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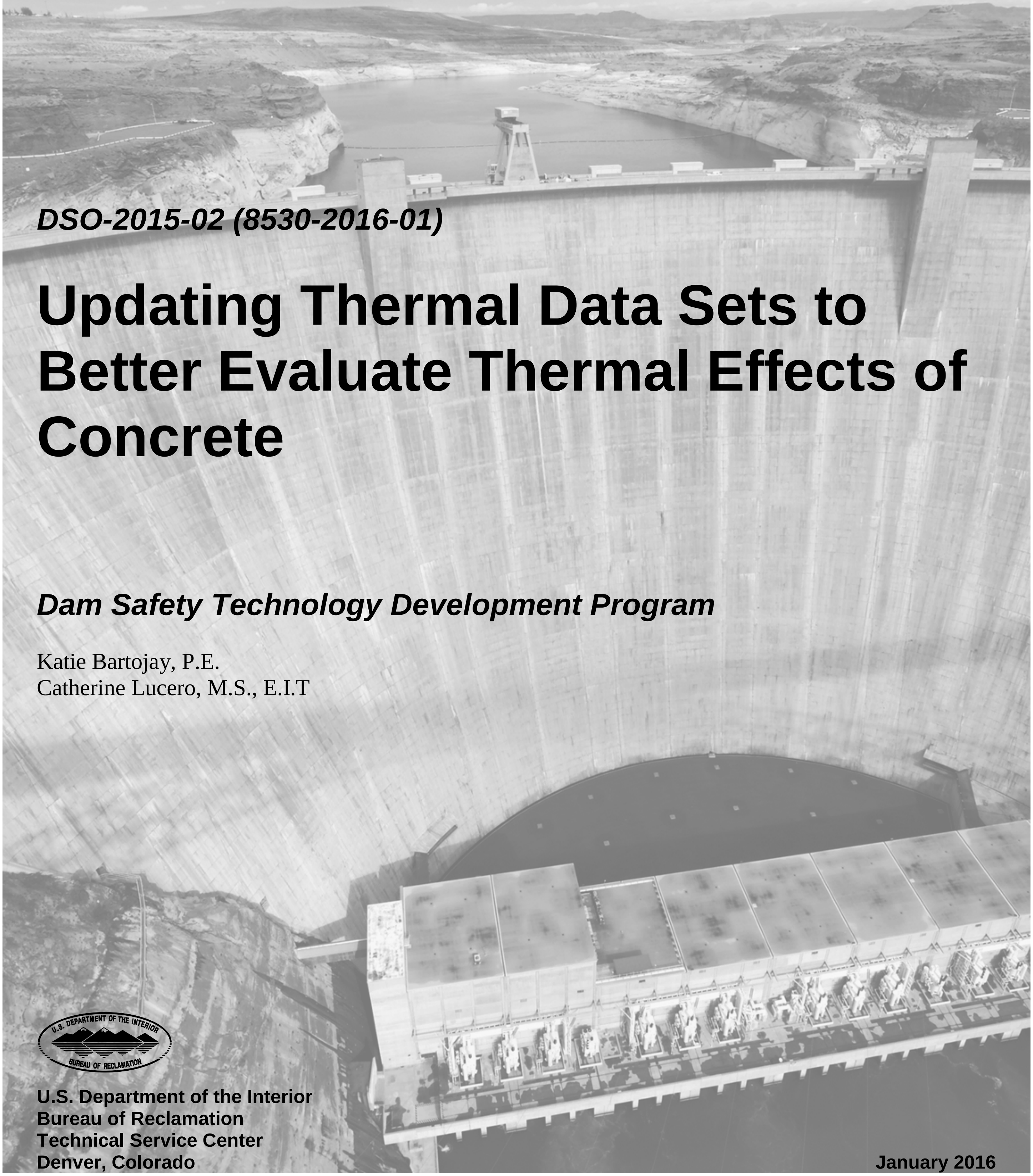

DSO-2015-02 (8530-2016-01)

Updating Thermal Data Sets to Better Evaluate Thermal Effects of Concrete

Dam Safety Technology Development Program

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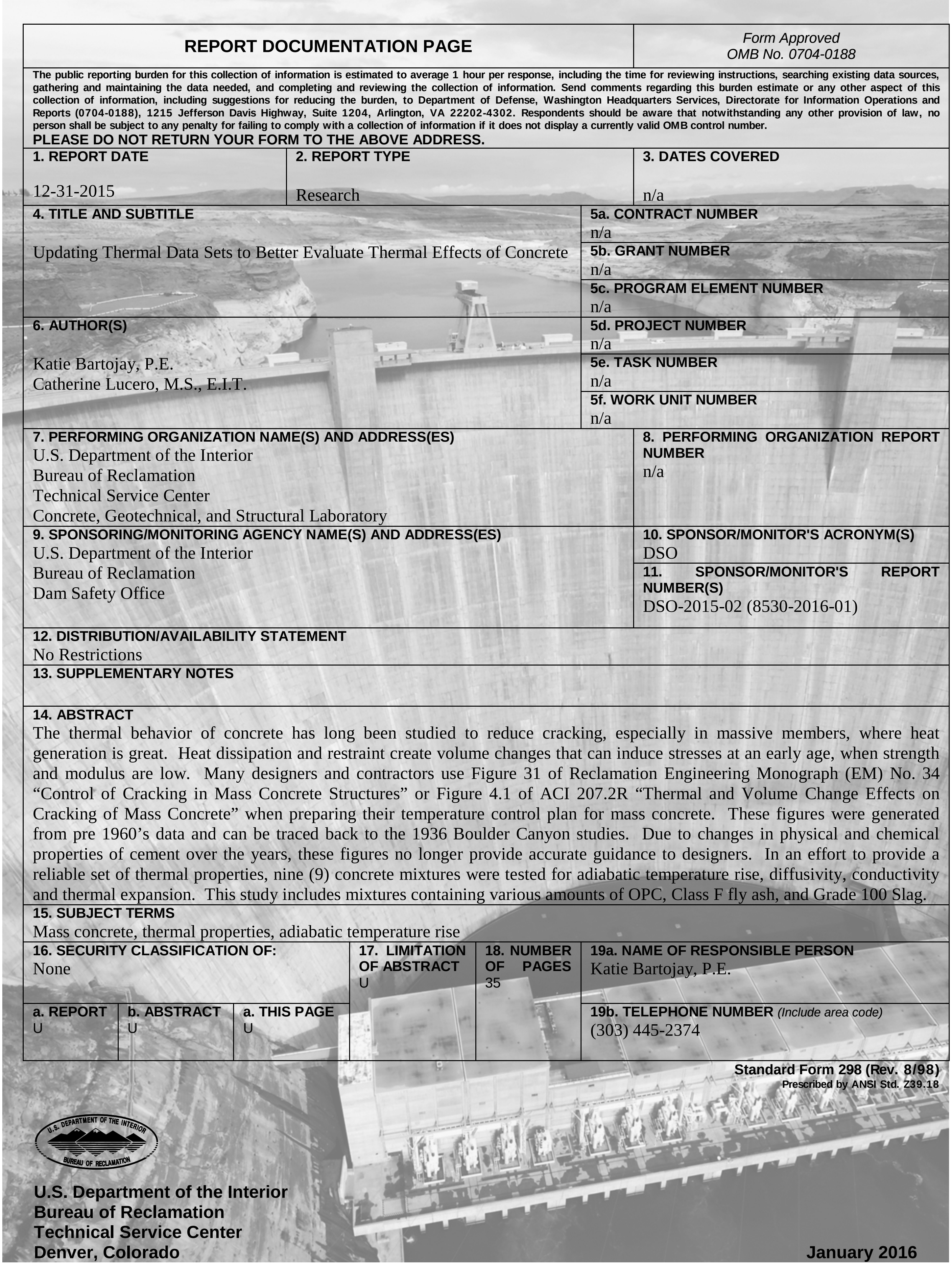
U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

January 2016



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14. ABSTRACT

The thermal behavior of concrete has long been studied to reduce cracking, especially in massive members, where heat generation is great. Heat dissipation and restraint create volume changes that can induce stresses at an early age, when strength and modulus are low. Many designers and contractors use Figure 31 of Reclamation Engineering Monograph (EM) No. 34 “Control of Cracking in Mass Concrete Structures” or Figure 4.1 of ACI 207.2R “Thermal and Volume Change Effects on Cracking of Mass Concrete” when preparing their temperature control plan for mass concrete. These figures were generated from pre 1960’s data and can be traced back to the 1936 Boulder Canyon studies. Due to changes in physical and chemical properties of cement over the years, these figures no longer provide accurate guidance to designers. In an effort to provide a reliable set of thermal properties, nine (9) concrete mixtures were tested for adiabatic temperature rise, diffusivity, conductivity and thermal expansion. This study includes mixtures containing various amounts of OPC, Class F fly ash, and Grade 100 Slag.

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prepared by

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Dam Safety Technology Development Program
Concrete, Geotechnical, and Structural Laboratory, 86-68530

DSO-2015-02 (8530-2016-01)

Updating Thermal Data Sets to Better Evaluate Thermal Effects of Concrete

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Abbreviations

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
C_2S	dicalcium cilicate
C_3A	tricalcium aluminate
C_3S	tricalcium silicate
C_4AF	tetracalcium aluminoferrite
CH	calcium hydroxide
CSH	calcium silicate hydrate
EM	Engineering Monograph
NMSA	nominal maximum size of aggregate
OPC	ordinary portland cement
PCA	Portland Cement Association
RSMC	reinforced structural mass concrete
SCM	supplementary cementitious material
w/c	water to cement ratio
w/cm	water to cementitious materials ratio

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A large quantity of cementitious materials was required to complete this research. The Concrete, Geotechnical, and Structural Laboratory would like to thank LafargeHolcim Cement for providing the cement and slag, and Salt River Materials Group for providing the Class F fly ash used in this study.

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Abstract

The thermal behavior of concrete has long been studied to reduce cracking, especially in massive members, where heat generation is great. Heat dissipation and restraint create volume changes that can induce stresses at an early age, when strength and modulus are low. Many designers and contractors use Figure 31 of Reclamation Engineering Monograph (EM) No. 34 "Control of Cracking in Mass Concrete Structures" or Figure 4.1 of ACI 207.2R "Thermal and Volume Change Effects on Cracking of Mass Concrete" when preparing their temperature control plan for mass concrete. These figures were generated from pre 1960's data and can be traced back to the 1936 Boulder Canyon studies. Due to changes in physical and chemical properties of cement over the years, these figures no longer provide accurate guidance to designers. In an effort to provide a reliable set of thermal properties, nine (9) concrete mixtures were tested for adiabatic temperature rise, diffusivity, conductivity and thermal expansion. This study includes mixtures containing various amounts of OPC, Class F fly ash, and Grade 100 Slag.

Introduction

The need to understand the thermal behavior of concrete arose with the construction of Boulder Dam in the 1930's. The Bureau of Reclamation conducted numerous tests on cement hydration and compiled the results in "Special Cements for Mass Concrete" [1]. It has been the basis of other design guides such as Reclamation Engineering Monograph (EM) No. 34 "Control of Cracking in Mass Concrete Structures" [2] and ACI 207.2R "Report on Thermal and Volume Change Effects on Cracking of Mass Concrete" [3]. There have been substantial changes in the cement industry since publication of the 1936 publication, including changes to the physical and chemical properties of cement that influence the heat of hydration.

Existing data (pre-1960) used to forecast heat generation (for cement types Type I, II, III, and IV) does not accurately represent the behavior of modern concrete mixtures including those containing supplementary cementitious materials (SCMs) and increased cementitious content from 4 to 7 or more sacks. As a result, both Reclamation and contractors rely on data that can generally underpredicts temperature rise at lower total cementitious contents and over predicts at higher total cementitious contents [4].

Cement Chemistry and Hydration Reactions

Cement hydration is an exothermic process. Many factors will influence the rate of heat generation including the chemical composition, fineness and quantity of cement, the type and amount of SCMs, and the water to cement ratio [5].

There are four main components of cement that contribute to the heat generation: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF). The majority of cement is composed of C_3S by mass. Type II and V cements limit the amount of C_3A to increase sulfate resistance. A decrease in C_3A will decrease the heat of hydration because of its large contribution to enthalpy as seen in Table 1. Type III cement may have more C_3S, but the early strength development and heat evolution is typically from the increased fineness. The theoretical ultimate heat of hydration can be calculated by multiplying the enthalpy of each phase by the mass fraction of each phase found on the cement mill certificate. For example, the Type I/II cement used in this study has a theoretical ultimate heat of hydration of 472.8 J/g or 112.9 cal/g.

Table 1. Enthalpy of complete hydration for major phases of cement. From Bentz et. al [4].

Phase	Enthalpy (J/g)	Enthalpy (cal/g)
C_3S	517	123.5
C_2S	262	62.6
C_3A	1144	273.3
C_4AF	725	173.2

Supplementary cementitious materials (SCMs) are primarily used in mass concrete to lower the heat output of concrete. There are two ways that SCMs reduce the heat of hydration: by inherently having a lower heat of hydration compared to cement and by diluting the amount of cement per cubic yard in the mixture. SCMs are not always inherently hydraulic like cement. Instead of reacting with water, the silica in SCMs react with calcium hydroxide (CH), which is a reaction product of the silicate phases of cement, to form calcium silicate hydrate (CSH). Since this reaction occurs later, the contribution to heat and strength gain also occurs later. Heat of hydration for pozzolanic cements range from 315 to 420 J/g (75.2-100.3 cal/g) [7].

Over the last century, the construction industry has shifted focus to completing projects quickly, and rapid strength development is desirable in most concrete applications. Therefore, the cement industry has followed suit and ceased production of Type IV (low heat) cement in the US due to low demand. Cement fineness has increased over the years to increase the rate of hydration and achieve high early strength.

Temperature Rise in Mass Concrete

Mass concrete is defined in ACI 207 as: "any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change, to minimize cracking." There is no limit to the largest or smallest size dimension of the concrete section to be considered "mass concrete." However, as mass concrete sections increase in section size, or cementitious contents become quite high, thermal cracking can become a problem because the thermal volume contraction of the exterior concrete is restrained by the high temperature expansion of interior concrete. When thermal stresses exceed the tensile strain capacity of the concrete at any given time thermal cracking occurs. To lower internal stresses, the temperature gradients for un-reinforced mass concrete sections are normally limited to about 35 °F. Thermal shock is avoided by preventing rapid surface temperature drops.

The internal temperature of mass concrete is traditionally controlled by (in order of precedence):

1. limiting the total cementitious materials content of the mixture through use of the largest practicable maximum size aggregate

2. using the highest possible percentage of pozzolan
3. lowering the initial placing temperature of the concrete
4. embedding cooling coils in the concrete to dissipate the heat

In some cases, the test age for the design strength is extended from 28 to 56 or 90 days and even 1 year age (using traditional fog-cured test specimens). By extending the design strength age requirement, designers can take advantage of the slow strength development of concrete containing pozzolans and reduce the initial heat generation that can lead to thermal cracking. Large-sized reinforced structures in power and pumping plants have historically also controlled internal temperature rise by the same traditional means as mass concrete dams, such as lowering the placing temperature, reducing the cementitious contents, and using 1.5- to 3-inch NMSA structural concrete.

Reinforced structural mass concrete (RSMC) presents a more difficult problem for controlling the internal temperature. Higher design compressive strengths lead to an increase in the cementitious content of the mixture and early strength needs can limit the pozzolan content of the mixture to less than 25 percent by mass of total cementitious materials. Reinforcing steel congestion and pumps used to transport the concrete prevent use of larger NMSA. Unlike traditional mass concrete projects where the volume of concrete predicates the erection of an onsite batch plant, concrete for many RSMC projects are supplied by local ready-mix concrete plants that have smaller aggregates sizes available and limited ability to control the temperature of concrete as batched. In addition, reinforcing steel and formwork make it difficult to embed cooling pipes. High strength or high performance concretes only exacerbate the problems of thermal heat generation due to even higher cementitious contents.

The rapid construction trend has also moved the industry away from seasonal construction schedules where summer or winter placements were limited or prohibited.

Current Guidance for Evaluating Thermal Effects

There are several common methods designers use to estimate temperature rise of concrete. The most common two are established by ACI and PCA. There are several other methods, but many designers use the following two methods for their simplicity. The temperatures calculated from these methods are used to analyze the thermal stresses anticipated in very massive structures or to establish temperature control plans to be used during construction, so the accuracy of the predictions is important.

ACI Manual of Concrete Practice

Designers rely on ACI 207.2R-07, “Report on Thermal and Volume Change Effects on Cracking of Mass Concrete”, for guidance in estimating temperature rise of concrete [3]. The curves are based on 4-sack concrete mixtures from the

1936 Boulder Canyon studies (Appendix C). The same data is presented in Reclamation's Engineering Monograph 34 (Appendix D).

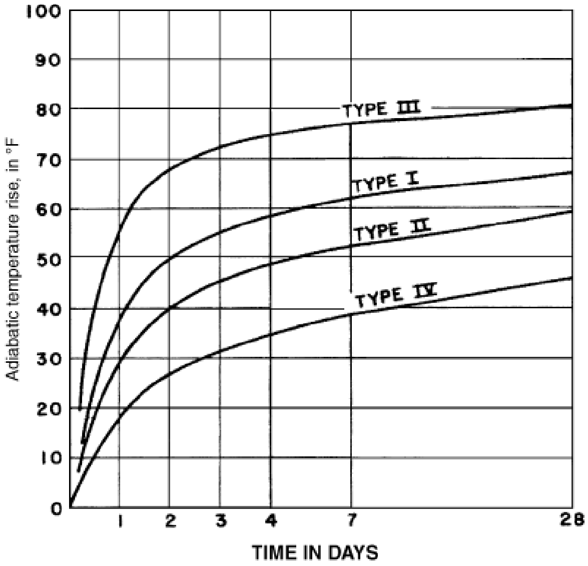


Figure 1. Temperature rise of mass concrete containing 376 lb/yd^3 (223 kg/m^3) of various types of cement produced before 1960. From ACI 207.2R-9 [6].

In its most basic form, the figure is intended as a baseline to estimate the temperature rise of concrete based on the type and amount of cement. The document states:

"Because the cement is the active heat producer in a concrete mixture, the temperature rise of concrete with cement contents differing from 376 lb/yd^3 (223 kg/m^3) can be estimated closely by multiplying the values shown on the curves by a factor representing the proportion of cement."

Therefore, in theory, a first approach would be to take the 28 (or 7, 14, etc.) day temperature rise for the cement type used from Figure 1, divide by 376 lb/yd^3, then multiply by the amount of cement per cubic yard for the mixture in question. See Appendix E for examples of using the ACI temperature rise method.

If no specific thermal performance data is available, Equation 1 can be used to estimate the adiabatic temperature rise (H_g) in °F.

$$H_g(°F) = \frac{1.8 \cdot h_g \cdot w_c}{27 \cdot C_p \cdot \gamma_c} \qquad \textit{Equation 1}$$

where 1.8 is the conversion factor from Celsius to Fahrenheit, 27 is the conversion factor from yd^3 to ft^3, h_g is the 28-day heat of hydration of the cement in cal/g, w_c is the weight of cement in pounds per cubic yard of concrete, C_p is the specific heat of concrete in cal/g·°C, and γ_c is the unit weight of concrete in lb/ft^3.

The specific heat of concrete can be assumed to be 0.22 cal/g·°C or it can be measured. The heat of hydration of cement can be measured or estimated from the provided table in ACI 207.2R-07 which has been replicated in Table 2. It should be noted that there are no corrections for the use of SCMs although the document states that it can be assumed that a pozzolan will only produce about half as much heat as the cement it replaces. If SCMs are used, the heat of hydration would have to be measured in order for Equation 1 to be accurate.

Table 2. Fineness and 28-day heat of hydration for various cement types.

Cement Type	ASTM C115 Wagner Fineness (cm^2/g)	ASTM C204 Blaine Fineness (cm^2/g)[1]	28-day heat of hydration (cal/g)
I	1790	3196	87
II	1890	3375	76
III	2030	3625	105
IV	1910	3411	60

[1] Calculated value [7] [8]

It is well established that modern cements are finer than those listed in Table 2 [10]. ACI 207.2R establishes some guidance on correcting for fineness by using Figure 4.2 and Example 8 (Section 4.7), however the procedure is not explicitly clear. The first source of error comes from the fact that the fineness values listed in Figures 4.1 and 4.2 are from ASTM C115 (aka Wagner Fineness [10]) and modern cements are specified with ASTM C204 (aka Blaine Fineness [11]). Literature cites C204 values to be approximately double that of C115 values or more specifically, as 1.78 times C115 values [8] [9]. Figure 4.2 in ACI 207.2R-07 (shown in Figure 2) shows the heat generated as a percentage of 28 day heat for different values of cement fineness. Essentially, the figure shows that the finer the cement, the more rapidly the heat evolves to reach the 28 day value. This figure does not give 28-day heat of hydration values for different fineness values, but they can be determined with ASTM C186 and are sometimes listed on cement mill certificates.

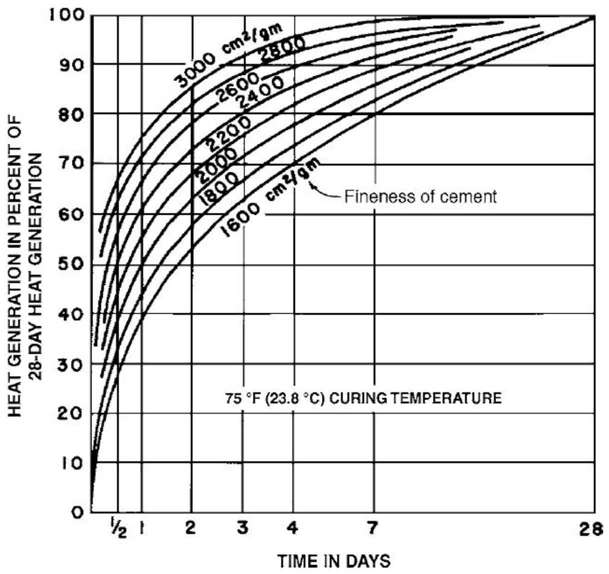


Figure 2. Rate of heat generation as affected by Wagner fineness of cement. From ACI 207.2R-07 [6].

Portland Cement Association

The Portland Cement Association (PCA) published a document as a practical guide for predicting and managing concrete temperatures [12]. The most simplistic method for estimating total temperature rise is expressed in Equation 2 [13]. This equation assumes Type I or Type II cement and does not have any factors to apply to correct for different cement types.

$$T(^\circ F) = 0.16 \cdot \sum c_i W_i$$

Equation 2

where c_i is the equivalent cement factor and W_i is the weight (lb/yd^3) for each cementitious material or pozzolan. A list of equivalent cement factors is given in Table 3.

Table 3. Equivalent cement factors for common SCMs [11].

Material	Equivalent Cement Factor (unitless)
Cement	1.0
Fly Ash (Class F)	0.5
Fly Ash (Class C)	0.8
Silica Fume or Metakaolin	1.25
Slag (50% cement replacement)	0.9
Slag (70% cement replacement)	0.8

The factor of 0.16 used in Equation 2 is a rise in temperature (in degrees Fahrenheit) per pound of cement. Some earlier documents published by PCA use a factor of 0.14 [12], however 0.16 was used in a recent 2014 publication and appears to be more widely accepted [13]. This value is loosely based on the rule of thumb that every 100 lbs of cement will increase the temperature by 10 to 15 °F [14]. According to PCA's Design and Control of Concrete Mixtures, the equation is valid for mixtures containing 500 to 1000 lb/yd^3 of cement [14]. See Appendix E for examples of using the PCA temperature rise method.

Research Objective

The objective of this research is to present ACI and the concrete industry with new adiabatic temperature rise curves for concrete. Currently, adiabatic heat rise curves provided via ACI 207.2R and Reclamation EM 34 do not accurately represent the thermal behavior of modern concrete mixtures as documented in DSO-2012-02 [4]. Analytical methods provided by ACI and PCA result in a figure that is close to the anticipated temperature rise, but generally under predicts temperature rise at lower total cementitious contents and over predicts at higher total cementitious contents. Lack of accuracy provided by the outdated adiabatic concrete temperature curves can cause a greater potential for thermally induced cracking in concrete.

The objective of this research is to develop heat rise curves for modern mixtures (i.e. higher cementitious content, supplementary cementitious materials, smaller aggregate size, etc.) to be used as guidance for Reclamation and other industry designers. Additionally, a new simple procedure for estimating temperature rise will be introduced.

Laboratory Study

Nine concrete mixtures were prepared and tested in the laboratory. All concrete contained Type I/II cement with the properties listed in Table 4. Class F fly ash and Grade 100 slag were used as SCMs. See Appendix A for mill certificates of all materials used.

Table 4. Chemical and physical properties of cementitious materials.

	Type I/II Cement (%)	Class F Fly Ash (%)	Gr. 100 Slag (%)
Chemical Properties			
SiO_2	19.7	57.78	
Al_2O_3	4.5	22.82	
Fe_2O_3	3.2	7.35	
CaO	64.3	3.56	
MgO	2.6	1.31	
SO_3	3.6	0.29	0.02
Loss on Ignition	2.6	0.29	
C_3S	62	--	
C_2S	7	--	
C_3A	6	--	
C_4AF	9	--	
Physical Properties			
Air Content (%)	7		3.5
Blaine Fineness (cm^2/g)	3830		620

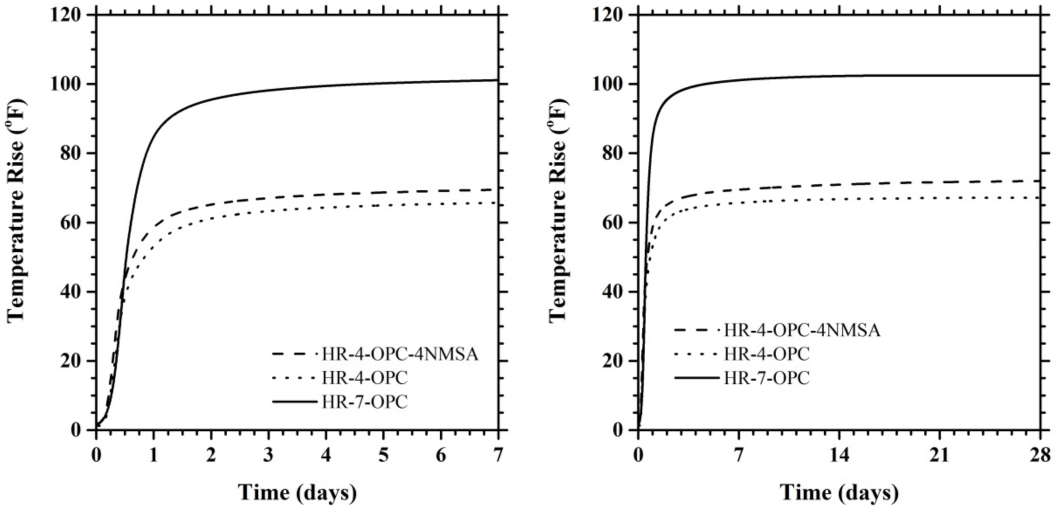
Mixture proportions are summarized in Table 5. The first mixture (HR-4-OPC-4NMSA) was derived from the 1936 Boulder Canyon temperature rise study that was later incorperated into ACI 207.2R [1] (see Appendix C for the original mixture proportions). The remaining mixtures in the study contained a ¾” NMSA. The 7-sack mixtures were selected to represent those more commonly found in RSMC structures. In addition to measuring the adiabatic temperature rise, the concrete was tested for specific heat, diffusivity, conductivity, and thermal expansion.

Table 5. Summary of mixture proportions

Mixture ID	Cement (lb/yd^3)	Fly Ash (lb/yd^3)	Slag (lb/yd^3)	Sand (lb/yd^3)	Coarse Aggregate (lb/yd^3)	Water (lb/yd^3)	w/cm
HR-4-OPC-4NMSA	376			921	2651	205	0.55
HR-4-OPC	384			1180	2300	224	0.58
HR-7-OPC	671			1366	1750	260	0.39
HR-7-OPC-0.58	671			1048	1750	389	0.58
HR-7-Slag50	329		329	1365	1750	266	0.40
HR-7-Slag70	198		462	1654	1750	266	0.40
HR-7-FA25	494	165		1268	1775	280	0.42
HR-7-FA50	329	329		1252	1750	274	0.42
HR-7-FA75	165	494		1258	1700	260	0.39

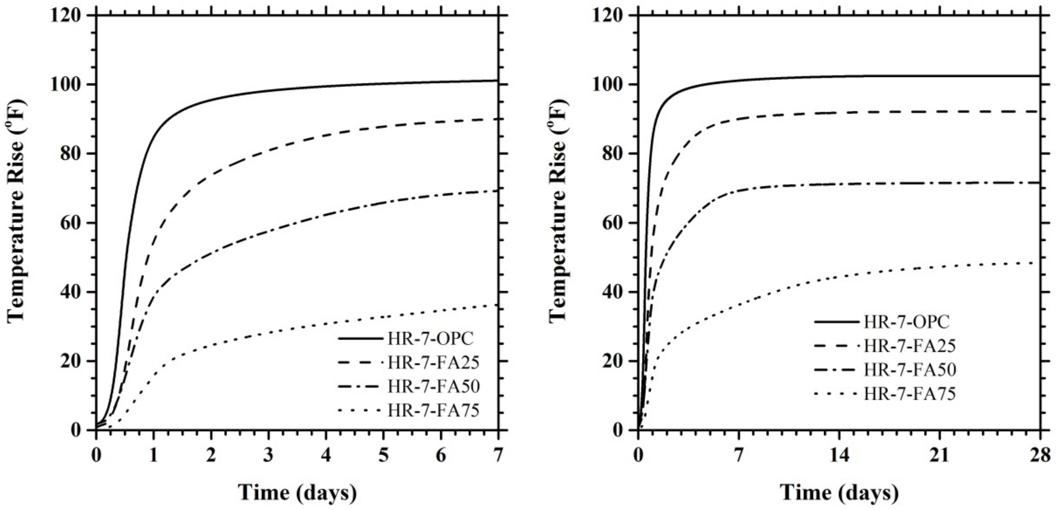
Adiabatic Temperature Rise

The adiabatic temperature rise of nine concrete mixtures was tested in the laboratory in accordance with USBR 4911, *Temperature Rise of Concrete* [15]. In mass concrete placements, there is very little heat dissipation; therefore, adiabatic temperature rise testing is the most accurate laboratory measurement for determining the maximum temperature in the center of the placement in the field. The 7-day and 28-day temperature rise results are presented in Figure 3, Figure 4, and Figure 5. Individual results for each mixture are included in Appendix B.



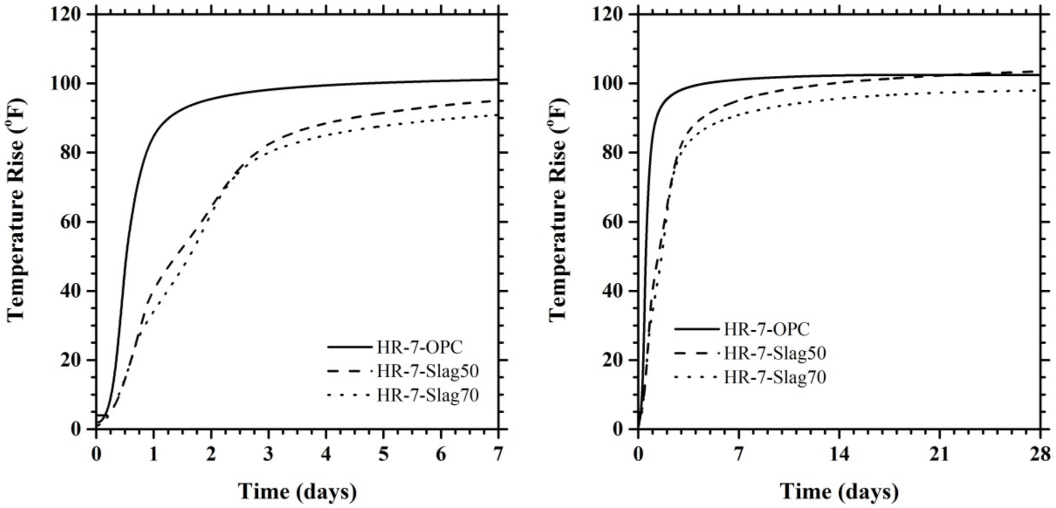
(a) **(b)**

Figure 3. a) 7-day and b) 28-day adiabatic temperature rise of mixtures containing 100 % Portland cement.



(a) (b)

Figure 4. a) 7-day and b) 28-day adiabatic temperature rise of mixtures containing Class F Fly Ash.



(a) (b)

Figure 5. a) 7-day and b) 28-day adiabatic temperature rise of mixtures containing Grade 100 Slag.

In order to check the dependence of temperature rise on the w/c, an additional 7-sack mixture was designed with a high w/c of 0.58, using the same aggregate as the 4-sack mixture. The test was run for 7 days before it was terminated since results closely matched the 7-sack mixture with a lower w/c of 0.39. The results are shown in Figure 6 below.

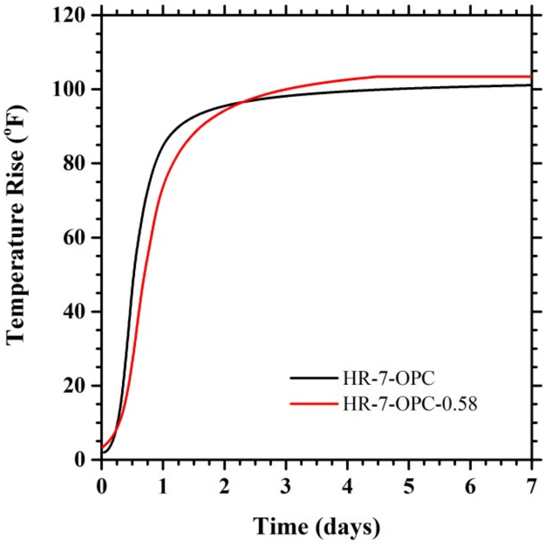


Figure 6. Influence of w/c on adiabatic temperature rise for 7 days.

Thermal Properties

Thermal properties of concrete are highly dependent on aggregate type and moisture condition [16]. All of the concrete with ¾” NMSA contained St. Vrain River alluvium aggregate which consisted of primarily quartzite (42.7%) and granite (30.0%) with small (less than 10 %) amounts of sandstone, chert, and cherty volcanic rocks. The 4” NMSA concrete mix (HR-4-OPC-4NMSA) contained crushed aggregate that was predominantly granite (72%). All concrete was tested at (or very near) saturation. As shown in Table 6, the measured properties are generally consistent with recommendations made by ACI 207.2R-07 [3].

Specific Heat

Specific heat is the amount of heat required to raise the temperature of a unit mass of material one degree [8]. Testing was performed in accordance with USBR 4907, “Specific Heat of Aggregates, Concrete, and Other Materials” [15]. An 8- by 16-inch cylindrical specimen was cast with a 1.5-inch center hole extending the length of the specimen. The specimen was placed inside a calorimeter for testing over a temperature range of 35°F to 135°F. The specific heat at 50, 100 and 150 °F for each concrete mixture is shown in Figure 7.

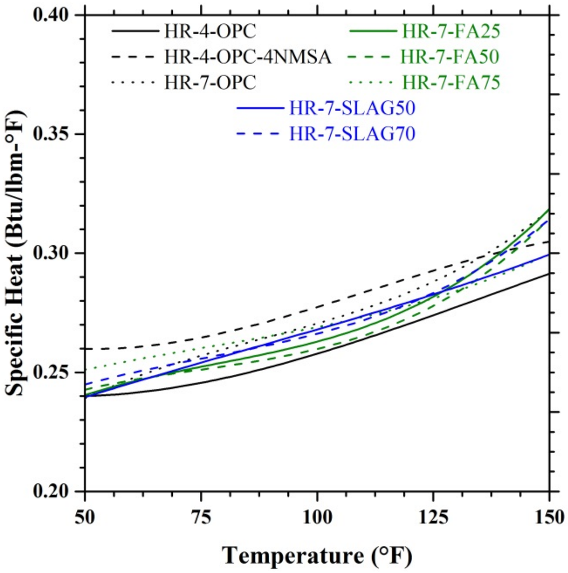


Figure 7. (Measured) Specific heat of concrete at 28 days age.

Thermal Diffusivity

Thermal diffusivity measures the rate at which temperature changes take place in the concrete and is defined as an index of the facility with which a material will undergo temperature change [16].

Testing was performed in accordance with USBR 4909, “Thermal Diffusivity of Concrete” [15]. Three 6- by 12-inch cylinders are cast with a thermocouple placed at the center. The specimens were fog cured for 28 days. The three specimens were then tested over three temperature ranges of 35°F to 75°F, 75°F to 115°F, and 115°F to 155°F. The amount of free water in concrete is a major factor influencing the measured diffusivity [16]. The concrete sample was submerged while testing so the values obtained are higher than concrete at a lower relative humidity or dry.

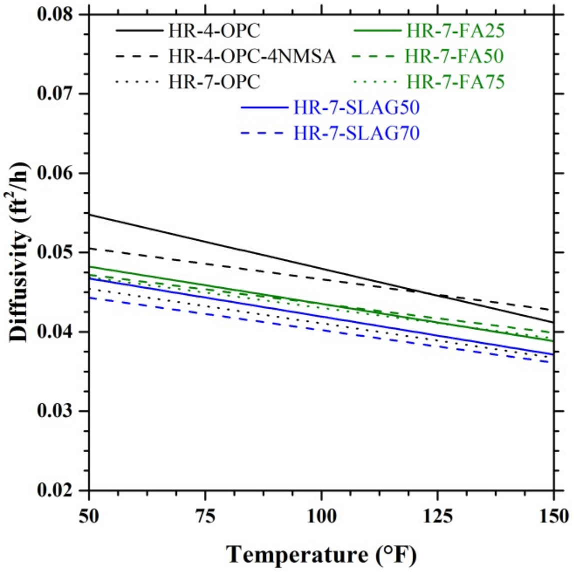


Figure 8. (Measured) Diffusivity of concrete at 28-days age.

Thermal Conductivity

Conductivity is the rate at which heat is transmitted through a unit material. Thermal conductivity is calculated from the specific heat (*C*), diffusivity (h^2), and concrete density (ρ). The coefficient of thermal conductivity (*K*) represents the uniform flow of heat though a thickness of material when subjected to a unit temperature difference between two faces.

$$K = C\rho h^2$$ *Equation 3*

Mixtures containing fly ash have a lower density compared to OPC concrete and mixtures with slag. This causes the conductivity to be lower.

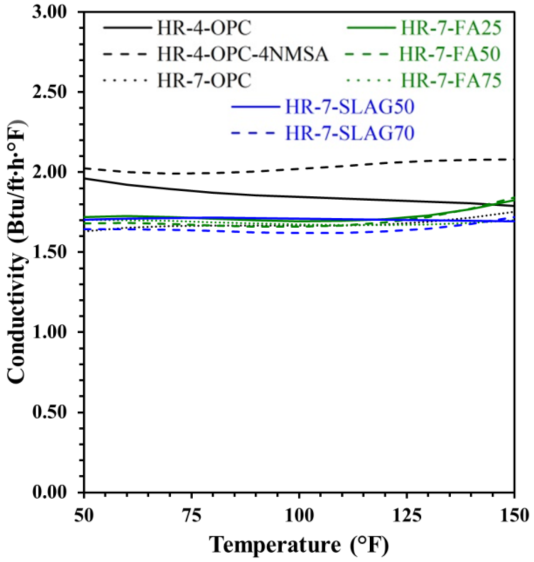


Figure 9. (Calculated) Conductivity of concrete at 28-days age.

Coefficient of Linear Thermal Expansion

The thermal coefficient of linear expansion indicates the rate of the change in a unit length of a material per degree of temperature change. Typical values for concrete range from 5 to 7 millionths/°F. Coarse aggregate type will have a significant effect on the coefficient of thermal expansion since it occupies the bulk of the concrete by volume.

Testing was performed on saturated specimens in accordance with USBR 4910, “Coefficient of Linear Thermal Expansion of Concrete”. 4- by 3- by 14- inch prisms were cast and fog cured for 28 days. Six 2- by 2- by 4- inch specimens were cut from the prism. The six specimens were tested over a temperature range of 35°F to 150°F. The moisture content of the concrete influences the measured thermal expansion, so the samples were kept in a 100% humidity fog room and submerged in water prior to testing to maintain saturation.

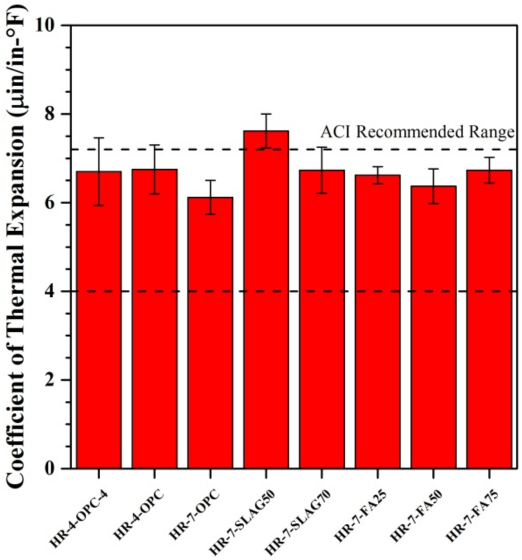


Figure 10. (Measured) Coefficients of thermal expansion of concrete at 28-days age.

Table 6. Summary of thermal properties, highlighted values are outside the range of recommended values from ACI

Thermal Property	Concrete Temperature (°F)	DS-HR-4-OPC-4NMSA	DS-HR-4-OPC	DS-HR-7-OPC	DS-HR-7-Slag50	DS-HR-7-Slag70	DS-HR-7-FA25	DS-HR-7-FA50	DS-HR-7-FA75	Recommended range of values (From ACI 207.2R)[1]
Density (lb/ft^3)	--	153.9	149.2	150.3	152.3	151.4	148.6	146.8	144.7	--
Diffusivity (ft^2/h)	50	0.051	0.055	0.045	0.047	0.044	0.048	0.047	0.047	0.043 - 0.058
	100	0.047	0.048	0.041	0.042	0.040	0.044	0.044	0.043	
	150	0.043	0.041	0.037	0.037	0.036	0.039	0.040	0.039	
Specific Heat (Btu/lbm·°F)	50	0.261	0.240	0.239	0.238	0.245	0.240	0.243	0.254	0.20-0.25
	100	0.282	0.258	0.271	0.264	0.266	0.263	0.260	0.279	
	150	0.317	0.292	0.318	0.290	0.314	0.319	0.315	0.324	
Conductivity (Btu/ft·h·°F)	50	2.03	1.96	1.63	1.69	1.64	1.72	1.68	1.72	1.54 - 2.00
	100	2.03	1.85	1.67	1.69	1.62	1.70	1.66	1.74	
	150	2.09	1.79	1.76	1.64	1.72	1.84	1.84	1.84	
Coefficient of Thermal Expansion (µin/in·°F)	--	6.70 ± 0.76	6.75 ± 0.55	6.12 ± 0.38	7.62 ± 0.38	6.73 ± 0.52	6.62 ± 0.19	6.37 ± 0.39	6.43 ± 0.29	4.0 - 7.2

[1] Values represent range of recommended values for quartzite and granite

Discussion of Laboratory Results

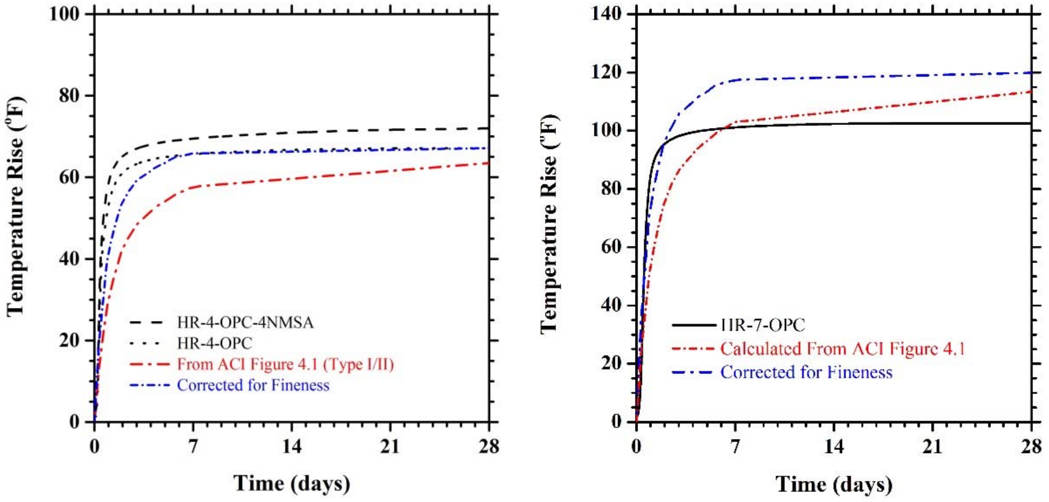
Adiabatic Temperature Rise

The mixtures with a low cement content were designed to be directly comparable with the mixtures used in the Boulder Canyon studies. Figure 11a shows the two 4-sack mixtures (in black) compared directly to the figure found in ACI 207.2R-07 (in red). If taken at face value, data from ACI Figure 4.1 will cause designers to underestimate the temperature rise.

Obviously, modern cements differ from those used in the 1930’s, especially in their fineness. The rate of heat evolution will increase with an increase in cement fineness. According to the current guidance provided by ACI listed in Table 2, the average Blaine fineness for a Type I/II cement is 3290 cm^2/g whereas the fineness of the cement used in this study is 3830 cm^2/g. When corrected for fineness (from Figure 4.2 of ACI 207.2R-9), estimated temperature rise is very close to the measured values as shown in Figure 11a. In order to accurately correct for cement fineness, the 28-day heat of hydration must be known or measured for the finer cement. Although Figure 4.2 of ACI 207.2R-9 is provided to correct for fineness, the document does not give explicit guidance on how to interpret and use the plot.

When corrected for fineness, the temperature curves from ACI and the newly acquired data correspond well at the base condition of 376 lb/yd^3 of cement. However, modern concrete mixtures often contain a larger amount of cement in order to meet increasingly higher strength requirements. ACI 207.2R-9 states that values from Figure 4.1 can be multiplied by the amount of cement in the mixture to estimate temperature rise. The results of the calculated temperature rise are compared in Figure 11b both with and without a correction for fineness. In this case, the temperature rise is overestimated in both cases, by 10% and 16% respectively, suggesting that it may not be accurate to simply multiply the temperature rise by the cement content per cubic yard.

The *w/c* of the 7-sack mixture was much lower than that of the 4-sack mixtures. To directly compare the 4-sack mixtures with 7-sack mixtures, an additional test was run with a concrete containing 7-sacks of cement and a high *w/c* of 0.58. These proportions are unsuitable for structural concrete, as the high w/c will lead to poor workability, excess water, high porosity, and low strength. There is no significant difference in the temperature rise of the two mixtures, only 2 °F at 7 days as shown in Figure 6. While the w/c will influence the reaction kinetics and the heat of hydration, it does not ultimately influence the temperature rise of the concrete. The results emphasize that it is not good practice to simply multiply the ACI figure values by the cement content.



(a) **(b)**

Figure 11. Comparison of ACI 207.2R-09 Figure 2.1 with and without correction for fineness and new adiabatic temperature curves for (a) 376 lbs of Type I/II cement and (b) 671 lbs of Type I/II cement per cubic yard of concrete.

Class F fly ash is very effective at lowering the temperature rise of concrete as shown in Figure 4. Class F fly ash has a high siliceous and aluminous fraction that possesses little to no cementitious properties. Fly ash does not contribute to the hydration reaction until the calcium aluminates in the cement produce calcium hydroxide. The reaction between silica in fly ash and calcium hydroxide is slow, and the corresponding heat generation and temperature rise is slow as well [8] [17]. This is very advantageous from a heat-mitigation standpoint, but can be a disadvantage because the corresponding strength development is slower. In massive structures, the mitigation of heat generation is more important than high early strength, so high quantities of Class F fly ash are appropriate.

The addition of slag does not appreciably decrease the temperature rise to the same degree that Class F fly ash does. However, it does change the rate of thermal activity at early ages. At 7 days, the temperature is approximately 6% and 10% below the OPC mixture for the 50% and 70% slag mixtures, respectively. The slag used in this study was Grade 100 which indicates a moderate activity index (strength between 95 and 115% of neat OPC [18]) and behaves similarly to cement. To effectively decrease the temperature rise, Grade 80 slag with a low activity index should be considered. Conversely, Grade 120 slag with a higher activity index would generate more heat.

From Figure 12 it can be seen that there is a wide discrepancy between the calculated and measured values of temperature rise. Most calculated values are within 20 % of the measured value, in fact, the OPC mixtures with the ¾” rock are within 10 %. Most of the error is introduced when SCMs are used. Since the

ACI equation (Equation 1) does not specify which pozzolans contribute roughly half as much heat as cement, it greatly underestimates the temperature rise of mixtures containing slag.

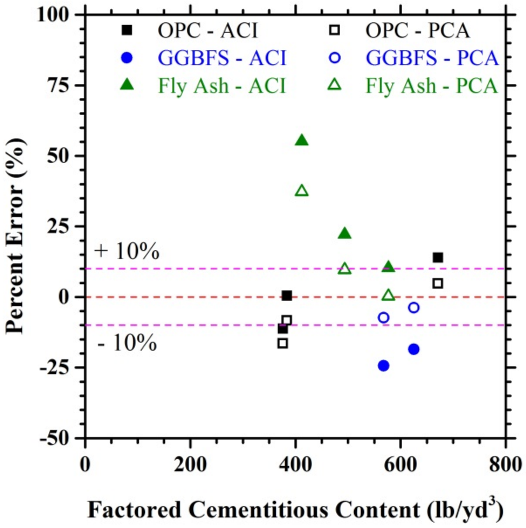


Figure 12. Error between calculated and measured temperature rise. Factored cementitious content is determined using the PCA method (Table 3).

It is clearly shown in Figure 12 that the calculated heat rise is overestimated in mixtures containing Class F fly ash. Equation 2 assumes the relationship between fly ash replacement and temperature rise is linear. However, there is a nonlinear decrease in temperature rise with an increased dosage of fly ash as shown in Figure 13. A quadratic decrease in temperature rise with the addition of pozzolans was also noted by Chini and Parham [19].

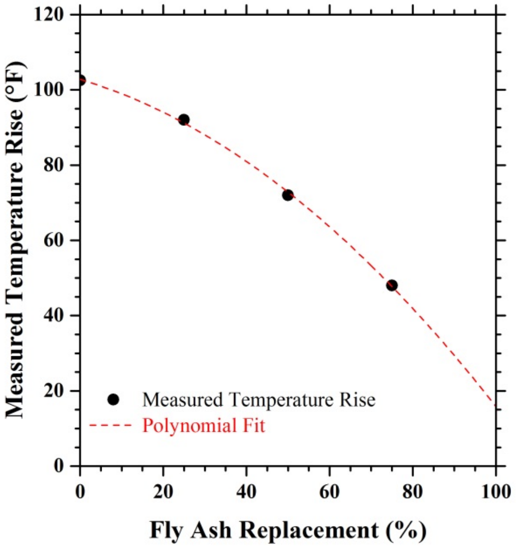


Figure 13. Measured adiabatic temperature rise as a function of Class F fly ash replacement. Second-order polynomial fit R^2=0.9991.

Table 7. Comparison of calculated and measured 28-day temperature rise.

Mixture ID		HR-4-OPC-4	HR-4-OPC	HR-7-OPC	HR-7-OPC-0.58	HR-7-Slag50	HR-7-Slag70	HR-7-FA25	HR-7-FA50	HR-7-FA75
Description		**4.5" NMSA 4 sack OPC**	**3/4" NMSA 4 sack OPC**	**3/4" NMSA 7 sack OPC**	**3/4" NMSA 7 sack OPC - 0.58 w/c**	**3/4" NMSA 7 sack 50% Slag**	**3/4" NMSA 7 sack 70% Slag**	**3/4" NMSA 7 sack 25% Fly Ash**	**3/4" NMSA 7 sack 50% Fly Ash**	**3/4" NMSA 7 sack 75% Fly Ash**
28-day Adiabatic Temperature Rise (°F)	**Calculated, Equation 1 (ACI)**	64	67	117	123	80	70	101	88	74
	Calculated, Equation 2 (PCA)	60	61	107	107	100	91	92	79	66
	Measured, USBR 4911	72	67	103	103[1]	104	98	92	72	48

[1] Temperature at 7 days, no 28 day data

The two principles that the ACI and PCA guidance and Equation 1 and Equation 2 are based on are:

1. The amount of cement in a mixture is linearly proportional to the temperature rise.
2. The amount of SCMs added to a mixture is linearly proportional to the decrease in temperature rise.

According to this research, both of these assumptions are incorrect. At low cement content (for the Type I/II cement used in this study), temperature rise is approximately 0.18 °F/lb_{cement}. At high cement contents, the temperature rise is approximately 0.15 °F/lb_{cement}. Therefore, one factor (such as PCA's 0.16 °F/lb_{cement} [13] or 0.14 °F/lb_{cement} [12]) cannot be universally used for all concrete mixtures.

Thermal Properties

The specific heats of all the concrete mixtures were approximately the same at 50 to 100 °F with coefficients of variation of 3.1 and 3.2 %, respectively. At high temperatures (150 °F), concrete containing SCMs had a slightly higher specific heat compared to OPC mixtures. ACI 207.2R-07 suggests the use of 0.20 to 0.25 Btu/lbm·°F when test data is not available. Most of the mixtures had a specific heat above that range, particularly at elevated temperatures as shown in Table 6.

The thermal diffusivity of the concrete used in this study was fairly constant across a temperature range of 50 to 150 °F as shown in Figure 8. The average values of diffusivity across all mixtures tested were 0.048 ± 0.003, 0.043 ± 0.003, and 0.039 ± 0.002 ft^2/h at 50, 100 and 150 °F, respectively. ACI 207 recommends the use of 0.058 ft^2/h for concrete containing quartzite and 0.043 ft^2/h for concrete containing granite. The measured values are more consistent with the recommended value for granite despite there being only 30% granite in the aggregate.

The calculated conductivity was 1.76 ± 0.14, 1.76 ± 0.12, and 1.85 ± 0.16 Btu/ft·h·°F at 50, 100 and 150 150 °F, respectively. ACI recommends a value of 2.0 Btu/ft·h·°F for quartzite and 1.5 Btu/ft·h·°F for granite. The measured conductivity falls between those two values.

The measured coefficient of thermal expansion did not vary greatly between specimens which is consistent with previous research [3]. The average coefficient of thermal expansion was 6.67 µin/in·°F with a coefficient of variation of 6.20 %. The value recommended by ACI 207.2R is 6.1 to 7.2 µin/in·°F for concrete containing quartzite and 4 to 5 µin/in·°F for concrete containing granite. Since the concrete contained predominantly quartzite (approximately 43%), the measured value is close to the value recommended by ACI.

The thermal properties are largely dependent on the coarse aggregate type. The coarse aggregate occupies the largest fraction of volume in concrete. The slightly varying thermal properties in HR-4-OPC-4 can be attributed to the composition of the 4” rock used which contained a significantly greater quantity of granite compared to the ¾” rock.

Recommendations for Estimating Heat Rise in Mass Concrete

There are several programs that designers can use to model the temperature rise of concrete. Some are not applicable to mass concrete with large dimensions and others are cumbersome and require advanced material characterization to obtain an accurate result [20] [21]. Many designers rely on rules of thumb such as those outlined in the ACI 207 or EM 34 documents, but as shown in this testing program, they can produce errors up to 30%. The benefit of the ACI guidance is that it is a quick and relatively straightforward method that any designer can easily understand and calculate. One of the goals of this paper is to provide designers with up to date data and revised guidance on how to use that data in order to more accurately estimate temperature rise of mass concrete.

These two fundamental differences in thought can be expressed graphically as shown in Figure 14. The designer can use a set of empirically derived plots to determine the temperature rise per pound of *total cementitious material* (Step 1 of Figure 14). This value is dependent on the cement type used, and the sketch in Figure 14 is based on the Type I/II cement used in this current research, however the lines for a Type I and Type II are sketched to show the theoretical differences expected to be seen with other cement types. Next, the designer would determine the percent decrease in temperature due to the addition of Class F fly ash (Step 2 of Figure 14). The calculation simply becomes

$$T(^\circ F) = T_{cem} \cdot W - (T_{cem} \cdot W) \cdot T_{FA} \qquad \textit{Equation 4}$$

where T_{cem} is the temperature rise per pound of total cementitious material ($^\circ F/lb_{cement}$) from Step 1, W is the total weight of cementitious materials per cubic yard, and T_{FA} is the percent decrease in temperature due to the fly ash from Step 2.

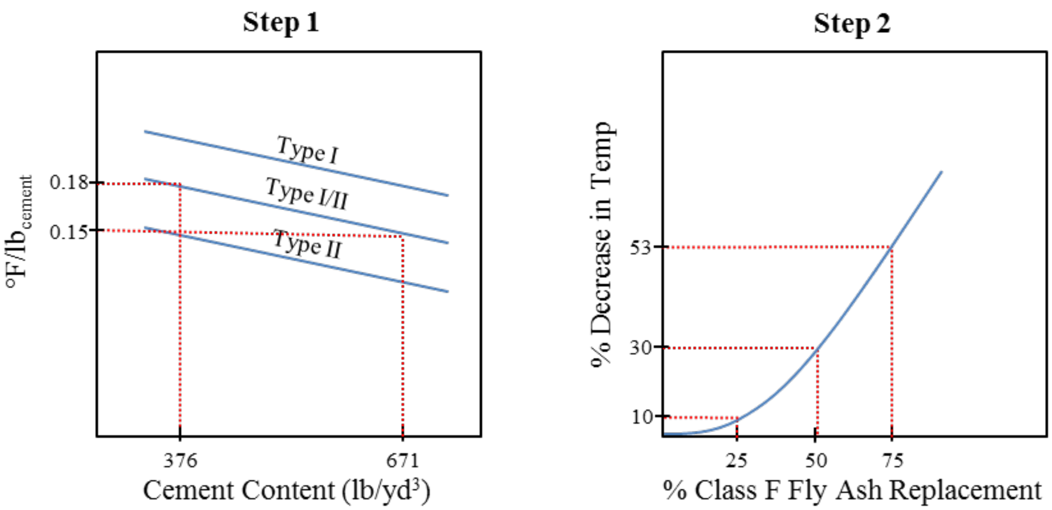


Figure 14. Suggested new procedure for estimating adiabatic temperature rise. Sketches are not to scale.

More data should be collected to verify this method but the outlook is promising. Of course, testing the heat of hydration or adiabatic temperature rise is the ideal course of action. This method would give designers a more accurate figure on which to base their preliminary mixture design.

Aside from data collected during this laboratory study, the new recommended method was applied to mixtures from previous Reclamation projects. A summary of the mixture proportions and comparison of calculated and measured values are found in Table 8. Mixtures shaded in grey used Type I/II cement and Class F fly ash or Grade 100 slag so they are expected to have the closest estimations since the basis of the new method was established using those same materials. The first three mixtures used a Type II cement which is similar and was estimated relatively accurately with the new calculation method.

The percent difference between the current methods (from PCA and ACI) and the new recommended method is shown in Figure 15. All of the values calculated by the new method are within 10% of the measured value. As noted earlier, the established methods tend to underestimate the temperature rise in mixtures with low cement content and overestimate the temperature rise at high cement contents.

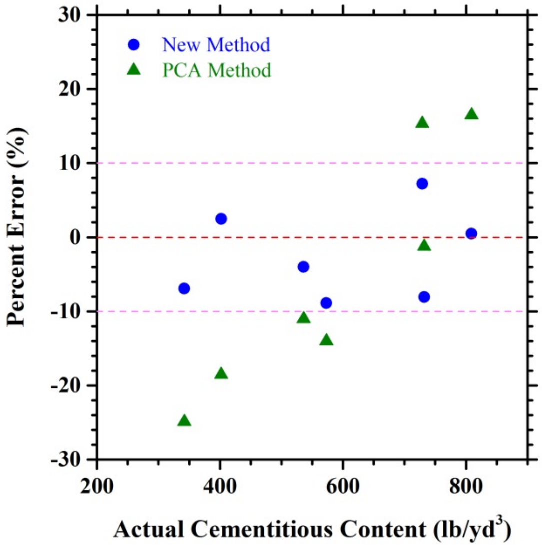


Figure 15. Comparison of error between calculated and measured values of temperature rise using the new recommended method and the PCA method for previous Reclamation projects.

At a minimum, it is recommended that the current guidance add a caveat to the equations presented. The methods presented by ACI and PCA are recommended for mixtures containing 500 to 1000 lb/yd^3 of cement. From this research and comparison with previous projects, the values from Equation 1 and Equation 2 are only accurate in a much narrower range of cement contents, from approximately 400 to 550 lb/yd^3. Additionally, there should be a different equivalent cement factor for higher SCM replacement levels. At lower volumes, the equivalent cement factor of 0.5 for Fly Ash is appropriate, but at higher volumes (between 50 and 75 %), there is less heat contributed to the concrete so a factor of 0.4 or lower would be more appropriate.

Table 8. Comparison of calculated and measured temperature rise for previous Reclamation projects using Class F fly ash or Grade 100 Slag

MIXTURE ID		**Stony Gorge**	**New Waddell**	**New Waddell**	**New Waddell**	**Minidoka**	**Canton**	**Canton**
Description		**Diaphragm Wall**	**Bridge Pier**	**Intake Tower Wall**	**Intake Tower Footing**	**Trial Batch 20% Mass**	**Trial Batch CDF-12**	**Trial Batch CDF-H**
Materials	**Equivalent Cement Factor**	**Type II**	**Type II**	**Type II**	**Type II**	**Type I/II**	**Type I/II**	**Type I/II**
Cement (Type I or II)	1	552	647	583	459	376	240	201
Fly Ash (Class F)	0.5	180	162	146	114	160	102	
GGBFS 50% replacement	0.9							201
Fine Aggregate	-	1427	1260	1182	1000	1158	1033	1021
Coarse Aggregate	-	1566	1520	1740	2240	1795	2586	2502
Water	-	264	265	255	205	242	145	181
Total Cementitous Used	-	732	809	729	573	536	342	402
% Pozzolan Used	-	25%	20%	20%	20%	30%	30%	0%
w/cm		0.36	0.33	0.35	0.36	0.45	0.42	0.45
Factored Cementitious (Gajda)		642	728	656	516	456	291	382
Factor from PCA (Gajda) (°F/lb)		0.16	0.16	0.16	0.16	0.16	0.16	0.16
Factor from New Method (°F/lb)		0.15	0.14	0.15	0.17	0.17	0.20	0.19
Calculated Adiabatic Temperature Rise (From PCA)	**T(°F)**	103	116	105	83	73	47	61
Calculated Adiabatic Temperature Rise (New Method)	**T(°F)**	**96**	**100**	**98**	**87**	**79**	**58**	**77**
USBR 4911 Adiabatic Temperature Rise	**T(°F)**	**--**	**--**	**--**	**--**	**--**	**62**	**75**
Temperature Rise Recorded in Field	**T(°F)**	**104**	**100**	**91**	**96**	**82**	**--**	**--**

Conclusions

- The adiabatic temperature rise curves from EM 34 and ACI 207.2R-07 have been traced directly back to the 1936 Boulder Canyon studies performed by Reclamation [1].
- Cements produced today differ greatly compared to those used in studies referenced in the ACI 207 and Reclamation EM 34 documents. The fineness and chemical composition is such that strength can be gained in early ages, which contributes to higher heats of hydration. Corrections for fineness must be made when estimating temperature rise from the currently published temperature rise curves.
- When corrected for fineness, the adiabatic temperature curves for a concrete containing 376 lb/yd^3 of Type I/II cement corresponded well to the figure provided by ACI from the 1930's Boulder Canyon studies.
- Modern concrete mixtures vary greatly from those pre-1960's. Specifically, strength requirements cause designers to use concrete with high (over 600 lb/yd^3) cement contents. This study has shown that there is not a linear correlation between temperature rise and cement content. At low Type I/II cement contents (approximately 400 lb/yd^3), each pound of cement contributes 0.18 °F. At higher cement contents (approximately 600 lb/yd^3), each pound of cement contributes 0.15 °F.
- Class F fly ash is very effective in reducing the heat generation and temperature rise of concrete. The percent decrease in temperature with respect to ash replacement is a second order polynomial, meaning very significant reductions in temperature can be made with high replacements (> 50 % by mass). However, strength gain is slow.
- A new method for estimating temperature rise has been presented that provides a lower percent error compared to what is currently presented in ACI and Reclamation guidance.
- The thermal properties of concrete (diffusivity, conductivity, specific heat and thermal expansion) are highly dependent on aggregate type. The results from this study are consistent with the suggested values given in Chapter 3 of ACI 207.2R-07.
- Future research should further evaluate a wider range of SCMs including Grades 80 and 120 of slag and natural pozzolans for further mitigating heat generation.

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Appendix A. Mill Certificates

Material Certification Report

Material:	Portland Cement	Test Period:	01-Apr-2014
Type:	I-II	To:	30-Apr-2014

Certification

This Holcim cement meets the specifications of ASTM C150 for Type I-II cement, and complies with AASHTO M85 specifications for Type I-II cement.

General Information

Supplier:	Holcim (US) Inc.	Source Location:	Ste. Genevieve Plant
Address:	2942 US Highway 61 Bloomsdale, MO 63627		2942 US Highway 61 Bloomsdale, MO 63627
Telephone:	636-524-8155	Contact:	Erin Watson
Date Issued:	14-May-2014		

The following information is based on average test data during the test period.
The data is typical of cement shipped by Holcim; individual shipments may vary.

Tests Data on ASTM Standard Requirements

Chemical

Item	Limit[A]	Result
SiO_2 (%)	-	19.7
Al_2O_3 (%)	6.0 max	4.5
Fe_2O_3 (%)	6.0 max	3.2
CaO (%)	-	64.3
MgO (%)	6.0 max	2.6
SO_3 (%)	3.0 max[B]	3.6
Loss on Ignition (%)	3.0 max	2.6
Insoluble Residue (%)	0.75 max	0.45
CO_2 (%)	-	1.3
Limestone (%)	5.0 max	3.3
$CaCO_3$ in Limestone (%)	70 min	89
Inorganic Processing Addition (%)	5.0 max	0.0
Potential Phase Compositions[C]:		
C_3S (%)	-	62
C_2S (%)	-	7
C_3A (%)	8 max	6
C_4AF (%)	-	9
$C_3S + 4.75C_3A$ (%)	-	91.3

Physical

Item	Limit[A]	Result
Air Content (%)	12 max	7
Blaine Fineness (m^2/kg)	260 min	383
Autoclave Expansion (%) (C151)	0.80 max	0.10
Compressive Strength MPa (psi):		
3 days	12.0 (1740) min	30.0 (4350)
7 days	19.0 (2760) min	36.5 (5300)
Initial Vicat (minutes)	45-375	78
Mortar Bar Expansion (%) (C1038)	-	0.009

Tests Data on ASTM Optional Requirements

Chemical

Item	Limit[A]	Result
Equivalent Alkalies (%)	0.60 max	0.54

Physical

Item	Limit[A]	Result
False Set (%)	50 min	75

Notes

[A] Dashes in the limit / result columns mean Not Applicable.

[B] It is permissible to exceed the specification limit provided that ASTM C1038 Mortar Bar Expansion does not exceed 0.020 % at 14 days.

[C] Adjusted per Annex A1.6 of ASTM C150 and AASHTO M85.

[D] Test result represents most recent value and is provided for information only. Analysis of Heat of Hydration has been carried out by CTLGroup, Skokie, IL.

Equavalent Alkalies (%) Minimum = 0.5, Maximum = 0.58

This data may have been reported on previous mill certificates.

Additional Data

Inorganic Processing Addition Data

Item	Result[A]
Type	-
Amount (%)	-
SiO_2 (%)	-
Al_2O_3 (%)	-
Fe_2O3 (%)	-
CaO (%)	-
SO_3 (%)	-

Base Cement Phase Composition

Item	Result
C_3S (%)	64
C_2S (%)	7
C_3A (%)	6
C_4AF (%)	10

By , Quality Manager

Material Certification Report

Brand: Envirocore™ Family of Products
Material: GranCem® Slag Cement
Grade: 100
Date Range: April 1-30, 2014
Lot Number: Multiple Lots

Certification

This cement meets the requirements of ASTM specification C989 for Grade 100 Slag Cement

General Information

Supplier:	Holcim (US) Inc.	Source Location:	Chicago Skyway Plant
Address:	3020 East 103rd Street Chicago, IL 60617		3020 East 103rd Street Chicago, IL 60617
Telephone:	Roberto Carrillo/773-768-1717 x 06	Contact:	Roberto Carrillo/773-768-1717 x 06
Date Issued:	02-Jun-2014		

The following information is based on average test data during the test period.
The data is typical of cement shipped by Holcim; individual shipments may vary.

Test Data on ASTM Standard Requirements

Chemical

Item	Limit[A]	Result
Sulfide S (%)	2.5 max	0.99
Sulfate Ion - SO_3 (%)	-	0.02

Physical

Item	Limit[A]	Result
+45 µm (No. 325) Sieve (%)	20 max	0.54
Blaine Fineness (m2/kg)	-	620
Air Content (%)	12 max	3.5
Slag Activity Index (%)		
Avg 7 Day Index	75 min	85
Avg 28 Day Index	95 min	121
Compressive Strength - MPa (psi):		
Slag + Reference Cement		
7 Day	-	25 (3660)
28 Day	-	46 (6680)
Reference Cement[B]		
7 Day	-	30 (4300)
28 Day	-	38 (5540)

Reference Cement Qualification Data

Chemical

Item	Limit[A]	Result
Total Alkalies as Na_2O (%)	0.60 - 0.90	0.84
C_3S	-	55.3
C_2S	-	16.6
C_3A	-	7.9
C_4AF	-	8.8

Physical

Item	Limit[A]	Result
Blaine Fineness (m^2/kg)	-	368
Compressive Strength - MPa (psi):		
7 Day	-	30.3 (4390)
28 Day	34.5 (5000) min	38.9 (5640)

Notes

[A] Dashes in the limits columns means Not Applicable

[B] Reference cement results from procedure "Preparation of Specimens". Information on Reference Cement qualification available upon request.

Specific Gravity: 2.89

This data may have been reported on previous mill certificates. It is typical of the cement being currently shipped which was produced in April of 2014

SALT RIVER MATERIALS GROUP - PHOENIX CEMENT COMPANY
CHOLLA CLASS F FLY ASH - ASTM C618 LOT TESTING RESULTS
2014

																		STRENGTH ACTIVITY		UNIFORMITY			
Date	Lot Number	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	$S0_3$ (%)	Loss on Ignition (%)	Total SAF (%)	Total Alkalies (%)	Available Alkalies (%)	Moisture Content (%)	Fineness +325 (%)	Specific Gravity	Autoclave Expan (%)	Water Req (%)		7 day Index	28 day Index	Average Plus 325	Average Sp Grv	Variation Plus 325	Variation Sp Grv
01-02-14	2341	57.52	23.84	6.93	4.15	1.47	0.31	0.30	88.29	1.47	0.40	0.03	24	2.18	-0.03	96		80	92	21	2.22	-3.03	0.04
01-05-14	2342	57.32	23.77	6.59	3.96	1.44	0.29	0.38	87.68	1.35	0.39	0.03	23	2.18	-0.02	96		78	85	22	2.22	-1.53	0.04
01-09-14	2343	57.69	23.80	6.64	3.82	1.48	0.29	0.31	88.13	1.31	0.39	0.09	22	2.16	-0.02	96		80	85	22	2.21	0.20	0.05
01-12-14	2344	56.84	22.43	7.83	3.49	1.42	0.29	0.25	87.10	1.47	0.36	0.04	24	2.20	-0.01	96		84	89	22	2.20	-1.96	0.00
01-15-14	2345	57.53	23.40	6.06	3.49	1.46	0.23	0.23	86.99	1.45	0.38	0.04	24	2.19	-0.01	96		84	89	23	2.20	-1.12	0.01
01-19-14	2346	59.17	23.22	5.88	3.68	1.51	0.25	0.22	88.27	1.30	0.40	0.07	22	2.18	-0.01	96		83	89	23	2.20	0.60	0.02
01-22-14	2347	58.26	23.07	5.56	3.78	1.60	0.24	0.16	86.89	1.40	0.40	0.04	24	2.20	-0.03	96		79	89	23	2.19	-0.51	-0.01
01-26-14	2348	60.10	23.21	5.52	3.52	1.54	0.23	0.15	88.83	1.64	0.38	0.05	22	2.18	-0.05	96		81	89	23	2.19	1.48	0.01
01-30-14	2349	57.23	23.15	6.17	3.74	1.44	0.20	0.20	86.55	1.65	0.36	0.06	22	2.17	-0.01	96		83	90	23	2.19	0.98	0.02
02-02-14	2350	56.58	23.60	6.08	4.21	1.53	0.25	0.19	86.26	1.37	0.39	0.05	24	2.20	-0.01	95		84	88	23	2.19	-1.23	-0.01
02-05-14	2351	56.82	23.05	6.72	3.89	1.47	0.26	0.24	86.59	1.39	0.32	0.05	24	2.18	-0.05	96		77	87	23	2.18	-1.18	0.00
02-09-14	2352	57.12	21.60	7.40	3.90	1.38	0.29	0.22	86.12	1.52	0.38	0.06	24	2.22	0.01	96		79	81	23	2.18	-0.96	-0.04
02-13-14	2353	57.41	22.18	7.24	3.58	1.49	0.25	0.20	86.83	1.41	0.38	0.06	23	2.25	-0.01	97		80	89	23	2.19	-0.01	-0.06
02-16-14	2354	57.83	22.34	7.39	3.13	1.43	0.23	0.26	87.56	1.36	0.37	0.05	23	2.20	0.01	96		78	86	23	2.20	0.07	0.00
02-20-14	2355	58.16	21.07	7.80	3.19	1.41	0.23	0.24	87.03	1.32	0.35	0.06	22	2.20	-0.01	96		79	86	23	2.20	0.90	0.00
02-24-14	2356	57.86	22.15	7.51	3.27	1.44	0.24	0.30	87.52	1.36	0.41	0.03	22	2.21	0.01	96		78	80	23	2.20	1.33	-0.01
02-27-14	2357	56.90	22.29	7.40	3.16	1.44	0.24	0.26	86.59	1.25	0.38	0.03	26	2.23	-0.01	96		81	84	23	2.20	-3.16	-0.03
03-02-14	2358	59.17	23.22	6.75	3.23	1.47	0.23	0.29	89.14	1.21	0.41	0.60	23	2.24	-0.01	96		81	89	23	2.20	0.77	-0.04
03-06-14	2359	57.24	22.32	7.60	3.26	1.38	0.25	0.26	87.16	1.14	0.40	0.06	24	2.23	0.01	97		81	79	23	2.21	-0.76	-0.02
03-08-14	2360	58.78	21.70	7.88	3.08	1.35	0.25	0.29	88.36	1.41	0.38	0.05	26	2.23	-0.01	97		75	82	24	2.22	-1.89	-0.01
03-11-14	2361	57.58	21.66	7.65	3.34	1.37	0.26	0.22	86.89	1.42	0.40	0.04	25	2.25	-0.01	97		80	85	24	2.22	-1.08	-0.03
03-15-14	2362	57.10	22.13	8.01	3.33	1.33	0.26	0.25	87.24	1.55	0.38	0.03	25	2.23	-0.02	96		74	80	24	2.23	-1.12	0.00
03-18-14	2363	56.53	21.70	7.27	3.66	1.33	0.28	0.26	85.50	1.60	0.38	0.06	23	2.20	-0.01	96		80	87	24	2.23	0.53	0.03
03-22-14	2364	55.88	21.61	7.85	3.74	1.36	0.31	0.28	85.34	1.50	0.39	0.07	24	2.23	-0.02	96		81	90	24	2.22	-0.20	-0.01
03-26-14	2365	58.49	23.65	6.81	3.67	1.22	0.24	0.20	88.95	1.48	0.37	0.03	23	2.22	-0.01	96		80	83	24	2.23	1.32	0.01
03-31-14	2366	58.62	22.42	7.70	3.90	1.29	0.30	0.30	88.74	1.52	0.35	0.07	23	2.25	-0.02	96		80	87	24	2.23	0.61	-0.02
04-04-14	2367	58.15	23.04	7.95	3.74	1.18	0.28	0.28	89.14	1.57	0.44	0.05	21	2.24	-0.01	96		75	89	24	2.23	3.12	-0.01
04-07-14	2368	58.51	23.00	7.99	3.74	1.24	0.30	0.28	89.50	1.43	0.46	0.04	21	2.24	-0.02	95		83	90	24	2.23	2.99	-0.01
04-11-14	2369	58.15	22.66	7.93	3.88	1.33	0.29	0.30	88.74	1.50	0.39	0.03	22	2.25	-0.01	95		80	89	24	2.23	1.54	-0.02
04-15-14	2370	58.03	23.32	7.65	3.65	1.31	0.26	0.27	89.00	1.46	0.35	0.06	20	2.25	-0.01	95		90	90	23	2.23	3.16	-0.02
04-19-14	2371	58.41	23.27	7.25	3.73	1.38	0.27	0.32	88.93	1.38	0.35	0.08	21	2.22	-0.01	96		82	87	23	2.24	1.85	0.02
04-22-14	2372	57.80	22.39	7.53	3.67	1.37	0.26	0.28	87.72	1.38	0.36	0.05	23	2.20	-0.02	96		79	91	22	2.23	-0.68	0.03
05-01-14	2373	58.09	24.39	7.26	2.94	1.94	0.28	0.26	89.74	1.39	0.37	0.01	23	2.20	0.02	96		86	83	22	2.23	-1.03	0.03
05-01-14	2374	59.55	23.52	5.58	3.26	1.51	0.23	0.34	88.65	1.66	0.42	0.06	22	2.20	-0.03	95		76	85	22	2.23	0.32	0.03
05-04-14	2375	61.24	21.98	6.29	2.75	1.45	0.19	0.25	89.51	1.95	0.48	0.02	22	2.21	-0.01	95		79	88	22	2.23	-0.53	0.02
05-07-14	2376	58.78	20.60	7.57	3.36	1.42	0.25	0.20	86.95	1.59	0.48	0.04	22	2.23	-0.04	95		86	91	22	2.23	0.15	0.00
05-10-14	2377	56.91	21.04	8.08	3.21	1.43	0.22	0.23	86.03	1.76	0.46	0.04	21	2.21	-0.01	95		72	76	22	2.22	1.00	0.01
05-14-14	2378	57.58	20.90	8.50	3.26	1.49	0.25	0.27	86.98	1.54	0.40	0.08	24	2.22	-0.01	96		82	89	22	2.22	-1.87	0.00
05-18-14	2379	59.18	21.62	7.22	2.92	1.22	0.23	0.28	88.02	1.62	0.41	0.03	24	2.19	-0.01	98		74	86	22	2.22	-1.55	0.03
05-21-14	2380	59.57	22.78	7.21	3.24	1.27	0.22	0.26	89.56	1.56	0.38	0.05	23	2.21	-0.02	97		78	88	22	2.21	-1.08	0.00
05-25-14	2381	59.51	22.78	7.11	3.42	1.31	0.24	0.26	89.40	1.36	0.34	0.05	22	2.19	-0.03	97		75	79	22	2.21	0.03	0.02
05-27-14	2382	60.64	23.56	6.53	3.19	1.37	0.23	0.32	90.73	1.44	0.47	0.06	20	2.18	-0.04	97		78	84	23	2.21	2.29	0.03
05-30-14	2383	58.31	22.90	6.41	2.70	1.36	0.22	0.27	87.62	1.41	0.51	0.07	23	2.18	-0.03	96		83	88	22	2.20	-0.46	0.02
06-03-14	2384	57.92	22.27	6.84	3.13	1.41	0.22	0.23	87.03	1.40	0.48	0.07	23	2.22	-0.02	96		83	86	22	2.20	-0.55	-0.02

SALT RIVER MATERIALS GROUP - PHOENIX CEMENT COMPANY
CHOLLA CLASS F FLY ASH - ASTM C618 LOT TESTING RESULTS
2014

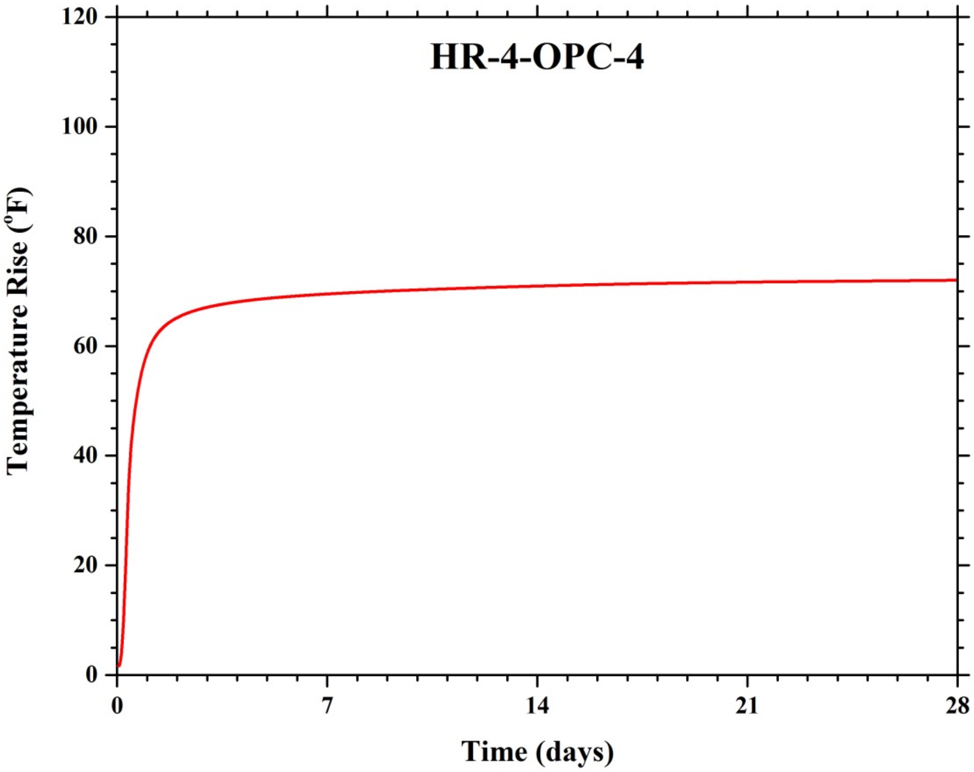
																	STRENGTH ACTIVITY		UNIFORMITY			
Date	Lot Number	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	$S0_3$ (%)	Loss on Ignition (%)	Total SAF (%)	Total Alkalies (%)	Available Alkalies (%)	Moisture Content (%)	Fineness +325 (%)	Specific Gravity	Autoclave Expan (%)	Water Req (%)	7 day Index	28 day Index	Average Plus 325	Average Sp Grv	Variation Plus 325	Variation Sp Grv
06-06-14	2385	57.72	23.13	7.00	3.21	1.43	0.23	0.28	87.85	1.44	0.41	0.05	23	2.21	-0.03	96	84	83	22	2.20	-1.04	-0.01
06-09-14	2386	55.51	23.77	7.41	3.00	1.36	0.25	0.28	86.69	1.41	0.50	0.03	23	2.21	-0.03	96	83	84	22	2.20	-0.78	-0.01
06-13-14	2387	56.92	23.81	6.66	2.85	1.41	0.20	0.26	87.39	1.43	0.48	0.05	22	2.22	-0.03	95	78	88	23	2.20	0.54	-0.02
06-13-14	2388	56.61	24.41	7.17	2.99	1.38	0.23	0.30	88.19	1.33	0.48	0.02	23	2.23	-0.02	95	81	92	23	2.20	-0.61	-0.03
06-20-14	2389	57.82	23.20	6.19	2.70	1.36	0.23	0.31	87.21	1.47	0.46	0.03	21	2.22	-0.05	96	81	91	23	2.20	2.05	-0.02
06-25-14	2390	59.47	24.38	6.08	2.83	1.07	0.23	0.37	89.93	1.62	0.42	0.06	20	2.23	0.01	96	80	98	22	2.21	2.67	-0.02
06-28-14	2391	56.62	24.23	6.81	3.17	1.41	0.26	0.44	87.66	1.55	0.48	0.07	22	2.23	-0.02	96	80	94	22	2.21	0.22	-0.02
07-02-14	2392	56.34	22.96	7.01	3.37	1.39	0.28	0.24	86.31	1.67	0.44	0.06	22	2.24	-0.02	96	83	90	22	2.21	0.40	-0.03
07-06-14	2393	56.36	22.99	7.25	3.58	1.43	0.27	0.30	86.60	1.53	0.44	0.08	22	2.23	-0.02	96	78	82	22	2.22	0.62	-0.01
07-10-14	2394	56.88	23.21	7.20	3.46	1.43	0.29	0.33	87.29	1.36	0.37	0.10	22	2.25	0.03	97	77	85	22	2.22	0.43	-0.03
07-13-14	2395	55.17	23.60	7.25	4.26	1.48	0.28	0.39	86.02	1.54	0.42	0.10	20	2.24	-0.03	96	83	88	22	2.23	1.62	-0.01
07-17-14	2396	56.31	22.62	8.14	3.41	1.41	0.33	0.31	87.07	1.59	0.41	0.06	20	2.24	-0.01	96	76	92	22	2.23	1.58	-0.01
07-19-14	2397	57.70	22.17	7.45	3.10	1.39	0.31	0.27	87.32	1.65	0.42	0.07	22	2.25	-0.01	96	78	88	21	2.23	-1.25	-0.02
07-22-14	2398	56.46	22.77	7.55	3.11	1.36	0.32	0.32	86.78	1.73	0.46	0.04	21	2.20	0.03	96	77	88	21	2.24	-0.04	0.04
07-26-14	2399	55.08	22.82	8.18	3.59	1.46	0.42	0.28	86.08	1.64	0.45	0.09	22	2.20	-0.04	96	85	89	21	2.23	-0.48	0.03
07-29-14	2400	54.58	22.99	8.72	3.48	1.46	0.44	0.32	86.29	1.53	0.39	0.08	20	2.21	0.01	96	88	88	21	2.23	1.20	0.02
08-02-14	2401	54.79	22.34	9.50	3.81	1.43	0.44	0.29	86.63	1.53	0.46	0.06	20	2.22	-0.03	96	86	87	21	2.23	1.09	0.01
08-05-14	2402	55.95	22.52	9.07	3.58	1.36	0.46	0.26	87.54	1.62	0.45	0.05	21	2.22	-0.02	96	80	90	21	2.23	-0.43	0.01
08-10-14	2403	54.86	22.69	8.85	3.60	1.45	0.39	0.28	86.40	1.43	0.52	0.07	20	2.23	-0.01	96	82	93	21	2.23	1.52	0.00
08-14-14	2404	56.89	23.05	8.03	3.79	1.02	0.41	0.36	87.97	1.48	0.54	0.01	20	2.26	-0.03	97	85	89	21	2.23	0.47	-0.03
08-17-14	2405	58.13	22.46	8.01	3.78	1.28	0.37	0.25	88.60	1.65	0.56	0.32	22	2.22	-0.02	96	80	0	21	2.23	-1.59	0.01
08-20-14	2406	56.39	21.48	8.29	3.90	1.41	0.32	0.25	86.16	1.88	0.50	0.07	21	2.23	-0.02	96	80	88	21	2.23	0.27	-0.01
08-24-14	2407	56.76	21.95	8.50	3.66	1.49	0.36	0.24	87.21	1.76	0.49	0.07	20	2.24	0.01	96	80	89	21	2.22	0.98	-0.02
08-26-14	2408	57.18	22.30	7.42	3.60	1.44	0.35	0.22	86.90	1.97	0.36	0.07	22	2.24	0.01	96	78	89	21	2.22	-1.08	-0.02
08-30-14	2409	56.49	22.48	7.26	3.72	1.40	0.40	0.23	86.23	1.74	0.41	0.08	23	2.24	-0.02	96	79	86	21	2.23	-2.00	-0.01
09-02-14	2410	56.52	22.40	7.52	3.82	1.46	0.38	0.37	86.44	1.43	0.35	0.08	23	2.25	-0.01	96	75	85	21	2.23	-2.51	-0.02
09-05-14	2411	54.31	21.95	7.65	3.66	1.38	0.32	0.46	83.91	1.58	0.68	0.06	25	2.20	-0.01	96	75	82	21	2.24	-4.22	0.04
09-08-14	2412	54.92	22.34	7.67	4.20	1.44	0.33	0.42	84.93	1.45	0.51	0.06	26	2.22	-0.01	96	76	83	22	2.23	-4.37	0.01
09-11-14	2413	55.47	22.25	8.30	3.39	1.41	0.36	0.37	86.02	1.49	0.56	0.06	23	2.22	-0.04	98	80	81	22	2.23	-1.02	0.01
09-13-14	2414	57.18	23.59	8.52	3.88	0.95	0.33	0.35	89.29	1.62	0.55	0.03	27	2.22	-0.02	96	76	80	23	2.23	-4.06	0.01
09-16-14	2415	57.27	23.23	8.58	3.94	0.87	0.33	0.35	89.08	1.73	0.58	0.05	27	2.23	-0.03	97	77	83	23	2.23	-3.28	0.00
09-20-14	2416	59.44	22.13	7.80	3.75	0.93	0.33	0.37	89.37	1.54	0.62	0.06	25	2.23	-0.02	97	74	79	24	2.23	-1.33	0.00
09-22-14	2417	59.51	22.12	8.00	3.71	0.94	0.36	0.38	89.63	1.58	0.56	0.06	25	2.22	-0.02	97	78	87	24	2.23	-1.04	0.01
09-27-14	2418	55.89	21.08	7.18	4.51	0.71	0.33	0.33	84.15	1.49	0.41	0.05	25	2.20	-0.01	98	80	90	25	2.23	-0.41	0.03
10-01-14	2419	58.48	23.67	7.24	4.59	0.95	0.28	0.34	89.39	1.38	0.41	0.05	24	2.20	-0.04	97	75	84	25	2.22	1.09	0.02
10-05-14	2420	57.78	23.74	7.07	4.33	0.91	0.32	0.29	88.59	1.54	0.42	0.06	25	2.21	-0.01	97	84	95	25	2.22	0.52	0.01
10-10-14	2421	58.72	23.79	7.08	3.99	0.99	0.29	0.19	89.59	1.61	0.33	0.11	24	2.22	0.04	96	84	83	25	2.22	1.55	-0.01
10-14-14	2422	57.54	24.59	7.57	4.01	1.12	0.34	0.18	89.70	1.58	0.39	0.05	25	2.25	-0.05	96	80	84	25	2.22	0.20	-0.03
10-19-14	2423	57.27	23.29	7.91	3.42	1.07	0.25	0.31	88.47	1.72	0.45	0.07	24	2.23	-0.04	97	77	79	25	2.22	0.52	-0.01
10-23-14	2424	59.11	24.10	6.89	3.07	1.07	0.31	0.30	90.10	1.82	0.46	0.06	24	2.20	0.04	97	80	80	25	2.22	1.29	0.02
10-26-14	2425	57.53	24.00	7.97	3.66	1.18	0.30	0.32	89.50	1.52	0.43	0.08	25	2.24	-0.05	97	78	88	25	2.22	0.14	-0.02
10-30-14	2426	59.01	23.55	7.68	3.94	1.19	0.31	0.38	90.24	1.51	0.50	0.03	26	2.25	-0.02	97	77	82	24	2.22	-1.43	-0.03
11-03-14	2427	62.34	23.46	6.84	3.51	1.20	0.30	0.36	92.64	1.84	0.48	0.03	24	2.24	-0.01	97	77	85	25	2.22	0.98	-0.02
11-07-14	2428	60.78	22.82	6.45	3.02	1.00	0.22	0.33	90.05	1.84	0.50	0.07	25	2.23	0.03	97	77	91	24	2.22	-0.91	-0.01

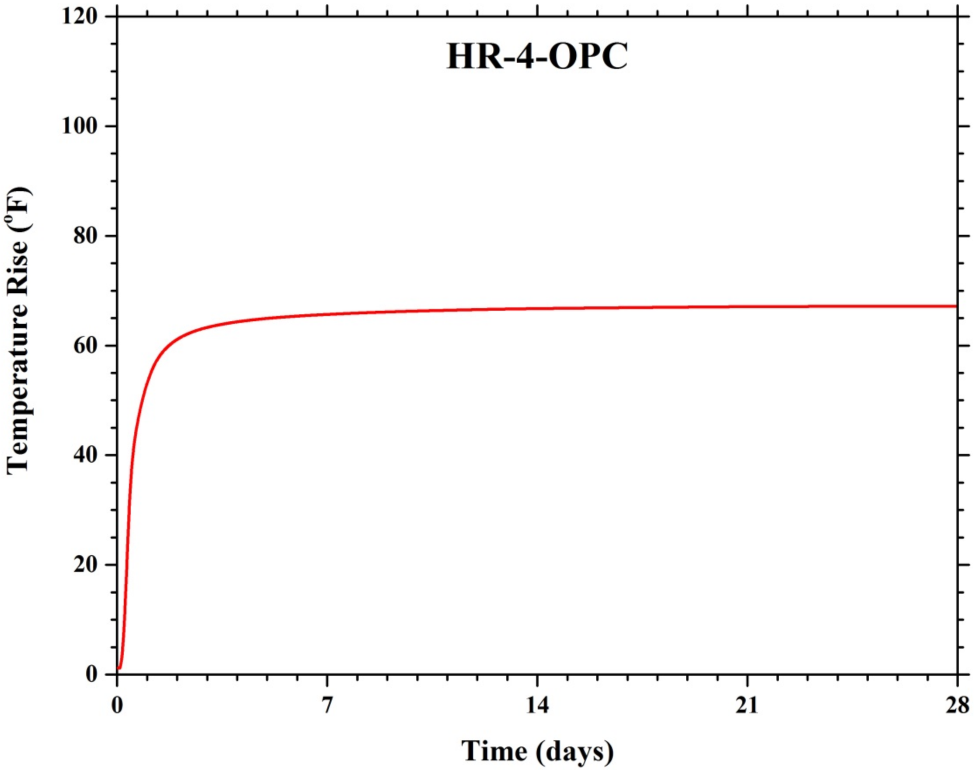
SALT RIVER MATERIALS GROUP - PHOENIX CEMENT COMPANY
CHOLLA CLASS F FLY ASH - ASTM C618 LOT TESTING RESULTS
2014

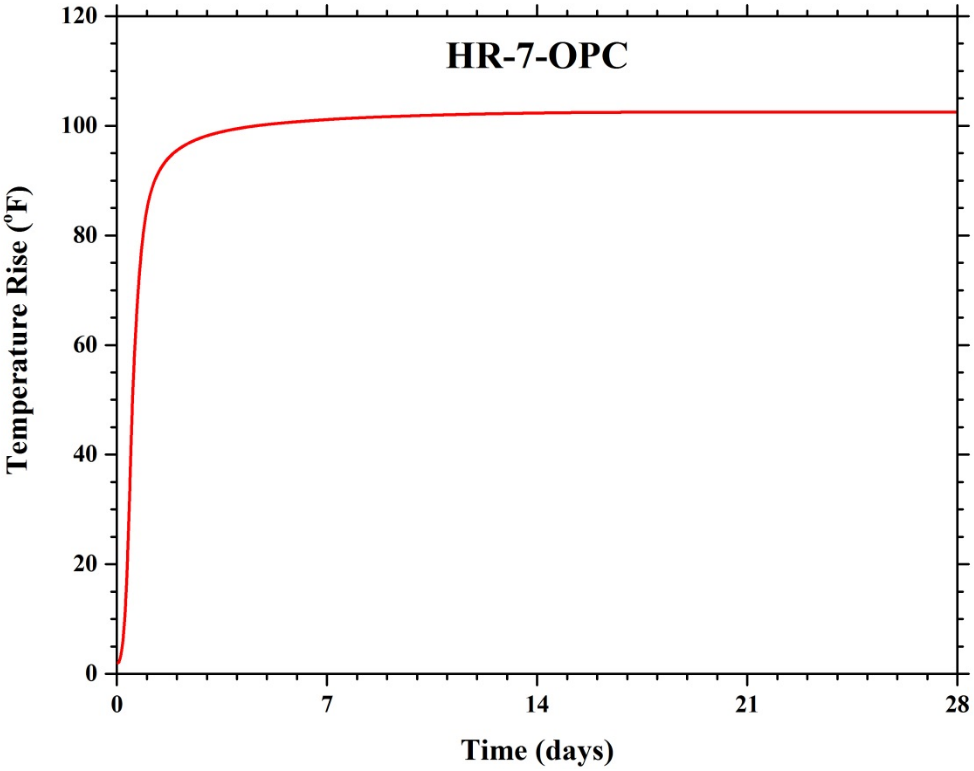
																	STRENGTH ACTIVITY		UNIFORMITY			
Date	Lot Number	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	$S0_3$ (%)	Loss on Ignition (%)	Total SAF (%)	Total Alkalies (%)	Available Alkalies (%)	Moisture Content (%)	Fineness +325 (%)	Specific Gravity	Autoclave Expan (%)	Water Req (%)	7 day Index	28 day Index	Average Plus 325	Average Sp Grv	Variation Plus 325	Variation Sp Grv
11-11-14	2429	60.23	21.77	7.33	3.35	0.83	0.25	0.29	89.33	1.79	0.50	0.02	26	2.23	-0.03	96	81	81	24	2.23	-2.07	0.00
11-15-14	2430	60.86	21.52	7.59	3.72	1.42	0.28	0.35	89.97	1.49	0.56	0.06	25	2.20	-0.01	96	73	84	25	2.23	-0.72	0.03
11-20-14	2431	60.15	22.71	7.79	4.22	1.17	0.32	0.44	90.65	1.66	0.54	0.04	26	2.21	-0.03	96	77	83	25	2.23	-1.54	0.02
11-24-14	2432	58.40	22.81	7.57	4.28	1.18	0.29	0.35	88.78	1.74	0.42	0.06	26	2.20	-0.03	96	73	87	25	2.23	-0.56	0.03
11-29-14	2433	59.55	23.34	7.38	3.94	0.85	0.28	0.36	90.27	1.62	0.34	0.05	26	2.16	-0.03	96	75	87	25	2.22	-0.36	0.06
12-03-14	2434	58.96	23.24	6.36	4.05	1.18	0.24	0.31	88.56	1.80	0.48	0.07	25	2.17	-0.05	96	75	84	25	2.22	0.12	0.05
12-08-14	2435	58.83	24.18	6.22	3.42	1.16	0.28	0.24	89.23	1.89	0.43	0.13	22	2.16	-0.02	96	77	77	25	2.21	3.90	0.05
12-13-14	2436	59.73	23.15	6.70	3.64	1.19	0.30	0.24	89.58	1.91	0.46	0.13	23	2.17	-0.02	96	79	85	25	2.21	2.55	0.04
12-17-14	2437	60.22	23.47	6.85	3.80	1.20	0.31	0.23	90.54	1.89	0.44	0.11	20	2.15	-0.02	96	83	89	25	2.20	4.93	0.05
12-20-14	2438	57.06	23.18	8.05	3.57	1.15	0.30	0.25	88.29	1.79	0.53	0.09	24	2.16	-0.03	96	79	79	24	2.19	0.51	0.03

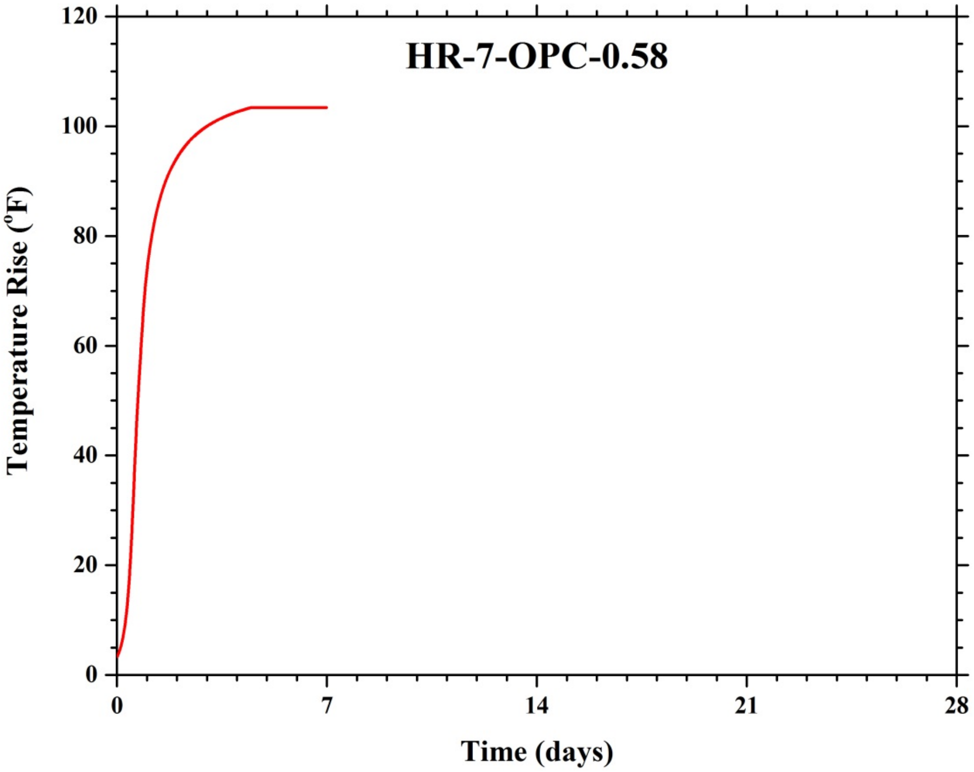
Number	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98
Minimum	54.31	20.60	5.52	2.70	0.71	0.19	0.15	83.91	1.14	0.32	0.01	20	2.15	-0.05	95	72	0	21	2.18	-4.37	-0.06
Average	57.78	22.82	7.35	3.56	1.31	0.29	0.29	87.94	1.55	0.44	0.07	23	2.21	-0.02	96	80	85	23	2.22	-0.08	0.00
Maximum	62.34	24.59	9.50	4.59	1.94	0.46	0.46	92.64	1.97	0.68	0.60	27	2.26	0.04	98	90	98	25	2.24	4.93	0.06
St Dev	1.57	0.86	0.77	0.40	0.20	0.06	0.06	1.56	0.17	0.07	0.06	1.83	0.03	0.02	0.50	3.49	9.64	1.33	0.01	1.67	0.02

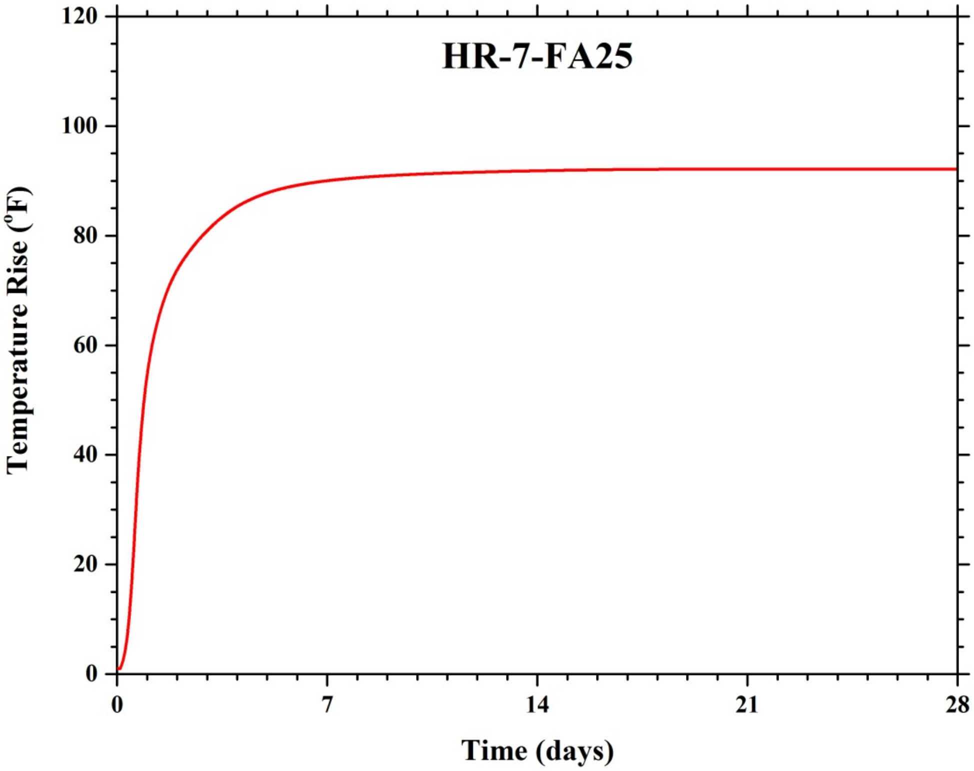
Appendix B. Adiabatic Temperature Rise Curves

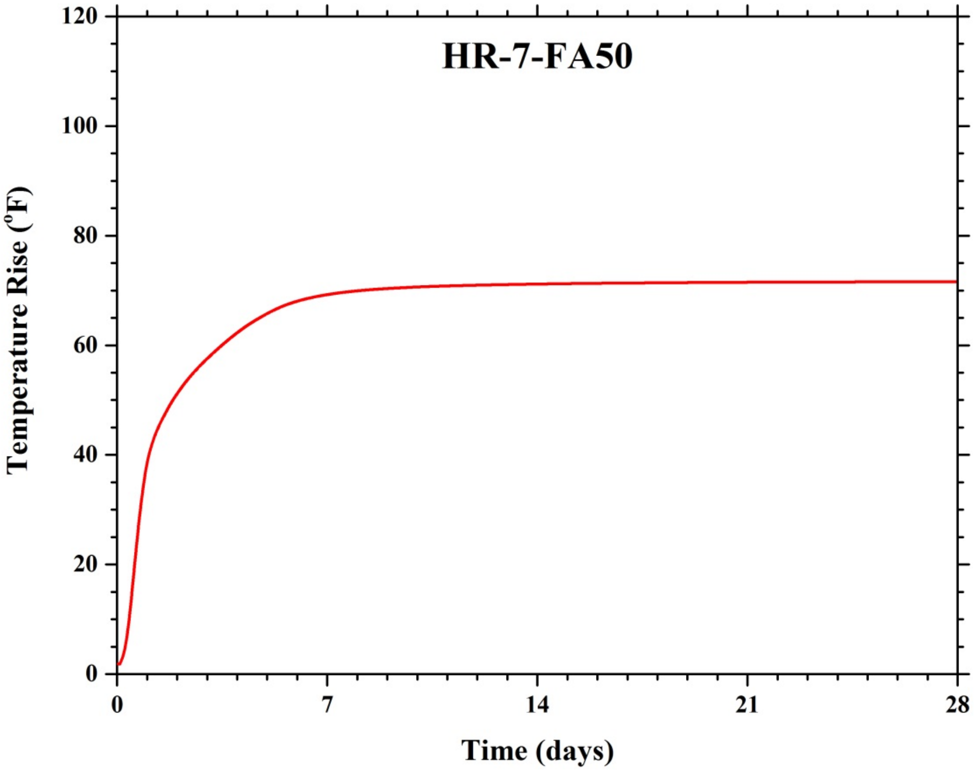

HR-4-OPC-4
Temperature Rise (°F)
0
20
40
60
80
100
120
Time (days)
0
7
14
21
28

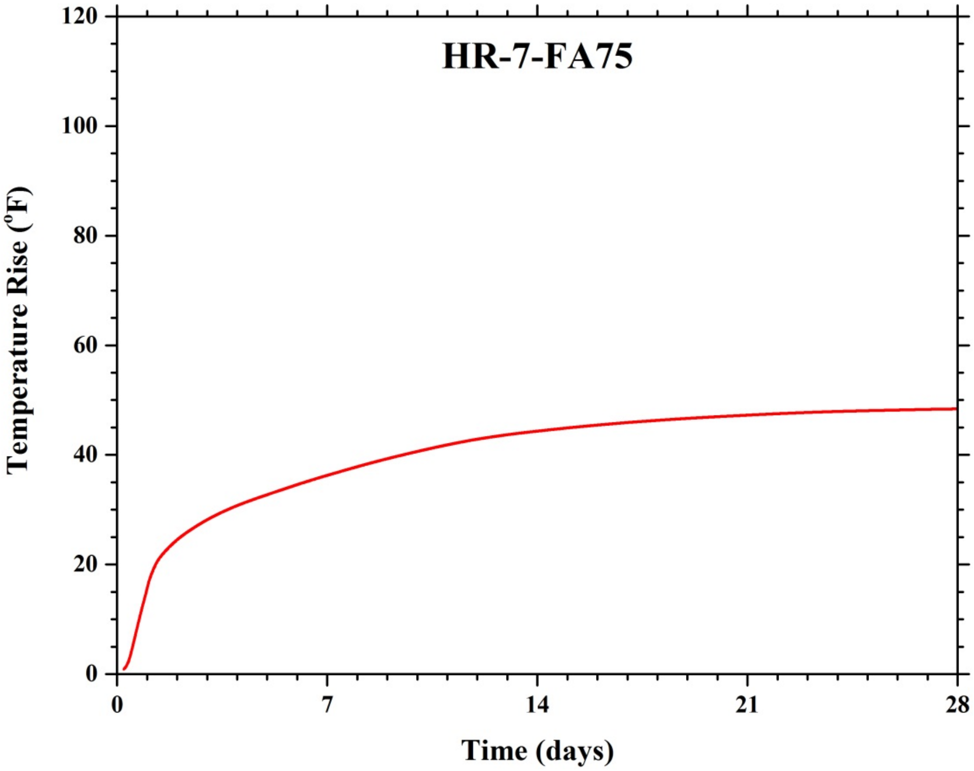

HR-4-OPC
Temperature Rise (°F)
0
20
40
60
80
100
120
Time (days)
0
7
14
21
28

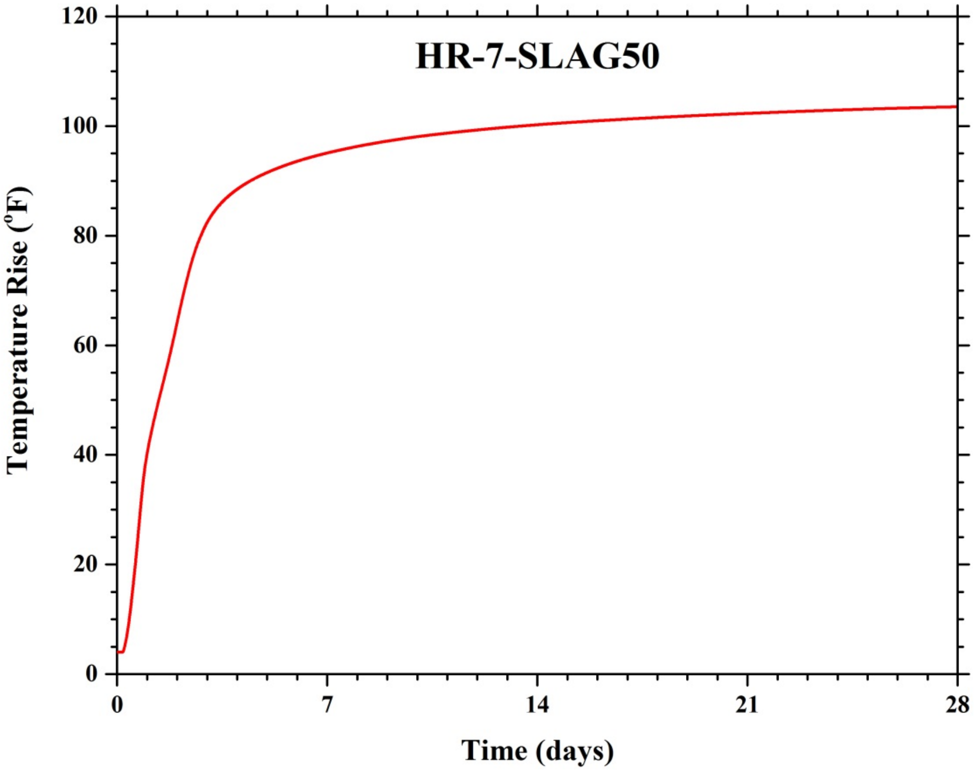

HR-7-OPC
Temperature Rise (^{o}F)
0
20
40
60
80
100
120
0
7
14
21
28
Time (days)

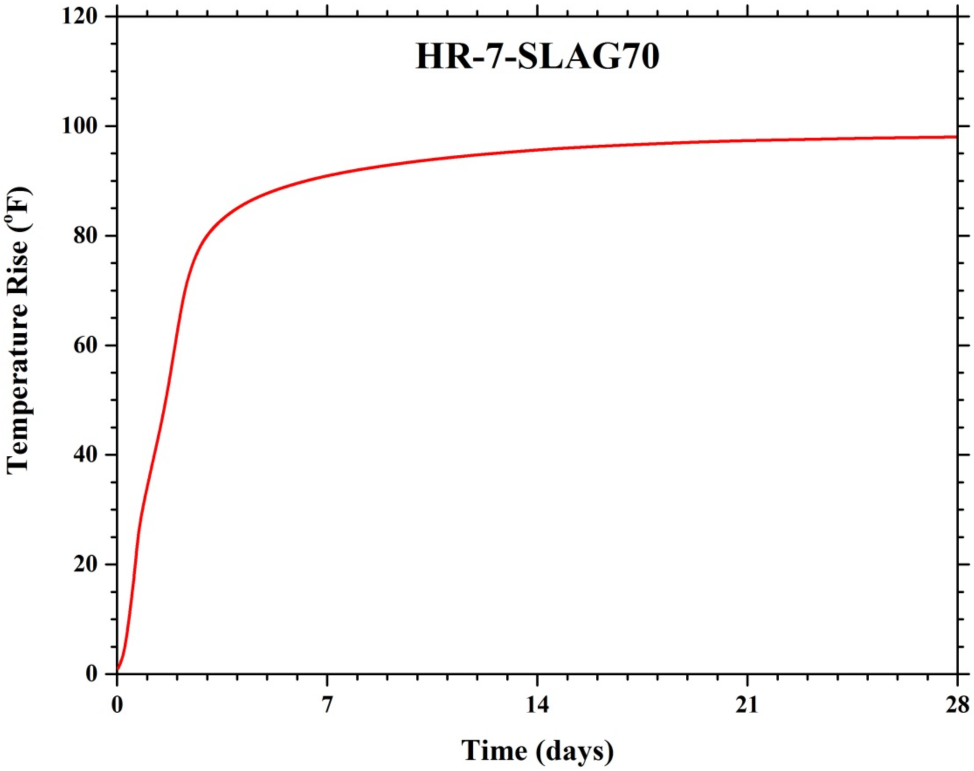

HR-7-OPC-0.58
Temperature Rise (^{o}F)
0
20
40
60
80
100
120
0
7
14
21
28
Time (days)


HR-7-FA25
Temperature Rise (°F)
120
100
80
60
40
20
0
0
7
14
21
28
Time (days)


HR-7-FA50
Temperature Rise (°F)
120
100
80
60
40
20
0
0
7
14
21
28
Time (days)


HR-7-FA75
Temperature Rise (°F)
0
20
40
60
80
100
120
Time (days)
0
7
14
21
28


HR-7-SLAG50
Temperature Rise (°F)
0
20
40
60
80
100
120
Time (days)
0
7
14
21
28


HR-7-SLAG70
Temperature Rise (^{o}F)
0
20
40
60
80
100
120
Time (days)
0
7
14
21
28

Appendix C. Temperature Rise from Savage et al. (1936)

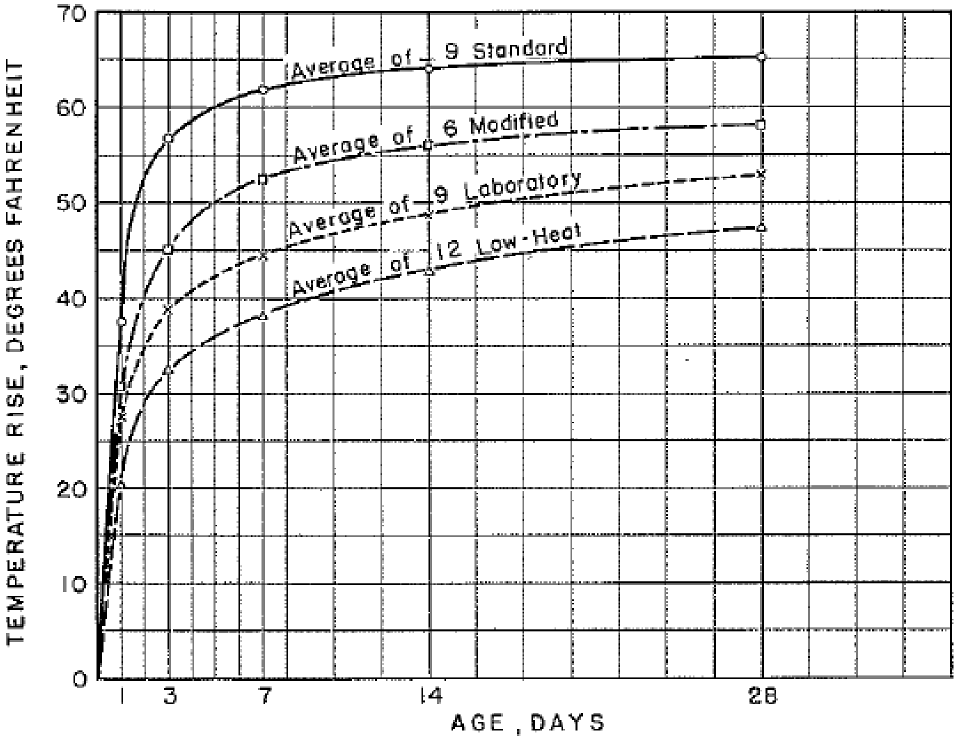


FIGURE 15—AVERAGE VALUES OF TEMPERATURE RISE IN MASS CONCRETE FOR VARIOUS TYPES OF CEMENTS

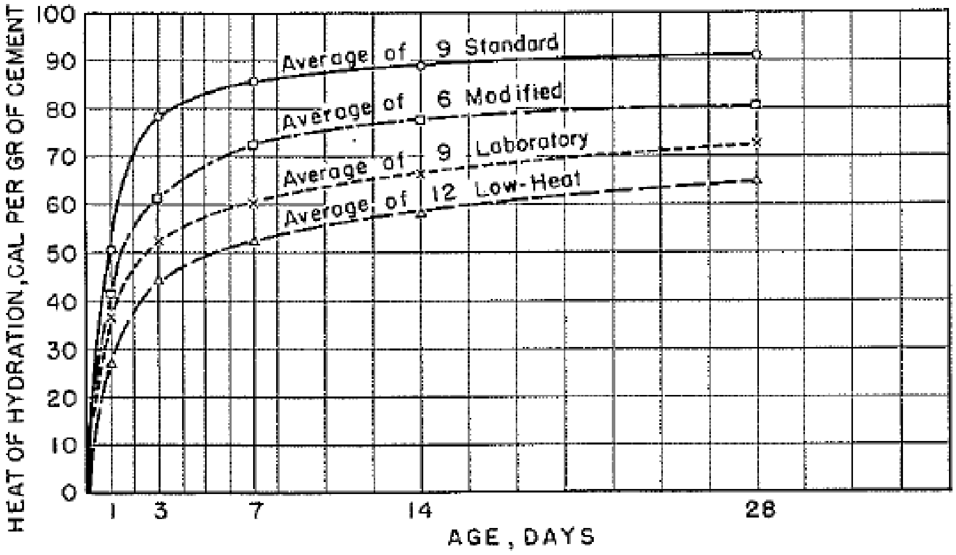


FIGURE 16—AVERAGE VALUES OF HEAT OF HYDRATION FOR VARIOUS TYPES OF PORTLAND CEMENTS

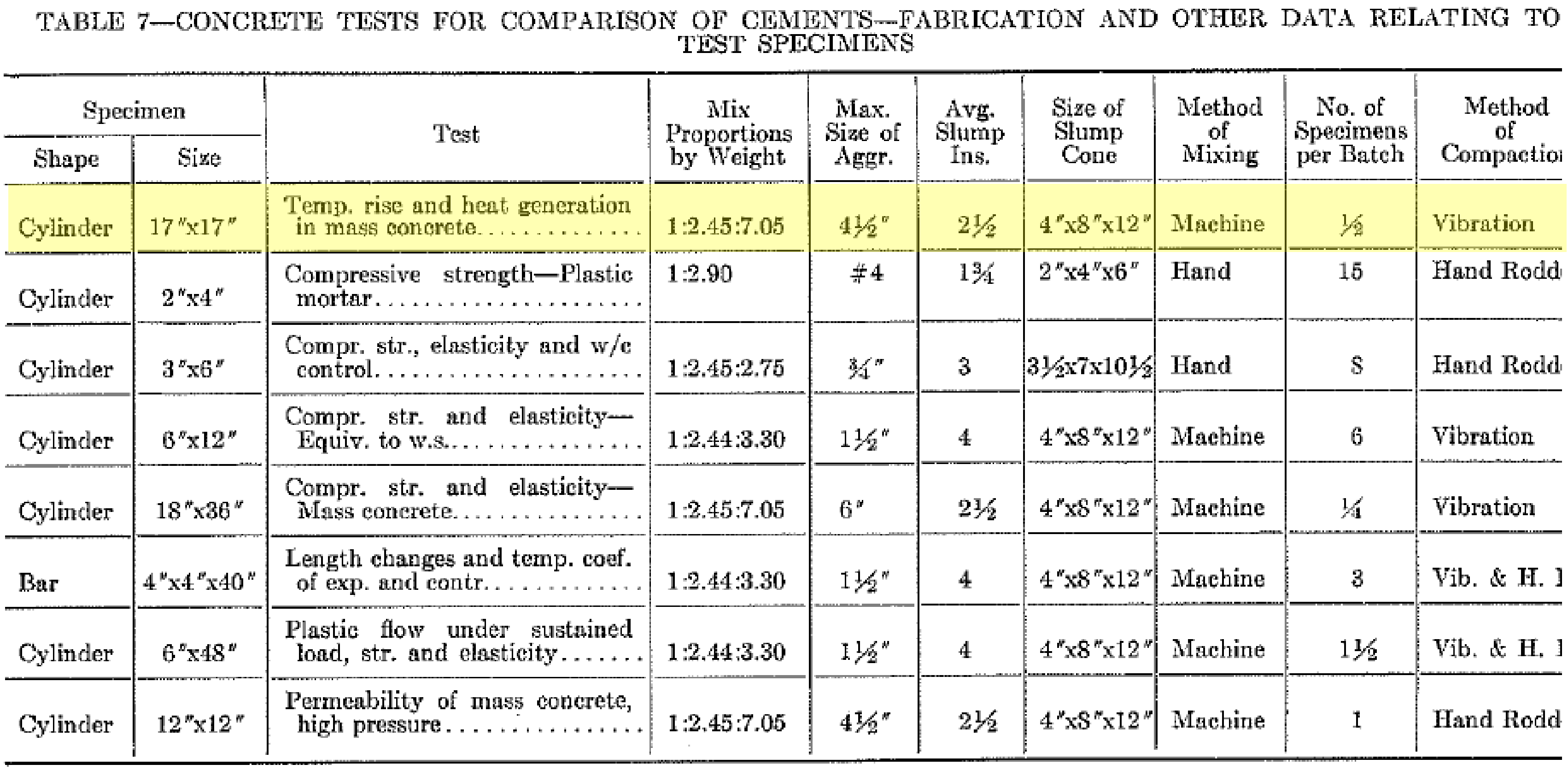
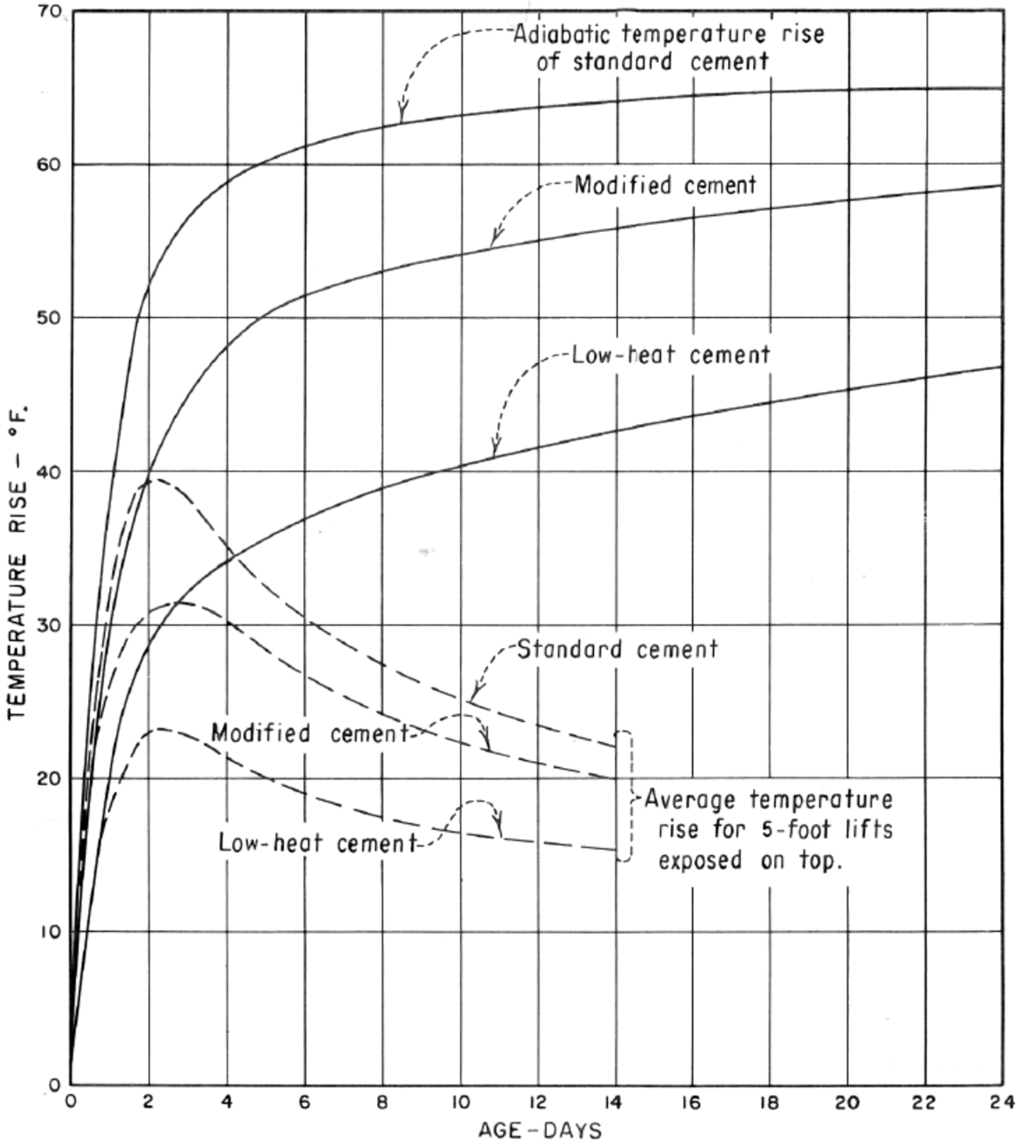


TABLE 7—CONCRETE TESTS FOR COMPARISON OF CEMENTS—FABRICATION AND OTHER DATA RELATING TO TEST SPECIMENS

Specimen		Test	Mix Proportions by Weight	Max. Size of Aggr.	Avg. Slump Ins.	Size of Slump Cone	Method of Mixing	No. of Specimens per Batch	Method of Compactio
Shape	Size								
Cylinder	17″x17″	Temp. rise and heat generation in mass concrete.............	1:2.45:7.05	4½″	2½	4″x8″x12″	Machine	½	Vibration
Cylinder	2″x4″	Compressive strength—Plastic mortar......................	1:2.90	#4	1¾	2″x4″x6″	Hand	15	Hand Rodd
Cylinder	3″x6″	Compr. str., elasticity and w/c control......................	1:2.45:2.75	¾″	3	3½x7x10½	Hand	8	Hand Rodd
Cylinder	6″x12″	Compr. str. and elasticity—Equiv. to w.s.................	1:2.44:3.30	1½″	4	4″x8″x12″	Machine	6	Vibration
Cylinder	18″x36″	Compr. str. and elasticity—Mass concrete................	1:2.45:7.05	6″	2½	4″x8″x12″	Machine	¼	Vibration
Bar	4″x4″x40″	Length changes and temp. coef. of exp. and contr............	1:2.44:3.30	1½″	4	4″x8″x12″	Machine	3	Vib. & H.
Cylinder	6″x48″	Plastic flow under sustained load, str. and elasticity.......	1:2.44:3.30	1½″	4	4″x8″x12″	Machine	1½	Vib. & H.
Cylinder	12″x12″	Permeability of mass concrete, high pressure................	1:2.45:7.05	4½″	2½	4″x8″x12″	Machine	1	Hand Rodd

Appendix D. Temperature Rise from Engineering Monograph 34

42 CONTROL OF CRACKING IN MASS CONCRETE STRUCTURES



Cement content - 1 bbl per cu yd
Diffusivity - 0.050 ft^2/hr

FIGURE 31.—*Temperature rise in mass concrete—type of cement.*

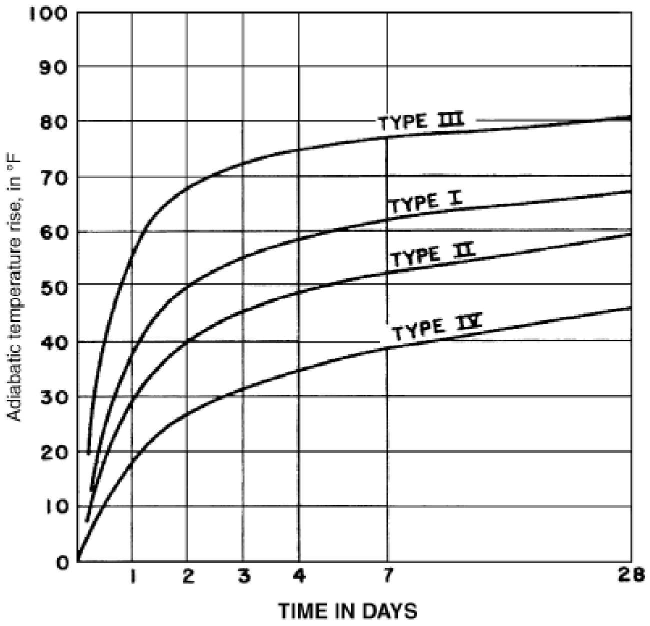
Appendix E. Example Calculations

Example 1 - Simple ACI Method

Given: Type II Cement
670 lb/yd^3 cement

Find: 28-day adiabatic temperature rise (°F)

Step 1:
Determine 28-day temperature rise for a Type II cement from Figure 4.2 of ACI 207.2R-07



$$T_{A\text{-}28} = 60\ °F$$

Step 2:
Correct for cement content. Figure 4.2 is based on 376 lb/yd^3

$$T_{A\text{-}28} = 60\ °F \times (670\ lb/yd^3)/(376\ lb/yd^3)$$

$$T_{A\text{-}28} = 60\ °F \times 1.78$$

$$\mathbf{T_{A\text{-}28} = 107\ °F}$$

Example 2 - ACI Method - Correcting for Fineness

Given: Type I/II Cement
670 lb/yd^3 cement
Blaine Fineness - 3900 cm^2/g
28-day Heat of Hydration - 86 cal/g
Find: Temperature Rise at 7 days

Step 1:
Assume Type I/II cement is an average of Type I and Type II cement. Determine fineness and heat of hydration of ACI cement

Cement Type	Wagner Fineness	Blaine Fineness	28-d HoH
I	1790	3196	87
II	1890	3375	76
I/II	*1840*	*3286*	*81.5*

Step 2:
Determine adiabatic temperature rise at 7 days and 28 days. Take average of Type I and Type II curve

$$T_{7\text{-}I} = 61\ °F,\ T_{28\text{-}I} = 68\ °F$$

$$T_{7\text{-}II} = 51\ °F,\ T_{28\text{-}II} = 60\ °F$$

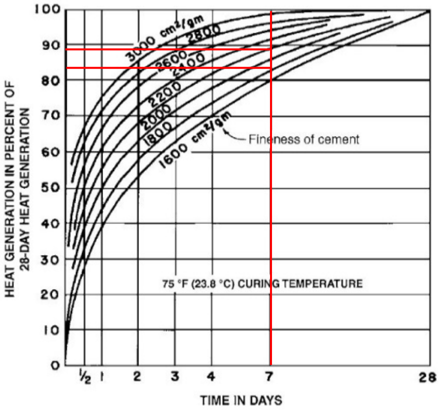
$$T_{7\text{-}I/II} = 56\ °F,\ T_{28\text{-}I/I}I = 64\ °F$$

Step 3:
Convert Blaine Fineness to Wagner Fineness (use factor of 0.56)

Wagner Fineness = 3900 x 0.56 = 2184 cm^2/g

Round up to 2200 cm^2/g

Step 4:
Correct for fineness using Figure 4.3 of ACI 207.2R-07. Use lines for 1800 cm^2/g and 2200 cm^2/g



$$f_{1800} = 82$$

$$f_{2200} = 89$$

$$\text{Correction factor at 7 days} = 89/82 = 1.08$$

Step 5:
Correct for heat of hydration. Use Equation 4-2 from ACI 207.2R-07. For a concrete mixture containing 376 lb of cement per
cubic yard of concrete: $H_a = 0.76h_g$ (°F). First, correct for 28-day, then reduce for 7-day

$$H_a = 0.76*(86-81.5) = 3.4\ °F \text{ (28-day correction)}$$

$$H_a = 3.4\ °F \times (56\ °F/64\ °F) = 3\ °F \text{ (7-day correction)}$$

Step 6:
Apply fineness correction factor and increased temperature from heat of hydration to base 7-day temperature rise

$$T_{7\text{-}I/II} = 56\ °F$$

$$T_{7\text{-}I/II\text{-}corrected} = 1.08 \times (56 + 3)\ °F = 63.7$$

$$\boldsymbol{T_{7\text{-}I/II\text{-}corrected} \approx 64\ °F}$$

Example 3 - Simple PCA Mathod

Given: Type II Cement, Class F Fly Ash
670 lb/yd^3 total cementitious, 50% Fly Ash
Find: 28-day adiabatic temperature rise (°F)

Step 1:
Calculate the equivalent cement content based on the equation from the PCA book "Mass Concrete for Buildings and Bridges".

Material	Equivalent Cement Factor
Cement	1
Fly Ash (Class F)	0.5
Fly Ash (Class C)	0.8
Silica Fume or Metakaolin	1.25
Slag (50% replacement)	0.9
Slag (70% replacement)	0.8

$$C_{eq} = \sum c_i W_i$$

$$C_{eq} = (1 \times 335\ lb/yd^3) + (0.5 \times 335\ lb/yd^3)$$

$$C_{eq} = 502.5\ lb/yd^3$$

Step 2:
Calculate the temperature rise of concrete. A factor of 0.14 is used, per the 2007 publication, although a factor of 0.16 has been used in more recent publications by the author.

$$T_{A\text{-}28} = 0.14 \times 502.5\ lb/yd^3$$

$$\boldsymbol{T_{A\text{-}28} = 70.35\ °F}$$

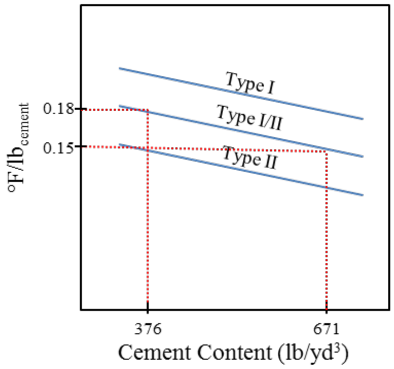
Example 4 - New Proposed Method

Given: Type I/II Cement, Class F Fly Ash

550 lb/yd^3 total cementitious, 50% Fly Ash

Find: 28-day adiabatic temperature rise (°F)

Step 1:
Determine the temperature rise per lb of cementitious content for a Type I/II cement. Interpolate between 376 and 671 lb/yd^3

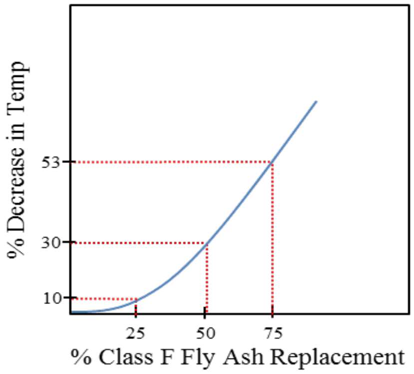


$$0.15 - y = (671-550) \times (0.15-0.18)/(671-376)$$
$$0.15 - y = -0.0123$$
$$y = 0.162 \text{ °F/lb}$$

Step 2:
Calculate the temperature rise for a 100% cement mixture

$$T_A = 0.162 \text{ °F/lb} \times 550 \text{ lb}$$
$$T_A = 89 \text{ °F}$$

Step 3:
Correct for the addition of 50% Class F Fly Ash



A 50% replacement would yield a 30% reduction in temperature rise

$$T_A = 89 \text{ °F} - (89 \times 0.30)$$
$$\mathbf{T_A = 62 \text{ °F}}$$