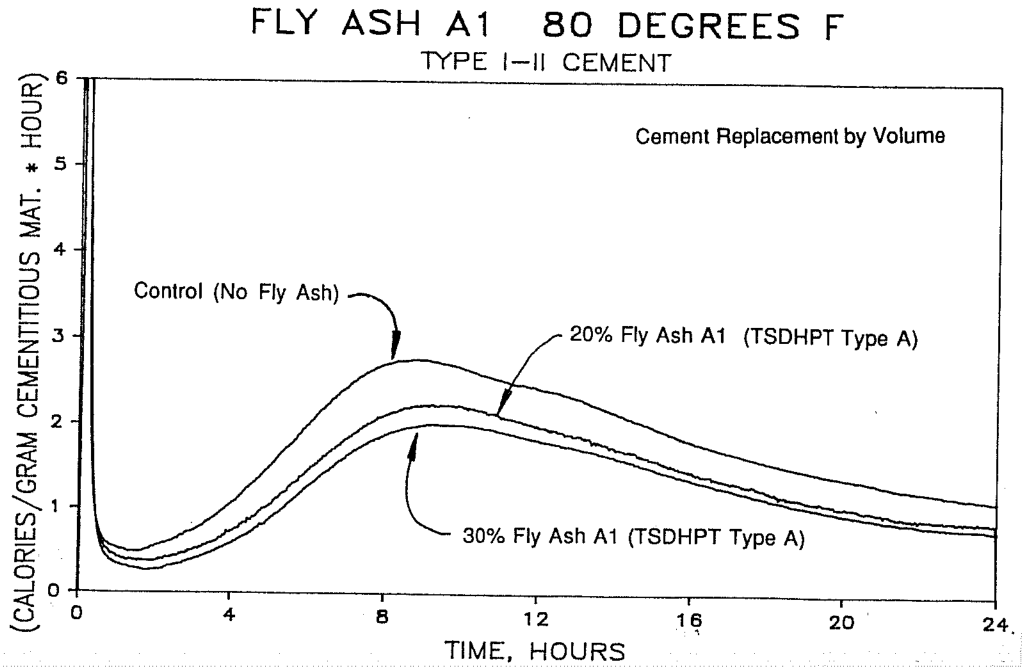
FLY ASH B2 60 DEGREES F

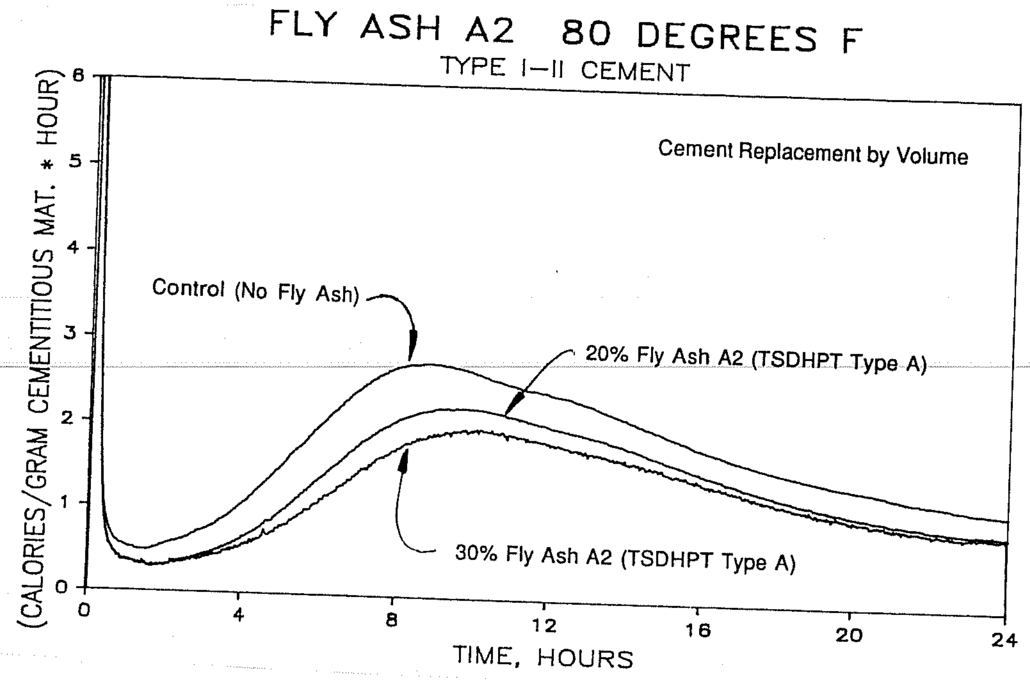
TYPE III CEMENT

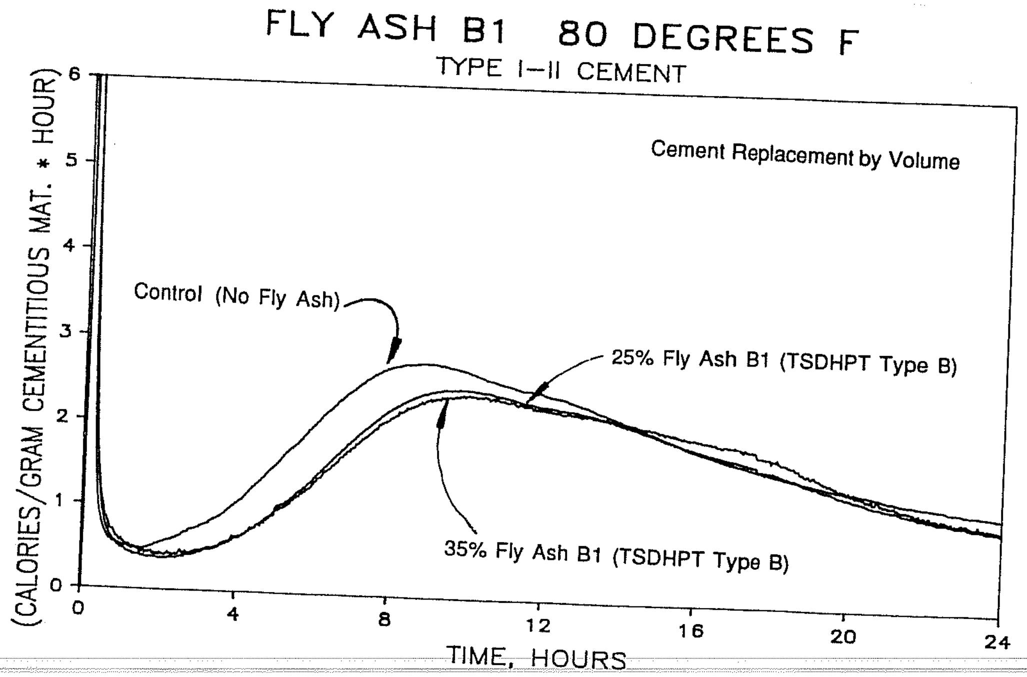

FLY ASH A1 80 DEGREES F
TYPE I CEMENT
Cement Replacement by Volume
20% Fly Ash A1 (TSDHPT Type A)
Control (No Fly Ash)
30% Fly Ash A1 (TSDHPT Type A)
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
TIME, HOURS
0
4
8
12
16
20
24

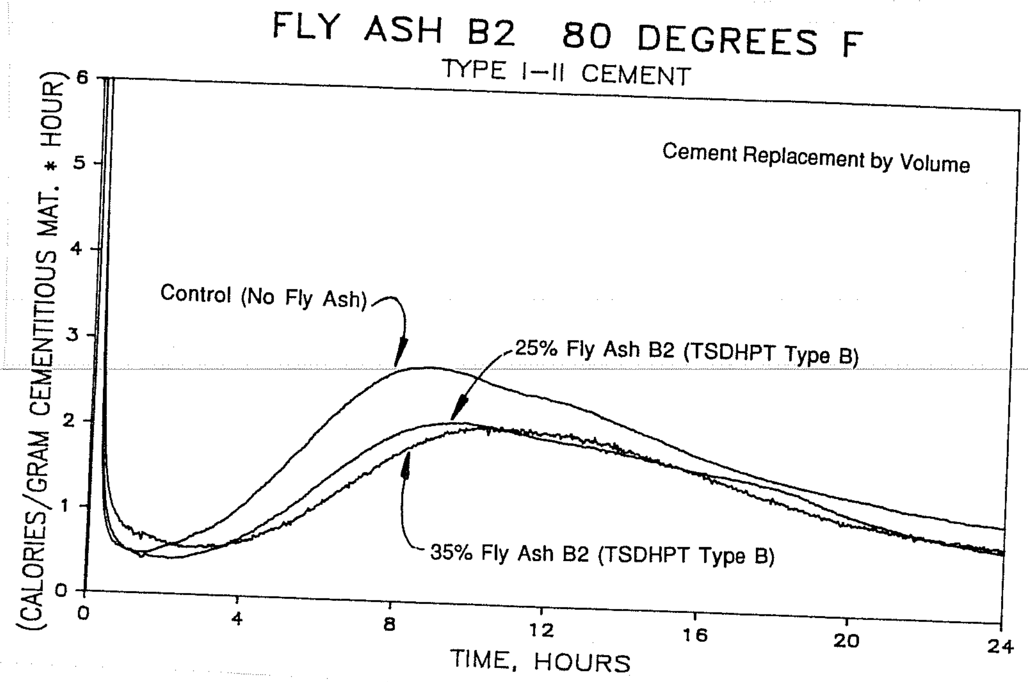

FLY ASH A2 80 DEGREES F
TYPE I CEMENT
Cement Replacement by Volume
20% Fly Ash A2 (TSDHPT Type A)
Control (No Fly Ash)
30% Fly Ash A2 (TSDHPT Type A)
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
TIME, HOURS
0
4
8
12
16
20
24

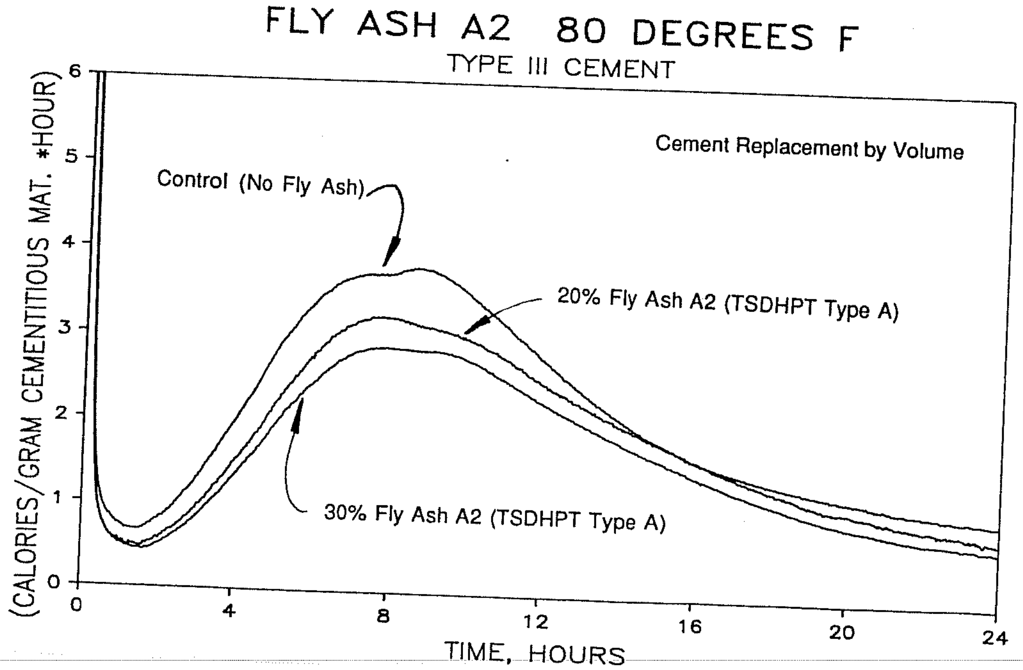

FLY ASH B1 80 DEGREES F
TYPE I CEMENT
Cement Replacement by Volume
Control (No Fly Ash)
25% Fly Ash B1 (TSDHPT Type B)
35% Fly Ash B1 (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
0
4
8
12
16
20
24
TIME, HOURS

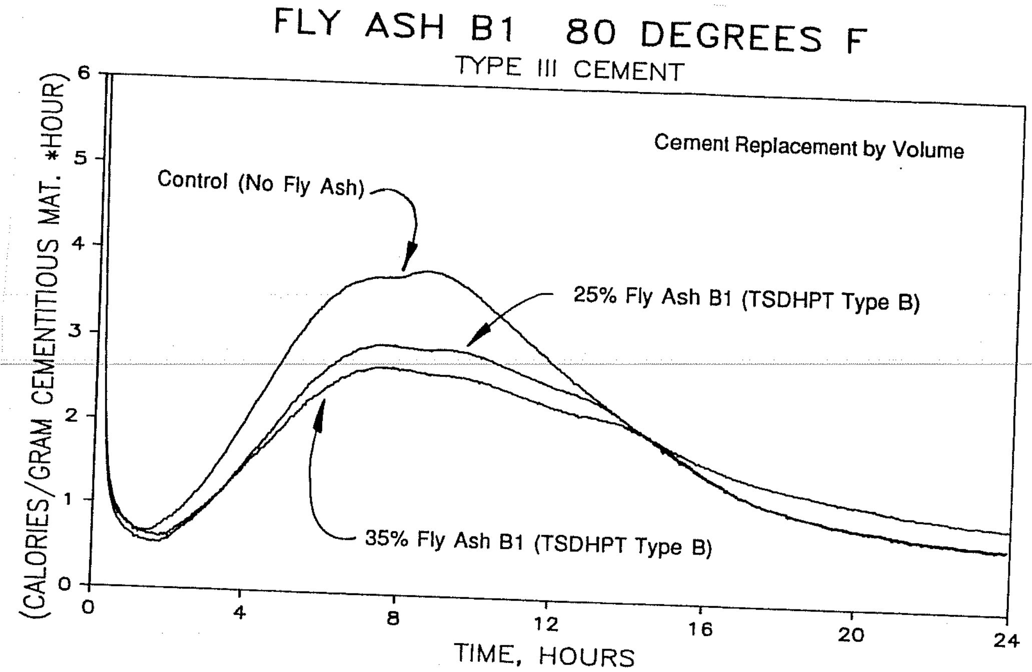

FLY ASH A1 80 DEGREES F
TYPE I–II CEMENT
Cement Replacement by Volume
Control (No Fly Ash)
20% Fly Ash A1 (TSDHPT Type A)
30% Fly Ash A1 (TSDHPT Type A)
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
0
4
8
12
16
20
24
TIME, HOURS

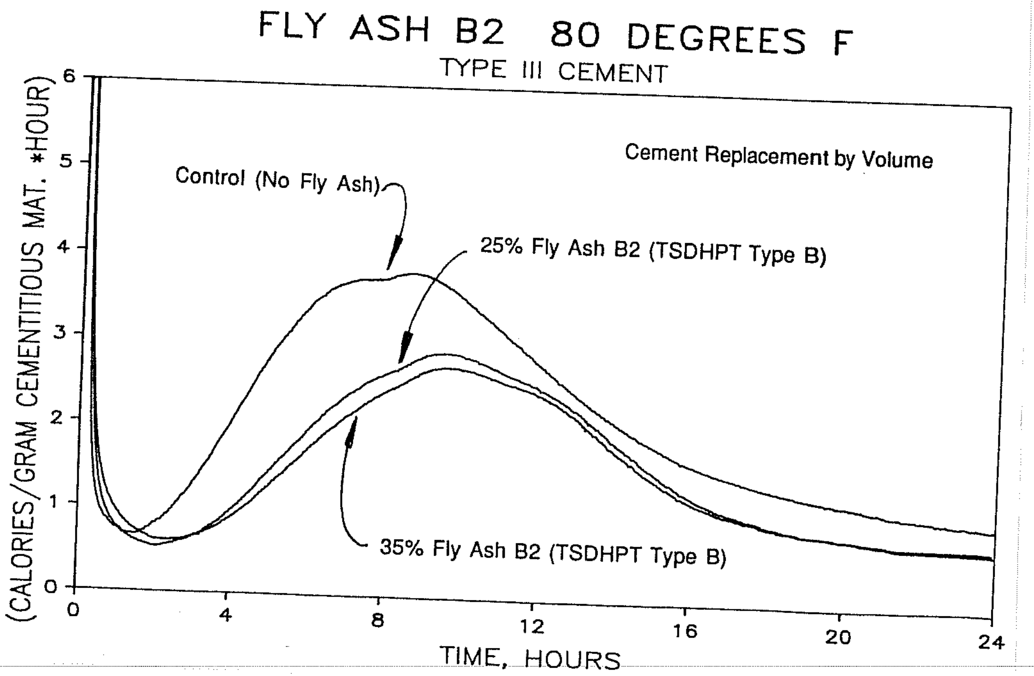

FLY ASH A2 80 DEGREES F
TYPE I–II CEMENT
Cement Replacement by Volume
Control (No Fly Ash)
20% Fly Ash A2 (TSDHPT Type A)
30% Fly Ash A2 (TSDHPT Type A)
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
TIME, HOURS
0
4
8
12
16
20
24

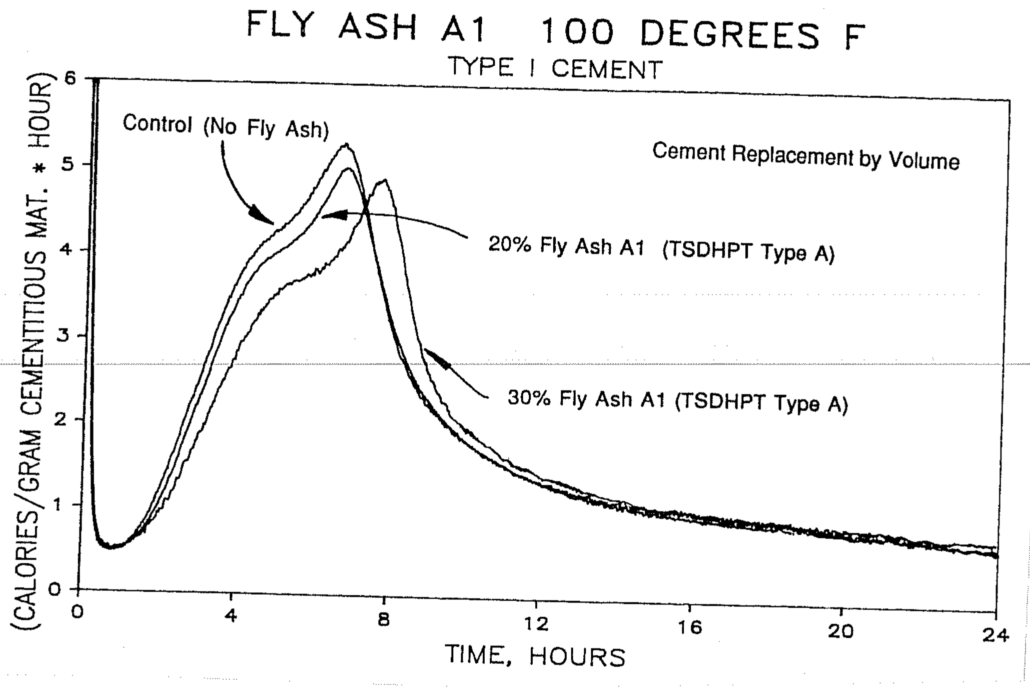

FLY ASH B1 80 DEGREES F
TYPE I–II CEMENT
Cement Replacement by Volume
Control (No Fly Ash)
25% Fly Ash B1 (TSDHPT Type B)
35% Fly Ash B1 (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
TIME, HOURS
0
4
8
12
16
20
24

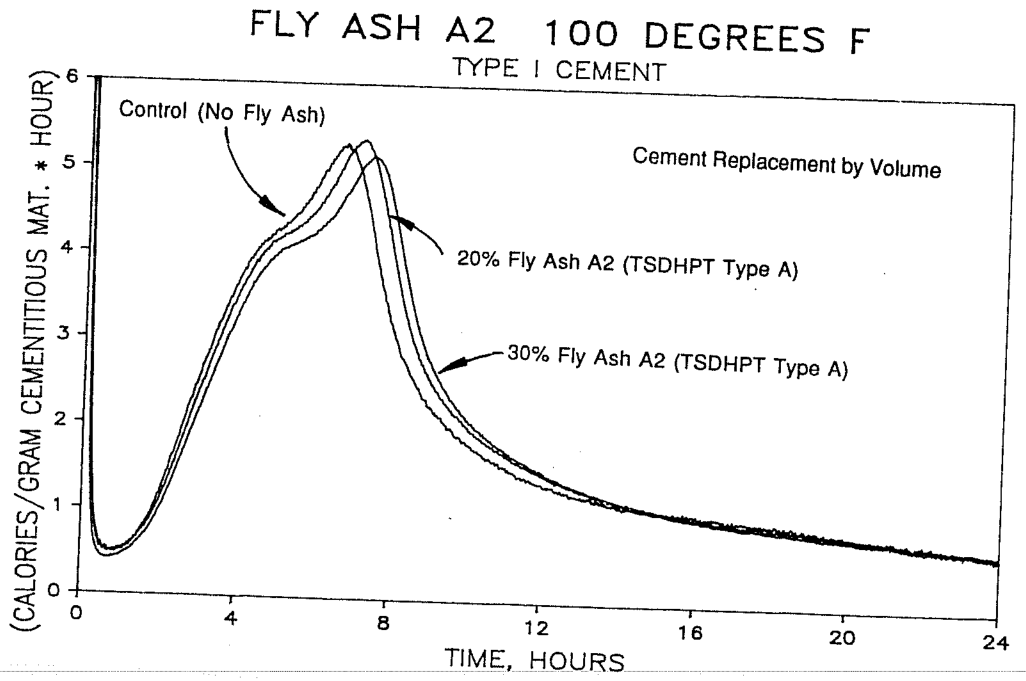

FLY ASH B2 80 DEGREES F
TYPE I–II CEMENT
Cement Replacement by Volume
Control (No Fly Ash)
25% Fly Ash B2 (TSDHPT Type B)
35% Fly Ash B2 (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
0
4
8
12
16
20
24
TIME, HOURS

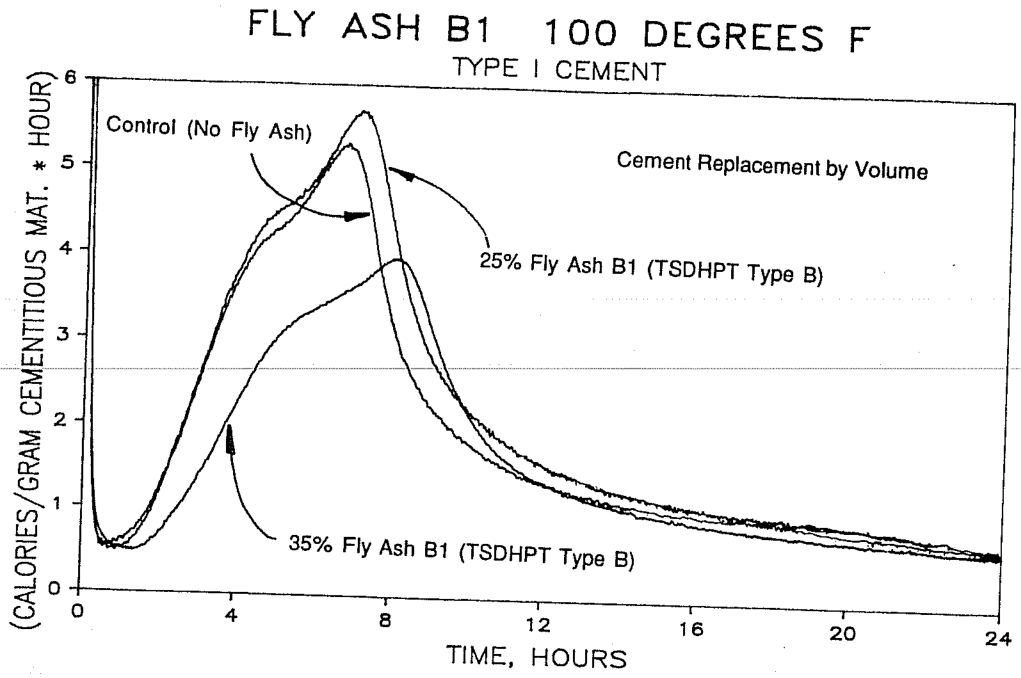

FLY ASH A2 80 DEGREES F
TYPE III CEMENT
Cement Replacement by Volume
Control (No Fly Ash)
20% Fly Ash A2 (TSDHPT Type A)
30% Fly Ash A2 (TSDHPT Type A)
(CALORIES/GRAM CEMENTITIOUS MAT. *HOUR)
0
1
2
3
4
5
6
0
4
8
12
16
20
24
TIME, HOURS

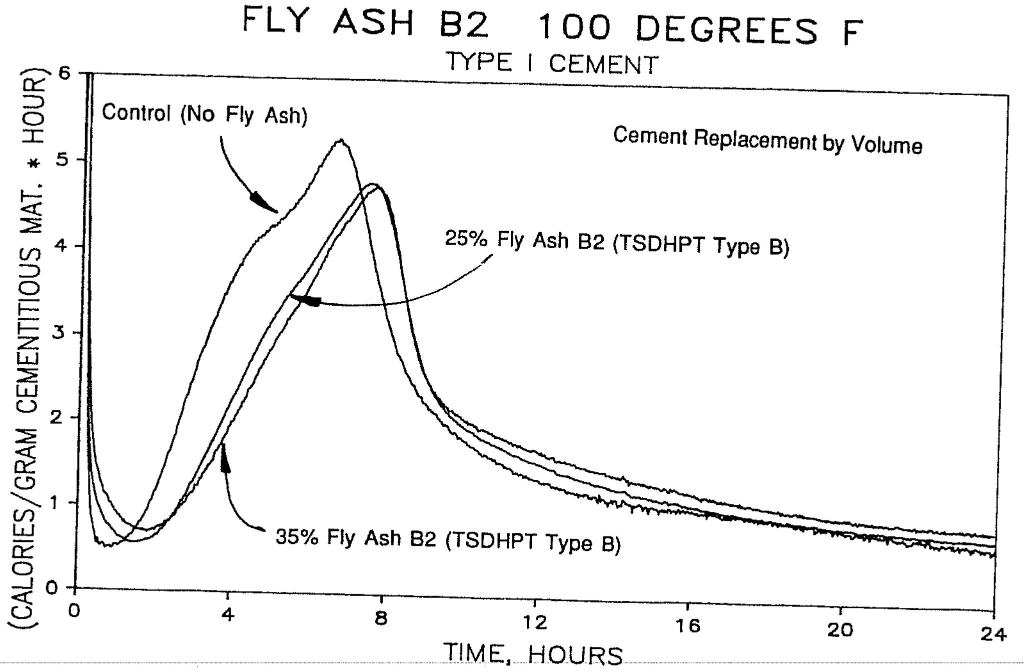

FLY ASH B1 80 DEGREES F
TYPE III CEMENT
Cement Replacement by Volume
Control (No Fly Ash)
25% Fly Ash B1 (TSDHPT Type B)
35% Fly Ash B1 (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT. *HOUR)
0
1
2
3
4
5
6
TIME, HOURS
0
4
8
12
16
20
24

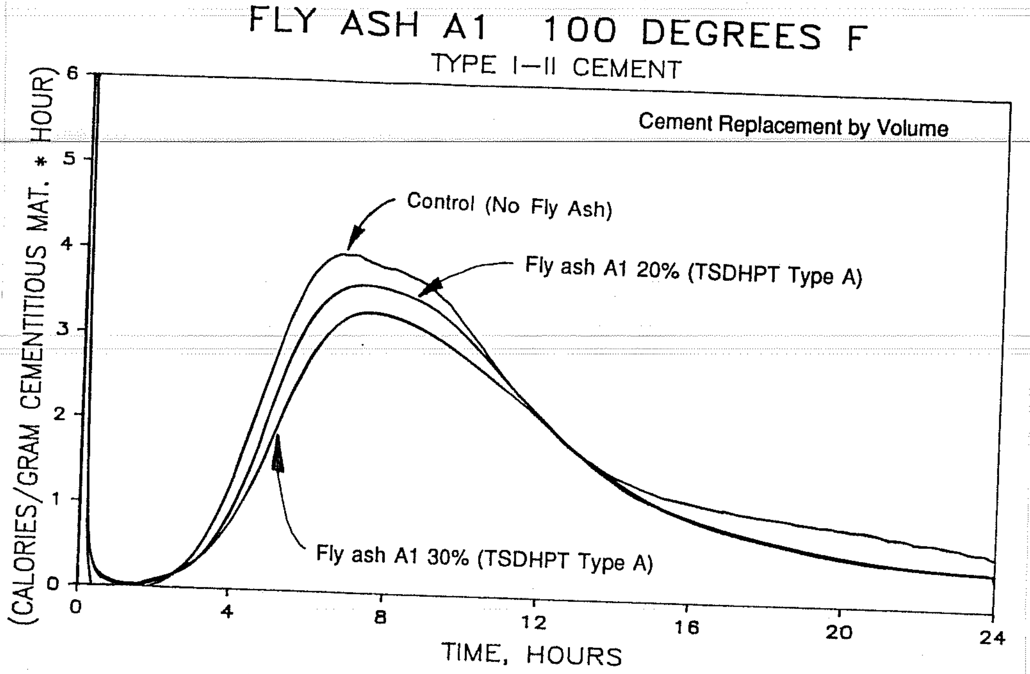

FLY ASH B2 80 DEGREES F
TYPE III CEMENT
Cement Replacement by Volume
Control (No Fly Ash)
25% Fly Ash B2 (TSDHPT Type B)
35% Fly Ash B2 (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT. *HOUR)
0
1
2
3
4
5
6
TIME, HOURS
0
4
8
12
16
20
24

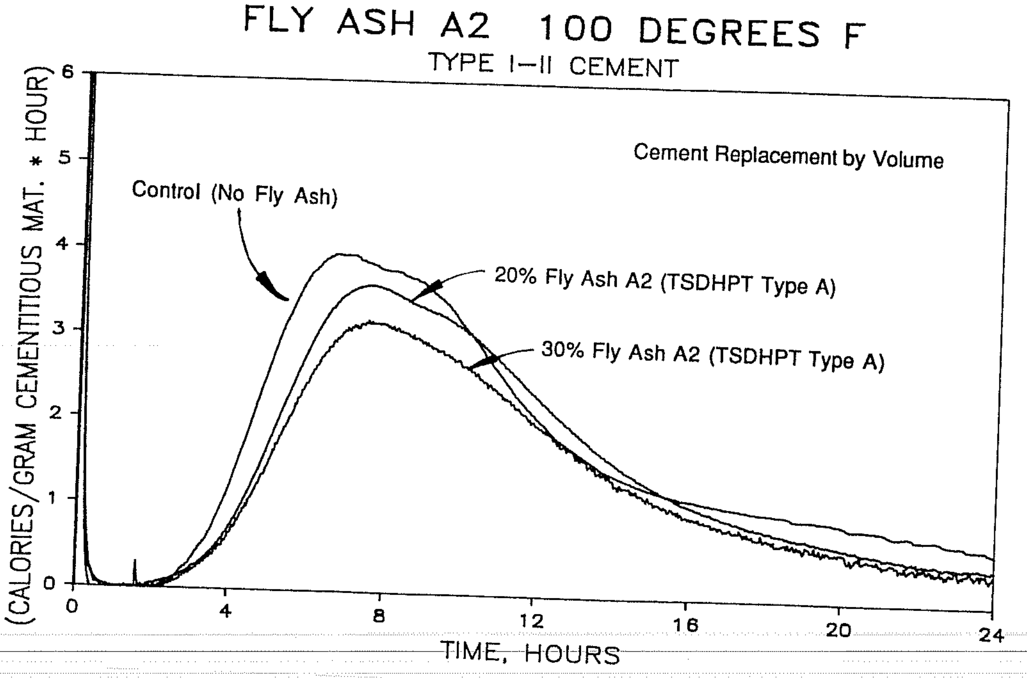

FLY ASH A1 100 DEGREES F
TYPE I CEMENT
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
TIME, HOURS
0
4
8
12
16
20
24
Control (No Fly Ash)
Cement Replacement by Volume
20% Fly Ash A1 (TSDHPT Type A)
30% Fly Ash A1 (TSDHPT Type A)

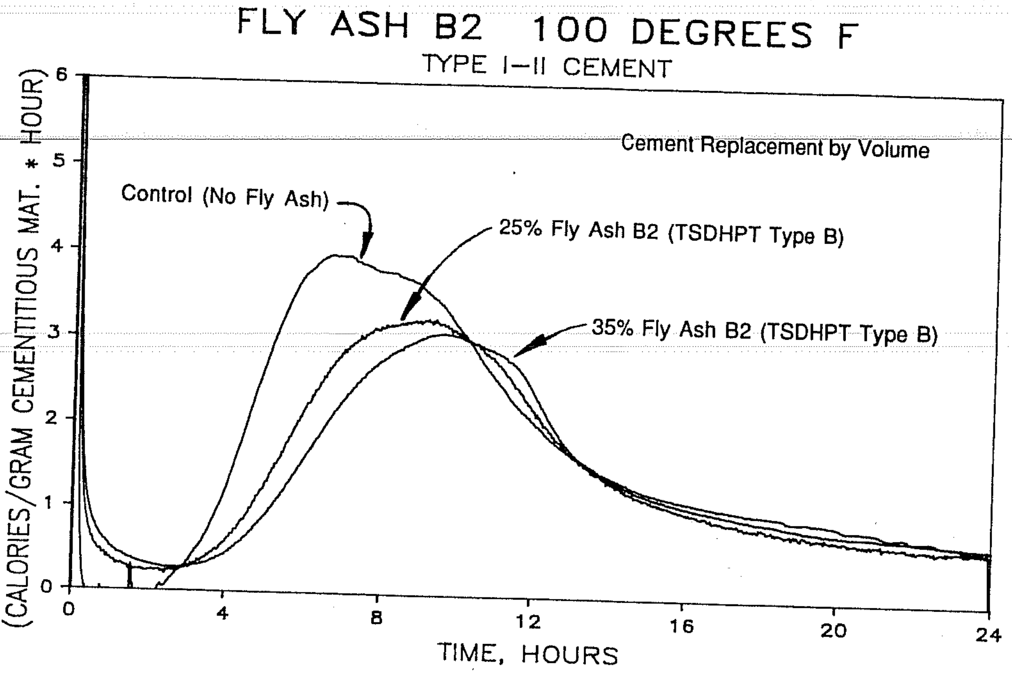

FLY ASH A2 100 DEGREES F
TYPE I CEMENT
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
TIME, HOURS
0
4
8
12
16
20
24
Control (No Fly Ash)
Cement Replacement by Volume
20% Fly Ash A2 (TSDHPT Type A)
30% Fly Ash A2 (TSDHPT Type A)

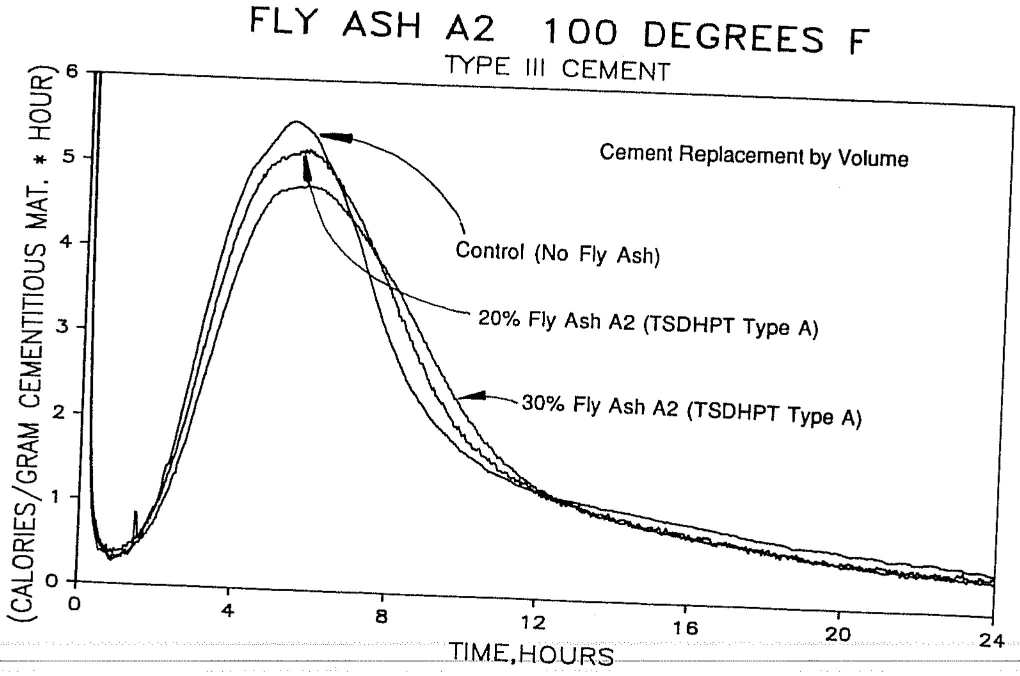

FLY ASH B1 100 DEGREES F
TYPE I CEMENT

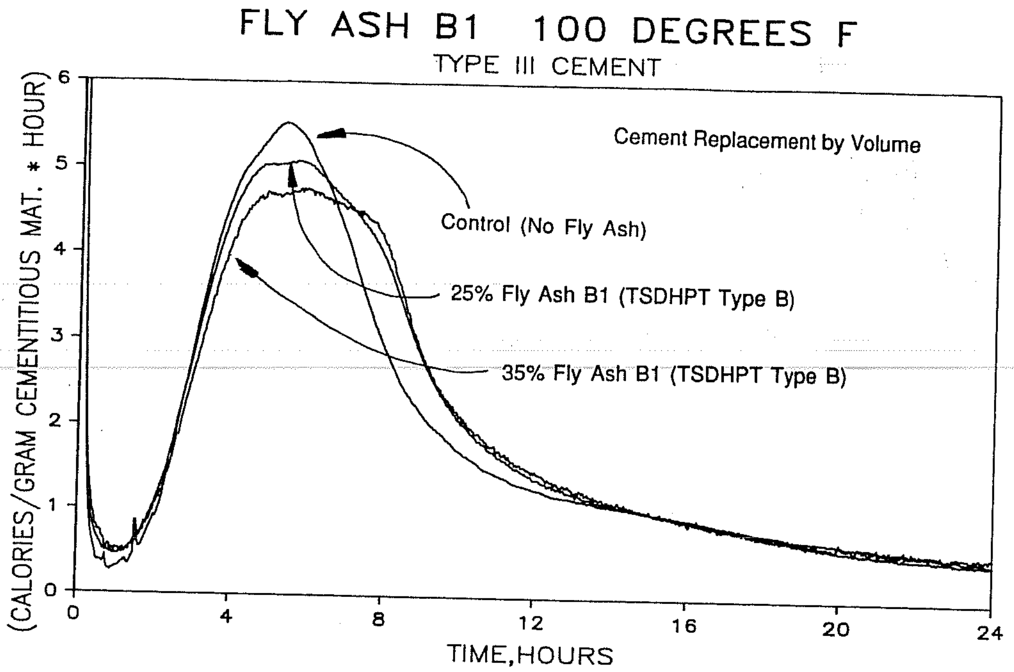

FLY ASH B2 100 DEGREES F
TYPE I CEMENT

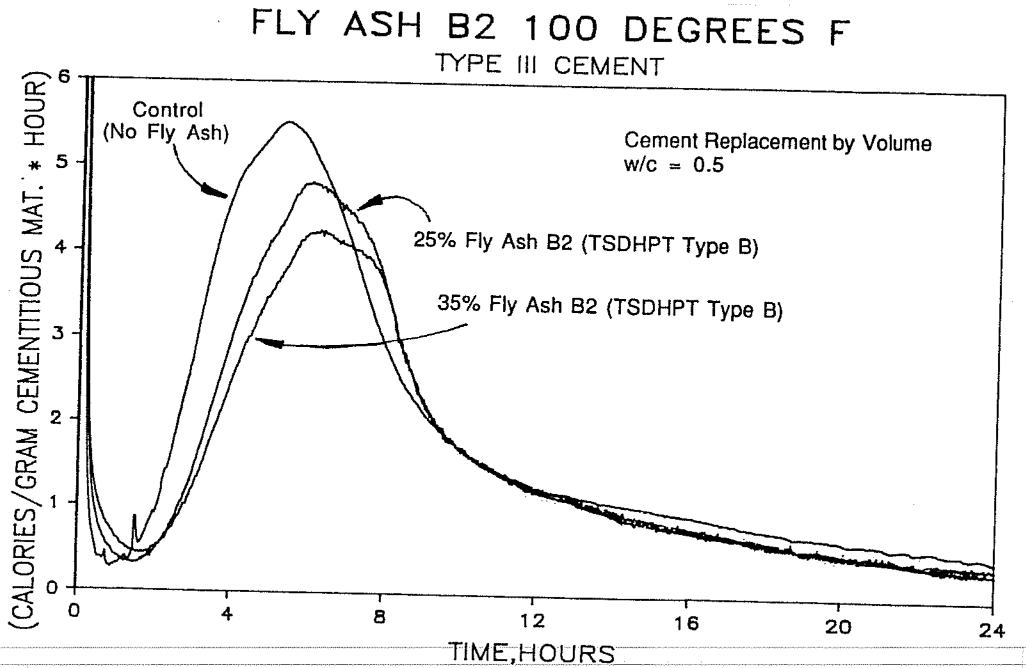

FLY ASH A1 100 DEGREES F
TYPE I–II CEMENT
Cement Replacement by Volume
Control (No Fly Ash)
Fly ash A1 20% (TSDHPT Type A)
Fly ash A1 30% (TSDHPT Type A)
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
0
4
8
12
16
20
24
TIME, HOURS

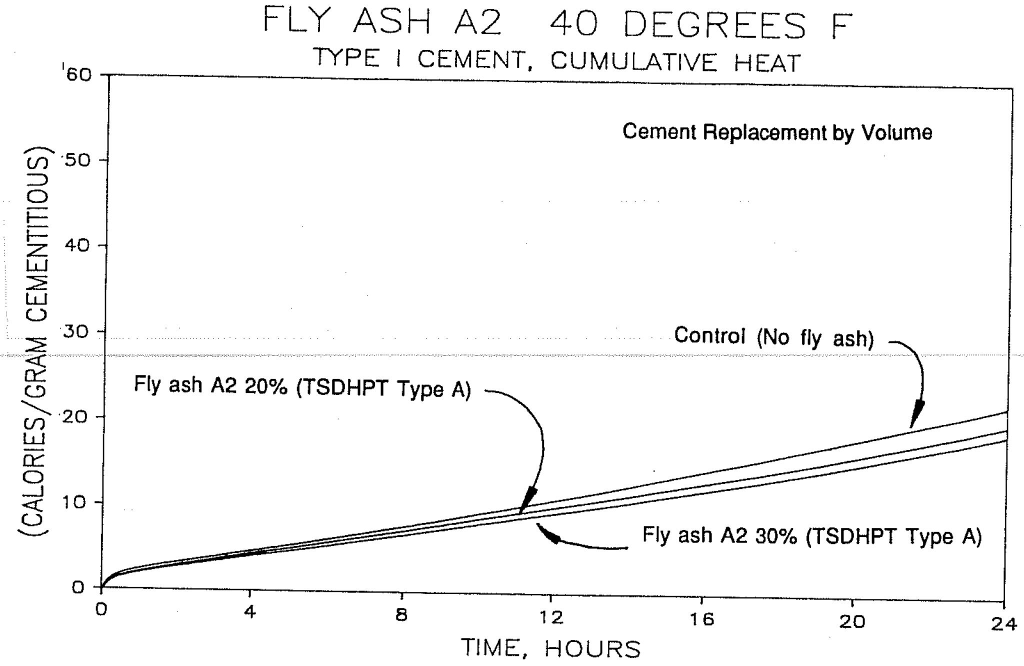

FLY ASH A2 100 DEGREES F
TYPE I–II CEMENT
Cement Replacement by Volume
Control (No Fly Ash)
20% Fly Ash A2 (TSDHPT Type A)
30% Fly Ash A2 (TSDHPT Type A)
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
0
4
8
12
16
20
24
TIME, HOURS

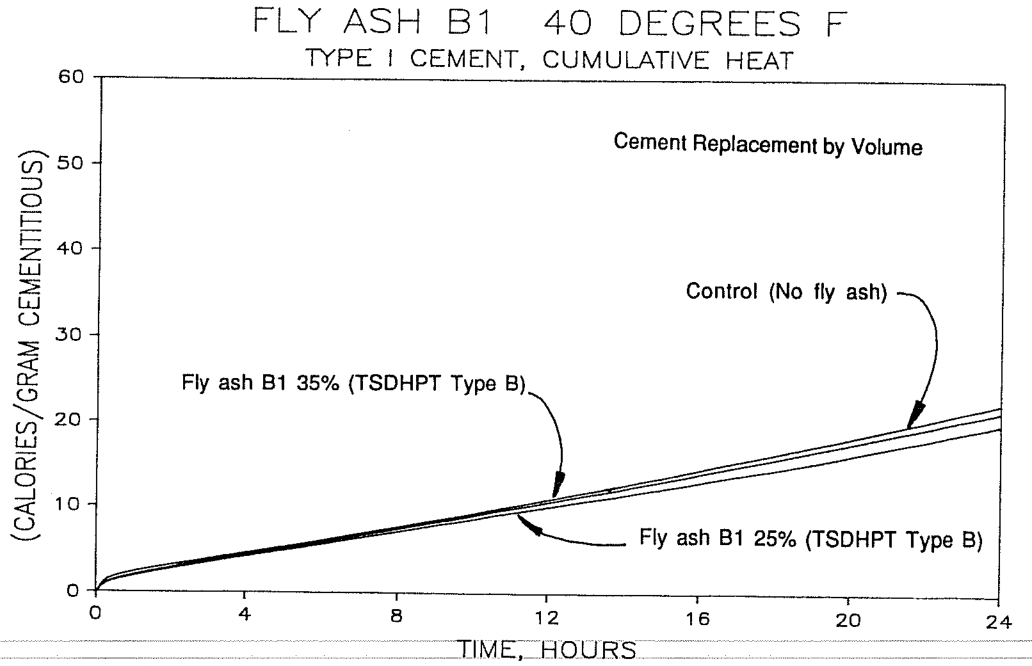

FLY ASH B2 100 DEGREES F
TYPE I–II CEMENT
Cement Replacement by Volume
Control (No Fly Ash)
25% Fly Ash B2 (TSDHPT Type B)
35% Fly Ash B2 (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
TIME, HOURS
0
4
8
12
16
20
24

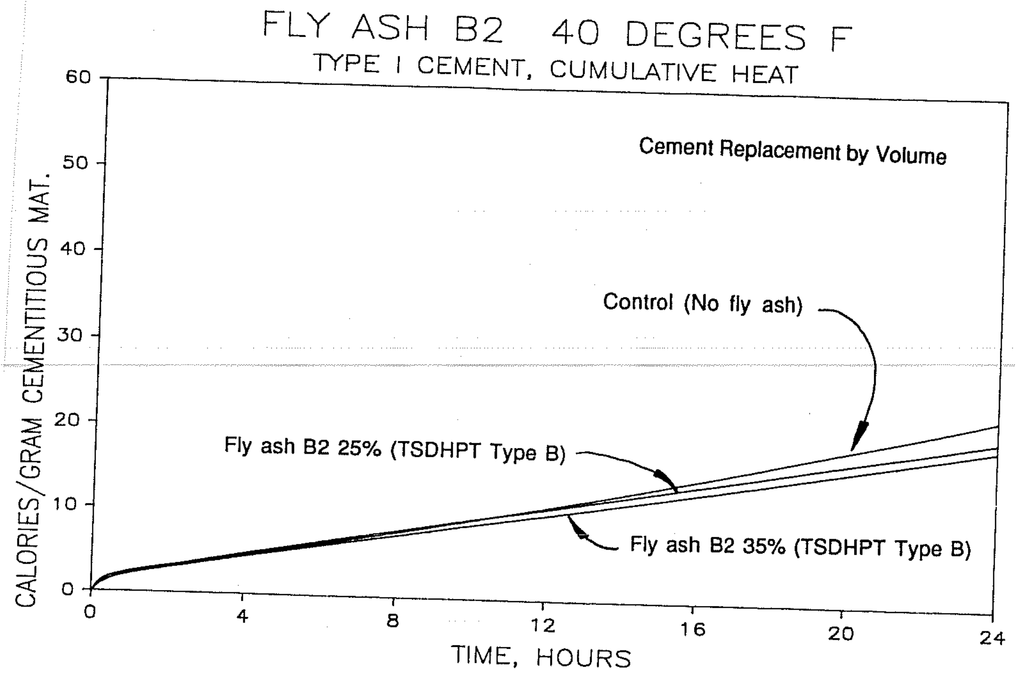

FLY ASH A2 100 DEGREES F
TYPE III CEMENT
Cement Replacement by Volume
Control (No Fly Ash)
20% Fly Ash A2 (TSDHPT Type A)
30% Fly Ash A2 (TSDHPT Type A)
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
TIME,HOURS
0
4
8
12
16
20
24

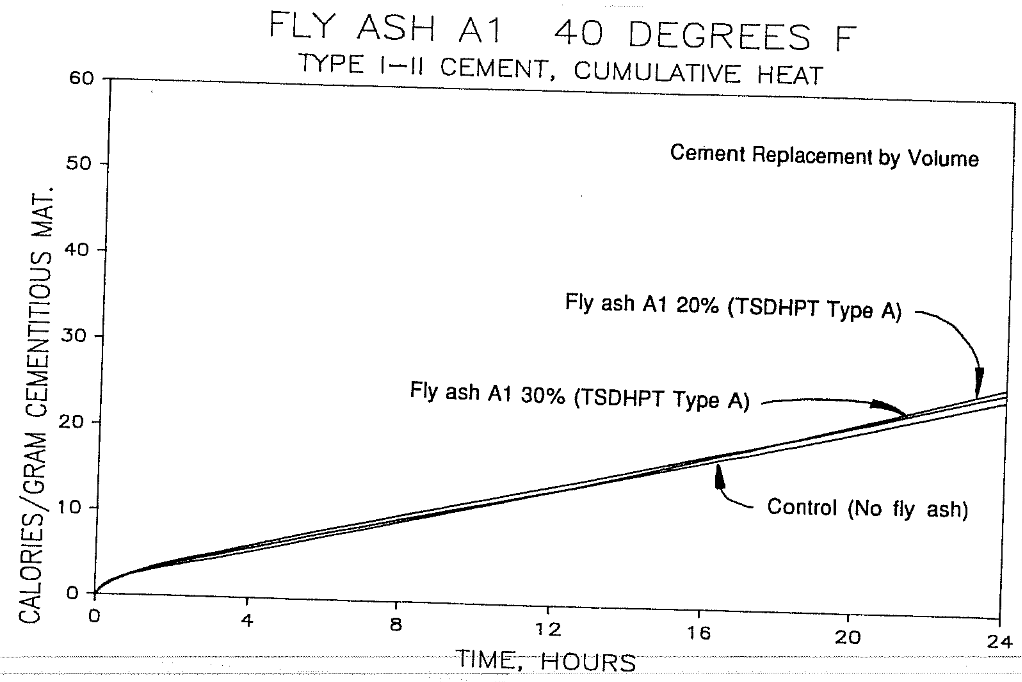

FLY ASH B1 100 DEGREES F
TYPE III CEMENT
Cement Replacement by Volume
Control (No Fly Ash)
25% Fly Ash B1 (TSDHPT Type B)
35% Fly Ash B1 (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
0
4
8
12
16
20
24
TIME,HOURS

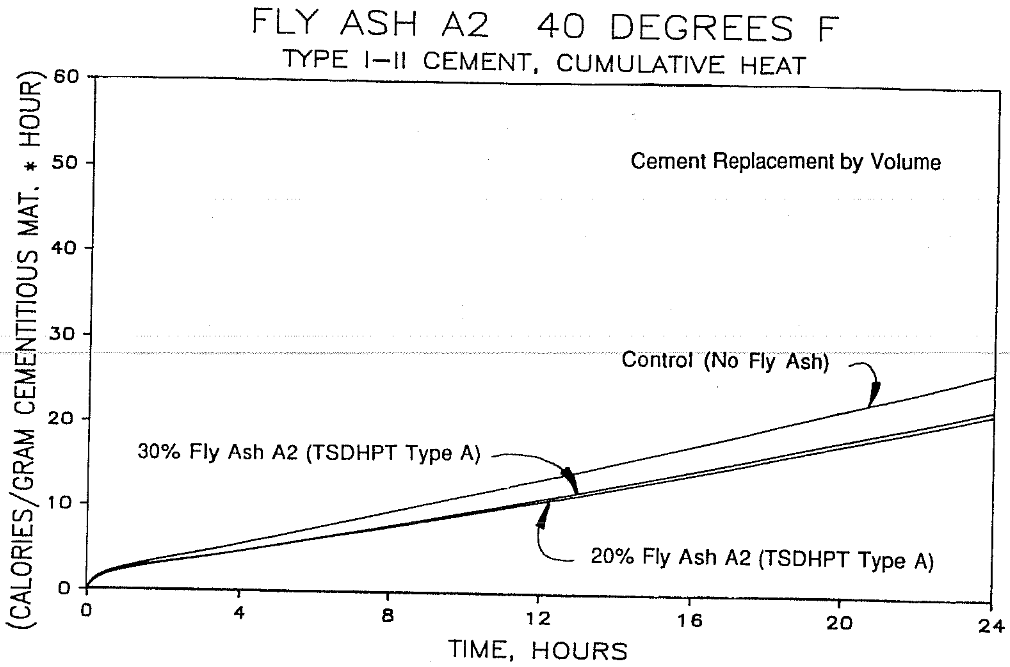

FLY ASH B2 100 DEGREES F
TYPE III CEMENT
Control
(No Fly Ash)
Cement Replacement by Volume
w/c = 0.5
25% Fly Ash B2 (TSDHPT Type B)
35% Fly Ash B2 (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
0
1
2
3
4
5
6
0
4
8
12
16
20
24
TIME,HOURS

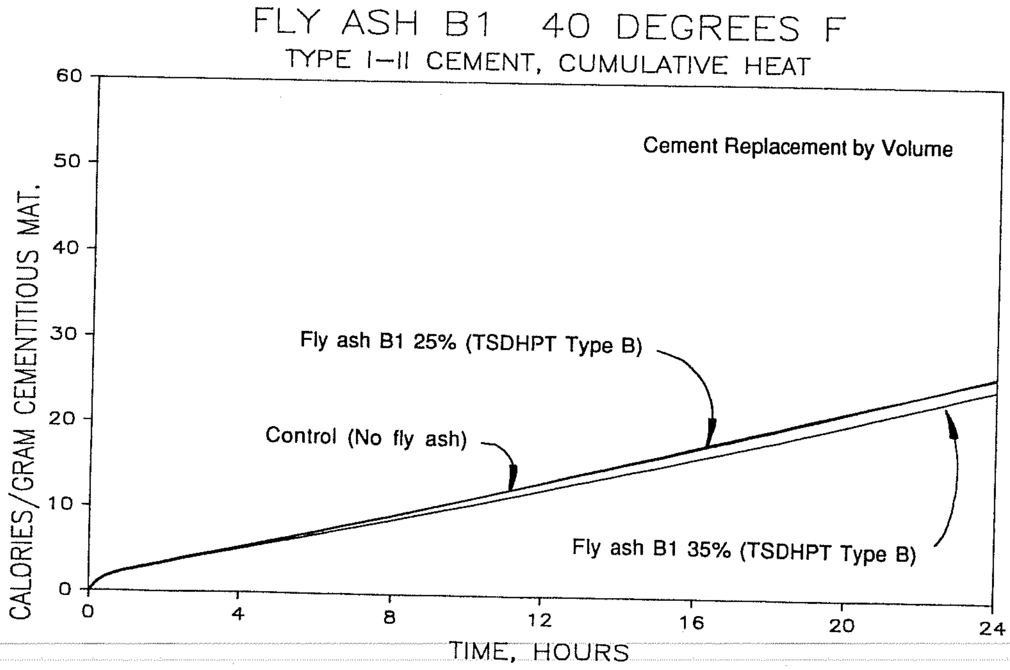

FLY ASH A2 40 DEGREES F
TYPE I CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash A2 20% (TSDHPT Type A)
Fly ash A2 30% (TSDHPT Type A)
(CALORIES/GRAM CEMENTITIOUS)
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24

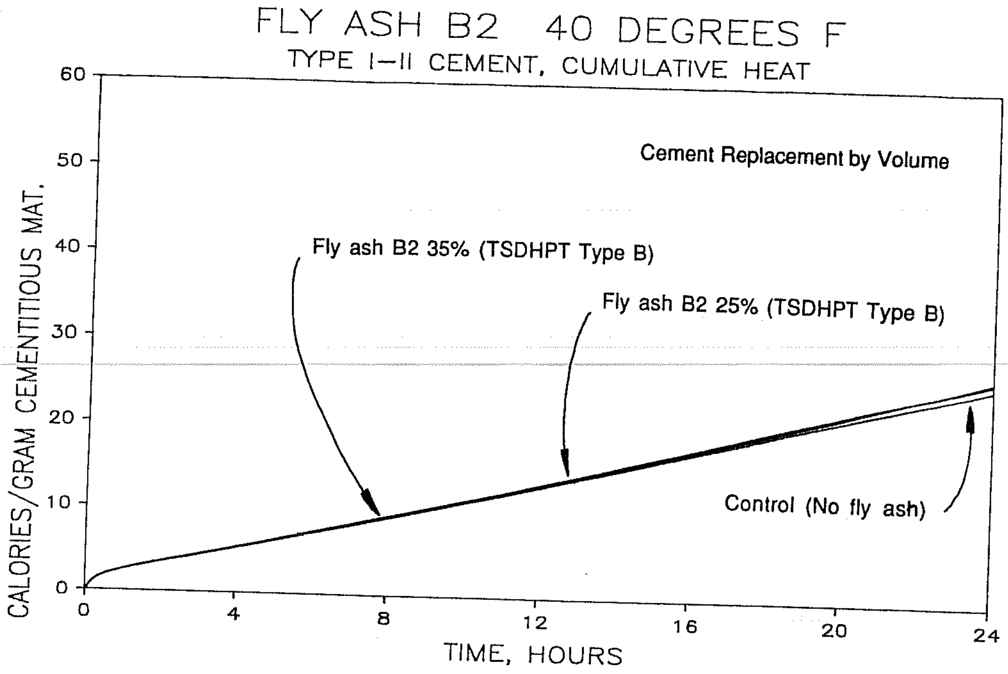

FLY ASH B1 40 DEGREES F
TYPE I CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash B1 35% (TSDHPT Type B)
Fly ash B1 25% (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS)
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24

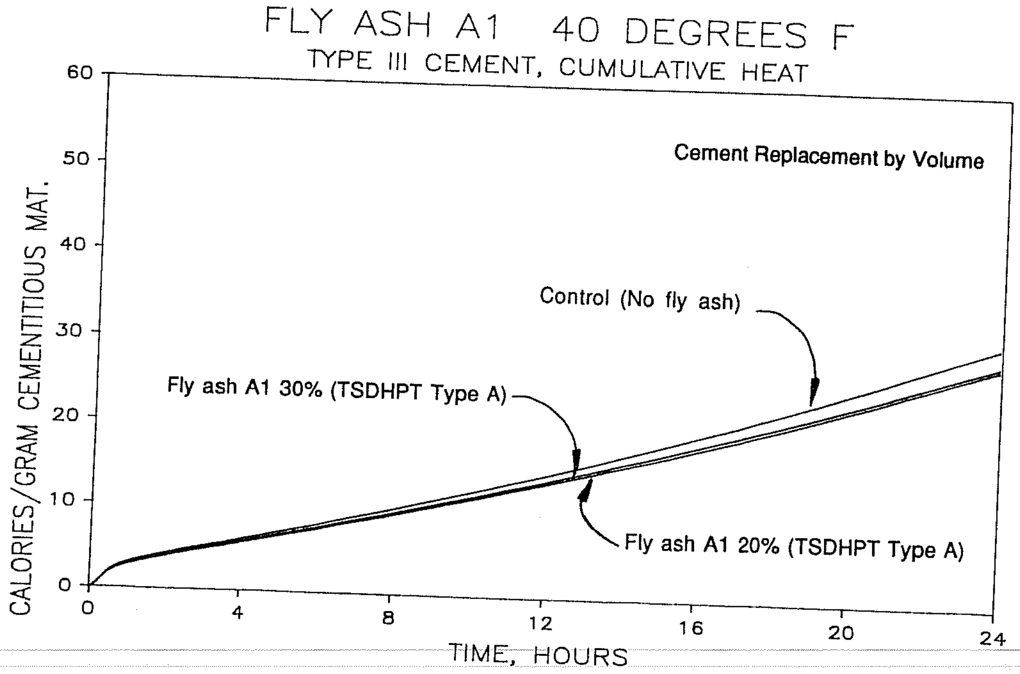

FLY ASH B2 40 DEGREES F
TYPE I CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash B2 25% (TSDHPT Type B)
Fly ash B2 35% (TSDHPT Type B)
CALORIES/GRAM CEMENTITIOUS MAT.
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24

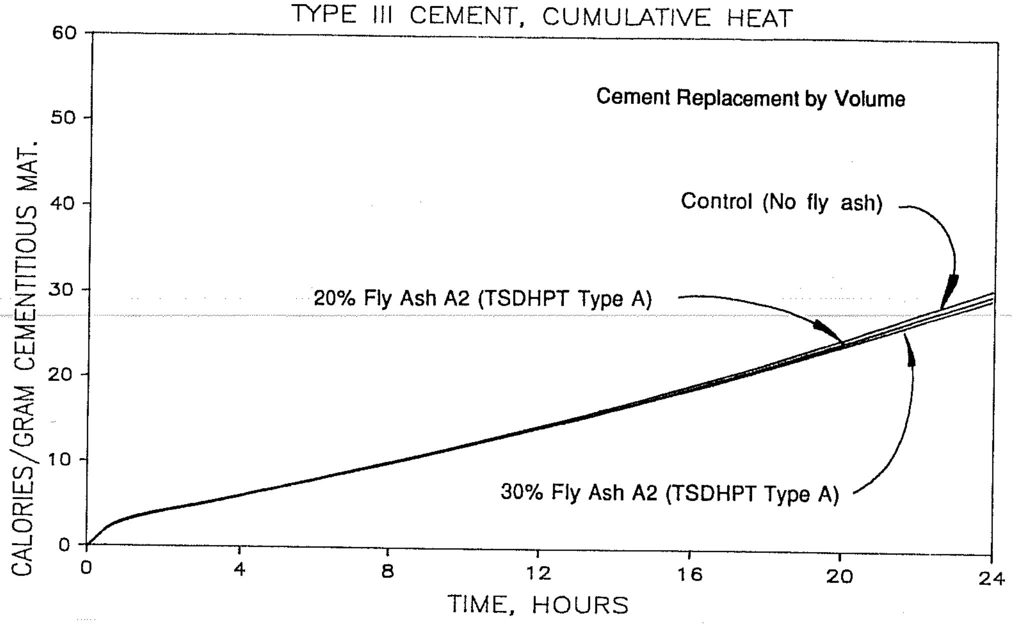

FLY ASH A1 40 DEGREES F
TYPE I–II CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Fly ash A1 20% (TSDHPT Type A)
Fly ash A1 30% (TSDHPT Type A)
Control (No fly ash)
CALORIES/GRAM CEMENTITIOUS MAT.
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24


FLY ASH A2 40 DEGREES F
TYPE I–II CEMENT, CUMULATIVE HEAT
(CALORIES/GRAM CEMENTITIOUS MAT. * HOUR)
60
50
40
30
20
10
0
Cement Replacement by Volume
Control (No Fly Ash)
30% Fly Ash A2 (TSDHPT Type A)
20% Fly Ash A2 (TSDHPT Type A)
0
4
8
12
16
20
24
TIME, HOURS


FLY ASH B1 40 DEGREES F
TYPE I–II CEMENT, CUMULATIVE HEAT
CALORIES/GRAM CEMENTITIOUS MAT.
60
50
40
30
20
10
0
Cement Replacement by Volume
Fly ash B1 25% (TSDHPT Type B)
Control (No fly ash)
Fly ash B1 35% (TSDHPT Type B)
0
4
8
12
16
20
24
TIME, HOURS

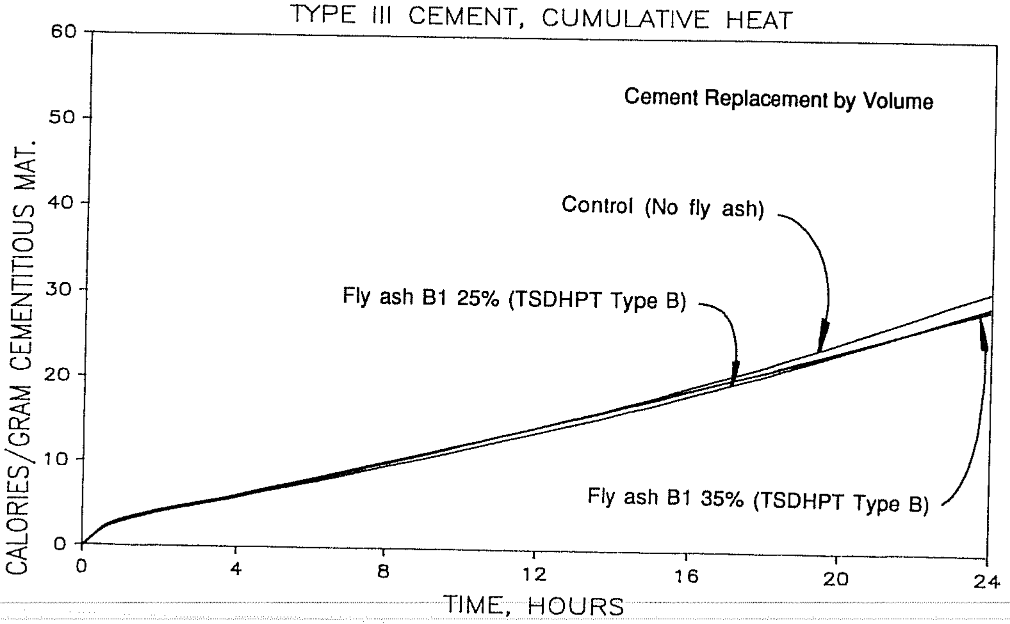

FLY ASH B2 40 DEGREES F
TYPE I–II CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Fly ash B2 35% (TSDHPT Type B)
Fly ash B2 25% (TSDHPT Type B)
Control (No fly ash)
CALORIES/GRAM CEMENTITIOUS MAT.
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24


FLY ASH A1 40 DEGREES F
TYPE III CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash A1 30% (TSDHPT Type A)
Fly ash A1 20% (TSDHPT Type A)
CALORIES/GRAM CEMENTITIOUS MAT.
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24



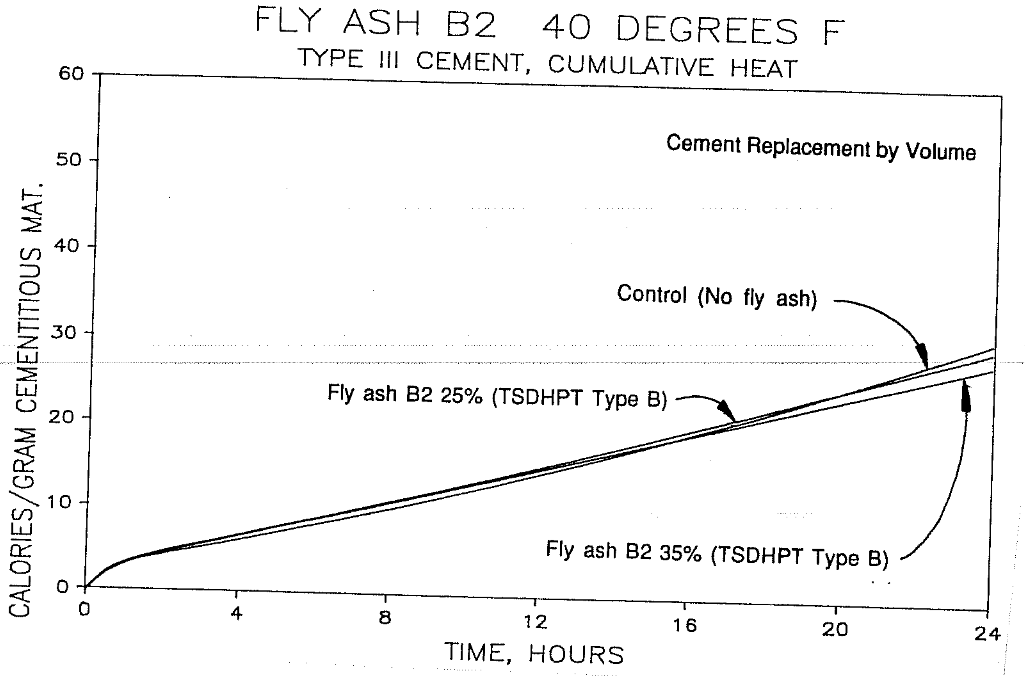
FLY ASH A2 40 DEGREES F

TYPE III CEMENT, CUMULATIVE HEAT



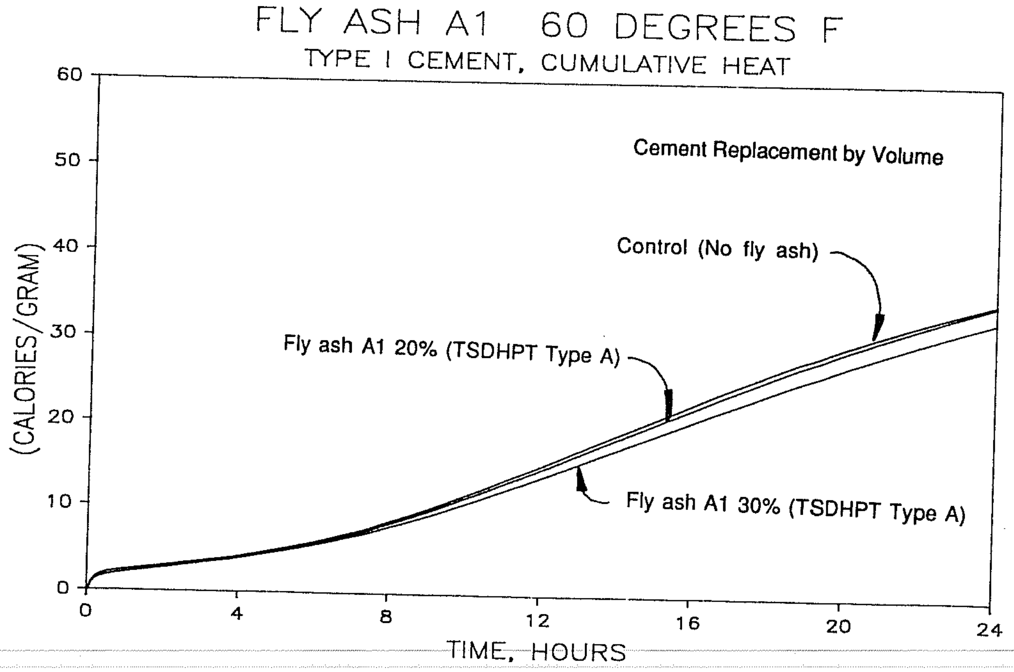
FLY ASH B1 40 DEGREES F

TYPE III CEMENT, CUMULATIVE HEAT



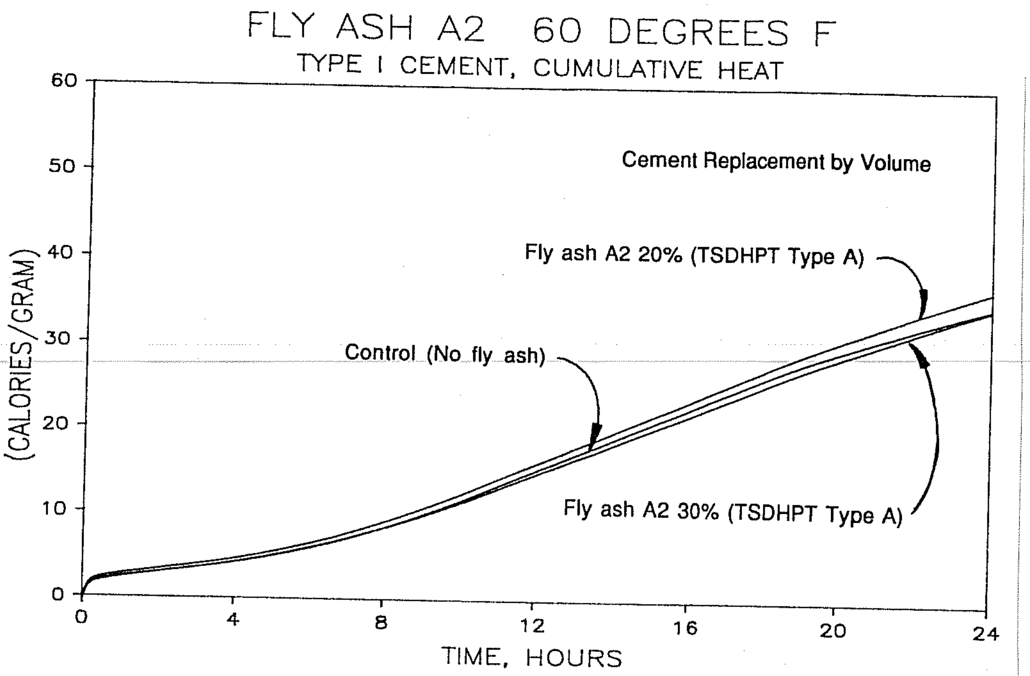
FLY ASH B2 40 DEGREES F

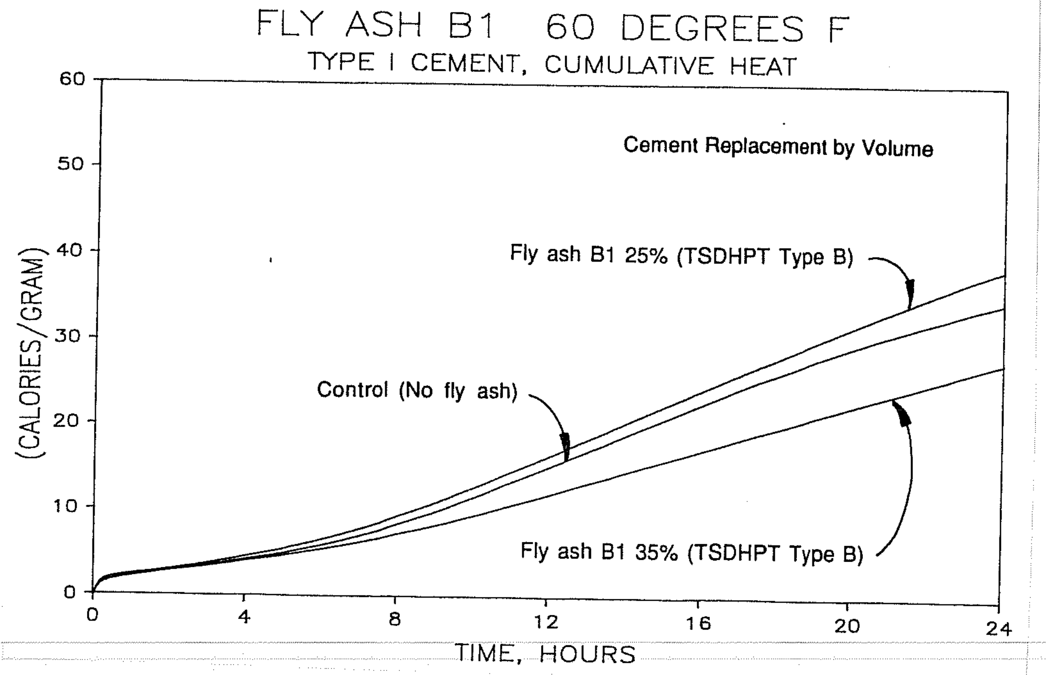
TYPE III CEMENT, CUMULATIVE HEAT

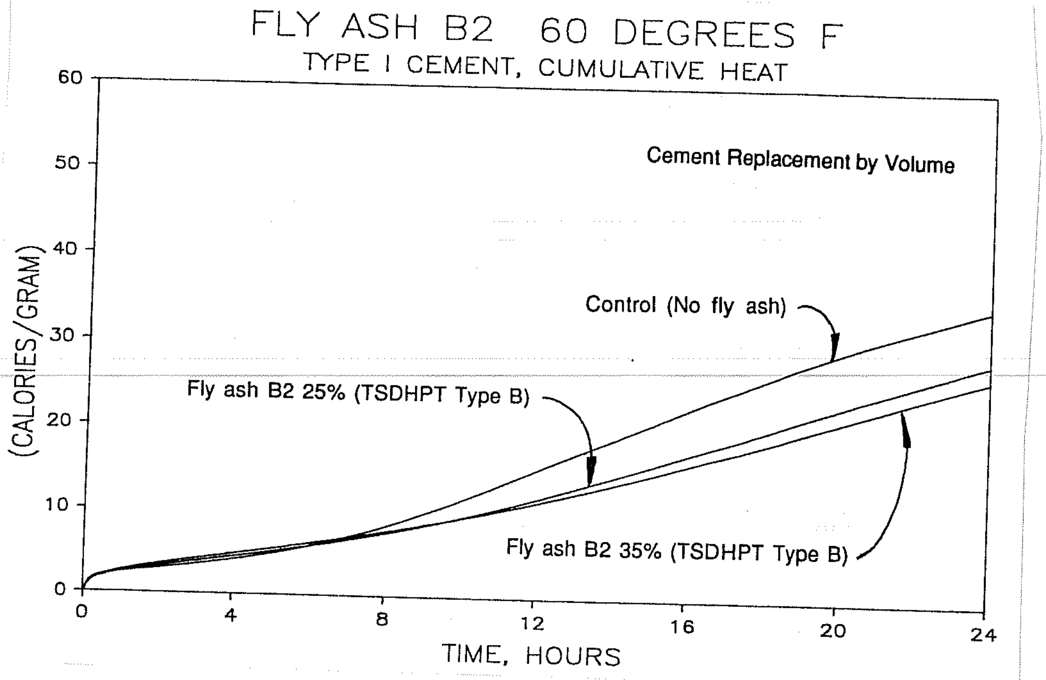


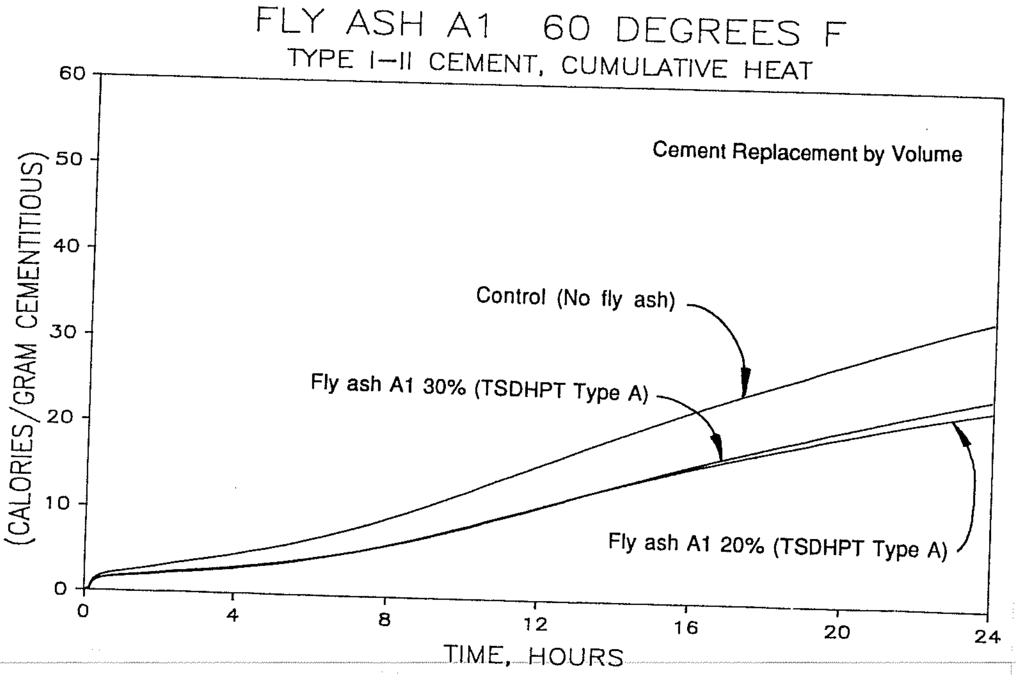
FLY ASH A1 60 DEGREES F

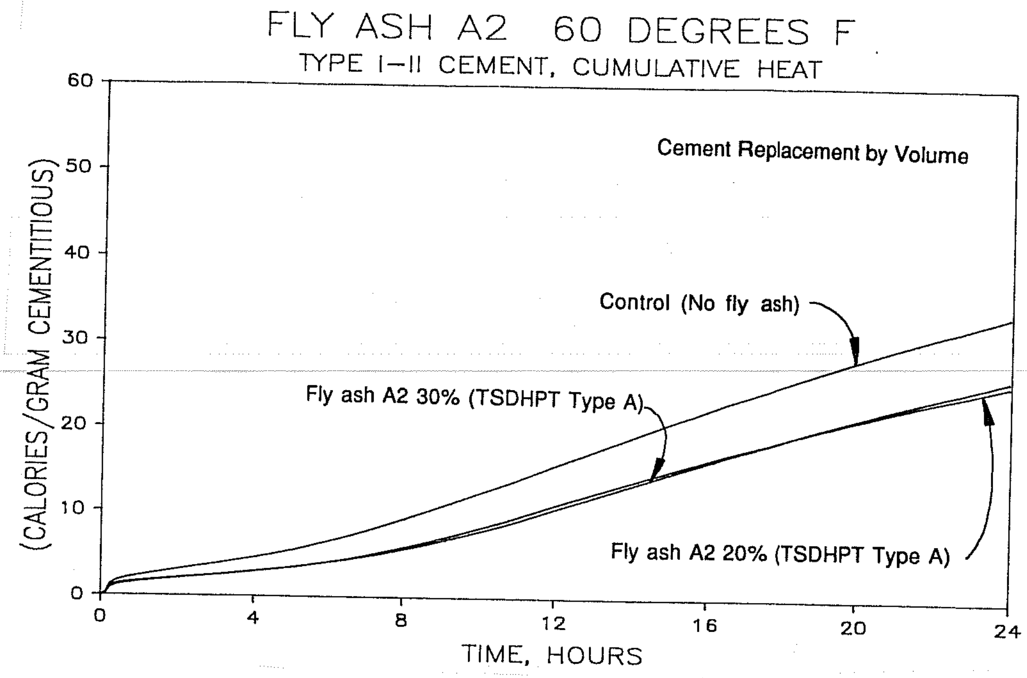
TYPE I CEMENT, CUMULATIVE HEAT


FLY ASH A2 60 DEGREES F
TYPE I CEMENT, CUMULATIVE HEAT
(CALORIES/GRAM)
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24
Cement Replacement by Volume
Fly ash A2 20% (TSDHPT Type A)
Control (No fly ash)
Fly ash A2 30% (TSDHPT Type A)


FLY ASH B1 60 DEGREES F
TYPE I CEMENT, CUMULATIVE HEAT
(CALORIES/GRAM)
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24
Cement Replacement by Volume
Fly ash B1 25% (TSDHPT Type B)
Control (No fly ash)
Fly ash B1 35% (TSDHPT Type B)

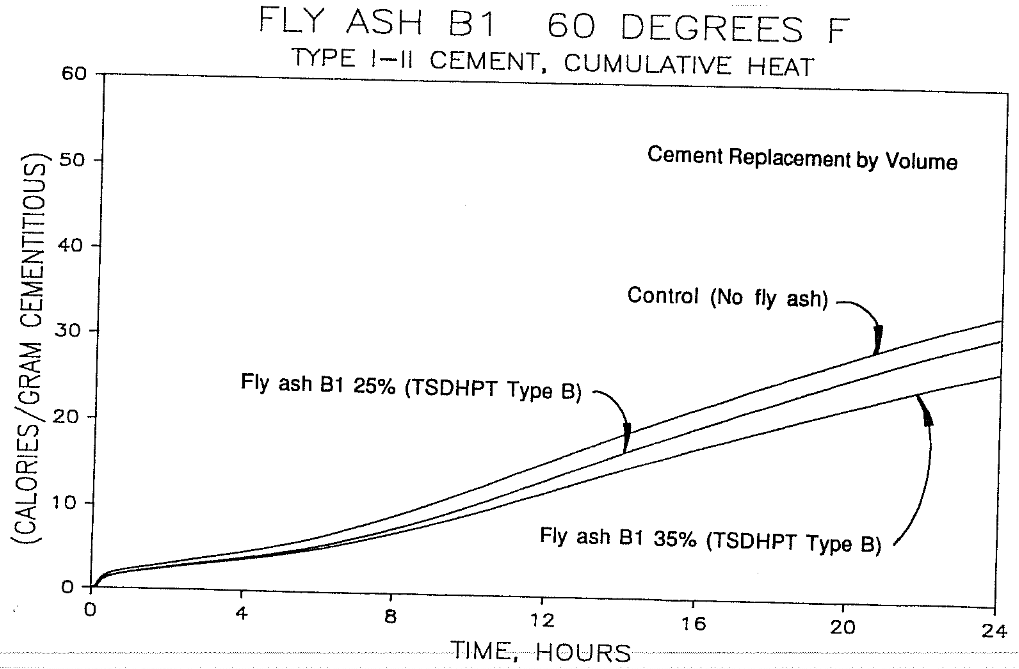

FLY ASH B2 60 DEGREES F
TYPE I CEMENT, CUMULATIVE HEAT
(CALORIES/GRAM)
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24
Cement Replacement by Volume
Control (No fly ash)
Fly ash B2 25% (TSDHPT Type B)
Fly ash B2 35% (TSDHPT Type B)


FLY ASH A1 60 DEGREES F
TYPE I–II CEMENT, CUMULATIVE HEAT
(CALORIES/GRAM CEMENTITIOUS)
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24
Cement Replacement by Volume
Control (No fly ash)
Fly ash A1 30% (TSDHPT Type A)
Fly ash A1 20% (TSDHPT Type A)



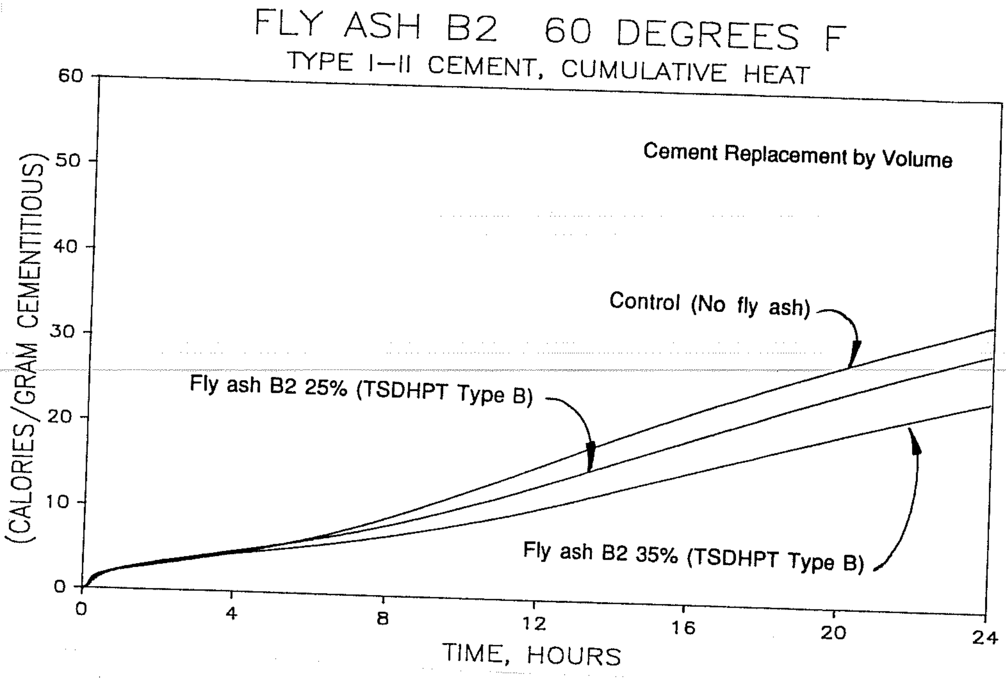
FLY ASH A2 60 DEGREES F

TYPE I—II CEMENT, CUMULATIVE HEAT

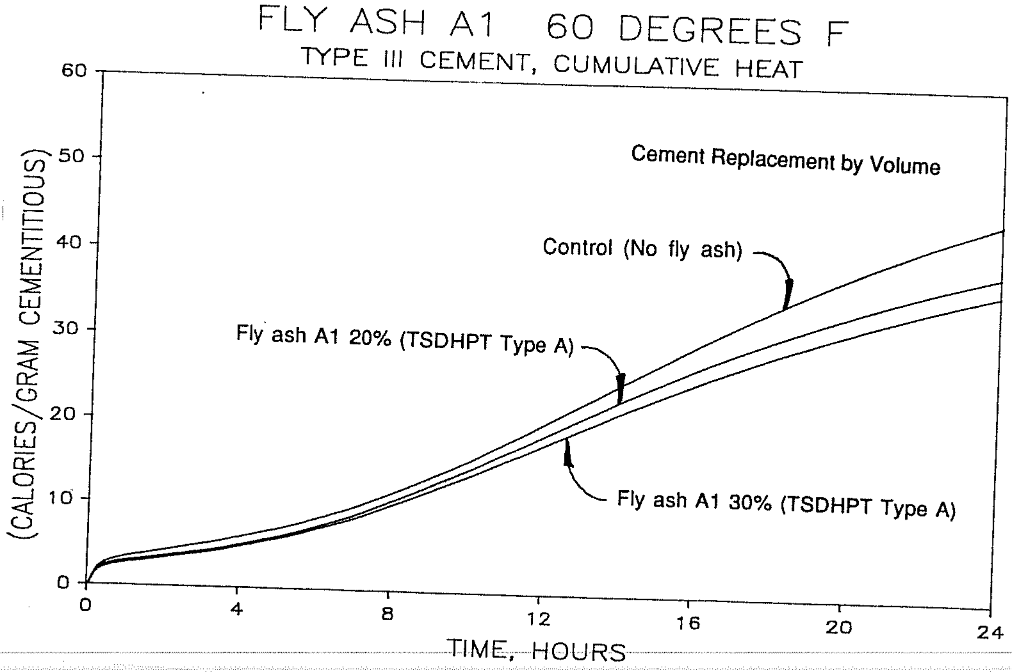


FLY ASH B1 60 DEGREES F

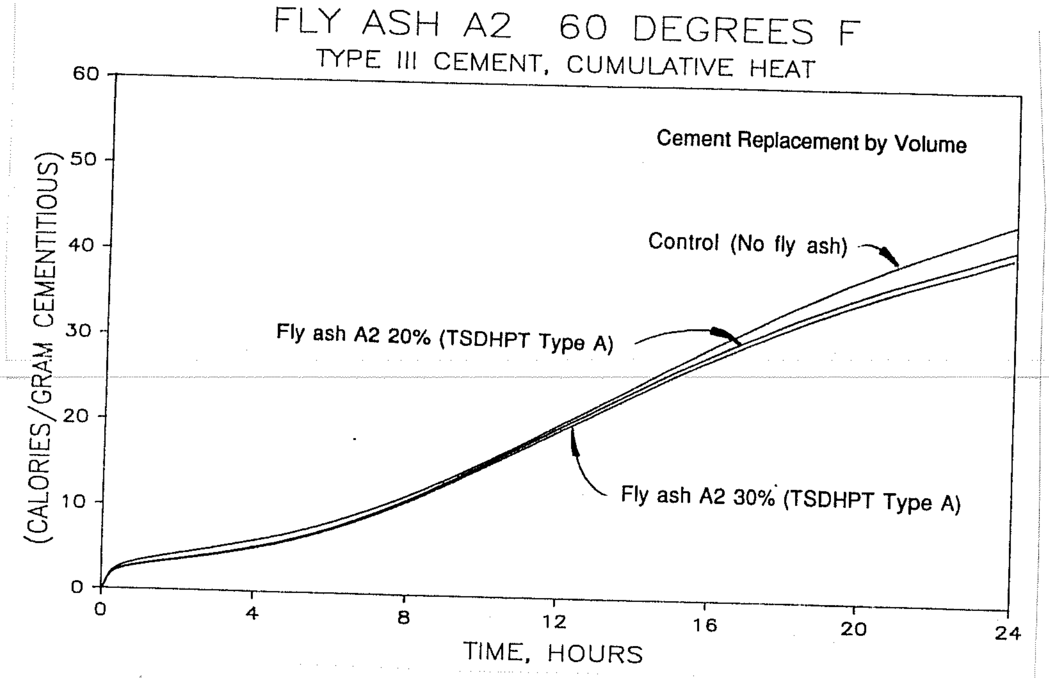
TYPE I—II CEMENT, CUMULATIVE HEAT

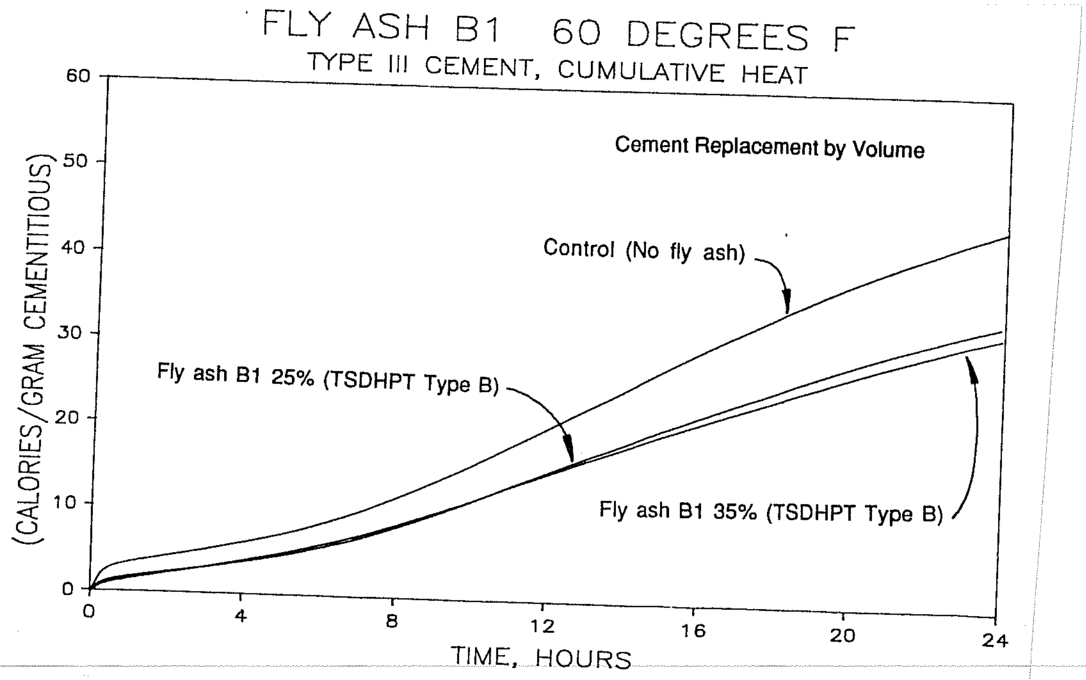

FLY ASH B2 60 DEGREES F

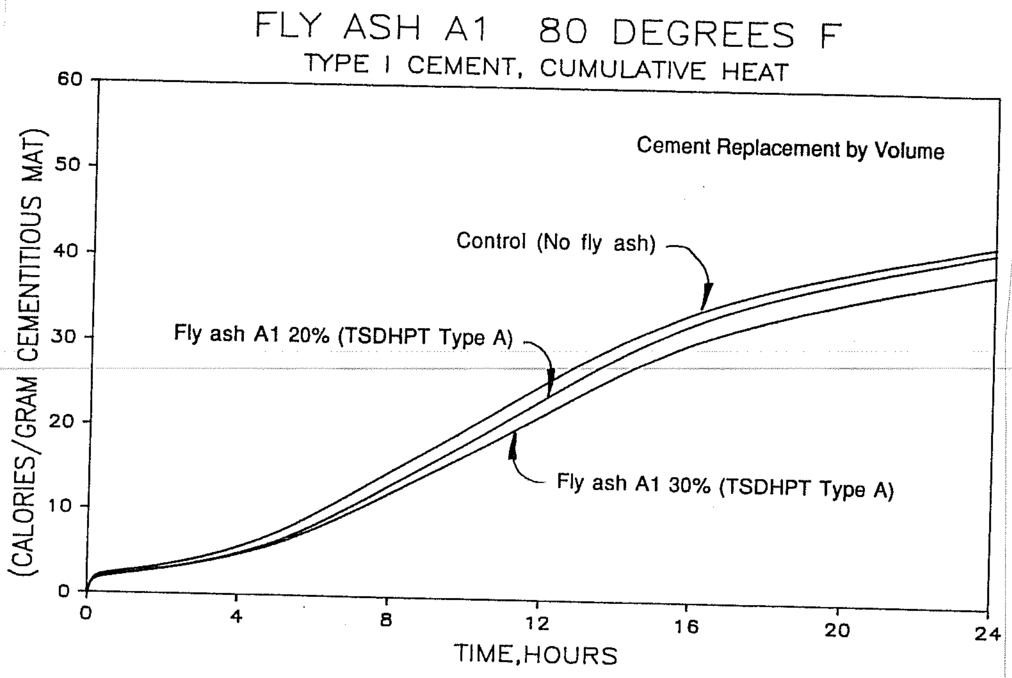
TYPE I–II CEMENT, CUMULATIVE HEAT

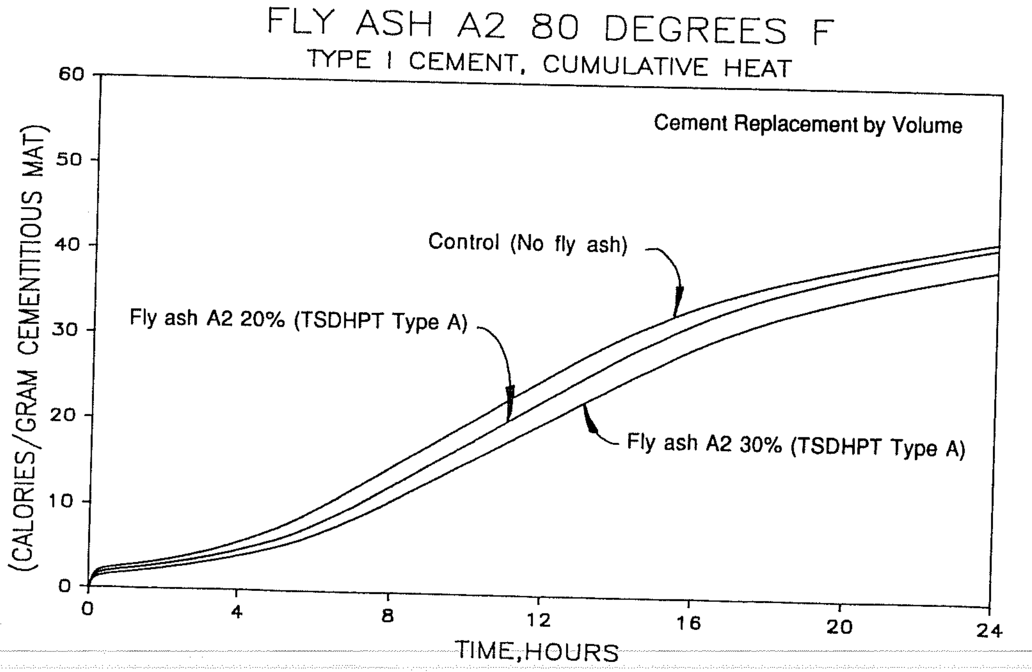

FLY ASH A1 60 DEGREES F

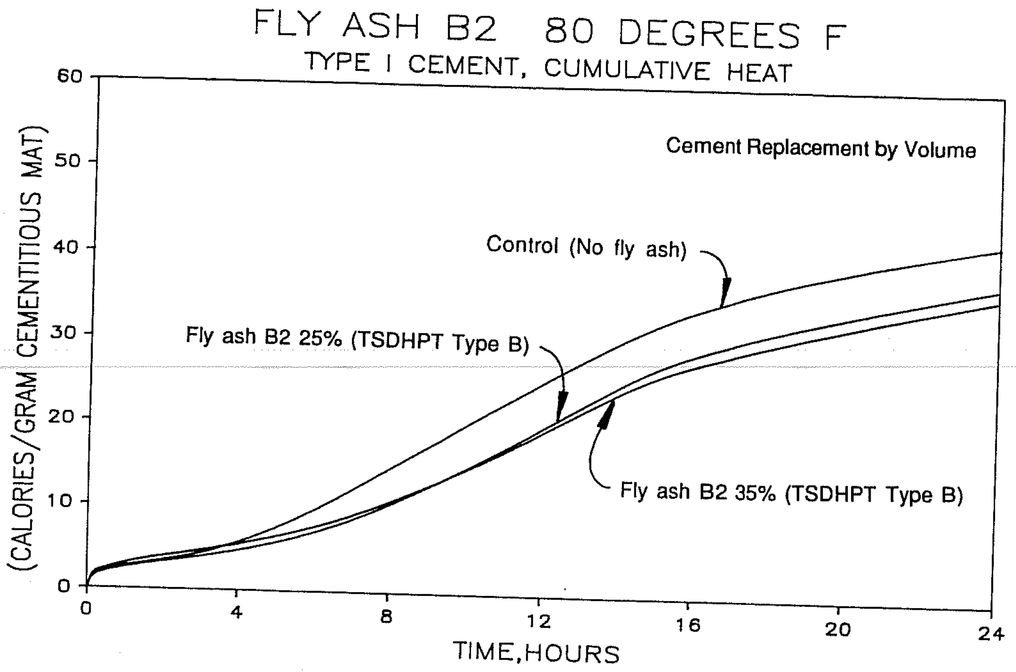
TYPE III CEMENT, CUMULATIVE HEAT

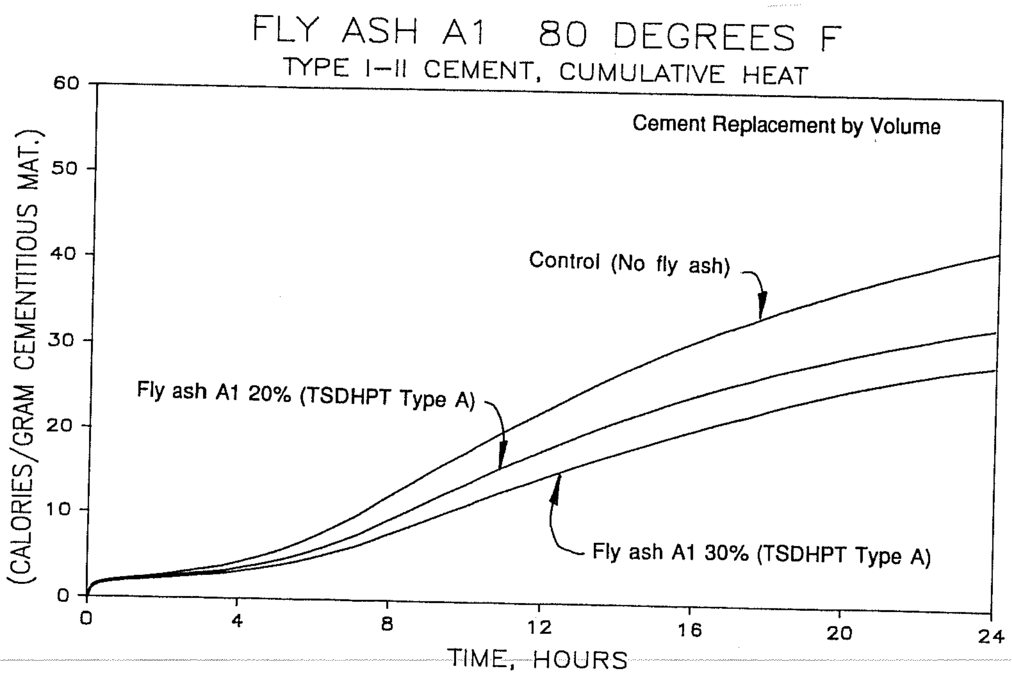

FLY ASH A2 60 DEGREES F
TYPE III CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash A2 20% (TSDHPT Type A)
Fly ash A2 30% (TSDHPT Type A)
(CALORIES/GRAM CEMENTITIOUS)
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24

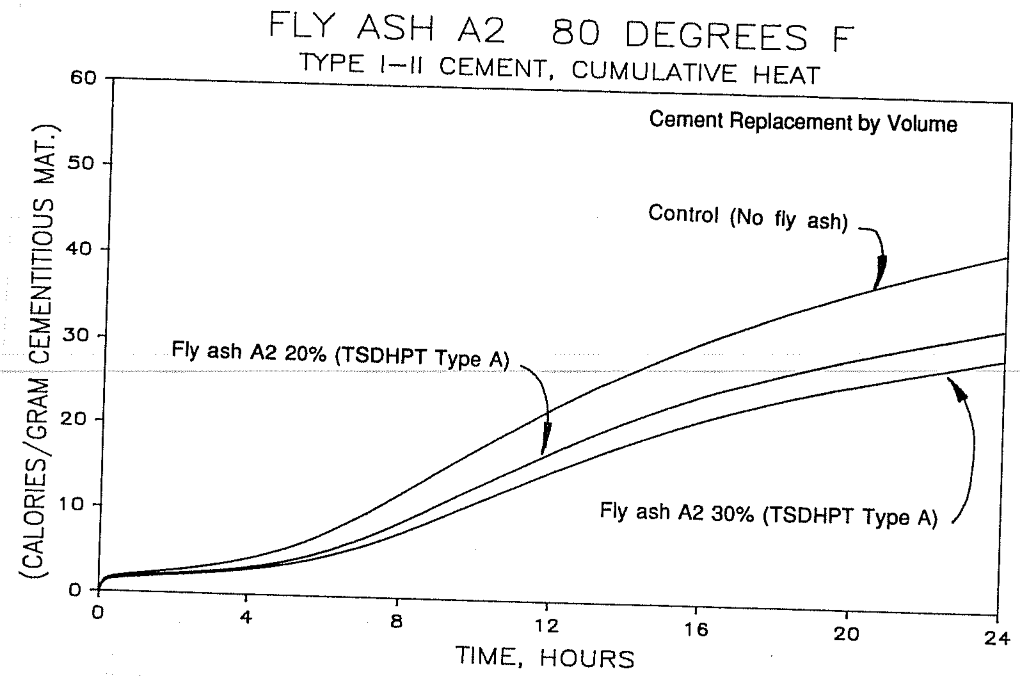

FLY ASH B1 60 DEGREES F
TYPE III CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash B1 25% (TSDHPT Type B)
Fly ash B1 35% (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS)
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24

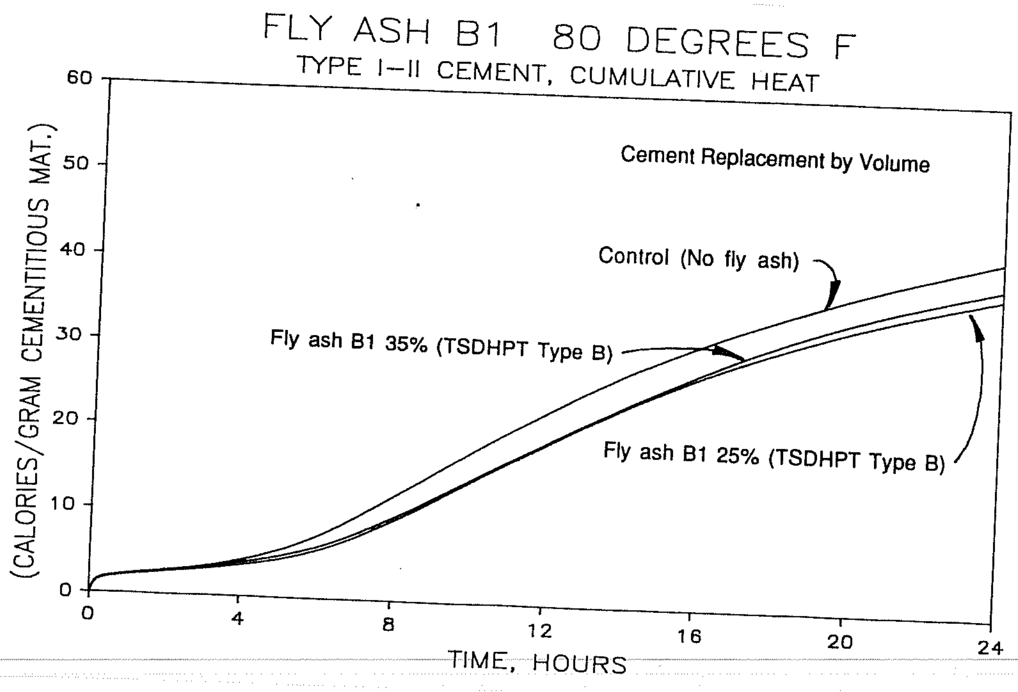

FLY ASH A1 80 DEGREES F
TYPE I CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash A1 20% (TSDHPT Type A)
Fly ash A1 30% (TSDHPT Type A)
(CALORIES/GRAM CEMENTITIOUS MAT)
0
10
20
30
40
50
60
TIME,HOURS
0
4
8
12
16
20
24


FLY ASH A2 80 DEGREES F
TYPE I CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash A2 20% (TSDHPT Type A)
Fly ash A2 30% (TSDHPT Type A)
(CALORIES/GRAM CEMENTITIOUS MAT)
0
10
20
30
40
50
60
TIME,HOURS
0
4
8
12
16
20
24


FLY ASH B2 80 DEGREES F
TYPE I CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash B2 25% (TSDHPT Type B)
Fly ash B2 35% (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT)
0
10
20
30
40
50
60
0
4
8
12
16
20
24
TIME,HOURS


FLY ASH A1 80 DEGREES F
TYPE I–II CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash A1 20% (TSDHPT Type A)
Fly ash A1 30% (TSDHPT Type A)
(CALORIES/GRAM CEMENTITIOUS MAT.)
0
10
20
30
40
50
60
0
4
8
12
16
20
24
TIME, HOURS


FLY ASH A2 80 DEGREES F
TYPE I–II CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash A2 20% (TSDHPT Type A)
Fly ash A2 30% (TSDHPT Type A)
(CALORIES/GRAM CEMENTITIOUS MAT.)
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24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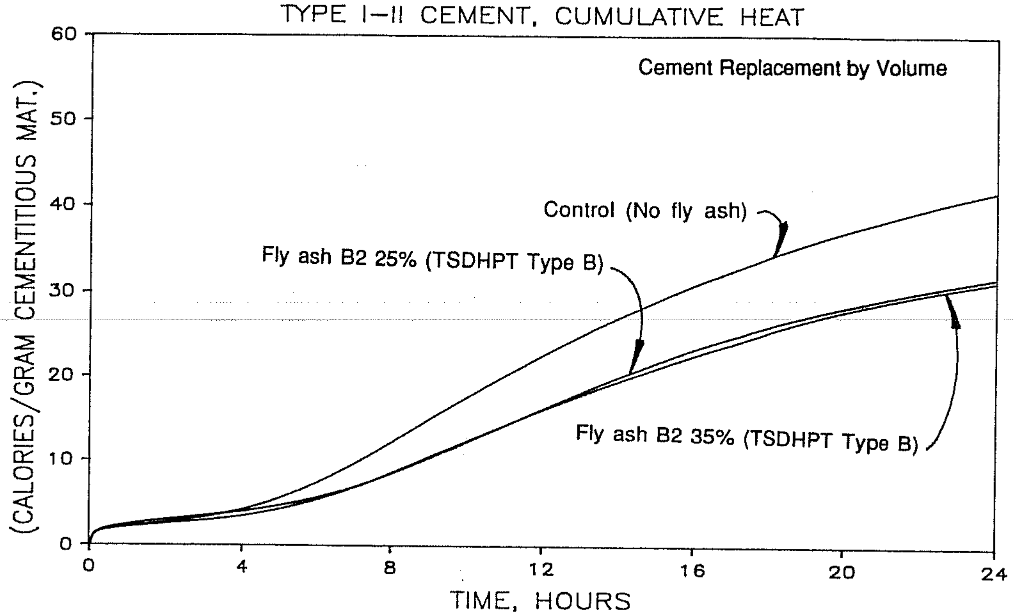
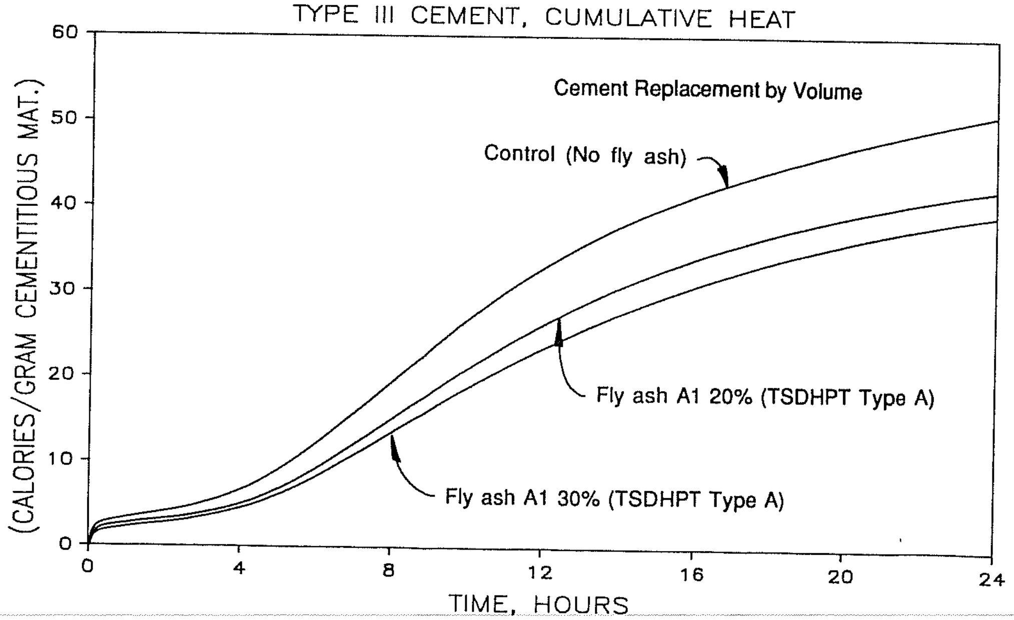
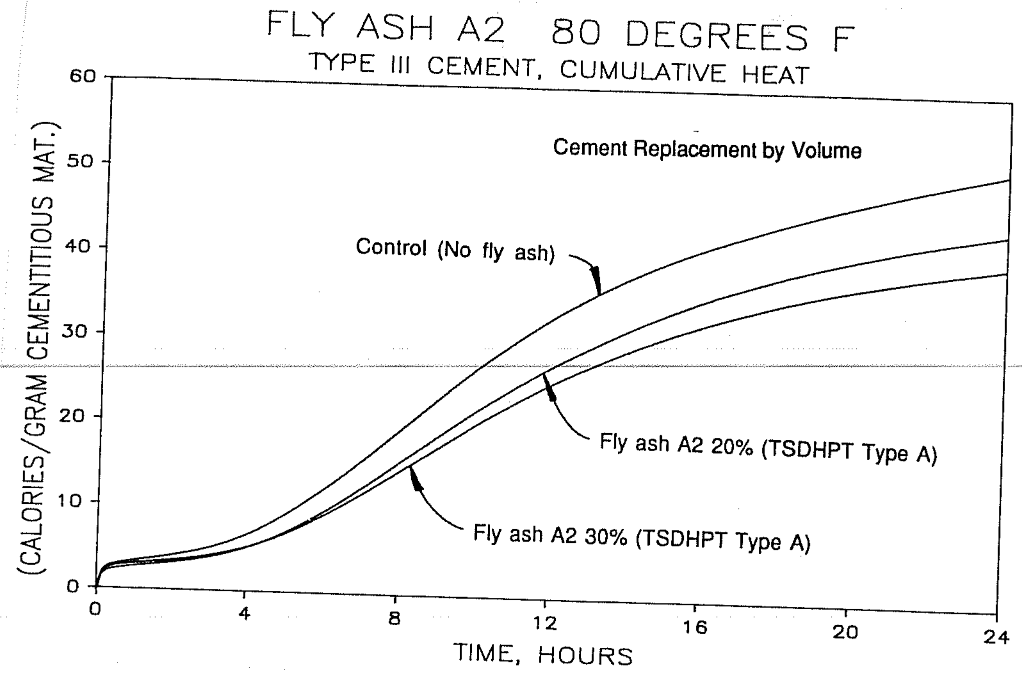
TYPE I–II CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash B1 35% (TSDHPT Type B)
Fly ash B1 25% (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT.)
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24

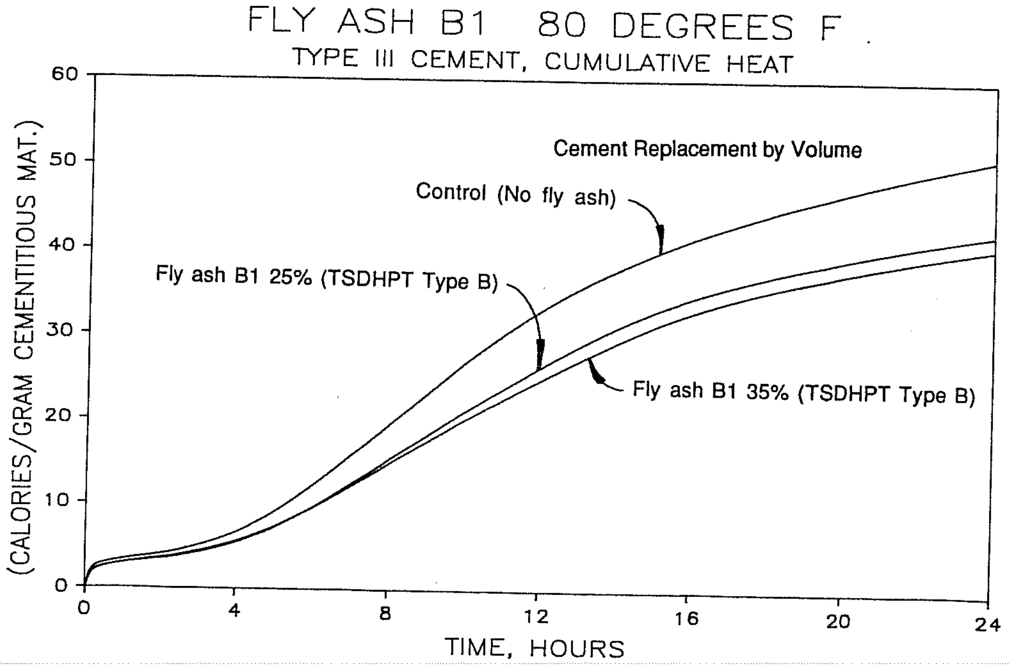
FLY ASH B2 80 DEGREES F
TYPE I–II CEMENT, CUMULATIVE HEAT



FLY ASH A1 80 DEGREES F
TYPE III CEMENT, CUMULATIVE HEAT




FLY ASH A2 80 DEGREES F
TYPE III CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash A2 20% (TSDHPT Type A)
Fly ash A2 30% (TSDHPT Type A)
(CALORIES/GRAM CEMENTITIOUS MAT.)
0
10
20
30
40
50
60
0
4
8
12
16
20
24
TIME, HOURS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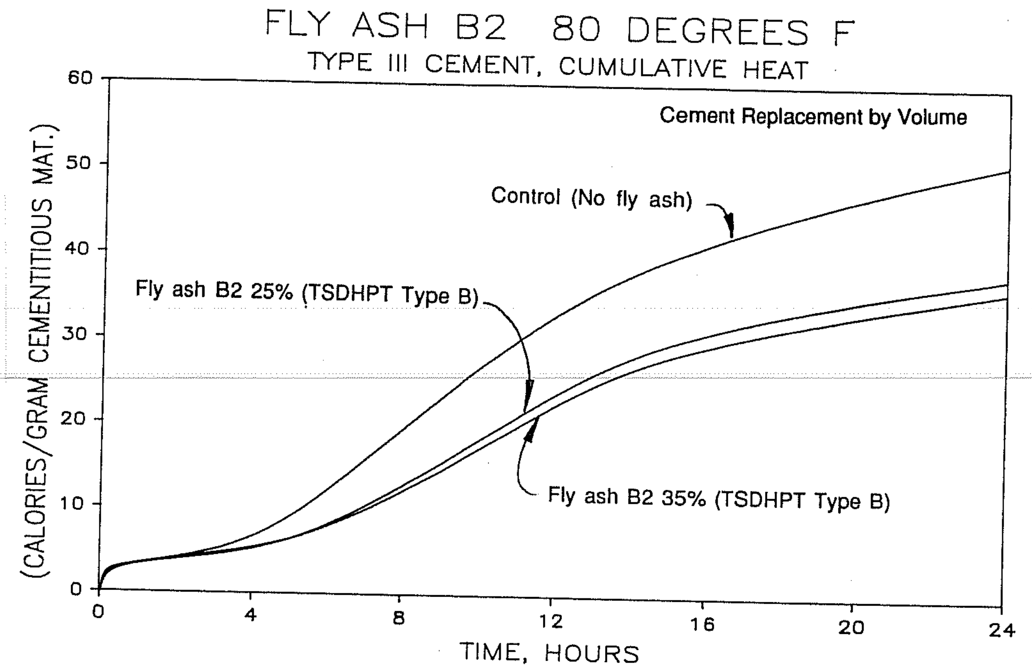
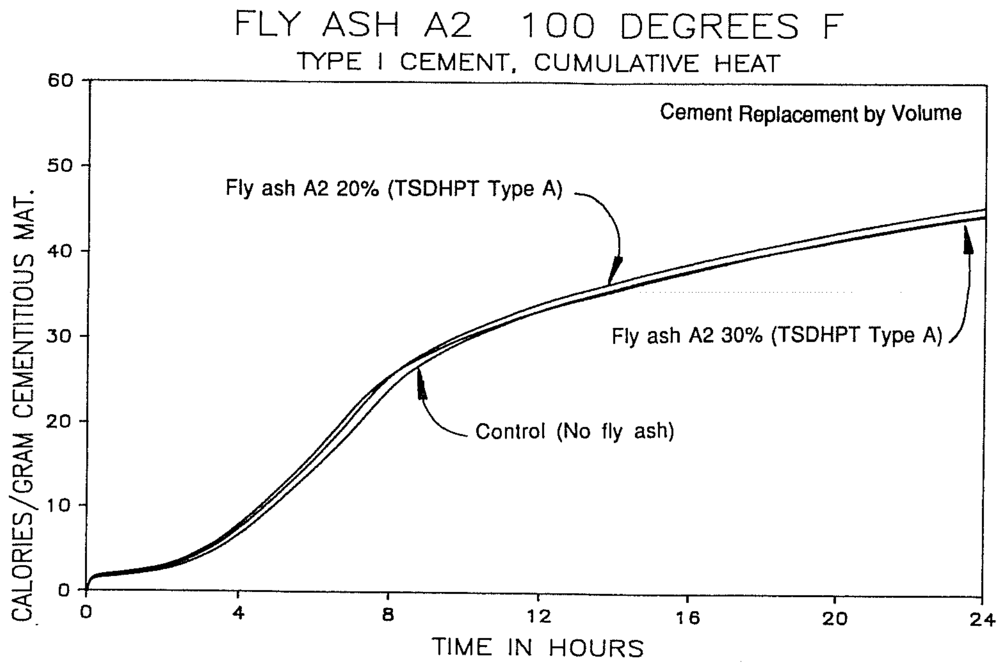
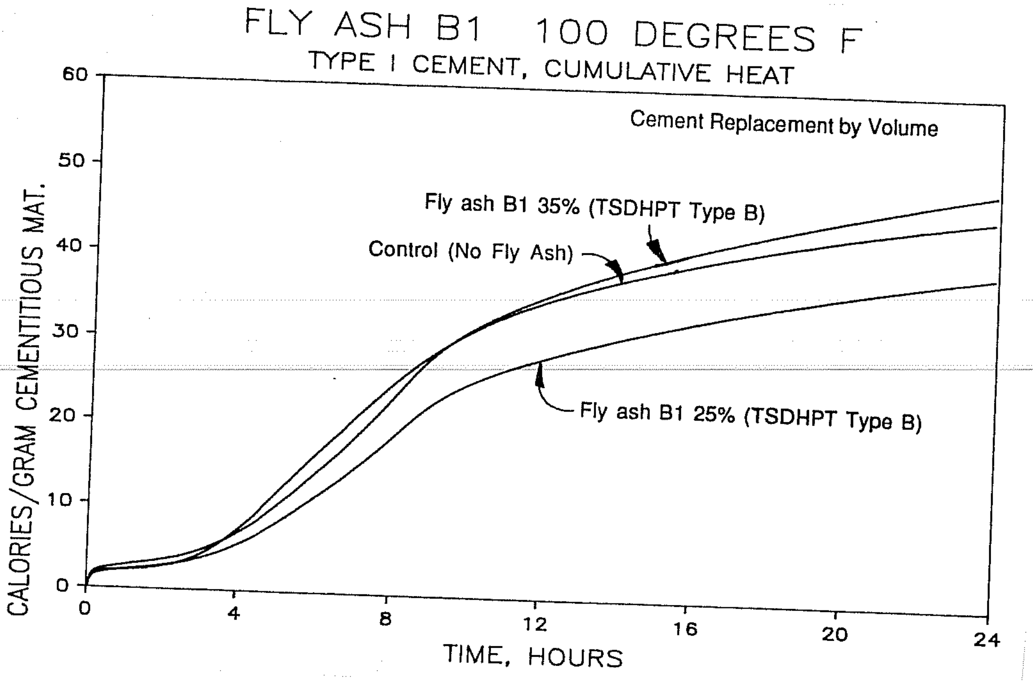
TYPE III CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash B1 25% (TSDHPT Type B)
Fly ash B1 35% (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT.)
0
10
20
30
40
50
60
0
4
8
12
16
20
24
TIME, HOURS


FLY ASH B2 80 DEGREES F
TYPE III CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash B2 25% (TSDHPT Type B)
Fly ash B2 35% (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT.)
0
10
20
30
40
50
60
0
4
8
12
16
20
24
TIME, HOURS


FLY ASH A2 100 DEGREES F
TYPE I CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Fly ash A2 20% (TSDHPT Type A)
Fly ash A2 30% (TSDHPT Type A)
Control (No fly ash)
CALORIES/GRAM CEMENTITIOUS MAT.
0
10
20
30
40
50
60
0
4
8
12
16
20
24
TIME IN HOURS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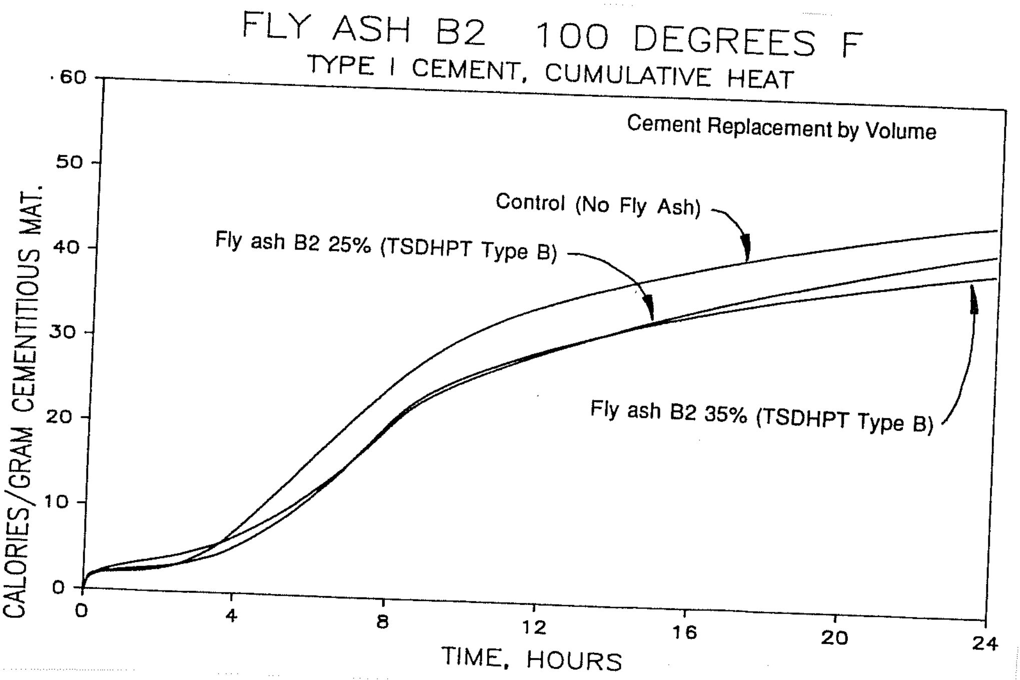
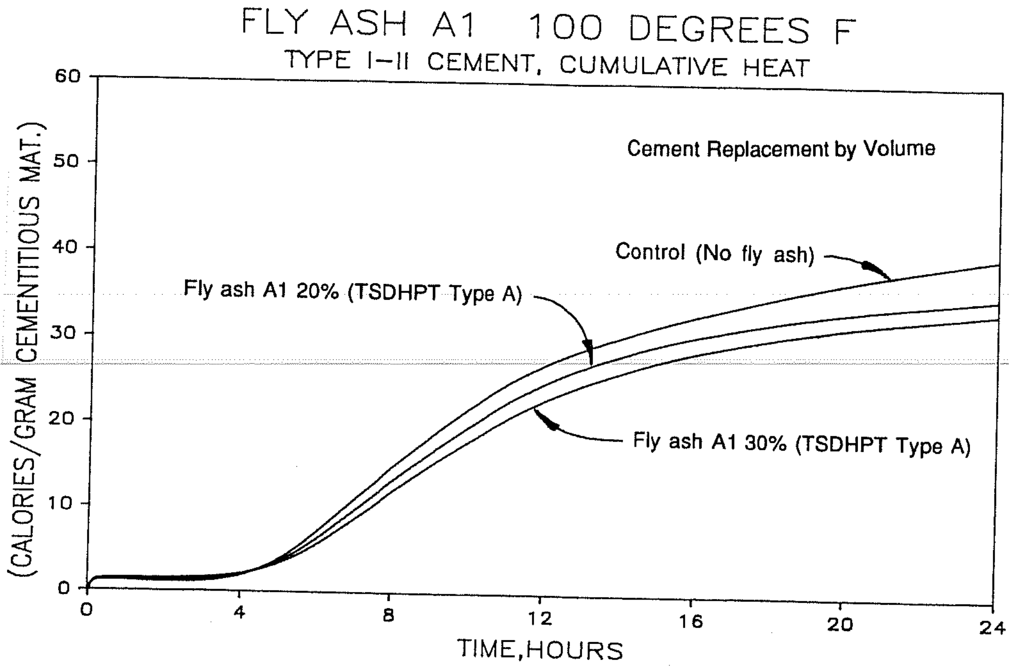
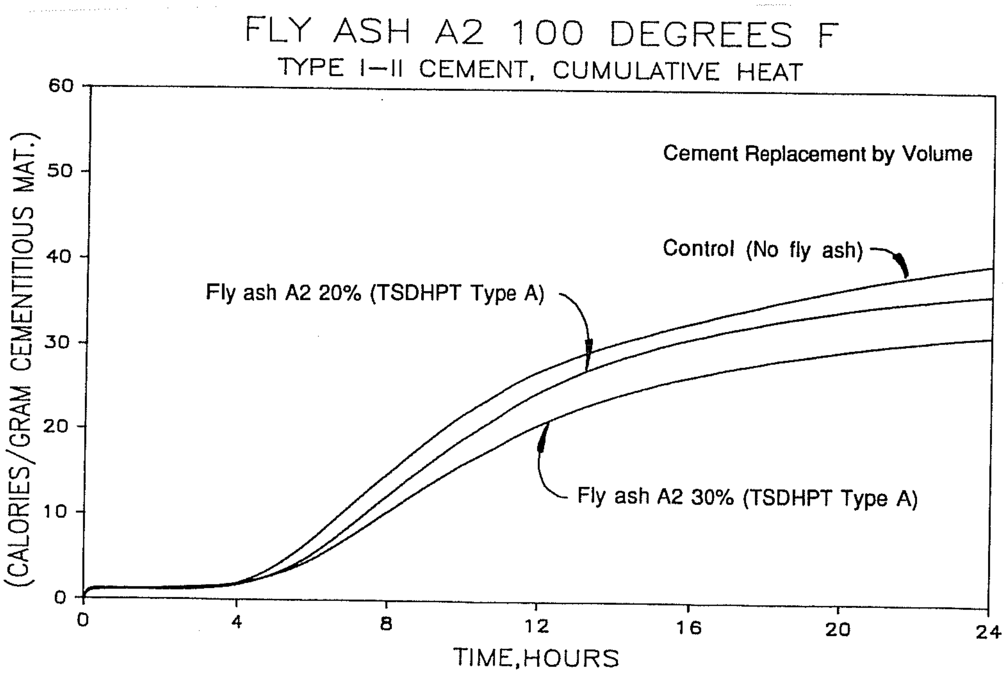
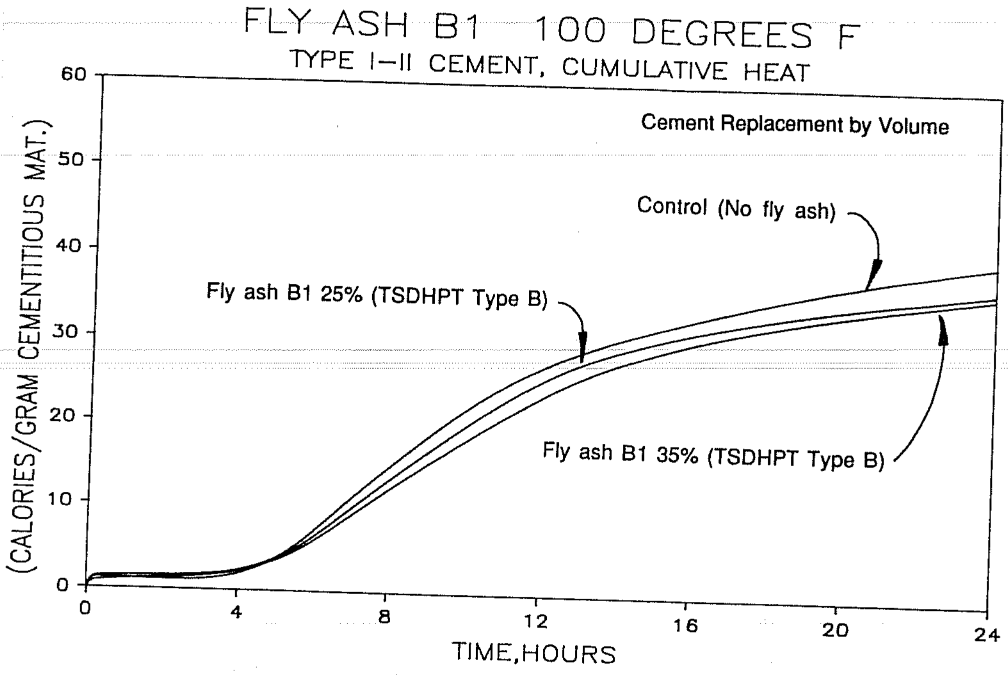
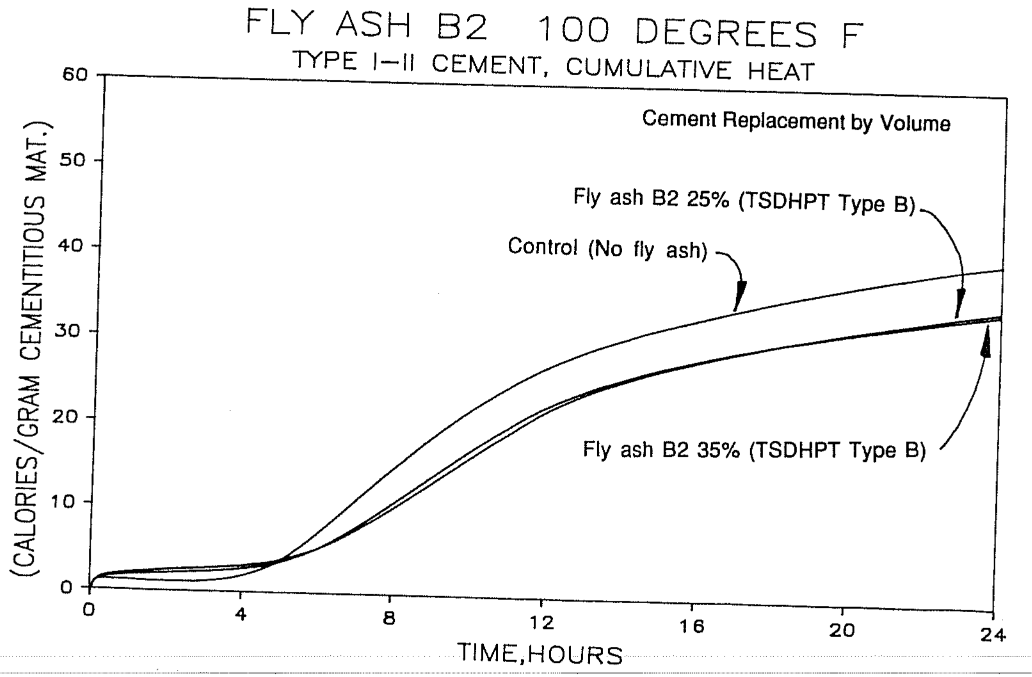
TYPE I CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Fly ash B1 35% (TSDHPT Type B)
Control (No Fly Ash)
Fly ash B1 25% (TSDHPT Type B)
CALORIES/GRAM CEMENTITIOUS MAT.
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24

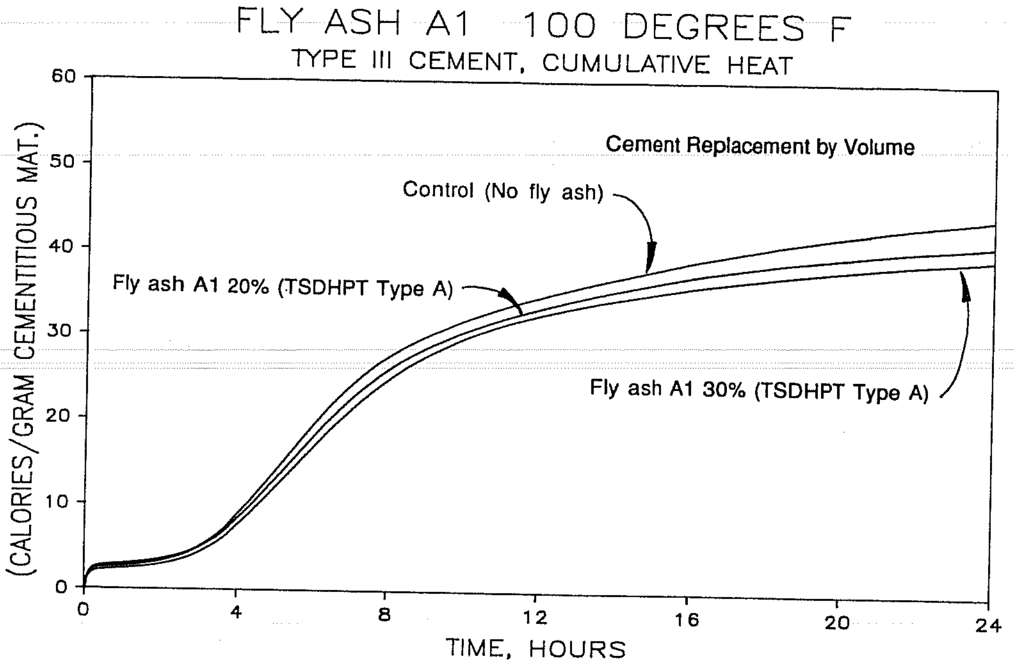

FLY ASH B2 100 DEGREES F
TYPE I CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No Fly Ash)
Fly ash B2 25% (TSDHPT Type B)
Fly ash B2 35% (TSDHPT Type B)
CALORIES/GRAM CEMENTITIOUS MAT.
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24

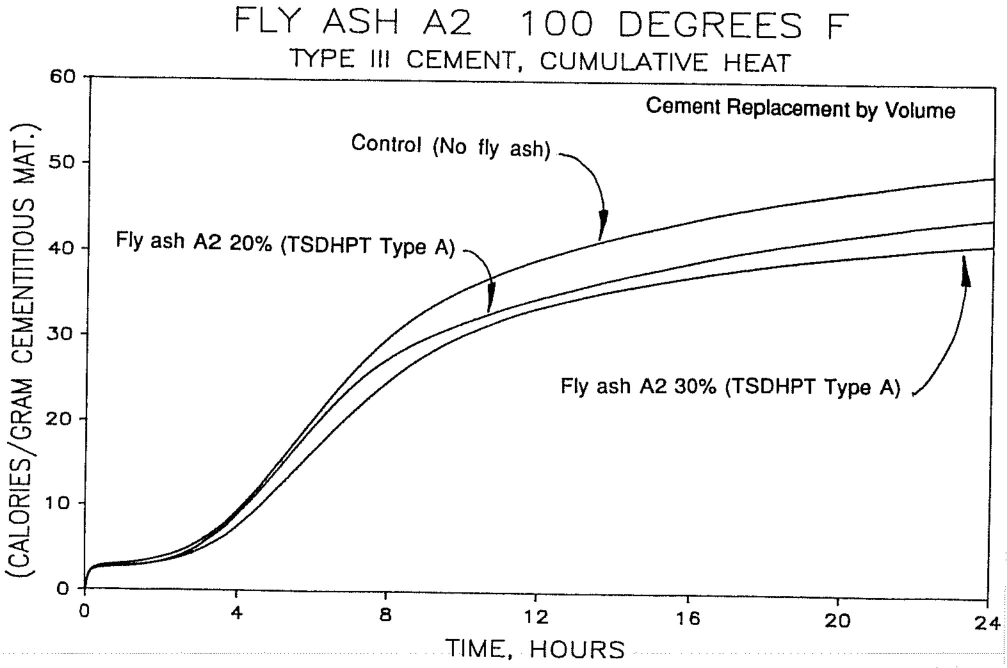

FLY ASH A1 100 DEGREES F
TYPE I–II CEMENT, CUMULATIVE HEAT
(CALORIES/GRAM CEMENTITIOUS MAT.)
60
50
40
30
20
10
0
0
4
8
12
16
20
24
TIME,HOURS
Cement Replacement by Volume
Control (No fly ash)
Fly ash A1 20% (TSDHPT Type A)
Fly ash A1 30% (TSDHPT Type A)

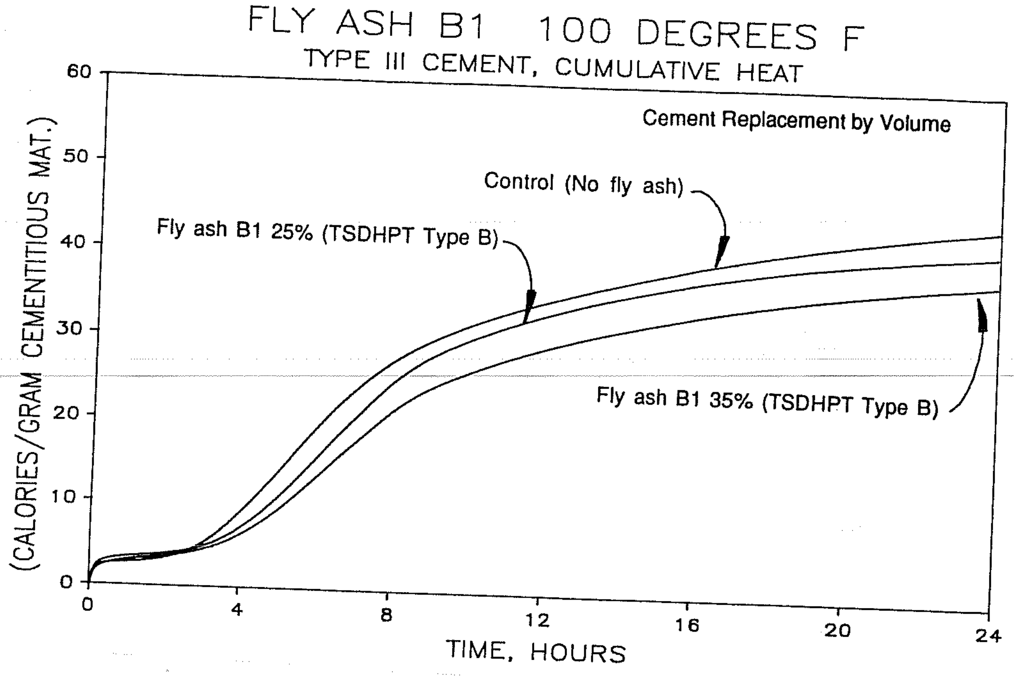

FLY ASH A2 100 DEGREES F
TYPE I–II CEMENT, CUMULATIVE HEAT
(CALORIES/GRAM CEMENTITIOUS MAT.)
60
50
40
30
20
10
0
0
4
8
12
16
20
24
TIME,HOURS
Cement Replacement by Volume
Control (No fly ash)
Fly ash A2 20% (TSDHPT Type A)
Fly ash A2 30% (TSDHPT Type A)


FLY ASH B1 100 DEGREES F
TYPE I–II CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash B1 25% (TSDHPT Type B)
Fly ash B1 35% (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT.)
0
10
20
30
40
50
60
0
4
8
12
16
20
24
TIME,HOURS


FLY ASH B2 100 DEGREES F
TYPE I–II CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Fly ash B2 25% (TSDHPT Type B)
Control (No fly ash)
Fly ash B2 35% (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT.)
0
10
20
30
40
50
60
0
4
8
12
16
20
24
TIME,HOURS


FLY ASH A1 100 DEGREES F
TYPE III CEMENT, CUMULATIVE HEAT
(CALORIES/GRAM CEMENTITIOUS MAT.)
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24
Cement Replacement by Volume
Control (No fly ash)
Fly ash A1 20% (TSDHPT Type A)
Fly ash A1 30% (TSDHPT Type A)


FLY ASH A2 100 DEGREES F
TYPE III CEMENT, CUMULATIVE HEAT
(CALORIES/GRAM CEMENTITIOUS MAT.)
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24
Cement Replacement by Volume
Control (No fly ash)
Fly ash A2 20% (TSDHPT Type A)
Fly ash A2 30% (TSDHPT Type A)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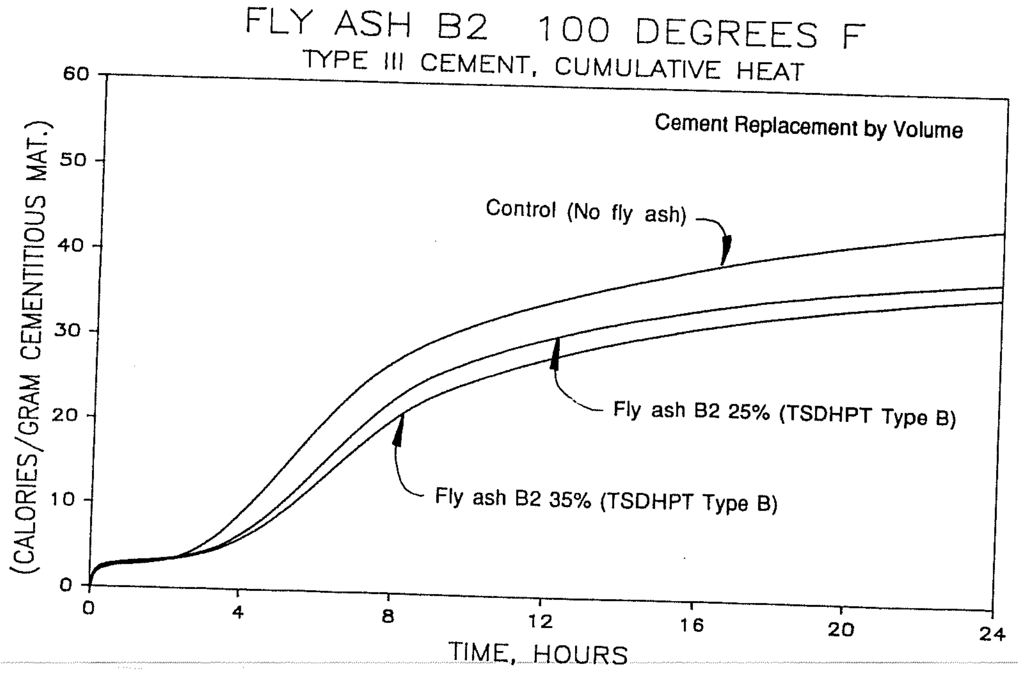
TYPE III CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash B1 25% (TSDHPT Type B)
Fly ash B1 35% (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT.)
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24


FLY ASH B2 100 DEGREES F
TYPE III CEMENT, CUMULATIVE HEAT
Cement Replacement by Volume
Control (No fly ash)
Fly ash B2 25% (TSDHPT Type B)
Fly ash B2 35% (TSDHPT Type B)
(CALORIES/GRAM CEMENTITIOUS MAT.)
0
10
20
30
40
50
60
TIME, HOURS
0
4
8
12
16
20
24

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