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BUREAU OF RECLAMATION
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MEMORANDUM

To: Technology Development Program Manager, Dam Safety Office
Attn: 84-44000 (LKrosley)

From: Catherine Lucero, Civil Engineer
Concrete, Geotechnical, and Structural Laboratory (86-68530)

Catherine Lucero

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Date: 2017.09.29 09:27:05 -06'00'

Subject: Dam Safety Technology Development Report DSO-2017-05 – Comparison of Thermal Properties Models of Concrete

A report on Comparison of Thermal Properties Models of Concrete, DSO-2017-05 from the Dam Safety Technology Development Program has been prepared by the Technical Service Center at the request of the Dam Safety Office. The report will be available in Adobe Acrobat Format on the Dam Safety website and will also be loaded into DSDAMS.

This transmittal concludes the work on the Technology Development Report. If you have any questions, please contact me at 303-445-2343 or at cllucero@usbr.gov.

cc (w/att):
DSDaMS
Archives
86-68530 (Bartojay)

RECLAMATION

Managing Water in the West

Comparison of Thermal Property Models for Concrete

Concrete, Geotechnical, and Structural Laboratory, 86-68530, DSO-2017-05 (8530-2017-29)

Dam Safety Technology Development Program

U.S. Department of the Interior
Bureau of Reclamation

September 2017

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Thermal effects from cement hydration and environmental factors can lead to thermal gradients within the concrete section and induce thermal cracking. Temperature effects are especially important in mass concrete, where the size of the placement can produce large amounts of heat with relatively little surface area to dissipate it. Even in smaller placements, concrete containing high cement contents or supplementary cementitious materials (SCMs) such as silica fume can produce high temperatures. There are several approaches for estimating temperature rise of concrete. Some of these tools could be beneficial to Reclamation's designers when determining placement size or determining if a temperature control plan is required.

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Concrete, Geotechnical, and Structural Laboratory, 86-68530
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Comparison of Thermal Properties Models for Concrete

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Acronyms and Abbreviations

ACI	American Concrete Institute
CGSL	Concrete, Geotechnical, and Structural Laboratory
IC	isothermal calorimetry
OPC	ordinary portland cement
RSMC	reinforced structural mass concrete
SCM	supplementary cementitious material
SEM	scanning electron microscopy
USBR	United States Bureau of Reclamation
VCCTL	Virtual Cement and Concrete Testing Laboratory
XRD	x-ray diffraction

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Abstract

Thermal effects from cement hydration and environmental factors can lead to thermal gradients within the concrete section and induce thermal cracking. Temperature effects are especially important in mass concrete, where the size of the placement can produce large amounts of heat with relatively little surface area to dissipate it. Even in smaller placements, concrete containing high cement contents or supplementary cementitious materials (SCMs) such as silica fume can produce high temperatures. There are several approaches for estimating temperature rise of concrete. Some of these tools could be beneficial to Reclamation's designers when determining placement size or determining if a temperature control plan is required.

Past experience with temperature prediction models is limited, especially as they relate to Reclamation's unique and massive structures. Adiabatic temperature testing is usually carried out at the Concrete, Geotechnical, and Structural Laboratory (CGSL) to develop accurate temperature rise curves. This work aims to compare the adiabatic temperature rise from simulations with Reclamation's experimentally measured temperature rise. Additionally, recommendations are presented on which approach would be suitable for a particular application or a particular mix design (i.e. straight cement, cement plus Class N pozzolan, etc.).

Background

The Schmidt Method was developed in the 1930's as a simplified finite difference method to determine temperature rise in concrete elements. It is cited in Reclamation's Engineering Monograph No. 34 "Control of Cracking in Mass Concrete" to estimate the temperature distribution in mass concrete structures over time [1]. The Schmidt method is also the basis for several finite element programs used in private industry.

The method works by determining a new temperature at a node at the current time as the average of the temperature of neighboring nodes in the prior time step, plus any temperature rise associated with the heat added to the node. The additional temperature added at each time step is the temperature rise associated with cement hydration. Many designers use the temperature rise curves from ACI 207.2R-07, but those curves were developed during the Boulder Canyon studies in the 1930s [2]. Recent DSO research showed the guidance in ACI 207 documents and Reclamation's Engineering Monograph 34 were inaccurate for modern cements and SCMs [3]. Since the temperature contribution of the concrete is such an important variable, it is crucial to have accurate adiabatic temperature rise data.

There are several programs and models that are designed to predict temperature rise of concrete. Some are specifically for mass concrete elements while others can be used for any application. The criteria to classify an element as "mass concrete" is not always straightforward. According to ACI 207 Committee on Mass Concrete, mass concrete is any concrete placement large enough where thermal effects are a major concern. In high strength concrete containing high volumes of cement, placement sizes can be relatively small and still generate enough heat to cause thermal cracking as shown in Figure 1 [4]. A computer model to predict heat rise can be more cost effective than testing, if the model is accurate for a wide range of concrete mixtures and materials.

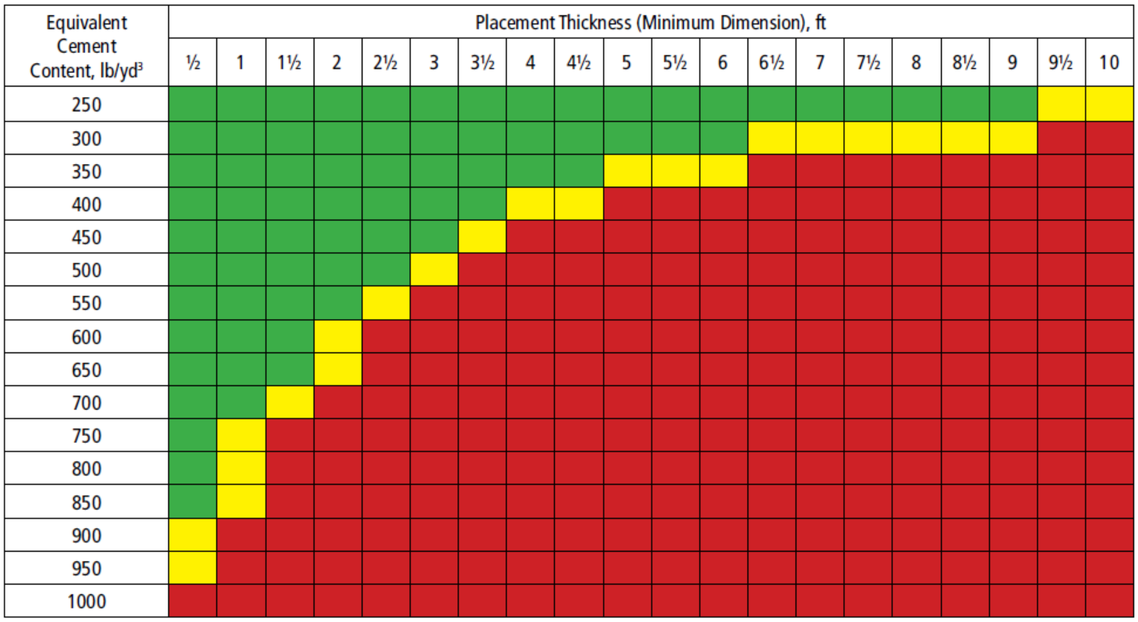

Figure 1. Chart of placement versus equivalent cement content for normal weight concrete. Red is mass concrete, yellow is a buffer zone that is left to the discretion of the specifier.

Objective

The objective of this research is to compare the results of publicly available simulated and measured adiabatic temperature rise of mass concrete. The results will provide insight into which programs are applicable to Reclamation structures and their accuracy as compared to lab or field measured values. Additionally, other programs and methods that calculate semi-adiabatic (field condition) temperature rise will be compared. Other proprietary methods are known to exist in the concrete industry, but these methods have not been evaluated at this time.

Adiabatic Models

Measured Adiabatic Temperature Rise

Adiabatic temperature rise can be measured using USBR 4911 [5]. While this test method accurately measures the temperature rise of concrete, it requires a large sample (approximately 4.8 ft^3 of concrete) and runs for a long duration (56 or more days). While the test is expensive to run, it uses the materials in question and directly measures the temperature rise of a specific concrete mix.

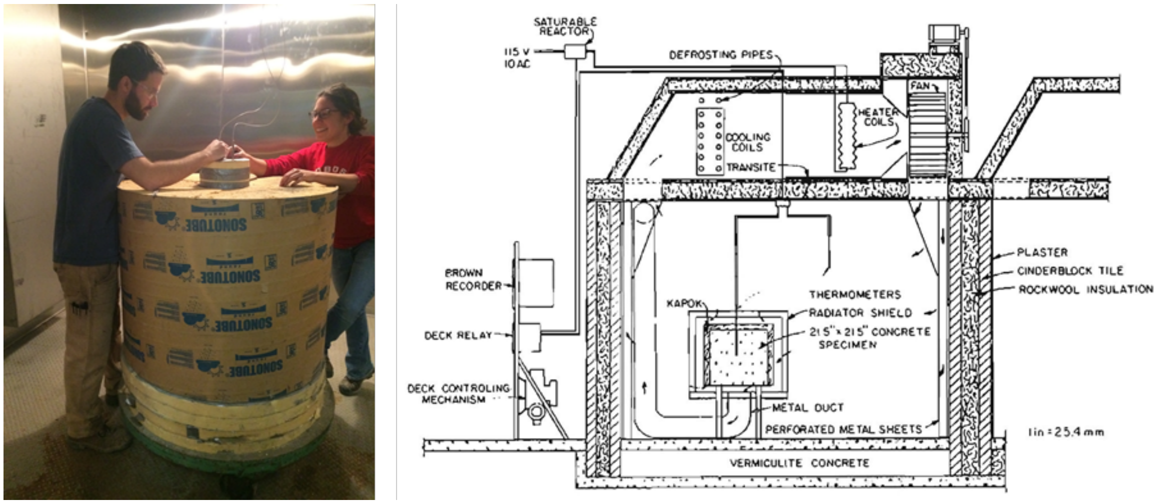

Figure 2. Test specimen for adiabatic temperature rise and room configuration.

Basic Heat of Hydration Calculation

Equation 1 from ACI 207.2R-07, "Report on Thermal and Volume Change Effects on Cracking of Mass Concrete" can be used to estimate the adiabatic temperature rise (H_g) in °F.

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

Equation 1

Where:

1.8 = conversion factor from Celsius to Fahrenheit
27 = conversion factor from yd^3 to ft^3
h_g = 28-day heat of hydration of the cement in cal/g
w_c = weight of cement in pounds per cubic yard of concrete
C_p = specific heat of concrete in cal/g·°C
γ_c = 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. ACI 207.2R-07 recommends the use of 0.20 to 0.25 cal/g·°C [2]. The value used for specific heat can change the calculated temperature drastically. For example, consider a concrete with a cement that has a 28-day heat of hydration of 87 cal/g (364 J/g), 600 lb/yd^3 cement, and a unit weight of 150 lb/ft^3. Using C_p of 0.20 results in a temperature rise of 116 °F. Using C_p of 0.25 results in a temperature rise of 92.8 °F. There is a 22% difference in the calculated values just by changing the specific heat. The specific heat capacity can be calculated from a law of mixtures (by mass). Table 1 lists the specific heat of components of concrete. The specific heat of concrete is calculated by the sum of the heat capacity of the individual constituent multiplied by the mass fraction of the constituent (from the mix design).

Table 1. Heat capacities of concrete components [6].

Component	Heat Capacity	
	J/g°C	cal/ g°C
Siliceous Aggregate	0.75	0.179
Limestone Aggregate	0.84	0.201
Cement	0.75	0.179
Silica Fume	0.75	0.179
Fly Ash	0.72	0.172
Slag	0.8	0.191
Limestone Powder	0.818	0.195
Water	4.18	0.998

The heat of hydration of cement can be measured using isothermal calorimetry in accordance with ASTM C1702-15 [7]. The CGSL can measure the heat signature of cementitious pastes using a TA Instruments TamAIR 8-channel isothermal calorimeter (IC). The paste sample and calorimeter are shown in Figure 3.

Figure 3. Paste sample (approx. 5 grams) used for isothermal calorimetry.

Using Equation 1 is a very basic approach to take data from the IC and convert to temperature rise. As the name implies, isothermal calorimetry is performed at one temperature (23 °C for this study), although cement hydration is a temperature-dependent process.

The values for temperature rise in Tables 3 through 5 are from previously published studies [3], [8]. Table 2 describes the mixtures being compared; the complete mix designs can be found in the previously mentioned references. Information on the cementitious materials used can be found in Appendix A.

Table 2. Description of mixtures used to compare calculated and measured temperature rise

Mix ID	Description	Cementitious Material (lb/yd^3)	Percent SCM Replacement	w/cm
OPC-7	7-sack straight cement	671	0	0.58
OPC-4	4-sack straight cement	384	0	0.39
OPC-7-0.58	7-sack straight cement with 0.58 w/cm	671	0	0.58
FA-25	7-sack with Class F fly ash	659	25	0.42
FA-50	7-sack with Class F fly ash	659	50	0.42
FA-75	7-sack with Class F fly ash	659	75	0.39
NCC-15	Nevada Cement Co. Class N Pozzolan	543	15	0.45
NCC-25	Nevada Cement Co. Class N Pozzolan	543	25	0.45
NCC-35	Nevada Cement Co. Class N Pozzolan	543	35	0.45

In general, the temperature rise for mixtures containing pozzolans were accurately calculated using the heat of hydration when compared to the measured temperature rise. The temperature rise was generally under-calculated in mixtures containing only portland cement. Overall, this very basic calculation can be used to get a ballpark estimation of the adiabatic temperature rise within the first 7 days, but is not accurate enough to use as an input into a finite element model. It is a suitable method to use for comparing different mixtures when evaluating the effect of a pozzolan on temperature rise.

Table 3. Calculated versus measured temperature rise for straight cement mixtures at 1, 3 and 7 days

Temperature Rise (°F)	OPC-7 [Calculated]	OPC-7 [Measured]	OPC-4 [Calculated]	OPC-4 [Measured]	OPC-7-0.58 [Calculated]	OPC-7-0.58 [Measured]
1-day	56.1	84.7	39.3	58.6	68.6	73.6
3-day	75.4	98.2	52.7	67.1	92.0	100.0
7-day	80.7	101.1	57.7	69.5	100.8	103.4

Table 4. Calculated versus measured temperature rise for mixtures containing Class F fly ash at 1, 3, and 7 days

Temperature Rise (°F)	FA-25 [Calculated]	FA-25 [Measured]	FA-50 [Calculated]	FA-50 [Measured]	FA-75 [Calculated]	FA-75 [Measured]
1-day	56.3	54.5	41.3	38.5	21.1	15.6
3-day	75.9	80.9	56.0	57.5	27.5	28.2
7-day	83.9	90.0	63.4	69.2	28.6	36.3

Table 5. Calculated versus measured temperature rise for mixtures containing Nevada Cement Co. Class N pozzolan at 1, 3, and 7 days

Temperature Rise (°F)	NCC-15 [Calculated]	NCC-15 [Measured]	NCC-25 [Calculated]	NCC-25 [Measured]	NCC-35 [Calculated]	NCC-35 [Measured]
1-day	59.1	63.1	56.4	58.6	67.6	48.3
3-day	78.6	82.7	75.0	76.6	89.6	71.6
7-day	83.1	86.1	79.2	81.7	95.2	78.4

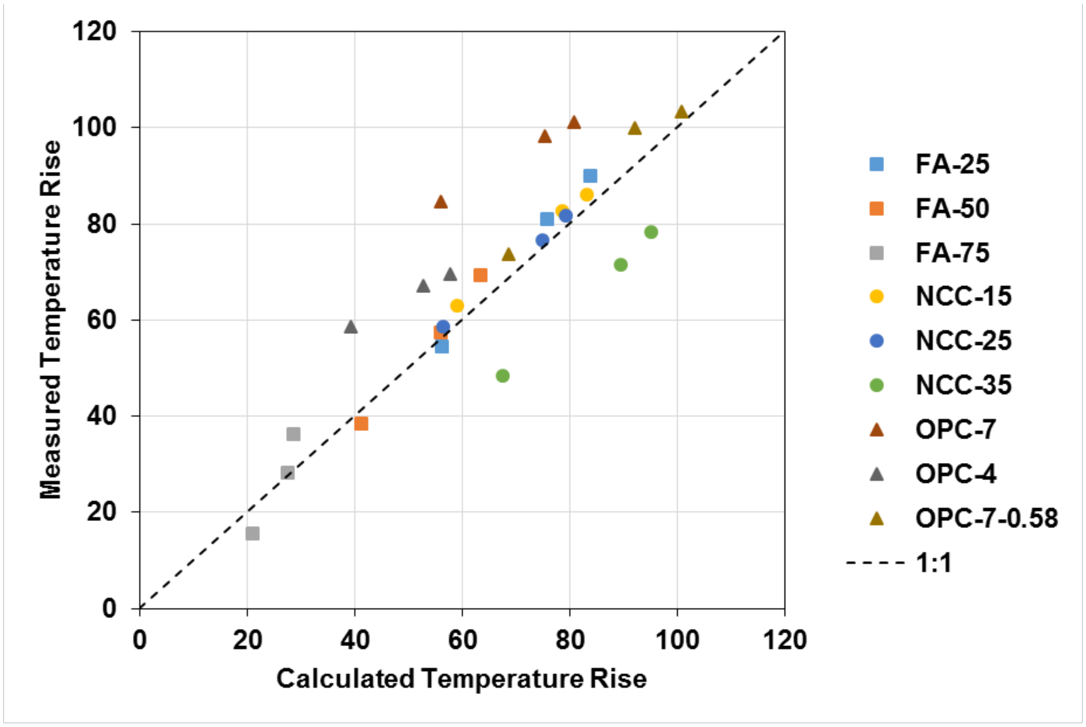

Figure 4. Comparison of measured and calculated temperature rise for fly ash, Class N pozzolans, and portland cement mixtures

NIST – Microstructure Model

This procedure is reported by Bentz et. al [6]. The model is based on the degree of hydration (α) of the system and converted to adiabatic temperature rise based on the heat released and the heat capacity at each time step.

The degree of hydration versus time is determined experimentally and fitted with a parabolic curve expressed as Equation 2. Degree of hydration can be determined using isothermal calorimetry (as cumulative heat released divided by the heat at complete hydration (Hu)) or non-evaporable water content [9]. The maturity method is then used to determine the equivalent time at a different temperature. The procedure can be modified to consider a pozzolanic reaction if there are pozzolans added to the mix.

$$H = \frac{H_u k \sqrt{t - t_0}}{1 + k\sqrt{t - t_0}}$$

Equation 2

Where:

H = cumulative heat
H_u = heat at complete hydration
t_0 = induction time
t = time
k = fitting constant.

From Figure 5, the parabolic model expressed as Equation 2 is compared to the measured heat release from the isothermal calorimeter at 23 °C. Overall it is a reasonable fit, although the slope of the model deviates at a relatively rapid rate after 96 hours.

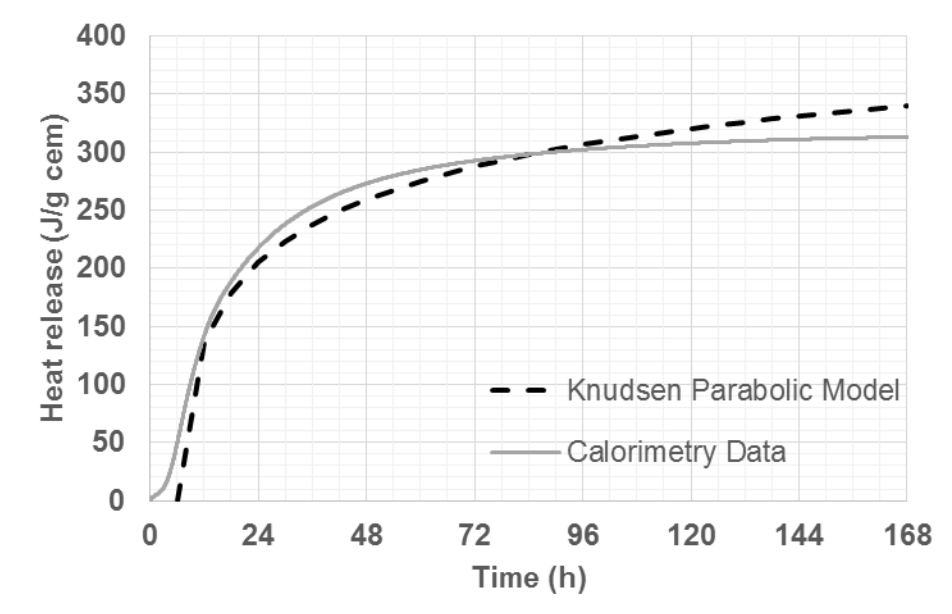

Figure 5. Comparison of calorimetry data and Equation 2, k = 0.17 h^{-1}, t_0 = 7 h, H_u = 497 J/g

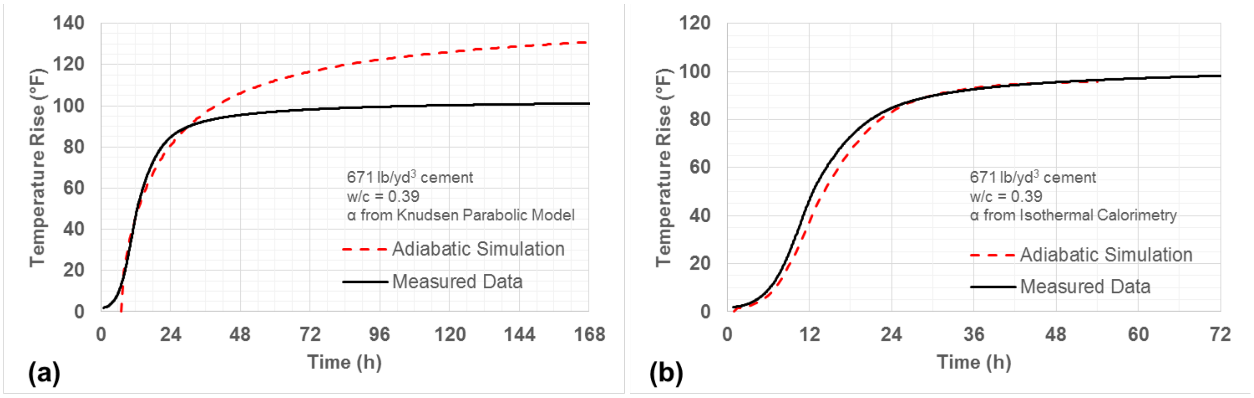

Figure 6. Example of a simulated temperature rise versus measured temperature rise using the approach by Bentz et al. using degree of hydration from (a) Knudsen parabolic model and (b) isothermal calorimetry data

If the degree of hydration with respect to time is accurately known, the temperature rise can be accurately predicted as shown in Figure 6b. Conversely, if the model and experimentally measured degrees of hydration over time do not agree over a full range of time (months), the predicted temperature rise will not be accurate as shown in Figure 6a. Figure 6a compares the simulated temperature rise to measured temperature rise over seven days while Figure 6b compares data over the first three days. The IC only collected data for 7 days (168 equivalent-age hours) which, based on the maturity method, corresponds to approximately 50 hours in real-time. There is variation in cement types and not every model is suitable for a wide range of cements. In order to calibrate a model accurately, the degree of hydration must be determined by measuring the non-evaporable water contained in a hardened paste at various times, for up to several months. Then an appropriate kinetic model can be determined and used to predict temperature rise over the span of several days.

This method can produce reliable temperature rise data provided that care is taken in the calibration of the hydration model.

Virtual Cement and Concrete Testing Laboratory (VCCTL)

The VCCTL was developed by the Materials and Structural Systems Division at the National Institute of Standards and Technology (NIST). The program models cement hydration in 3-D and subsequently can calculate other properties such as temperature rise, elastic properties (effective linear elastic moduli) and transport properties (relative diffusivity and formation factor) over a specified amount of time [10].

There are several pre-loaded Cement and Concrete Reference Laboratory (CCRL) cements as well as other cements that the user can select as shown in Figure 7. The user can select materials that are similar to their own or create a new file with information for a particular cement. The user must be familiar with characteristics of cement (chemical composition, fineness, etc) in order to choose an appropriate pre-loaded cement. If creating a new file, the user must input both chemical (phase composition from x-ray diffraction, XRD, analysis) and physical properties (particle size distribution) of the cement or any other SCMs. The input process is very detailed and requires a scanning electron microscope (SEM) image of the cement with segmented phases in order to complete the 3-D hydration model.

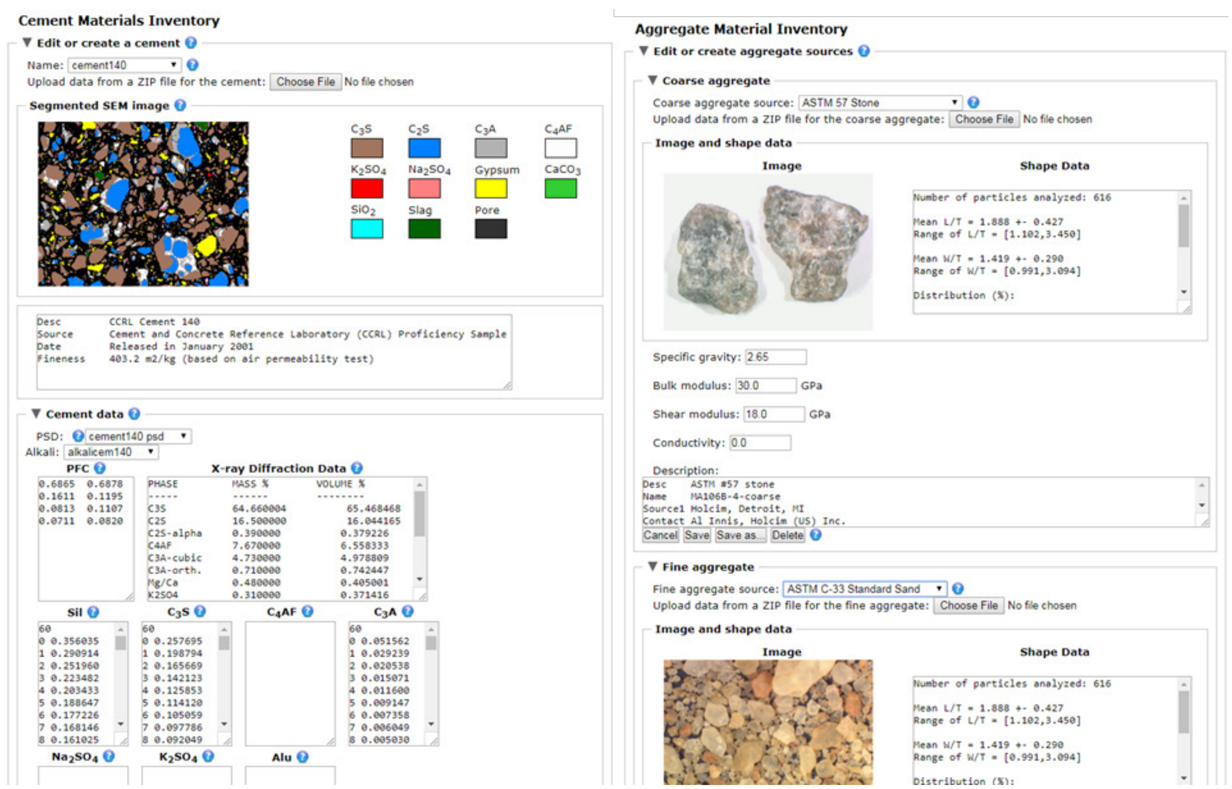

Figure 7. Example of cement materials and aggregate materials that can be selected in the VCCTL

The user also defines aggregate properties for mortar or concrete. The user can then define the mixture proportions and run the analysis. To hydrate the mix, the activation energy of the cement hydration, pozzolanic reaction and slag reactions must be entered. The default values are reasonable for most materials. The thermal conditions (isothermal, semi-adiabatic or adiabatic) must also be defined. Lastly, saturation conditions (saturated or sealed) must be defined before running the analysis.

Semi-Adiabatic Models

Concrete Works

Concrete Works is a product of research conducted at the University of Texas, Austin and funded by the Federal Highway Administration and the Texas Department of Transportation [11]. The user manual and more information can be downloaded from the University of Texas at Austin's Center for Transportation Research's website [12]. Since the program was developed for transportation infrastructure, the elements that can be modeled are restricted to those commonly seen in mass bridge construction. Some, such as rectangular columns, footings, etc. would be used in Reclamation construction.

The user defines mixture proportions, cement chemistry data, and aggregate type. The chemical and physical of the cement can be default values as shown in Figure 9. The mill certificate will include chemical and physical properties that are required by ASTM C150 and may or may not include optional requirements (such as equivalent alkalis). The user can only define Grade 120 slag, whereas typically one would more likely use a lower grade of slag to reduce the heat of hydration in mass concrete. The user cannot define or edit the chemical or physical properties of the slag, and there is limited flexibility for other SCMs. There is no option for a Class N pozzolan, so the user would have to substitute for Class F or C fly ash. The hydration model only considers the calcium oxide (CaO) in the fly ash, as shown in Figure 8. The default values for CaO content are shown in the screen capture and it should be noted that they are on the higher end of the spectrum for a typical Class F or Class C fly ash, which is conservative from a heat-generation standpoint [13]. The user should enter the CaO content that more accurately reflects the material being used. The hydration simulation is based on an empirical model incorporating the chemistry of the cementitious materials, the types of admixtures used and the equivalent-age method [14]. The more accurately the user can characterize the materials, the more accurately the software can predict the temperature rise.

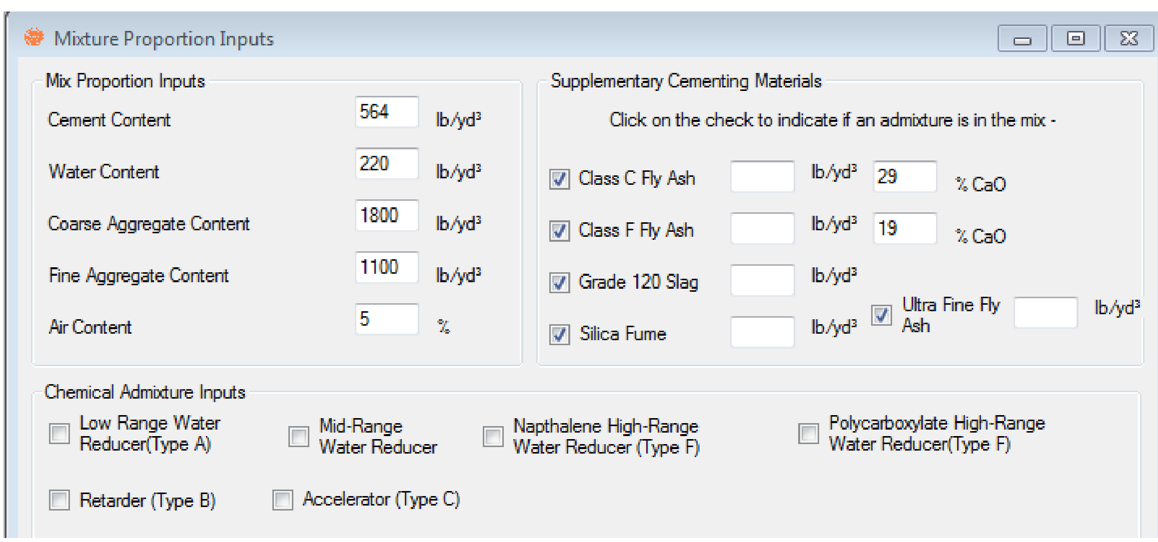

Figure 8. User defined mixture proportions showing default values in Concrete Works

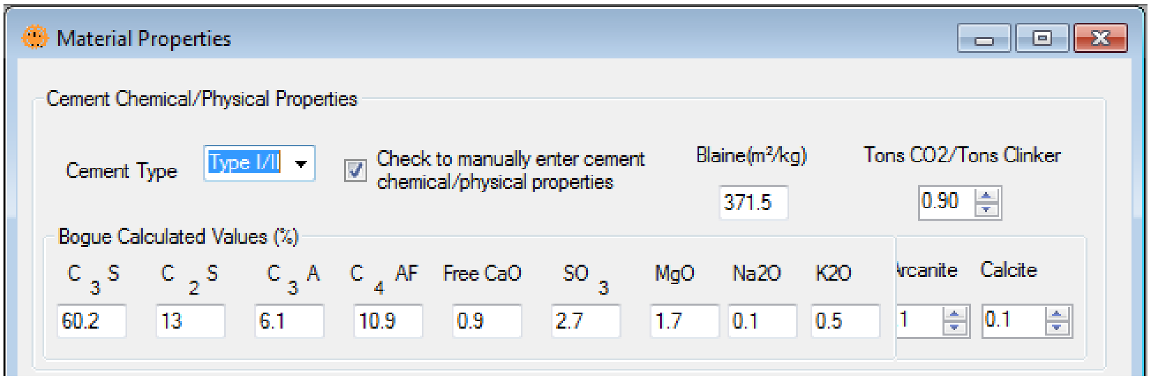

Figure 9. Cement properties that can be manually changed by the user

Additionally, environmental inputs such as ambient temperature, wind speed, and percent cloud cover can be defined. The output shows the spatial distribution of the temperature throughout the cross section of the member as well as the maximum temperature difference between the center and the outside. The program also calculates the cracking potential based on the maximum temperature difference and the predicted strength of the concrete at a given time.

There are several papers in the ACI Materials Journal documenting the development of the hydration models and thermal property models that went in to Concrete Works [14], [15]. While the program is generally user-friendly, it is recommended that someone familiar with the theory behind the models reviews the inputs and determines if they are representative of the mix in question.

Conclusions and Recommendations

- Using isothermal calorimetry is a cost-effective way to gather data to use in temperature-rise simulations.
    - Data can be measured accurately for about 7 days
    - Equation 1 can be used to easily convert heat of hydration to temperature rise reasonably accurately. However, is more suitable for comparison of materials and not for an input into a finite element model.
- The degree of hydration model (Bentz et al) can be used to accurately predict the adiabatic temperature rise
    - The degree of hydration must be determined experimentally and an appropriate equation must be used to fit the data.
        - The experimental data should be measured for up to 90 days to ensure there is a good fit with the chosen model.
        - In most cases, running a full adiabatic temperature rise test of the concrete mix in question would be more efficient than waiting 90 days to get degree of hydration data.
    - Extra consideration must be made for the addition of pozzolans
    - The simulated temperature rise could be used in a finite element model to predict temperature distributions in a concrete element.
- The VCCTL is a very sophisticated and powerful tool, but the user must be familiar with cement chemistry and hydration in order to make reasonable assumptions.
    - Uploading new cements or other materials requires detailed analysis (SEM, XRD, Particle Size Distribution, etc)
- Concrete Works is a convenient tool to use that simulates cement hydration (and subsequent temperature development) and incorporates concrete member geometry and environment to simulate temperature gradients throughout the element. The program is a "one stop shop" to determine cracking potential for a mass concrete element
    - Care must be taken to correctly define and choose the materials and construction/curing methods used on a project.
    - Only simple geometries with limited dimensions can be calculated.
- While there are many tools to predict adiabatic temperature rise, measuring it in the lab (USBR 4911) or a field trial is the best way to get a true temperature rise prior to placement of mass concrete.

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Appendix A – Materials Data Sheets

NEVADA CEMENT COMPANY

Post Office Box 840, Fernley, Nevada 89408 - 0840 (775) 575 - 2281

LABORATORY TEST REPORT
SAMPLE : Class "N" Pozzolan

Date: September 2016

Silo: 8

Customer:______________________ Bill of Lading: ______________________

Chemical Composition (%)-ASTM C-311			ASTM C 618 Specifications Class N
Total Silica, Aluminum, Iron:	79.3		70.0 Min
Silicon Dioxide:	65.8		
Aluminum Oxide:	12.8		
Iron Oxide:	0.7		
Moisture content	1.2		3.0 max
Sulfur Trioxide:	0.0		4.0 Max
Calcium Oxide:	1.1		
Loss on Ignition:	2.8		10.0 Max
Available Alkali As Na2O	1.4		
Physical Testing Results			
Density:	2.36		
Blaine:	4820		
Retained on -325 Sieve:	8.4	%	34 Max
20% 7 Days	83		75 Min
20% 28 Days	85		75 Min
20% Water Requirement	100		115 Max
25% 7 Days	76		
25% 28 Days	81		
25% Water Requirement	100		
Autoclave Expansion @ 20%	-0.02		0.8 Max

Nevada Cement Company complies with the requirements of the current ASTM C618 and AASHTO M 295 specifications for class "N" pozzolan. The material is tested following the current ASTM C311. The above data represents the average of the silo or bins ground during the month of August 2016 from which this material was shipped.
All test results are certifed to comply with the type specification designated.
We are not responsible for improper use or workmanship.

AASHTO Accredited since 1996

Eric Dutcher
Chief Chemist

Holcim

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 (%)	-
Fe2O3 (%)	-
CaO (%)	-
SO_3 (%)	-

Base Cement Phase Composition

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

By , Quality Manager

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