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Modeling Hydration of Cementitious Systems

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Concrete performance, including strength, susceptibility to delayed ettringite formation, and residual stress development are dependent on early-age temperature development. Concrete temperature prediction during hydration requires an accurate characterization of the concrete adiabatic temperature rise. This study presents the development of a model for predicting the adiabatic temperature development of concrete mixtures based on material properties (for example, cement chemistry and fineness and supplementary cementitious materials (SCM) chemistry), mixture proportions, and chemical admixture types and dosages. The model was developed from 204 semi-adiabatic calorimetry results and validated from a separate set of 58 semi-adiabatic tests. The final model provides a useful tool to assess the temperature development of concrete mixtures and thereby facilitate the prevention of thermal cracking and delayed ettringite formation in concrete structures.

Keywords: calorimetry; heat of hydration; modeling.

INTRODUCTION

Concrete temperature development during hydration is a major factor in determining the long-term strength, permeability, durability, and cracking probability. The mixture proportions, curing, and construction schedule can be optimized to control concrete temperature and improve concrete performance. To determine optimum mixture proportions and placement conditions, heat transfer software can be used to model the combined effects of the weather, member geometry, insulation, boundary conditions, and concrete heat of hydration to predict internal concrete temperatures. Such software requires the rate and amount of concrete heat generation as input parameters. Measuring the rate and amount of heat released during hydration to provide input for a model can take a week or longer per mixture in a specialized calorimeter and can be costly. Therefore, a comparison of several candidate mixtures using laboratory test results could require several weeks. A predictive model for the concrete heat released during hydration, based on the constituent materials and mixture proportions, would reduce the need for this costly testing. This study documents the test methods, materials, and statistical methods used to develop and validate a model for predicting the concrete heat release during hydration.

Concrete heat of hydration testing is conducted under isothermal, adiabatic, or semi-adiabatic conditions. Isothermal calorimetry measures the heat release rate for cement or mortar samples at a constant temperature and is performed using a conduction calorimeter. Isothermal calorimetry is generally best suited for determining the temperature sensitivity of a mixture. Adiabatic calorimetry measures the heat released for a concrete mixture that has no heat exchanged with the environment. Adiabatic testing requires the concrete to be completely thermally isolated from its surroundings, which is difficult to achieve under laboratory conditions. With semi-adiabatic calorimetry, instead of ensuring that no heat loss from the concrete occurs like with adiabatic calorimetry, the heat loss is measured and minimized by the use of insulation. The concrete adiabatic temperature rise is then back-calculated with the increased heat of hydration rate from the higher temperatures in adiabatic conditions taken into account. Semi-adiabatic calorimetry is much easier to perform than adiabatic calorimetry, and it can even be performed in the field.[1]

Higher temperature speeds the rate of the cementitious material hydration reactions. The influence of temperature on the hydration rate can be accounted for by the use of a maturity function. The equivalent age maturity function is commonly used with strength or degree of hydration calculations, as shown in Eq. (1)[2]

$$t_e(T_r) = \sum_0^t e^{-\frac{E_a}{R}\cdot\left(\frac{1}{T_C}-\frac{1}{T_r}\right)} \cdot \Delta t \tag{1}$$

where t_e (hours) is the equivalent age or time that the concrete would take to achieve the same property while being cured at an isothermal temperature at the reference temperature T_r (K); E_a is the apparent activation energy (J/mol); R is the universal gas constant (8.314 J/mol/K [10.732 ft^3 psia/°R/lb-mol]); T_C is the temperature of the concrete (K); and Δt is the time step used. In practical terms, the equivalent age of a concrete mixture is the amount of time that the concrete mixture would need to be cured at an isothermal reference temperature to reach the same property as the concrete under the different time-temperature history. The equivalent age maturity method has been shown to well account for the effects of different placement temperature[3] and curing conditions[1] on the concrete heat of hydration development.

The apparent activation energy term is a measure of the temperature sensitivity of the hydration reaction.[2,4,5] A mechanistic-empirical model was developed for predicting E_a by Poole[6] from isothermal calorimetry experiments, as shown in Eq. (2)

$$\begin{aligned} E_a = 41{,}230 + 1{,}416{,}000 \cdot \left[\left(p_{C_3A} + p_{C_4AF}\right) \cdot p_{Cement} \cdot p_{SO_3} \cdot p_{Cement}\right] \\ -347{,}000 \cdot p_{Na_2O_{eq}} - 19.8 \cdot Blaine \\ +29{,}600 \cdot p_{FA} \cdot p_{FA-CaO} + 16{,}200 \cdot p_{slag} - 51{,}600 \cdot p_{SF} \\ -3{,}090{,}000 \cdot WRRET - 345{,}000 \cdot ACCL \end{aligned} \tag{2}$$

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where p_{FA} is the wt.% fly ash in the mixture as a percent of total cementitious material; $p_{FA\text{-}CaO}$ is the wt.% CaO in fly ash; p_{slag} is the wt.% slag cement in the mixture as a percent of total cementitious material; p_{SF} is the wt.% silica fume in the mixture as a percent of total cementitious material; *Blaine* is the Blaine fineness of cement (m^2/kg); p_i is the mass of i component to total cement content ratio and $p_{Na_2O_{eq}}$ = wt.% Na_2O_{eq} in cement (0.658 × %K_2O + %Na_2O); *WRRET* is the ASTM Type B&D water reducer/retarder, wt.% solids per gram of cementitious material; *ACCL* is the ASTM Type C calcium-nitrate-based accelerator, wt. % solids per gram of cementitious material.

The concrete heat of hydration rate and total amount of heat produced are dependent on the concrete constituent materials used. C_3S and C_3A are known to be the largest contributors to the heat released by portland cement during hydration, making their contents in the cement a very important parameter.[7] Finer cement has a higher surface area-to-volume ratio, giving more surface in contact with water to react and a faster reaction. Supplementary cementitious materials (SCMs) generally release heat at a lower rate than portland cement, and the change in heat released is a function of the type and amount of SCM used.[8,9] Chemical admixtures, especially set control admixtures, can significantly affect the heat of hydration rate and the concrete element temperature development.[10] The water-cementitious materials ratio (*w/cm*) is also known to affect the total heat released per gram of cementitious material from hydration, as a higher *w/cm* will provide more water and available space for more of the cement to ultimately react.[11-15]

This study documents the development of a model for calculating the concrete heat of hydration based on a large data set of 204 concrete mixtures tested using semi-adiabatic calorimetry, evaluating the impacts of several compositional parameters. Additionally, a separate data set made up of the results of 42 semi-adiabatic calorimetry tests reported in the literature and 15 mixtures tested by the authors was used to validate the developed heat of hydration model. The goal of the hydration model is to provide a tool for practitioners to estimate the heat development in a variety of concrete mixtures without performing extensive time-consuming and costly experimental testing.

RESEARCH SIGNIFICANCE

A model that describes the effects of different concrete mixture constituents on hydration is needed to allow practitioners to quickly and accurately calculate the heat of hydration of different concrete mixtures to predict and optimize the concrete temperature development. This study presents an empirical model for calculating the heat of hydration of concrete mixtures. The model accounts for the effects of cement chemistry, aggregate type, *w/cm*, SCMs, chemical admixture type and dosage, and temperature on hydration.

BACKGROUND: EXISTING METHODS FOR HEAT OF HYDRATION DETERMINATION

The primary resource used by practitioners to guide decisions on heat development in mass concrete is ACI 207.2R, "Report on Thermal and Volume Change Effects on Cracking of Mass Concrete."[8] In the report, concrete adiabatic temperature rise curves are shown for different concrete placement temperatures and cement fineness based on calorimetry tests performed on cements over 60 years ago.[16] These curves provide rough guidance for standard cement types, but ACI 207.2R[8] recommends experimental testing to account for the effects of cement chemistry on the heat of hydration. With respect to SCMs, ACI 207.2R[8] provides very crude heat of hydration scale factors to account for the effects of fly ash, but ultimately suggests that testing be performed. For set control admixtures, ACI 207.2R[8] gives no guidance other than for the practitioner to ignore the contribution of these admixtures for preliminary calculations and perform testing when the results will be used for critical mass concrete structures.[8]

Another resource is an empirical model developed by Schindler and Folliard[9] for estimating the concrete heat of hydration. This model was based on semi-adiabatic calorimetry results from 13 concrete mixtures and heat of solution and conduction calorimetry results for 20 mixtures using a data set from Lerch and Ford.[9,17] The model has several years of use in pavement temperature predictions.[18] Schindler and Folliard[9] first assumed that the cement degree of hydration was proportional to the heat released, as shown in Eq. (3)

$$\alpha(t) = \frac{H(t)}{H_u} \tag{3}$$

where $\alpha(t)$ is the degree of hydration, $H(t)$ is the cumulative amount of heat released by the cement (J/gram) from time 0 to time t, and H_u is the total heat available for reaction (J/gram) as calculated from the cementitious properties in Eq. (4) and (5)

$$H_u = H_{cem} \cdot p_{cem} + 461 \cdot p_{slag} + 1800 \cdot p_{FA-CaO} \cdot p_{FA} \tag{4}$$

$$H_{cem} = 500 \cdot p_{C_3S} + 260 \cdot p_{C_2S} + 866 \cdot p_{C_3A} + 420 \cdot p_{C_4AF} + 624 \cdot p_{SO_3} + 1186 \cdot p_{FreeCa} + 850 \cdot p_{MgO} \quad (5)$$

where p_{cem} is the cement mass to total cementitious content ratio; and H_{cem} is the total heat of hydration of the cement (J/gram).[6,9,15,16,19-22] The coefficient used for slag cement of 461 was selected from literature values ranging from 355 to 461.[9,23,24] A three-parameter exponential degree of hydration was used to model the hydration development, as shown in Eq. (6)

$$\alpha(t_e) = \alpha_u \cdot \exp\left(-\left[\frac{\tau}{t_e}\right]^{\beta}\right) \quad (6)$$

where τ is the hydration time parameter (hours); β is the hydration slope parameter; and α_u is the ultimate degree of hydration. The τ term represents the time delay from mixing until setting; β represents the slope of the S-shaped curve; and α_u is the total amount of cement that has reacted at $t = \infty$, where $\alpha_u = 0$ for no hydration and $\alpha_u = 1$ is for complete hydration. Schindler and Folliard[9] then combined Eq. (1), (3) and (6) to give the heat release with time, as shown in Eq. (7)

$$Q_h(t) = H_u \cdot C_c \cdot \left(\frac{\tau}{t_e}\right)^{\beta} \cdot \left(\frac{\beta}{t_e}\right) \cdot \alpha_u \cdot \exp\left(-\left[\frac{\tau}{t_e}\right]^{\beta}\right) \cdot \exp\left(\frac{E_a}{R}\left(\frac{1}{T_r} + \frac{1}{T_c}\right)\right) \quad (7)$$

The concrete mixtures used for the semi-adiabatic testing by Schindler and Folliard[10] included three ASTM C150[25] Type I cements, one ASTM C618[26] Class F fly ash, one ASTM C618[26] Class C fly ash, and one ASTM C989[27] Grade 120 slag cement. Equations 8 through 10 show the equations developed by Schindler and Folliard[9] using nonlinear regression analysis to model α_u, τ, and β

$$\alpha_u = \frac{1.031 \cdot w/cm}{0.194 + w/cm} + 0.50 \cdot p_{FA} + 0.30 \cdot p_{slag} \leq 1.0 \quad (8)$$

$$\tau = 66.78 \cdot p_{C_3A}^{-0.154} \cdot p_{C_3S}^{-0.401} \cdot Blaine^{-0.804} \cdot p_{SO_3} \times \exp\left(2.187 \cdot p_{slag} + 9.50 \cdot p_{FA} \cdot p_{FA-CaO}\right) \quad (9)$$

$$\beta = 181.4 \cdot p_{C_3A}^{0.146} \cdot p_{C_3S}^{0.227} \cdot Blaine^{-0.535} \times p_{SO_3}^{0.558} \cdot \exp\left(-0.647 \cdot p_{slag}\right) \quad (10)$$

Equations 8 through 10 were validated using the results of eight semi-adiabatic calorimetry tests conducted at pavement field sites and published degree of hydration results.[14,28] The *w/cm* in Eq. (8) is derived from the research by Mills,[15] which showed that the ultimate degree of hydration of the cement is less than 100% and dependent on the *w/cm*.

A later study by Ge[29] developed equations for α_u, τ, and β of very similar form to those shown in Eq. (8) through (10). The model was based on a data set consisting of the results from 23 semi-adiabatic calorimetry tests and the same Lerch and Ford[17] data set used by Schindler and Folliard.[9] The key differences between this model and the Schindler and Folliard[9] model are that the total heat of hydration from slag is based off a slag cement Hydraulic Index based on the slag cement chemical composition, and the fly ash total heat of hydration used uses a linear but slightly different adjustment for the CaO content.

Both the Schindler and Folliard[9] and Ge[29] studies focused on concrete materials commonly used for pavements, and they may not be as accurate for concretes designed for other applications. Further, these models were based on data sets containing very few types and combinations of cementitious materials. Additionally, neither of the models account for the effects of chemical admixtures. It is clear that a model that accounts for a wider variety of cementitious materials and admixtures is needed to accurately predict concrete heat of hydration in structural and mass concrete applications.

EXPERIMENTAL MATERIALS AND METHODS

Semi-adiabatic calorimetry was used to quantify the heat of hydration parameters α_u, τ, and β, as described in Eq. (6), for 204 concrete mixtures with a wide range of compositions. Multi-variate regression analysis was used to develop a predictive model for the heat of hydration parameters. A separate set of 57 heat of hydration parameters was used to validate the developed empirical model.

Materials and experimental methods used for model development

Four ASTM C150[25] Type I cements (IA, IB, IC, and ID), ten Type I/II cements (I/IIA, I/IIB, I/IIC, I/IID, I/IIE, I/IIF, I/IIG, I/IIH, I/IIJ, and I/IIK), two Type III cements (IIIA and IIIB), and one Type V cement (V) were used in the model development. Table 1 shows the chemical and physical properties of the cements tested. Chemical and physical properties for the nine ASTM Class F fly ashes, four ASTM Class C fly ashes, two slag cements, one ultra-fine fly ash (UFFA), and one silica fume used in the model development are shown in Table 2. A variety of commercially available chemical admixtures were used, including an ASTM C494[30] Type A low-range water reducer (LRWR), an ASTM C494 Type B&D low-range water-reducer/retarder (WRRET), an ASTM C494 Type A and F midrange water reducer (MRWR), an ASTM C494 Type F naphthalene sulfonate high-range water reducer (HRWR), an ASTM C494 Type F polycarboxylate high-range water reducer (PCHRWR), a calcium nitrate based ASTM C494 Type C accelerator (ACCL), and air entraining agents (AEA). The concrete was mixed according to ASTM C192.[31] The mixture proportions are shown in Appendix A, Tables A-1 to A-17.[*]

Semi-adiabatic calorimetry was performed using three commercial calorimeters and one constructed by the authors described elsewhere.[3] The procedure for calculating the α_u, τ, and β values using Eq. (6) for a given concrete mixture from semi-adiabatic calorimetry was as follows:

- Cast, seal, and weigh 150 x 300 mm (6 x 12 in.) concrete cylinder according to ASTM C192.[31]

[*]The Appendix is available at **www.concrete.org** in PDF format as an addendum to the published paper. It is also available in hard copy from ACI headquarters for a fee equal to the cost of reproduction plus handling at the time of the request.

Table 1—Physical and chemical properties of cements tested for this study

	IA	IB	IC	ID	I/IIA	I/IIB	I/IIC	I/IID	I/IIE	I/IIF	I/IIG	I/IIH	I/IIJ	I/IIK	IIIA	IIIB	V
SiO_2, %	19.2	19.3	20.5	21.3	20.6	20.8	21.0	20.5	20.4	19.4	20.6	20.1	20.6	21.3	19.7	19.8	21.6
Al_2O_3, %	5.3	5.1	5.4	5.3	4.8	3.9	4.1	4.9	4.7	4.8	5.9	4.7	4.8	5.0	5.3	4.8	4.0
Fe_2O_3, %	2.3	3.1	2.0	1.9	3.2	3.7	3.8	3.3	3.4	3.2	2.7	3.0	3.2	3.3	2.0	3.6	5.3
CaO, %	63.2	61.5	64.5	63.6	64.3	64.5	63.4	64.4	64.8	65.2	63.0	64.2	63.9	62.0	64.1	64.3	63.1
MgO, %	1.1	2.6	1.2	1.3	1.5	1.0	1.3	1.5	0.8	1.4	1.0	1.4	1.8	2.0	1.2	0.8	0.8
Na_2O, %	0.1	0.2	0.1	0.1	0.2	0.2	0.1	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.3
K_2O, %	1.0	0.9	0.6	0.6	0.4	0.6	0.6	0.4	0.7	0.4	0.8	0.5	0.5	0.4	0.5	0.7	0.2
Na_2O_{eq}, %	0.8	0.9	0.5	0.5	0.4	0.6	0.5	0.5	0.6	0.4	0.7	0.5	0.6	0.5	0.5	0.5	0.4
TiO_2, %	0.3	0.2	0.3	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.3	0.3	0.2	0.2
MnO_2, %	0.0	0.1	0.0	0.0	0.5	0.0	0.6	0.4	0.3	0.3	0.3	0.3	0.0	0.4	0.0	0.1	0.1
P_2O_5, %	0.2	0.2	0.2	—	0.1	0.0	0.2	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.2	0.3	0.0
SrO, %	0.1	0.2	0.1	—	0.1	0.0	0.2	0.1	0.2	0.0	0.2	0.0	0.1	0.0	0.1	0.0	0.1
BaO, %	0.0	0.0	0.0	—	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SO_3, %	3.2	4.2	3.4	3.6	2.8	2.4	3.0	2.8	2.7	2.4	3.1	2.5	2.5	2.6	4.4	3.5	2.7
LOI, %	4.1	2.4	1.8	—	1.2	2.7	1.5	1.4	1.6	2.4	1.8	2.7	2.0	2.4	2.0	1.9	1.6
Free CaO, %	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.6	0.0	0.5	0.0	0.5	0.0	0.0	0.0
ASTM C150 Bogue compounds																	
C_3S, %	63.1	46.2	58.3	49.0	60.4	66.5	56.5	60.7	64.9	68.8	47.5	65.3	59.9	45.2	60.2	64.1	49.9
C_2S, %	7.4	23.2	14.7	24.0	13.5	9.4	17.7	12.9	9.4	3.7	23.2	8.5	13.8	26.9	11.2	8.5	24.4
C_3A, %	10.3	8.7	11.0	10.9	7.3	4.0	4.6	7.5	6.8	7.3	11.1	7.5	7.3	7.5	10.6	6.5	1.8
C_4AF, %	7.0	9.6	6.1	5.7	9.7	11.4	11.5	10.0	10.3	9.6	8.3	9.1	9.8	10.1	6.2	10.9	16.1
Results from Rietveld analysis																	
C_3S, %	61.0	57.2	61.2	58.8	55.5	55.7	64.0	62.9	64.5	67.6	54.0	57.4	55.7	58.5	64.6	54.0	49.0
C_2S, %	15.6	15.1	16.0	19.2	17.4	21.1	15.3	11.0	15.3	7.3	18.6	16.0	18.0	13.8	11.8	21.7	26.4
C_3A, %	9.6	5.3	13.1	11.4	6.8	4.0	5.1	6.7	4.4	5.4	9.9	6.3	5.0	6.2	12.4	5.7	4.4
C_4AF, %	6.0	9.6	3.5	2.2	10.7	10.7	11.0	10.1	10.8	10.1	6.6	10.1	10.5	10.0	4.0	10.2	12.1
CSH_2 (gypsum), %	5.4	7.1	5.7	6.1	4.8	4.1	5.1	4.7	4.5	4.1	5.3	4.3	4.2	4.4	7.5	5.9	4.7
Periclase, %	0.0	0.9	0.0	0.8	0.6	0.0	0.0	0.6	0.0	0.5	0.0	0.7	1.1	0.9	0.0	0.0	0.0
Gypsum, %	0.4	6.6	1.4	2.6	0.9	0.0	1.6	2.2	1.5	1.6	2.4	1.2	2.3	1.6	2.4	0.0	2.3
Hemihydrate, %	1.2	0.8	1.5	1.9	1.9	2.5	0.6	1.8	0.5	2.2	1.1	2.1	0.9	2.7	2.4	3.7	2.0
Anhydrite, %	0.7	0.4	0.6	0.8	0.9	0.7	0.6	0.6	0.6	0.4	0.5	0.5	0.6	0.5	0.6	0.6	0.4
K_2SO_4, %	1.0	1.6	1.5	2.0	0.5	0.7	0.0	0.0	0.4	0.3	1.2	0.8	0.7	1.3	0.8	1.3	0.9
$CaCO_3$, %	3.6	1.7	0.8	0.0	2.5	3.2	1.0	2.8	1.2	3.6	5.7	4.0	4.1	3.2	0.7	1.5	2.5
Blaine (m^2/kg)	391	389	350	330	405	365	349	381	354	393	364	393	330	330	552	539	409

- Insert thermocouple into concrete cylinder, insert cylinder into semi-adiabatic calorimeter, and replace insulated calorimeter lid. Record temperature rise of concrete cylinder and heat flux in semi-adiabatic calorimeter for 150 hours.
- Calculate the concrete apparent activation energy E_a using Eq. (2) and H_u. A uniform increase in α_u was seen with the addition of silica fume, while the contribution of the silica fume to H_u was found to be between 290 and 370 J/gram, with a value of 330 J/gram selected for use in this study.[6] Equation (3) was updated to include the contribution of silica fume to H_u as shown in Eq. (11)

$$H_u = H_{cem} \cdot p_{cem} + 461 \cdot p_{slag} + 1800 \times p_{FA-CaO} \cdot p_{FA} + 330 p_{SF} \quad (11)$$

- Use a least-squares method to fit the simulated concrete cylinder temperature to the measured cylinder temperature by changing the α_u, τ, and β, as shown in Eq. (6).

Materials and experimental methods used for model validation

A separate heat of hydration database from semi-adiabatic calorimetry testing was developed for validation of the empirical model developed. The database contained

Table 2—Physical and chemical properties of SCMs tested for this study

	FF1	FF2	FF3	FF4	FF5	FF6	FF7	FF8	FF9	FC1	FC2	FC3	FC4	UFFA	SF	S1	S2
SiO_2, %	56.6	51.7	46.7	49.5	53.1	55.7	47.8	53.4	59.9	37.3	33.1	37.4	34.5	50.7	94.3	34.5	—
Al_2O_3, %	30.7	24.8	19.7	17.6	28.3	19.4	18.1	20.0	24.2	19.8	18.4	17.7	20.4	26.6	0.0	11.4	—
Fe_2O_3, %	4.9	4.2	5.1	5.5	8.1	4.2	5.0	7.2	4.8	6.2	5.4	5.9	5.7	4.7	0.1	0.7	—
CaO, %	0.7	13.1	18.4	19.5	1.3	13.1	19.9	12.2	5.1	23.1	28.9	25.9	26.5	10.9	0.5	41.7	—
MgO, %	0.7	2.3	3.0	2.8	1.0	2.9	3.3	2.8	1.2	4.6	5.3	5.2	4.7	2.2	0.6	7.3	—
Na_2O	0.1	0.2	1.8	0.6	0.5	0.8	0.8	0.5	0.3	1.7	1.6	1.6	1.8	0.4	0.1	0.1	—
K_2O	2.3	0.8	0.9	1.0	2.6	0.9	0.9	1.2	1.1	0.1	0.4	0.6	0.5	1.0	1.0	0.4	—
Na_2O_{eq}, %	1.6	0.7	2.3	1.2	2.3	1.4	1.4	1.3	1.1	1.8	1.9	2.0	2.1	1.1	0.7	0.4	—
SO_3, %	0.0	0.5	0.8	1.1	0.0	0.5	1.2	0.6	0.3	1.5	2.3	1.8	1.7	1.0	0.2	1.9	0.4
LOI, %	2.1	0.2	0.4	0.4	2.8	—	0.5	0.2	—	0.7	0.3	0.5	0.3	0.4	3.1	0.8	—
Blaine, m^2/kg	147	166	420	296	—	300	296	300	300	348	300	588	—	394	20000	332	552

mixture and heat of hydration parameters determined from semi-adiabatic calorimetry from 15 tests performed by the authors. Additionally, sufficient information was available from 13 tests on laboratory made concrete from Schindler and Folliard,[9] seven field tested concrete mixtures from Schindler,[28] and 22 concrete mixtures from Ge[29] to include them in the validation data set. The chemical and physical properties for the cements and SCMs tested by the authors for the validation study are included in Tables 1 and 2, whereas those from literature that were used in the validation data set are shown in Tables 3 and 4. The mixture proportions and heat of hydration parameters for the validation data set are contained in Appendix A, Table A-18.

EXPERIMENTAL TESTING AND MODEL DEVELOPMENT RESULTS

A nonlinear, multi-variate regression analysis was conducted to model the concrete heat of hydration parameters from the experimental data collected for the model data set. The first step used in the model development was to identify the trends in the hydration parameters that were visible without multi-variate regression analysis. Next, a specified number of combinations of the independent variables are analyzed and ranked according to their coefficient of determination (R^2). Additionally, the correlation coefficient $r(x_1, x_2)$ between each of the variables (x_1 and x_2) was calculated to ensure that the variables were truly independent. For the purposes of this study, $r(x_1, x_2) < 0.65$ was chosen as a sufficiently weak correlation between two variables to allow both to be included in the model for α_u, β, and τ. The combination of variables that had the highest R^2 and a correlation coefficient for any two variables less than 0.65 was considered a candidate for the model. Next, an analysis of variance (ANOVA) for Type I and III errors was performed on each potential variable combination. A Type I error measures the probability that the model shows a relationship between an independent variable and the dependent variable (in this case, E_a) when there is really no relationship.[32] A Type III error evaluates the probability that the choice of independent variables shows a statistical correlation, but that the wrong direction or variable has been chosen.[32] Variables with a probability greater than 5% of Type I or III errors were not included in the model.

A least squares regression analysis was used to determine the final coefficients used in the model. To use a least squares regression analysis however, it was necessary to break the data into discrete points. The degree of hydration at 18 different ages was calculated for the concrete mixtures using Eq. (1) through (5), which gave a discrete estimate of the degree of hydration for each concrete mixture. The experimental results were then compared to the modeled results from the nonlinear regression analysis. The regression analysis finally produced a multi-variate model of the hydration parameters (α_u, β, and τ).

Table 3—Physical and chemical properties of cements from literature

	AS1	AS2	AS3	AS4	AS5	AS6	AS7	AS8	AS9	Z1
SiO_2, %	—	—	—	—	—	—	19.9	20.9	20.1	20.8
Al_2O_3, %	—	—	—	—	—	—	5.7	5.0	5.3	4.5
Fe_2O_3, %	—	—	—	—	—	—	2.9	1.8	3.2	3.5
CaO, %	—	—	—	—	—	—	63.6	65.4	65.5	62.3
MgO, %	1.0	3.8	1.0	2.0	1.2	3.7	1.3	1.4	0.6	2.9
Na_2O, %	—	—	—	—	—	—	—	—	—	0.1
K_2O, %	—	—	—	—	—	—	—	—	—	0.7
Na_2O_{eq}, %	0.6	0.5	0.6	0.6	0.5	0.5	0.7	0.5	0.7	0.5
SO_3, %	2.8	2.3	3.4	2.8	3.2	2.3	3.5	2.9	3.3	2.8
LOI, %	—	—	—	—	—	—	1.9	1.4	1.2	0.1
Free CaO, %	0.8	0.8	2.3	2.0	1.0	0.7	2.9	1.0	0.8	—
C_3S, %	53.0	60.0	56.0	57.0	53.0	60.0	57.0	63.0	64.0	53.1
C_2S, %	23.0	14.0	16.0	18.0	21.0	14.0	14.0	12.0	9.0	19.5
C_3A (%)	6.0	5.3	11.0	6.0	5.0	6.0	10.0	10.0	8.0	6.1
C_4AF, %	10.0	10.0	7.0	10.0	12.0	10.0	8.0	6.0	10.0	10.5
Blaine, m^2/kg	374	362	342	350	350	362	358	354	367	373

Summary of hydration trends

The calculated heat of hydration parameters for the concrete mixtures in the model development data set are shown in Tables A-1 to A-17 in Appendix A. The 95% confidence level for statistically significant differences in heat of hydration parameters calculated from two different semi-adiabatic calorimetry tests is 8.8% for α_u, 20.9% for τ, and 16.9% for β.[3] Table 5 summarizes the effects of different SCMs, chemical admixtures, placement temperature, cement fineness, and *w*/*cm* on α_u, τ, and β.

Table 4—Physical and chemical properties of SCMs from literature

	FF10 AS	FF11 AS	FF12 AS	FF13 ZG	FC5 AS	FC6 AS	FC7 AS	FC8 AS	FC9 ZG	FC10 ZG	FC11 ZG	S3 AS	S4 ZG	S5 ZG	S6 ZG
SiO_2, %	57.3	58.2	54.1	45.3	32.7	39.6	32.4	35.6	31.8	32.6	46.9	—	35.7	37.2	37.3
Al_2O_3, %	—	—	26.2	23.0	—	—	—	21.4	19.0	19.3	15.1	—	11.2	9.2	9.0
Fe_2O_3, %	—	—	3.0	23.5	—	—	—	5.6	6.0	6.5	7.1	—	0.7	0.9	0.7
CaO, %	10.6	10.8	10.8	1.5	24.7	25.3	25.4	24.3	27.1	28.9	16.8	—	36.6	37.1	36.7
MgO, %	—	—	2.4	0.6	—	—	—	4.8	4.5	4.6	4.9	—	10.1	10.2	10.3
Na_2O, %	—	—	—	0.4	—	—	—	—	2.1	1.9	3.3	—	0.3	0.3	0.3
K_2O, %	—	—	—	1.8	—	—	—	—	0.3	0.4	2.2	—	0.4	0.4	0.4
Na_2O_{eq}, %	0.3	0.4	0.3	1.5	1.2	1.2	1.6	1.4	2.3	2.1	4.7	—	0.6	0.6	0.6
SO_3, %	—	—	0.3	0.3	—	—	—	1.2	3.5	2.5	1.3	1.6	—	—	—
LOI, %	—	—	0.1	1.6	—	—	—	0.3	0.2	0.1	0.1	—	—	—	—
Blaine, m^2/kg	—	—	—	—	—	—	—	—	—	—	—	506	—	—	—

Effect of *w/cm*

The *w/cm* was found to have a significant effect on the ultimate degree of hydration of the cement α_u,[3] confirming previous work.[15,32] The *w/cm* was found to have very little effect on the other hydration variables τ and β, mainly because an increase in *w/cm* does not greatly change the rate of hydration, only the total amount.[3]

Effect of cement

Cement chemical and physical properties were found to affect the heat of hydration parameters, although not as much as previously reported.[4,8] The τ value for all cements ranged from 9.3 hours for Type III cement to 15.0 hours for Type V cement, with an average value of approximately 12.0 hours. The cement fineness increased the heat of hydration rate only slightly compared to the Type I or Type I/II cements. This finding contrasts with the large effects of cement fineness on heat of hydration shown in ACI 207.2R,[9] perhaps because the cements used in this study were much finer than commonly available when the ACI 207.2R heat of hydration curves were developed.[34] The cement composition, particularly the C_3A content, did affect the heat of hydration development moderately.

Effect of SCM

Slag cement and Class C fly ash had a large and similar effect on the concrete heat of hydration. Both the slag cement and Class C fly ash retarded the concrete, as evidenced by an increase in τ. They also significantly decreased the rate of heat development as measured by β. For example, the addition of slag cement raised τ from 25 to 45 hours and lowered β from 0.75 to 0.45. The slag cement increased α_u up to a point, after which an increase in the slag cement replacement level decreased α_u. This means that the slag cement or Class C fly ash delays the heat released from hydration, but it does not necessarily reduce the total amount of heat. This means that more moderate size concrete structures that can dissipate much of the hydration heat to the environment during the first week of hydration are likely to benefit more from the use of Class C fly ash or moderate amounts of slag cement than larger concrete structures, such as dams, where the conditions are closer to being adiabatic. It should be noted that only Grade 120 slag cement was tested in this study. Other grades of slag cement could have different results.

Class F fly ash with very low CaO contents showed a decrease in the heat of hydration proportionate to the cement mass replacement during the 150 hours of hydration tested in this study. This indicates that the effects of fly ash on early-age hydration are mostly caused by dilution. UFFA affected the heat of hydration development similarly to the parent fly ash from which it was derived.[35] Like Class F fly ash, silica fume showed very little effect on the concrete heat of hydration rate. Silica fume did slightly increase α_u.

The pozzolanic reaction with SCMs in concrete is a slow reaction as evidenced by the large strength increase usually found between 28 and 91 days. Semi-adiabatic calorimetry was performed for each mixture for 150 hours in this study, and it may not have adequately characterized the heat of hydration after that point.

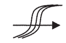
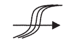
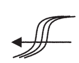
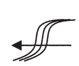
Effect of chemical admixtures

A variety of chemical admixtures were tested. ASTM Type A LRWR had a generally mild effect on the hydration parameters. The rate of hydration parameter β increased slightly with the use of LRWR. The LRWR had no effect on τ in most concrete mixtures, although a few mixtures had increased τ values. Types B and D LRWR/retarder (WRRET) increased both β and τ substantially, while lowering α_u. An ASTM Type C accelerator (ACCL) decreased τ. Figure 1 shows the effects of a WRRET and an ACCL on the adiabatic temperature rise for cement IA, with the decrease in time to setting apparent with the use of an ACCL and the increasing time to setting with increased WRRET dosage. Both the NHRWR and PCHRWR increased β, lowered α_u, but did not significantly affect τ. The MRWR tested was found to slightly retard hydration. LRWR, WRRET, and ACCL tended to show some interaction with SCMs. The addition of SCMs and chemical admixtures had a greater effect on the behavior of the mixture and tended to magnify the differences between cements. Further insights into the behavior of the admixtures were taken from the results of the multi-variate statistics analysis; these are discussed in the following sections.

Regression analysis results

Nonlinear regression analysis was performed on the calibration data set for each of the cement phase composition analysis methods used in the study, either calculated using Rietveld refinement[36] of the cement X-ray diffraction

Table 5—Effect of different mixture characteristics on exponential model hydration parameters

Variable	Range of tests	Effect on τ	Effect on β	Effect on α_u
Fly ash, % replacement	15 to 55			
Fly ash, CaO%	0.7 to 28.9			Varies
Slag cement	30 to 70%	Large 	Small 	Varies
Silica fume	5 to 10%	None	None	Small 
LRWR	0.22 to 0.29%	Varies	Small 	Varies
WRRET	0.18 to 0.53%	Large 	Large 	Large 
MRWR	0.34 to 0.74%	Large 	Small 	Varies
HRWR	0.78 to 1.25%	None	Small 	Large 
PCHRWR	0.27 to 0.68%	None	Small 	Large 
ACCL	0.74 to 2.23%	Small 	None	Varies
AEA	0.04 to 0.09%	None	None	None 
Increasing *w*/*cm*	0.32 to 0.68	None	None	Large 
Placement temperature	15 to 38°C (50 to 100°F)	None	None	None
Increase cement fineness	350 to 540 m^2/kg	Small 	Small 	Varies

Notes: LRWR is ASTM C494 Type A low-range water reducer; WRRET is ASTM C494 Types B and D low-range water reducer/retarder; MRWR is ASTM C494 Types A and F mid-range water reducer; HRWR is ASTM C494 Type F napthalene sulfonate high-range water reducer; PCHRWR is ASTM C494 Type F polycaboxylate high-range water reducer; and ACCL is ASTM C494 Type C accelerator.

pattern or using the Bogue method.[25] Cement phase composition analysis by Rietveld refinement is known to be more accurate, especially for the C_3A content.[37,38] Variables for each model were chosen so that only the method of cement analysis changed. The results based on Rietveld data[37] for α_u, β, and τ are shown in Eq. (12) through (14), respectively

$$\alpha_u = \frac{1.031 \cdot w/cm}{0.194 + w/cm} + \exp\begin{pmatrix} -0.297 - 9.73 \cdot p_{C_4AF} \cdot p_{cem} \\ -325 \cdot p_{Na_2O_{eq}} \cdot p_{cem} \\ -8.90 \cdot p_{FA} \cdot p_{FA-CaO} \\ -331 \cdot WRRET - 93.8 \cdot PCHRWR \end{pmatrix} \quad (12)$$

$$\tau = \exp\begin{pmatrix} 2.95 - 0.972 \cdot p_{C_3S} \cdot p_{cem} + 152 \cdot p_{Na_2O} \cdot p_{cem} + 1.75 \cdot p_{slag} \\ + 4.00 \cdot p_{FA} \cdot p_{FA-CaO} - 11.8 \cdot ACCL + 95.1 \cdot WRRET \end{pmatrix} \quad (13)$$

$$\beta = \exp\begin{pmatrix} -0.418 + 2.66 \cdot p_{C_3A} \cdot p_{cem} - 0.864 \cdot p_{slag} \\ + 108 \cdot WRRET + 32.0 \cdot LRWR + 13.3 \cdot MRWR \\ + 42.5 \cdot PCHRWR + 11.0 \cdot NHRWR \end{pmatrix} \quad (14)$$

where p_i is the mass of i component to total cement content ratio as determined by Rietveld analysis[37]; p_{Na_2O} is the wt.% Na_2O in cement; $p_{Na_2O_{eq}}$ is the wt.% alkalis as Na_2O equivalent; p_{cem} is the wt. % cement in mixture; LRWR is

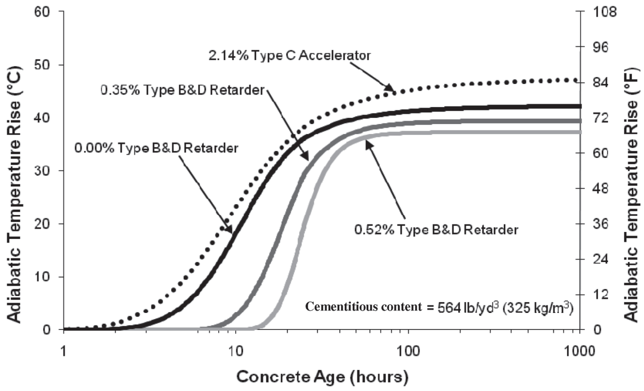


Fig. 1—Effects of WRRET and ACCL on adiabatic temperature rise of concrete containing Cement IA.

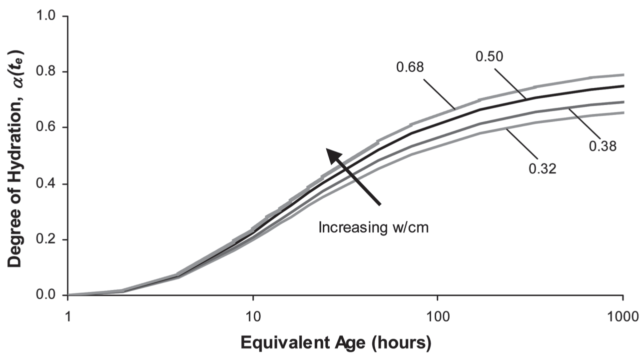


Fig. 2—Effect of w/cm *on degree of hydration.*

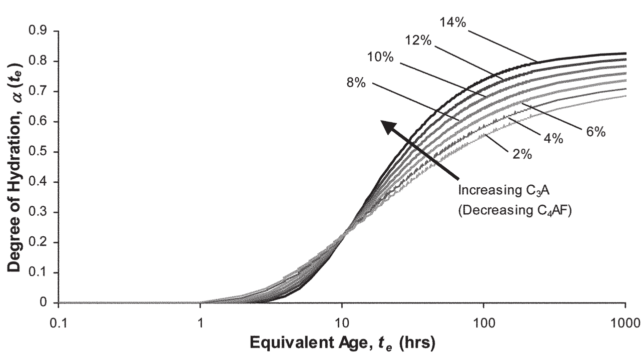


Fig. 3—Effect of C_3A/C_4AF on degree of hydration.

the ASTM Type A water reducer; MRWR is the midrange water reducer; NHRWR is the ASTM Type F naphthalene or melamine-based high-range water reducer; and PCHRW is the ASTM Type F polycarboxylate-based high-range water reducer. All SCM dosages are by mass ratio of cementitious material. All admixture dosages are percent solids (by mass) per mass of cementitious material.

The results based on oxide analysis and Bogue[25] calculations for α_u, β, and τ are shown in Eq. (15) to (17)

$$\alpha_u = \frac{1.031 \cdot w/cm}{0.194 + w/cm} + \exp\begin{pmatrix} -0.0885 - 13.7 \cdot p_{C_4AF} \cdot p_{cem} \\ -283 \cdot p_{Na_2O+0.658*K_2O} \cdot p_{cem} \\ -9.90 \cdot p_{FA} \cdot p_{FA-CaO} \\ -339 \cdot WRRET - 95.4 \cdot PCHRWR \end{pmatrix} \quad (15)$$

$$\tau = \exp\begin{pmatrix} 2.92 - 0.757 \cdot p_{C_3S} \cdot p_{cem} + 98.8 \cdot p_{Na_2O} \cdot p_{cem} + 1.44 \cdot p_{slag} \\ +4.12 \cdot p_{FA} \cdot p_{FA-CaO} - 11.4 \cdot ACCL + 98.1 \cdot WRRET \end{pmatrix} \quad (16)$$

$$\beta = \exp\begin{pmatrix} -0.464 + 3.41 \cdot p_{C_3A} \cdot p_{cem} - 0.846 \cdot p_{slag} \\ +107 \cdot WRRET + 33.8 \cdot LRWR + 15.7 \cdot MRWR \\ +38.3 \cdot PCHRWR + 8.97 \cdot NHRWR \end{pmatrix} \quad (17)$$

where p_i is the mass of i component to total cement content ratio as determined by Bogue[25] calculations; p_{Na_2O} is the wt.%Na_2O in cement; and $p_{Na_2O+0.658 \cdot K_2O}$ is the wt.% alkalis as Na_2O equivalent.

The coefficients in Eq. (12) through (14) were approximately the same as the coefficients in Eq. (15) through Eq. (17). The model fits the model development data set well. 95% of the error is within a degree of hydration of ±0.078, which suggest that the model is a statistically significant predictor of hydration behavior. The choice of Rietveld analysis[37] or Bogue calculations[25] made very little difference in the fit of the regression model to the data used in creating the model (R^2 for both models is 0.994), and the mixtures with points outside of the 95% confidence limits were the same for both models.

Modeled response of effects of *w/cm*

The *w/cm* was modeled with an equation first proposed by Mills,[15] and it was used in the proposed model because it modeled the effects of *w/cm* on degree of hydration better than an exponential relationship. Increases in the *w/cm* raise α_u and increase $\alpha(t_e)$, as shown in Fig. 2.

Modeled response of effects of cement chemistry

The cement characteristics that are modeled by equation through equation are limited to C_4AF and %Na_2O_{eq} (Na_2O + 0.658 x K_2O) for α_u, C_3S and Na_2O for τ, and C_3A for β. Additional variables were not justified by the ANOVA. Though not perfectly correlated, it is useful to examine the effects of C_3A and C_4AF on the degree of hydration together. Figure 3 shows that α_u and β increased as C_3A increased, which in most cements meant a corresponding decrease in C_4AF. The increase in α_u is likely an artifact of the calculation procedure necessary for semi-adiabatic calorimetry, rather than an error in the measurement of the heat of hydration of the crystalline compounds in the cement. Care should be taken in interpreting α_u values, as these values are calculated from fitting heat of hydration curves after 150 hours of testing, and calculated H_u values based on the cement chemistry. The amount of alkalis in the cement had a large effect on the degree of hydration: α_u decreased as %Na_2O_{eq} increased, whereas τ increased as %Na_2O increased. Increasing the alkalis in the cement generally retarded the hydration of the mixture.

Modeled response of behavior of SCMs

Increases in the percent of slag cement in a mixture raised τ and lowered β. There was very little difference between the model results based on Rietveld analysis[37] (Eq. (12) through (14)) and Bogue calculations[25] (Eq. (15) through (17)). The percentage of fly ash and its % CaO was found to affect the degree of hydration α_u and the time parameter τ. The τ value increases as both the percent CaO and percent fly ash in the mixture increases. Increases in the % CaO of the fly ash delays hydration and reduces α_u, although mixtures with higher % CaO fly ashes may still liberate more heat because of the higher H_u value.

Modeled response of behavior of chemical admixtures

Set control admixtures were found to have the most notable effect on hydration. For example, the addition of increasing dosages of WRRET caused β and τ to increase. Increasing the dosage of ACCL reduced τ and caused an accelerating shift in the hydration. The slope parameter β increased with the addition of NHRWR, PCHRWR, MRWR, and LRWR. The Rietveld-based model[37] shows a higher increase in β from the use of MRWR than with the Bogue-based model,[25] which is the only term in the model that is significantly different in the two models.

Validation of model using calibration data set

The Bogue model[25] was validated using data from further experimental tests and literature, as discussed previously, to examine the predictive ability of the model in Eq. (15) through (17). The cement compositions as determined from Rietveld refinement were not available for the concrete mixtures reported in the literature, so this model could not be as thoroughly validated. R^2 of the measured versus predicted $\alpha(t_e)$ for the validation data set was 0.98, indicating excellent predictive ability. Figure 4 shows that most of the data are within the confidence limits of the test method for the Bogue model.[25] Tests that deviated from the model were generally mixtures with high volumes of SCM (>50%) or high dosages of retarder, which were beyond the compositions of the materials tested in the development of this model. The validation tests suggest that the model presented in this study successfully predicts the degree of hydration for mixtures with varying cement chemistries, SCMs, and chemical admixtures within the range of materials tested in its development.

Model limitations

Ultimately, this empirical model is limited by several factors. The lack of information available for the materials used in an actual concrete mixture placed in the field is perhaps the biggest limitation to accurately model hydration. Information available about the cement, SCM, and admixture chemistries used in the field can be rather limited. The Rietveld analysis[37] is certainly more accurate than Bogue calculations,[25] but in many instances, only the Bogue compositions are available. CaO content is often the only information available about a fly ash, and it may not be the best predictor of the fly ash heat of hydration development. The same is true for chemical admixtures, which are composed of combinations of different chemicals that may alter hydration, so generalizing them by their ASTM classifications is an over-simplification. The user generally is only aware of the ASTM designation and the general composition of an admixture because much of this information is considered proprietary by manufacturers.

The accuracy of semi-adiabatic calorimetry limits the accuracy of the model. Most of the results in this study are within this range. Adiabatic calorimetry should be conducted if heat of hydration development for longer periods of time or greater accuracy is needed. Finally, regression models of calorimetry data are limited to quantifying the effects of different treatments whose effects on a concrete mixture are relatively easily observed from test data. A better model requires better knowledge of the mechanisms affecting hydration, which may require a much more detailed study on fly ash, slag cement, and silica fume solubility; interactions with gypsum; aluminates; and chemical admixture mechanisms.

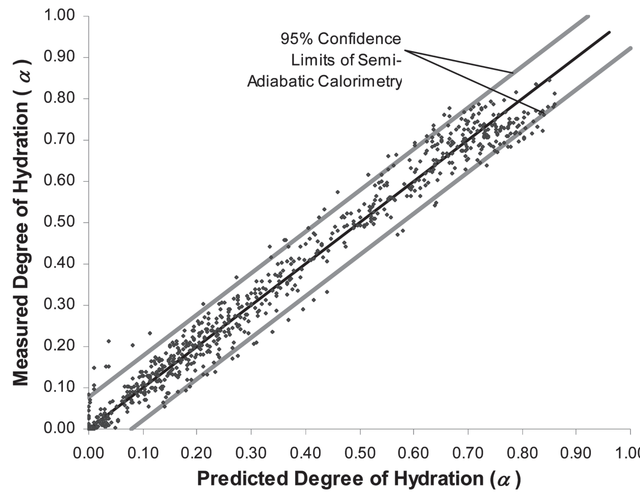


Fig. 4—Predicted-versus-measured degree of hydration for validation data set—Bogue model.

CONCLUSIONS

This paper presents the results of an empirical model of concrete hydration based on 204 semi-adiabatic calorimeter tests and validated by data from an additional 57 semi-adiabatic calorimeter tests. Activation energies used in the semi-adiabatic calorimetry calculations for each of the mixtures were calculated using a previously developed model that had been calibrated based on 116 isothermal calorimeter tests. The effects of cement chemistry, SCMs, and chemical admixtures on the concrete heat of hydration development were modeled using multi-variate nonlinear regression analysis. The model includes the effects of cement chemistry, fly ash, slag cement, silica fume, and some chemical admixtures. The model did an excellent job of predicting the heat of hydration of the validation data set, with an R^2 of 0.98. The analysis of the heat of hydration data also revealed that slag cement or Class C fly ash may be better suited for more moderate size concrete structures that can more easily dissipate heat because these materials reduce the rate of heat released from hydration, even if they do not reduce the total amount of heat released from hydration.

The model presented in this study accounts for only the major variables that affect the concrete heat of hydration development. The accuracy of the model is ultimately limited by the accuracy of the underlying test methods and the lack of information available on SCM composition (beyond CaO) and admixture composition. The results of the model may become inaccurate if high volumes of SCMs are used (>50%), or if large amounts of retarder are used. An analysis of the predicted heat of hydration for the validation data set showed that a knowledge of the particular chemical admixture ingredients used, and not just the class of admixture, would improve the presented heat of hydration model.

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APPENDIX A

Table A-1 - Concrete Mixture Proportions and Heat of Hydration Parameters for Cement I/IIA

Concrete Mixture								Chemical Admixture ASTM Designation								Hydration Parameters				
SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a	H_u	α_u	τ	β
				kg/m3				% solids of cementitious material								J/mol	J/g		hrs	
FF4	20	-	-	314	0.40	LS	0.45	-	0.29	-	-	-	-	0.17	-	28359	447	0.725	19.329	0.784

Note: 1 kg/m^3 = 1.69 lb/yd^3

Table A-2 - Concrete Mixture Proportions and Heat of Hydration Parameters for Cement I/IIB

Concrete Mixture								Chemical Admixture ASTM Designation								Hydration Parameters				
SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a	H_u	α_u	τ	β
				kg/m3				% solids of cementitious material								J/mol	J/g		hrs	
-	-	-	-	325	0.53	SRG	0.45	-	-	-	-	-	-	-	-	37165	463	0.716	11.362	0.765
-	-	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	37165	463	0.753	11.399	0.737
-	-	-	-	335	0.49	SRG	0.44	-	-	-	-	-	-	-	-	37165	463	0.689	10.189	0.784
-	-	-	-	335	0.44	SRG	0.45	-	0.35	-	-	-	-	-	-	26341	463	0.693	14.902	1.208
-	-	-	-	335	0.44	SRG	0.45	-	0.52	-	-	-	-	-	-	25000	463	0.691	23.341	1.680
-	-	-	-	335	0.44	SRG	0.45	-	-	-	0.78	-	-	-	-	37165	463	0.684	10.147	0.929
-	-	-	-	335	0.42	SRG	0.40	0.30	-	-	-	-	-	-	-	27325	463	0.677	11.383	1.137
-	-	-	-	335	0.42	SRG	0.40	0.30	-	-	-	-	-	0.03	-	27325	463	0.656	11.010	1.140
FC1	20	-	-	335	0.44	SRG	0.40	-	-	-	-	-	-	-	-	36675	453	0.670	19.161	0.605
FC1	30	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	36585	449	0.911	29.493	0.525
FC1	40	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	36598	444	1.000	43.451	0.495
FC2	20	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	37017	474	0.767	15.740	0.731
FC2	30	SF	5	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	34170	473	0.788	21.147	0.670
FC2	30	-	-	335	0.42	SRG	0.45	-	0.35	-	-	-	-	-	-	26274	480	0.739	34.268	1.103
FC2	30	-	-	335	0.44	SRG	0.40	-	-	-	-	-	-	-	-	37098	480	0.770	27.678	0.566
FC2	40	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	37283	486	0.819	32.424	0.610

FF1	20	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	35347	372	0.845	12.340	0.651
FF1	30	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	34592	327	0.836	11.920	0.655
FF1	30	-	-	335	0.42	SRG	0.40	-	0.35	-	-	-	-	-	-	25000	327	0.668	22.983	1.369
FF1	40	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	33942	282	0.902	13.310	0.665
FF2	15	UFFA	15	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	35595	388	0.803	15.513	0.670
FF2	20	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	36082	417	0.725	12.671	0.699
FF2	30	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	35696	395	0.776	16.492	0.593
FF2	30	-	-	335	0.42	SRG	0.45	-	0.35	-	-	-	-	-	-	25000	395	0.622	24.308	1.386
FF2	30	-	-	335	0.38	SRG	0.45	-	-	0.75	-	-	-	-	-	35696	395	0.692	23.180	0.839
FF2	40	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	35413	372	0.709	15.394	0.670
S1	50	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	41392	462	0.962	42.656	0.460
S1	50	-	-	335	0.44	SRG	0.45	-	-	-	-	-	0.72	-	-	38832	462	0.891	30.303	0.592
SF	10	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	31024	449	0.873	14.751	0.645
UFFA	15	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	36213	422	0.786	14.907	0.679

Note: 1 kg/m^3 = 1.69 lb/yd^3

Table A-3 - Concrete Mixture Proportions and Heat of Hydration Parameters for Cement I/IIC

Concrete Mixture								Chemical Admixture ASTM Designation								Hydration Parameters				
SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a	H_u	α_u	τ	β
				kg/m3				% solids of cementitious material								J/mol	J/g		hrs	
-	-	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	39437	446	0.793	12.778	0.709
-	-	-	-	335	0.44	SRG	0.45	-	0.35	-	-	-	-	-	-	28613	446	0.738	18.191	1.186
-	-	-	-	335	0.44	SRG	0.45	-	-	-	-	-	1.26	-	-	34957	446	0.875	11.968	0.638
-	-	-	-	335	0.44	SRG	0.45	-	-	-	0.78	-	-	-	-	39437	446	0.731	11.221	0.955
-	-	-	-	335	0.44	SRG	0.45	-	-	-	-	0.27	-	-	-	39437	446	0.750	12.294	0.783
-	-	-	-	335	0.44	SRG	0.45	-	0.25	-	-	-	-	-	-	32057	446	0.678	15.014	1.191
FC2	30	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	38503	468	0.852	26.859	0.566
FC2	30	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	37101	383	0.682	15.024	0.707
FC2	30	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	37990	437	0.839	23.940	0.561

FC2	30	-	-	335	0.44	SRG	0.45	-	-	-	0.78	-	-	-	-	38503	468	0.746	19.205	0.770
FF1	30	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	35997	316	0.788	13.123	0.676
S1	47	-	-	346	0.44	SRG	0.43	-	-	0.41	-	-	-	0.02	-	42168	453	0.987	39.812	0.485
S1	48	-	-	346	0.41	SRG	0.44	-	-	0.77	-	-	-	0.04	-	42176	453	0.942	42.587	0.580

Note: 1 kg/m^3 = 1.69 lb/yd^3

Table A-4 - Concrete Mixture Proportions and Heat of Hydration Parameters for Cement I/IID

Concrete Mixture								Chemical Admixture ASTM Designation								Hydration Parameters				
SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a	H_u	α_u	τ	β
				kg/m3				% solids of cementitious material								J/mol	J/g		hrs	
FF3	29	-	-	351	0.35	SRG	0.38	0.33	-	0.23	-	-	-	0.08	-	27069	438	0.726	15.401	1.104
FF3	31	-	-	362	0.35	SRG	0.38	0.19	-	0.33	-	-	-	0.07	-	31155	434	0.820	19.217	0.886
FF3	40	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	36750	421	0.815	15.594	0.656

Note: 1 kg/m^3 = 1.69 lb/yd^3

Table A-5 - Concrete Mixture Proportions and Heat of Hydration Parameters for Cement I/IIE

Concrete Mixture								Chemical Admixture ASTM Designation								Hydration Parameters				
SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a	H_u	α_u	τ	β
				kg/m3				% solids of cementitious material								J/mol	J/g		hrs	
FC1	40	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	37355	451	0.847	26.128	0.564
FF7	24	UFFA	9	330	0.34	SRG	0.41	0.21	-	-	0.54	-	-	0.03	[illegible]3006	30061	422	0.783	16.195	0.724
FF7	38	UFFA	5	294	0.32	SRG	0.41	0.25	-	-	0.56	-	-	0.03	-	28909	416	0.700	17.334	0.905
FF7	44	-	-	300	0.35	SRG	0.42	0.39	-	-	0.79	-	-	0.04	-	24928	423	0.807	18.280	0.735

FF7	45	UFFA	9	330	0.34	SRG	0.41	0.21	-	-	0.47	-	-	0.03	-	30012	398	0.696	18.348	0.771
FF7	55	-	-	330	0.34	SRG	0.41	0.21	-	-	0.43	-	-	0.03	-	30204	411	0.732	21.578	0.651
FF7	55	-	-	330	0.38	SRG	0.41	0.78	-	-	-	-	-	-	-	25000	411	0.717	27.537	0.774
FF7	55	-	-	330	0.38	SRG	0.41	0.78	-	-	-	-	-	0.03	-	25000	411	0.640	21.453	0.947
S1	30	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	40315	471	0.966	27.483	0.482
S1	40	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	41097	469	0.978	28.729	0.498
S1	50	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	42008	468	1.000	39.858	0.460

Note: 1 kg/m^3 = 1.69 lb/yd^3

Table A-6 - Concrete Mixture Proportions and Heat of Hydration Parameters for Cement I/IIF

Concrete Mixture								Chemical Admixture ASTM Designation								Hydration Parameters				
SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a	H_u	α_u	τ	β
				kg/m3				% solids of cementitious material								J/mol	J/g		hrs	
-	-	-	-	328	0.45	SRG	0.45	-	-	-	-	-	-	-	-	37882	462	0.811	13.008	0.803
-	-	-	-	297	0.53	SRG	0.45	-	-	-	-	-	-	-	-	37882	462	0.890	15.417	0.700
-	-	-	-	335	0.44	SRG	0.45	0.47	-	-	-	-	-	-	-	23122	462	0.816	13.966	1.215
-	-	-	-	335	0.44	SRG	0.45	-	0.24	-	-	-	-	-	-	30502	462	0.843	14.859	0.987
-	-	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	LN	37882	462	0.778	13.754	0.830
-	-	-	-	335	0.44	SRG	0.45	-	0.24	-	-	-	-	-	LN	30502	462	0.780	16.288	1.155
-	-	-	-	335	0.44	SRG	0.45	0.47	-	-	-	-	-	-	LN	23122	462	0.754	16.432	1.307
-	-	-	-	335	0.44	SRG	0.45	-	-	-	0.68	-	-	-	LN	37882	462	0.829	16.227	0.883
-	-	-	-	335	0.44	SRG	0.45	-	-	-	-	0.49	-	-	LN	37882	462	0.827	13.982	0.922
-	-	-	-	335	0.44	SRG	0.45	-	-	-	0.68	-	-	-	-	37882	462	0.799	14.865	0.906
-	-	-	-	335	0.44	SRG	0.45	-	-	-	-	0.49	-	-	-	37882	462	0.816	14.762	0.858
-	-	-	-	335	0.44	SRG	0.45	-	-	-	1.25	-	-	-	-	37882	462	0.767	14.271	0.944
-	-	-	-	335	0.44	SRG	0.45	-	-	-	-	0.41	-	0.02	-	37882	462	0.824	13.462	0.857
-	-	-	-	335	0.44	SRG	0.45	-	-	-	1.25	-	-	-	LN	37882	462	0.809	15.271	1.025

-	-	-	-	335	0.44	SRG	0.45	-	-	-	-	0.41	-	0.02	LN	37882	462	0.831	13.684	0.907
F5	50	-	-	291	0.53	SRG	0.45	-	-	-	-	-	-	-	-	33721	243	1.000	15.418	0.800
FC4	30	-	-	335	0.44	SRG	0.44	-	-	-	-	0.20	-	-	-	37272	466	0.936	29.916	0.695
FC4	30	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	37272	466	1.000	31.324	0.642
FF5	30	-	-	335	0.44	SRG	0.44	-	-	-	-	0.27	-	-	LN	35037	331	0.991	16.842	0.715
FF5	30	-	-	335	0.44	SRG	0.44	-	-	-	-	0.27	-	-	-	35037	331	0.879	16.844	0.745
FF5	50	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	33721	243	1.000	16.137	0.735
FF5	50	-	-	335	0.44	SRG	0.43	-	-	-	-	-	-	-	LN	33721	243	1.000	17.133	0.768
FF5	50	-	-	335	0.44	SRG	0.43	-	-	-	-	0.28	-	-	-	33721	243	1.000	17.778	0.677
S1	50	-	-	335	0.44	SRG	0.44	-	-	-	-	0.20	-	-	-	41624	461	0.864	32.665	0.585
S1	50	-	-	335	0.44	SRG	0.44	-	-	-	-	0.34	-	-	LN	41624	461	0.843	28.876	0.639

Note: 1 kg/m^3 = 1.69 lb/yd^3

Table A-7 – Concrete Mixture Proportions and Heat of Hydration Parameters for Cement I/IIG

Concrete Mixture								Chemical Admixture ASTM Designation								Hydration Parameters				
SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a	H_u	α_u	τ	β
				kg/m3				% solids of cementitious material								J/mol	J/g		hrs	
-	-	-	-	335	0.44	SRG	0.40	-	-	-	-	-	-	-	-	39999	456	0.788	11.582	0.801
FC3	20	-	-	316	0.40	SRG	0.40	0.31	-	-	-	-	-	0.03	-	28682	458	0.837	16.520	0.808

Note: 1 kg/m^3 = 1.69 lb/yd^3

Table A-8 - Concrete Mixture Proportions and Heat of Hydration Parameters for Cement I/IIH

Concrete Mixture								Chemical Admixture ASTM Designation								Hydration Parameters				
SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a	H_u	α_u	τ	β
				kg/m3				% solids of cementitious material								J/mol	J/g		hrs	

FC1	30	-	-	335	0.42	SRG	0.44	-	-	-	-	0.27	-	0.01	-	36601	464	0.887	30.035	0.765
FC1	30	-	-	335	0.44	SRG	0.44	-	-	-	-	0.27	-	0.01	LN	36601	464	0.828	27.312	0.857
FC4	30	-	-	335	0.44	SRG	0.44	-	-	-	-	0.20	-	-	LN	36900	483	0.850	26.053	0.769
FC4	30	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	LN	36900	483	0.908	29.247	0.682
FF5	30	-	-	335	0.42	SRG	0.44	-	-	-	-	0.27	-	0.02	-	34665	347	0.870	17.314	0.682
FF5	30	-	-	335	0.42	SRG	0.44	-	-	-	-	0.27	-	0.02	LN	34665	347	0.797	17.672	0.812

Note: 1 kg/m^3 = 1.69 lb/yd^3

Table A-9 - Concrete Mixture Proportions and Heat of Hydration Parameters for Cement I/IIJ

Concrete Mixture								Chemical Admixture ASTM Designation								Hydration Parameters				
SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a	H_u	α_u	τ	β
				kg/m3				% solids of cementitious material								J/mol	J/g		hrs	
-	-	-	-	307	0.42	SRG	0.40	-	0.24	-	-	-	-	0.03	-	31357	471	0.734	17.875	0.960
FF6	15	S2	35	307	0.44	LS	0.39	-	0.24	-	-	-	-	0.03	-	33083	432	0.766	28.149	0.774
FF6	20	-	-	307	0.42	LS	0.39	-	0.24	-	-	-	-	0.03	-	29962	424	0.685	20.650	0.842
FF6	35	-	-	307	0.42	LS	0.39	-	0.24	-	-	-	-	0.03	-	29232	389	0.708	23.641	0.818
FF6	35	-	-	307	0.39	LS	0.39	-	0.24	-	-	-	-	0.03	-	29232	389	0.738	29.213	0.658
FF9	35	-	-	307	0.39	LS	0.39	-	0.24	-	-	-	-	0.17	-	28399	338	0.768	23.335	0.897
S2	35	-	-	307	0.40	LS	0.39	-	0.24	-	-	-	-	0.03	-	33541	467	0.718	24.992	0.830

Note: 1 kg/m^3 = 1.69 lb/yd^3

Table A-10 - Concrete Mixture Proportions and Heat of Hydration Parameters for Cement I/IIK

Concrete Mixture	Chemical Admixture ASTM Designation	Hydration Parameters

SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a	H_u	α_u	τ	β
				kg/m3				% solids of cementitious material								J/mol	J/g		hrs	
FF8	25	-	-	349	0.45	SRG	0.40	-	0.23	-	-	-	-	0.02	-	29634	353	0.800	18.249	0.766

Note: 1 kg/m^3 = 1.69 lb/yd^3

Table A-11 - Concrete Mixture Proportions and Heat of Hydration Parameters for Cement IA

Concrete Mixture								Chemical Admixture ASTM Designation								Hydration Parameters				
SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a	H_u	α_u	τ	β
				kg/m3				% solids of cementitious material								J/mol	J/g		hrs	
-	-	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	38725	482	0.712	11.924	0.959
-	-	-	-	335	0.44	SRG	0.45	-	-	-	-	-	0.73	-	-	36165	482	0.774	12.597	0.887
-	-	-	-	335	0.44	SRG	0.45	-	-	-	-	-	1.25	-	-	34245	482	0.785	12.144	0.929
-	-	-	-	335	0.44	SRG	0.45	-	0.35	-	-	-	-	-	-	27901	482	0.674	19.300	1.592
-	-	-	-	335	0.40	SRG	0.46	-	0.35	-	-	-	-	-	-	27901	482	0.687	17.587	1.652
-	-	-	-	335	0.44	SRG	0.45	-	-	-	-	-	2.16	-	-	31045	482	0.803	10.653	0.793
-	-	-	-	335	0.38	SRG	0.45	-	-	-	-	0.27	-	-	-	38725	482	0.694	12.117	0.994
-	-	-	-	335	0.44	SRG	0.45	-	-	-	-	0.27	-	-	-	38725	482	0.645	11.682	1.138
-	-	-	-	335	0.38	SRG	0.45	-	-	-	-	0.27	-	-	3.8% CNI	38725	482	0.662	13.080	1.131
-	-	-	-	317	0.44	SRG	0.45	-	-	-	0.78	-	-	-	-	38725	482	0.690	13.474	1.165
-	-	-	-	332	0.44	SRG	0.45	-	-	-	-	-	-	-	-	38725	482	0.708	14.744	0.915
-	-	-	-	335	0.42	SRG	0.40	-	-	0.33	-	-	-	-	-	38725	482	0.648	15.732	1.109
FC1	20	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	37279	469	0.817	17.357	0.760
FC1	30	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	36791	462	0.841	22.172	0.724
FC1	30	-	-	335	0.44	SRG	0.45	-	-	-	-	-	1.25	-	-	32311	462	0.790	15.946	0.919
FC1	30	-	-	335	0.44	SRG	0.46	-	0.35	-	-	-	-	-	-	25967	462	0.696	28.086	1.560

FC1	40	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	36459	456	0.742	22.936	0.765
FC2	20	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	37621	490	0.764	17.377	0.823
FC2	30	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	37304	494	0.721	18.649	0.917
FC2	30	SF	5	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	34196	486	0.732	18.718	0.862
FC2	30	-	-	335	0.38	SRG	0.45	-	-	-	-	0.27	-	-	-	37304	494	0.699	19.031	0.913
FC2	30	-	-	335	0.38	SRG	0.45	-	-	-	0.78	-	-	-	-	37304	494	0.655	17.808	0.941
FC2	30	UFFA	8	335	0.32	SRG	0.44	-	-	-	-	0.68	-	-	-	36735	471	0.660	24.864	1.047
FC2	30	UFFA	12	335	0.32	SRG	0.44	-	-	-	-	0.58	-	-	-	36488	459	0.678	23.600	1.072
FC2	30	SF	5	335	0.32	SRG	0.44	-	-	-	-	0.68	-	-	-	34196	486	0.666	20.252	1.035
FC2	35	SF	5	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	34135	488	0.711	19.718	0.924
FC2	40	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	37143	497	0.714	23.678	0.915
FC3	30	SF	5	335	0.32	LS	0.44	-	-	-	1.25	-	-	-	-	33931	470	0.721	22.137	0.804
FC3	30	UFFA	8	335	0.32	LS	0.44	-	0.35	-	1.25	-	-	-	-	25258	430	0.773	38.680	1.468
FF1	20	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	35951	388	0.803	13.142	0.815
FF1	20	SF	5	335	0.44	SRG	0.44	-	0.06	-	-	-	-	-	-	30797	381	0.832	14.020	0.870
FF1	30	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	34798	341	0.889	14.032	0.817
FF1	40	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	33802	294	0.896	14.236	0.741
FF2	20	-	-	335	0.53	SRG	0.40	-	-	-	-	-	-	-	-	36687	433	0.851	16.263	0.744
FF2	20	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	36687	433	0.681	13.186	0.926
FF2	20	-	-	335	0.44	SRG	0.44	-	-	-	-	-	0.73	-	-	34127	433	0.753	16.396	0.915
FF2	21	-	-	322	0.44	SRG	0.45	-	-	-	-	-	-	0.07	-	36687	431	0.713	14.901	0.883
FF2	30	-	-	332	0.60	SRG	0.40	-	0.08	-	-	-	-	-	-	39233	410	0.862	16.736	0.758
FF2	30	-	-	335	0.45	SRG	0.42	-	-	-	-	-	-	-	-	35902	408	0.710	13.854	0.872
FF2	40	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	35274	384	0.701	16.104	0.834
FF4	20	-	-	314	0.40	LS	0.45	0.27	-	-	-	-	-	0.22	-	28196	456	0.645	15.589	0.855
S1	30	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	39597	476	0.889	21.291	0.638
S1	40	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	40200	474	0.918	26.055	0.592
S1	50	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	40960	472	0.735	21.698	0.757
S1	50	-	-	335	0.44	SRG	0.45	-	-	-	-	-	0.73	-	-	38400	472	0.737	23.750	0.780
SF	5	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	35383	475	0.713	11.764	1.026

Note: 1 kg/m^3 = 1.69 lb/yd^3

Table A-12 - Concrete Mixture Proportions and Heat of Hydration Parameters for Cement IB

Concrete Mixture								Chemical Admixture ASTM Designation								Hydration Parameters				
SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a	H_u	α_u	τ	β
				kg/m3				% solids of cementitious material								J/mol	J/g		hrs	
-	-	-	-	390	0.44	SRG	0.41	-	-	-	-	-	-	-	-	41290	463	0.721	14.340	0.897
-	-	-	-	335	0.50	SRG	0.43	-	-	-	-	-	-	-	-	41290	463	0.775	14.159	0.991

Note: 1 kg/m^3 = 1.69 lb/yd^3

Table A-13 - Concrete Mixture Proportions and Heat of Hydration Parameters for Cement IC

Concrete Mixture								Chemical Admixture ASTM Designation								Hydration Parameters				
SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a	H_u	α_u	τ	β
				kg/m3				% solids of cementitious material								J/mol	J/g		hrs	
-	-	-	-	335	0.42	SRG	0.40	0.30	-	-	-	-	-	-	-	30810	481	0.786	12.748	1.133
-	-	-	-	335	0.32	SRG	0.40	-	-	-	-	0.65	-	-	-	40650	481	0.710	12.780	1.147
-	-	-	-	335	0.32	SRG	0.40	-	-	-	-	0.65	-	-	-	40650	481	0.714	13.371	0.997
-	-	-	-	335	0.36	SRG	0.40	-	-	-	-	0.41	-	-	-	40650	481	0.661	12.214	1.059
-	-	-	-	335	0.40	SRG	0.40	-	-	-	-	0.20	-	-	-	40650	481	0.728	12.741	1.060
-	-	-	-	335	0.42	LS	0.40	-	-	-	-	0.41	-	-	-	40650	481	0.801	12.285	1.041
-	-	-	-	279	0.42	LS	0.40	0.30	-	-	-	-	-	-	-	30810	481	0.786	13.868	1.030
-	-	-	-	390	0.42	SRG	0.40	0.30	-	-	-	-	-	-	-	30810	481	0.735	11.665	1.136
-	-	-	-	362	0.38	SRG	0.40	-	-	-	-	0.22	-	-	-	40650	481	0.775	12.476	1.059
-	-	-	-	307	0.48	SRG	0.40	-	-	-	-	-	-	-	-	40650	481	0.896	15.164	0.831
-	-	-	-	279	0.53	SRG	0.40	-	-	-	-	-	-	-	-	40650	481	0.905	13.526	0.932
-	-	-	-	335	0.32	SRG	0.40	-	-	-	-	0.65	-	-	-	40650	481	0.664	15.581	1.318
-	-	-	-	390	0.32	SRG	0.40	-	-	-	-	0.65	-	-	-	40650	481	0.643	13.001	1.249

-	-	-	-	335	0.44	SRG	0.40	-	-	-	-	-	-	-	-	40650	481	0.793	13.804	0.847
-	-	-	-	335	0.42	SRG	0.40	-	0.35	-	-	-	-	-	-	29826	481	0.761	15.651	1.386
FC1	20	-	-	335	0.42	SRG	0.40	0.30	-	-	-	-	-	-	-	29258	468	0.903	16.634	0.897
FC1	30	-	-	335	0.44	LS	0.40	-	-	-	-	-	-	-	-	38566	462	0.747	16.782	0.904
FC1	30	-	-	335	0.42	SRG	0.40	-	0.35	-	-	-	-	-	-	27742	462	0.770	29.576	1.121
FC2	20	-	-	335	0.42	SRG	0.40	0.30	-	-	-	-	-	-	-	29600	489	0.803	19.815	1.087
FC2	30	-	-	335	0.44	SRG	0.40	-	-	-	-	-	-	-	-	39079	493	0.787	22.711	0.753
FC2	30	-	-	335	0.42	SRG	0.40	-	0.18	-	-	-	-	-	-	33667	493	0.812	26.436	0.951
FC2	30	-	-	335	0.42	SRG	0.40	0.30	-	-	-	-	-	-	-	29239	493	0.740	21.418	1.028
FC2	30	-	-	335	0.42	SRG	0.40	-	0.35	-	-	-	-	-	-	28255	493	0.662	32.018	1.324
FF1	20	-	-	335	0.42	SRG	0.40	0.30	-	-	-	-	-	-	-	27930	387	0.903	16.634	0.897
FF1	30	-	-	335	0.42	SRG	0.40	0.30	-	-	-	-	-	-	-	26733	340	0.970	16.300	0.876
FF1	30	-	-	335	0.44	SRG	0.40	-	-	-	-	-	-	-	-	36573	340	0.908	15.551	0.731
FF2	20	-	-	335	0.42	SRG	0.40	0.30	-	-	-	-	-	-	-	28666	432	0.854	16.789	0.962
FF2	30	-	-	335	0.42	SRG	0.40	0.30	-	-	-	-	-	-	-	27837	408	0.850	18.524	0.891
FF2	30	-	-	335	0.42	SRG	0.40	0.30	-	-	-	-	-	-	-	27837	408	0.886	19.407	0.843
FF2	30	-	-	335	0.42	SRG	0.40	0.30	-	-	-	-	-	-	-	27837	408	0.801	19.473	1.010
FF2	30	-	-	335	0.42	SRG	0.40	0.30	-	-	-	-	-	-	-	27837	408	0.822	15.221	0.954
FF2	30	-	-	335	0.44	SRG	0.40	-	-	-	-	-	-	-	-	37677	408	0.832	18.076	0.710
FF2	30	-	-	335	0.42	SRG	0.40	-	0.35	-	-	-	-	-	-	26853	408	0.761	24.152	1.314
S1	30	-	-	335	0.42	SRG	0.40	0.30	-	-	-	-	-	-	-	31532	475	1.000	21.332	0.751
S1	50	-	-	335	0.42	SRG	0.40	0.30	-	-	-	-	-	-	-	32824	471	0.905	26.534	0.685
S1	50	-	-	335	0.42	SRG	0.40	-	0.18	-	-	-	-	-	-	37252	471	0.797	26.550	0.694
S1	50	-	-	335	0.42	SRG	0.40	-	0.35	-	-	-	-	-	-	31840	471	0.699	26.202	1.094

Note: 1 kg/m^3 = 1.69 lb/yd^3

Table A-14 - Concrete Mixture Proportions and Heat of Hydration Parameters for Cement ID

Concrete Mixture	Chemical Admixture ASTM Designation	Hydration Parameters

SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM (kg/m3)	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a (J/mol)	H_u (J/g)	α_u	τ (hrs)	β
								% solids of cementitious material												
-	-	-	-	335	0.42	SRG	0.40	-	-	-	-	-	-	-	-	41299	459	0.837	13.971	0.884

Note: 1 kg/m^3 = 1.69 lb/yd^3

Table A-15 - Concrete Mixture Proportions and Heat of Hydration Parameters for Cement IIIA

Concrete Mixture								Chemical Admixture ASTM Designation								Hydration Parameters				
SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM (kg/m3)	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a (J/mol)	H_u (J/g)	α_u	τ (hrs)	β
								% solids of cementitious material												
-	-	-	-	390	0.32	SRG	0.40	-	0.32	-	1.25	-	-	-	-	29224	485	0.657	13.389	1.543
-	-	-	-	390	0.32	SRG	0.40	-	-	-	-	0.68	-	-	-	39064	485	0.614	11.186	1.387

Table A-16 - Concrete Mixture Proportions and Heat of Hydration Parameters for Cement IIIB

Concrete Mixture								Chemical Admixture ASTM Designation								Hydration Parameters				
SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM (kg/m3)	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a (J/mol)	H_u (J/g)	α_u	τ (hrs)	β
								% solids of cementitious material												
-	-	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	37344	474	0.726	9.351	0.893
-	-	-	-	390	0.32	SRG	0.40	-	-	-	-	0.68	-	-	-	37344	474	0.614	10.293	1.073
FC1	30	-	-	390	0.32	SRG	0.40	-	-	-	-	0.41	-	-	-	35021	456	0.596	13.786	0.919
FF2	20	-	-	390	0.32	SRG	0.40	-	-	-	-	0.41	-	-	-	35031	426	0.684	10.724	0.987

Note: 1 kg/m^3 = 1.69 lb/yd^3

Table A-17 - Concrete Mixture Proportions and Heat of Hydration Parameters for Cement V

Concrete Mixture								Chemical Admixture ASTM Designation								Hydration Parameters				
SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a	H_u	α_u	τ	β
				kg/m3				% solids of cementitious material								J/mol	J/g		hrs	
-	-	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	38597	419	0.714	14.864	0.807
-	-	-	-	335	0.44	SRG	0.45	-	0.35	-	-	-	-	-	-	27773	419	0.694	27.220	1.436
-	-	-	-	332	0.44	SRG	0.45	-	-	0.66	-	-	-	-	-	38597	419	0.790	20.784	0.919
FC2	30	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	37631	450	0.923	41.159	0.480
FC2	30	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	37631	450	0.926	43.866	0.490
FF1	30	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	35125	297	0.794	15.315	0.707
FF2	30	-	-	335	0.44	SRG	0.44	-	-	-	-	-	-	-	-	36229	364	0.691	16.590	0.695
FF5	30	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	35182	301	0.826	17.171	0.637
S1	30	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	39924	432	1.000	38.991	0.497
S1	40	-	-	418	0.35	SRG	0.45	-	-	-	0.78	-	-	-	-	40644	436	0.911	43.825	0.510
S1	40	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	40644	436	1.000	47.914	0.478
S1	40	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	40644	436	1.000	53.192	0.465
S1	50	-	-	335	0.44	SRG	0.45	-	-	-	-	-	-	-	-	41502	440	1.000	81.595	0.439

Note: 1 kg/m^3 = 1.69 lb/yd^3

TableA-18 - Concrete Mixture Proportions and Heat of Hydration Parameters for Validation Dataset

Concrete Mixture									Chemical Admixture ASTM Designation								Hydration Parameters				
Cement Used	SCM 1	SCM 1 %	SCM 2	SCM 2 %	Cement + SCM	w/cm	CA Type	FA/ (FA + CA)	A	B&D	MR	F-N	F-PC	C	AEA	Other	E_a	H_u	α_u	τ	β

					kg/m3				% solids of cementitious material								J/mol	J/g		hrs	
AS1	FF10	16	-	-	293	0.39	LS	0.44	-	0.18	-	-	-	-	0.08	-	36848	409	0.725	15.500	1.010
AS2	FC5	21	-	-	318	0.44	LS	0.37	-	0.21	-	-	-	-	0.04	-	36636	476	0.841	31.050	0.818
AS3	-	-	-	-	279	0.46	LS	0.36	-	0.16	-	-	-	-	0.02	-	45712	489	0.729	13.390	0.935
AS4	FC6	32	-	-	320	0.41	LS	0.41	-	0.24	-	-	-	-	0.05	-	35341	475	0.857	28.350	0.720
AS5	FF11	18	-	-	272	0.50	LS	0.41	-	0.35	-	-	-	-	0.04	-	39310	405	0.788	17.890	0.681
AS6	FC7	22	-	-	347	0.41	LS	0.39	-	0.19	-	-	-	-	0.07	-	38375	480	0.850	35.950	0.573
AS7	FC8	30	-	-	307	0.40	LS	0.42	-	0.12	-	-	-	-	0.03	-	40304	465	0.884	23.810	0.674
AS7	FC8	13	-	-	328	0.37	LS	0.41	-	0.12	-	-	-	-	0.02	-	43148	471	0.713	13.810	0.874
AS7	FC8	23	-	-	324	0.38	LS	0.41	-	0.12	-	-	-	-	0.02	-	41252	468	0.793	23.280	0.772
AS7	FC8	32	-	-	320	0.38	LS	0.41	-	0.12	-	-	-	-	0.03	-	39357	464	0.893	29.430	0.716
AS7	FC8	42	-	-	316	0.39	LS	0.41	-	0.12	-	-	-	-	0.03	-	37461	460	0.849	36.660	0.724
AS7	FF12	12	-	-	322	0.38	LS	0.41	-	0.12	-	-	-	-	0.03	-	40703	444	0.797	15.970	0.825
AS7	FF12	20	-	-	313	0.39	LS	0.41	-	0.12	-	-	-	-	0.03	-	37178	421	0.831	18.300	0.786
AS7	FF12	28	-	-	304	0.40	LS	0.41	-	0.12	-	-	-	-	0.03	-	33653	396	0.838	19.080	0.809
AS7	FF12	38	-	-	295	0.42	LS	0.41	-	0.13	-	-	-	-	0.03	-	30127	370	0.894	21.730	0.774
AS7	S3	28	-	-	327	0.38	LS	0.41	-	0.12	-	-	-	-	0.02	-	51510	472	0.822	25.220	0.625
AS7	S3	48	-	-	322	0.38	LS	0.41	-	0.12	-	-	-	-	0.03	-	55189	469	0.854	38.220	0.554
AS7	-	-	-	-	335	0.37	LS	0.43	-	0.11	-	-	-	-	0.02	-	45991	477	0.689	13.690	0.905
AS8	-	-	-	-	307	0.50	LS	0.41	-	0.12	-	-	-	-	0.03	-	41977	513	0.887	16.880	0.719
AS9	-	-	-	-	307	0.50	LS	0.41	-	0.12	-	-	-	-	0.03	-	46269	492	0.882	16.320	0.727
I/IIA	FF4	20	-	-	314	0.42	LS	0.45	0.27	-	-	-	-	-	0.17	-	28359	447	0.679	14.604	0.869
I/IIA	FF4	20	-	-	315	0.42	LS	0.45	0.27	-	-	-	-	-	0.17	-	28362	447	0.747	17.200	0.809
I/IIA	FF4	26	-	-	329	0.47	LS	0.44	0.20	0.07	-	-	-	-	0.08	-	28057	440	0.888	22.155	0.836
I/IIA	FF4	26	-	-	405	0.41	LS	0.40	0.05	0.23	-	-	-	-	0.07	-	27583	440	0.867	23.245	0.865
I/IIC	S1	48	-	-	346	0.40	LS	0.44	-	-	0.77	-	-	-	0.03	-	39775	453	1.000	38.444	0.532
I/IID	FF3	29	-	-	351	0.35	SRG	0.38	0.22	-	0.34	-	-	-	0.08	-	30513	438	0.804	13.502	0.884
I/IID	FF3	31	-	-	362	0.35	SRG	0.38	0.20	-	0.32	-	-	-	0.09	-	0	434	0.780	22.745	0.802
I/IIE	FF7	44	-	-	300	0.35	SRG	0.42	0.38	-	-	0.79	-	-	0.04	-	25000	423	0.666	21.988	0.672
I/IIG	FC3	20	-	-	316	0.40	Granite	0.40	0.31	-	-	-	-	-	0.03	-	28623	458	0.835	15.870	0.867
I/IIJ	S2	50	-	-	307	0.42	SRG	0.39	-	0.24	-	-	-	-	0.03	-	34929	466	0.694	28.081	0.830
IA	FC2	29	-	-	350	0.40	SRG	0.40	-	0.35	-	-	-	-	-	-	26480	493	0.668	36.796	1.735
IA	-	-	-	-	335	0.40	SRG	0.46	-	0.52	-	-	-	-	-	-	25000	482	0.652	25.214	2.404
IC	FF2	30	-	-	335	0.42	SRG	0.40	-	0.18	-	-	-	-	-	-	32265	408	0.726	17.499	1.321

IC	FF2	30	-	-	335	0.42	SRG	0.40	-	0.53	-	-	-	-	-	-	25000	408	0.700	39.675	2.147
IIIB	FF8	20	-	-	474	0.29	SRG	0.40	-	0.13	-	-	0.40	-	-	-	30545	397	0.674	12.649	1.328
Z1	FC10	30	-	-	335	0.40	LS	0.44	-	-	-	-	-	-	-	-	45113	486	0.840	35.469	0.800
Z1	FC11	30	-	-	335	0.40	LS	0.44	-	-	-	-	-	-	-	-	44037	420	0.810	24.677	0.773
Z1	FC9	4	S5	11	335	0.40	LS	0.44	0.30	-	-	-	-	-	-	-	36823	470	0.820	23.251	0.728
Z1	FC9	8	S5	23	335	0.40	LS	0.44	0.30	-	-	-	-	-	-	-	37447	470	0.850	32.728	0.647
Z1	FC9	11	S5	34	335	0.40	LS	0.44	0.30	-	-	-	-	-	-	-	38361	469	0.890	42.166	0.501
Z1	FC9	15	S5	45	335	0.40	LS	0.44	0.30	-	-	-	-	-	-	-	39565	469	0.950	80.048	0.429
Z1	FC9	11	S5	4	335	0.40	LS	0.44	0.30	-	-	-	-	-	-	-	36209	472	0.800	18.790	0.790
Z1	FC9	23	S5	8	335	0.40	LS	0.44	0.30	-	-	-	-	-	-	-	36220	474	0.820	24.972	0.673
Z1	FC9	34	S5	11	335	0.40	LS	0.44	-	-	-	-	-	-	-	-	45869	476	0.830	35.487	0.588
Z1	FC9	45	S5	15	335	0.40	LS	0.44	-	-	-	-	-	-	-	-	46461	477	0.950	61.246	0.497
Z1	FC9	15	-	-	335	0.40	LS	0.44	0.30	-	-	-	-	-	-	-	35903	473	0.800	21.648	0.826
Z1	FC9	30	-	-	335	0.40	LS	0.44	-	-	-	-	-	-	-	-	44955	476	0.820	27.000	0.721
Z1	FC9	45	-	-	335	0.40	LS	0.44	-	-	-	-	-	-	-	-	44950	479	0.870	33.639	0.647
Z1	FC9	60	-	-	335	0.40	LS	0.44	-	-	-	-	-	-	-	-	45234	481	0.900	50.328	0.575
Z1	FF13	30	-	-	335	0.40	LS	0.44	-	-	-	-	-	-	-	-	42682	338	0.830	16.120	0.788
Z1	S4	30	-	-	335	0.40	LS	0.44	0.30	-	-	-	-	-	-	-	38060	468	0.950	29.752	0.701
Z1	S5	15	-	-	335	0.40	LS	0.44	0.30	-	-	-	-	-	-	-	37129	469	0.780	19.379	0.753
Z1	S5	30	-	-	335	0.40	LS	0.44	0.30	-	-	-	-	-	-	-	38060	468	0.860	30.093	0.579
Z1	S5	45	-	-	335	0.40	LS	0.44	0.30	-	-	-	-	-	-	-	39281	466	0.930	49.334	0.499
Z1	S6	30	-	-	335	0.40	LS	0.44	0.30	-	-	-	-	-	-	-	38060	468	0.870	30.047	0.588
Z1	-	-	-	-	335	0.40	LS	0.44	0.30	-	-	-	-	-	-	-	36489	471	0.740	14.784	0.897
Z1	-	-	-	-	335	0.40	LS	0.44	0.30	-	-	-	-	-	-	-	36489	471	0.760	16.269	0.89

Note: 1 kg/m^3 = 1.69 lb/yd^3