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16. Abstract

The objective of this research project is to identify, develop, and evaluate a simple, economical, and reliable calorimetry device and test method for monitoring heat evolution of pavement concrete. The project contains three phases: phase I—identifying user needs for calorimeter tests, phase II—identifying potential calorimeter devices and developing test procedures, and phase III—verifying the test procedures and the potential applications of calorimetry in field. In this report, the work done in phases I and II is briefly summarized and the study of phase III is presented.

The phase III study includes three parts: (1) field calorimetry tests, (2) lab tests for the field materials, and (3) implementation of calorimetry into pavement performance prediction. The field tests were conducted at three selected sites: US 71 (Atlantic, Iowa), Highway 95 (Alma Center, Wisconsin), and US 63 bypass (Ottumwa, Iowa). A simple isothermal calorimetry and two semi-adiabatic calorimetry (AdiaCal and IQ drum) tests were conducted at these sites. The general concrete, such as slump, air content, unit weight, placement temperature, ASTM C403 set time, and pavement properties, such as subbase temperature and sawing time were also measured. In the lab tests of the field materials, nine robust mixes for each field site, with different variations in water reducer and/or fly ash dosages were developed. AdiaCal and isothermal calorimeter tests were performed for each of the robust mixes. IQ drum and ASTM C403 set time tests were conducted for selected mixes. To implement the calorimetry test results into concrete performance prediction, the HIgh PERformance PAVing (HIPERPAV) computer program was modified, the calculated hydration curve parameters from selected calorimetry tests were used as inputs for the modified HIPERPAV program, and the temperature developments of in-situ pavements were then predicted. The phase III test results confirmed the major findings drawn in the phase II study. The results indicate that both the AdiaCal and semi-adiabactic calorimetry tests can provide valuable information on concrete performance. AdiaCal calorimetry is particularly good for field concrete set time prediction, and it is sensitive to the sample temperature. Isothermal calorimetry can provide users more detailed information on cement hydration and provide more consistent test results. The thermal set times obtained from both the AdiaCal and isothermal calorimetry tests are closely related to those measured from the ASTM C403 tests. Using the calorimetry test curve as inputs for the HIPERPAV computer program, in-situ concrete pavement temperatures can be predicted adequately.

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DEVELOPING A SIMPLE AND RAPID TEST FOR MONITORING THE HEAT EVOLUTION OF CONCRETE MIXTURES FOR BOTH LABORATORY AND FIELD APPLICATIONS-PHASE III

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EXECUTIVE SUMMARY

Concrete quality control is critical for ensuring desired field concrete performance. A number of quality control test methods have been developed and some of them are routinely used in field. The test methods include slump, air content, and strength/maturity tests. Lately, various tests (such as false set, rheological, and calorimetry tests) are also developed for identifying the incompatibility of supplementary cementitious materials and chemical admixtures in concrete. Among these existing test methods, some of them are too simple to be accurate and some of them require expensive equipment, complex testing procedures, and/or extensive time, thus are not suitable for field application. Since cement hydration process directly influences concrete workability, setting behavior, strength gain rates, and microstructure development, it is believed that the deviations in the quantities and characteristics of the concrete constituents as well as effects of construction conditions can be detected and concrete performance can be predicted by one test—a calorimetry test—that monitors the heat of cement hydration in concrete.

The objective of the present research is to identify, develop, and evaluate a simple, economical, and reliable calorimetry device and test method for monitoring heat evolution of pavement concrete. This research project contains three phases:
Phase I: Identifying user needs for calorimeter tests, potential applications of calorimeter test results, and a potential calorimeter device for the phase II study (completed in December 2005)
Phase II: Developing test procedures and methods for interpreting the test results (completed in December 2007)
Phase III: Verifying the test procedures and the potential applications of calorimetry in field

In this report, the work done in phases I and II is briefly summarized and the study of phase III is presented. The phase III study includes three major parts: (1) field tests, (2) lab tests for the field materials, and (3) implementation of calorimetry into HIgh PERformance concrete PAVing (HIPERPAV) prediction. Three field sites, US 71 (Atlantic, Iowa), Highway 95 (Alma Center, Wisconsin), and US 63 bypass (Ottumwa, Iowa) were selected, and calorimetry tests were conducted at these field sites using different calorimeters: a simple isothermal calorimeter, as identified in the phase II study, and two semi-adiabatic calorimeters (AdiaCal and IQ drum). The set times of the field concrete were also measured according to ASTM C403, and general properties of the concrete and pavement (such as concrete slump, air content, unit weight, water/cement ratio [w/c], placement temperature, and pavement subbase temperature and sawing time) were also recorded. Robust tests were conducted in lab for these field concrete materials. Nine robust mixes for each field project, with 50% variations in water reducer (WR) and/or fly ash (FA) dosages from the mix proportion actually used in field were developed and studied. AdiaCal tests were performed for each robust mix, and isothermal calorimeter tests were performed for each robust mix at four different temperatures. Selected IQ drum tests and ASTM C403 set time tests were also performed in lab so as to compare the lab results with the field test results. A statistical analysis was conducted to analyze these test data. The activation energies are determined from the isothermal test results of heat signatures using the Arrhenius equation. Hydration curve parameters are back-calculated from both the isothermal tests and semi-adiabatic tests. Then the back-calculated hydration curve parameters are input into the HIPERPAV computer program which is modified to offer a window for users to define and input those parameters, in order to predict the pavement performance including the temperature in the in situ pavements and associated strength and stress development. A mathematical model and associated computation approach are also developed to convert the isothermal signature of cement mortar to the semi-adiabatic signature of cement concrete.

The results of the field tests conducted in the phase III study indicate the following:

- AdiaCal semi-adiabactic calorimetry tests, using concrete samples, can provide general information on concrete performance. The test results are very sensitive to the concrete placement temperature. (The temperature curves obtained from the AdiaCal calorimeter tests varied largely in the samples tested in the same day.) Thus, the test results are useable for set time prediction of field concrete but not desirable for accurate concrete quality control.
- Similar to the findings drawn in the phase II study, the thermal set times obtained from both AdiaCal and isothermal calorimetry tests are closely related to those from the ASTM C403 tests. Compared with the isothermal calorimetry test, the AdiaCal test is easy to operate.
- The simple isothermal calorimetry test results of samples at a given project were consistent. The test results of samples from different projects looked very different, demonstrating the subtle changes in these concrete materials and/or mixture proportions. As a result, the simple isothermal calorimeter could be a good tool for daily concrete quality control.
- In the simple isothermal calorimetry tests, concrete samples showed much larger variations than mortar samples. Therefore, mortar samples sieved from field concrete are recommended for field calorimetry tests.
- No incompatibility problem in the concrete studied was identified by the calorimetry tests.
- Neither the isothermal calorimeter nor AdiaCal showed good ability to identify changes in w/c ratio of the field concrete. Hence, the microwave method can be used as a supplementary test for such identification.
- Pavement sawing times were close to the final setting time in these three field projects, but no clear relationship was observed between the setting and sawing times.

The results from the lab tests for the field materials suggest the following:

- The results from the lab tests for the field materials are generally consistent with those from the corresponding field tests.
- The simple isothermal tests showed clearly a second peak related to the hydration of fly ash in the concrete mixes tested. Such a heat evolution peak was not generally observed from AdiaCal or IQ Drum tests.
- The thermal set times obtained form both AdiaCal and isothermal calorimetry tests were well-related to those from the ASTM C403 tests. The effects of WR dosage and FA replacement levels on concrete set time could be identified by both calorimetry test methods.
- The simple isothermal tests results illustrated that as testing temperature increased, the variation in thermal set time decreased. This implies that potential concrete set time and strength development problems might show in winter construction while fewer problems may be expected in summer construction.
- Testing/curing temperature had a more significant effect on concrete calorimetry parameters (thermal set time and the area under the heat evolution curve) than WR and FA. Compared with FA, WR has less effect on thermal set time. However, in different projects, WR had different effects on calorimetry parameters.
- The robust tests demonstrated that when the WR and/or FA amounts are 50% higher or lower than the designed dosage, the concrete heat-generation curves looked similar but shifted only

to the left or right, depending on the degree of the material variation. There was no incompatibility problem within these mixes tested at the designed testing temperature.
- The robust test method can be used for establishing acceptable heat evolution boundaries. Thus, field engineers can easily evaluate their calorimetry test results and use the calorimetry as a single tool for field concrete quality control.

The results from the theoretical models and HIPERPAV implementation indicate the following:

- The computed activation energies of the cementitious materials using the Arrhenius equation based on the isothermal test data are close to the values reported by other researchers.
- It seems that adding WR and FA replacement increases activation energy.
- The hydration curve parameter α_u increases, while β and τ decrease when decreasing the total heat of hydration Hu based on the isothermal test data.
- The calculated hydration curve parameter β, based on the isothermal test data, seems to be larger than that based on the semi-adiabatic test data, while the hydration curve parameter τ based on the isothermal test data seems to be smaller than that based on the semi-adiabatic test data.
- The simulated semi-adiabatic temperatures in terms of the isothermal heat signatures have a reasonable agreement with the measurements though there is some small delay at the early stage.
- The hydration curve parameters resulting from semi-adiabatic test data (as opposed to isothermal test data) are a better match to actual portland cement concrete (PCC) pavement temperatures. This result could be due to at least two reasons: (1) the semi-adiabatic test condition is closer to that of the in situ pavements; (2) the semi-adiabatic test is conducted on concrete as that of in situ pavement, while the isothermal test is conducted on the cement mortar.

The findings from the present research also imply that proper application of a simple calorimetry technique in lab and/or field will provide engineers with important information on concrete quality and performance that may otherwise require conducting many different tests.

1. INTRODUCTION

1.1 Research Background

Concrete quality control is critical for ensuring desired field concrete performance. A number of quality control test methods have been developed and routinely used in-field over decades, which include slump, air content, and strength tests. Set time of concrete is sometimes tested in lab to assist in the determination of the pavement finishing and sawing time. Maturity test methods have commonly been used in the field as a replacement for concrete strength tests. Due to increasing applications of various supplementary cementitious materials (SCMs) and admixtures in modern concrete, various tests (such as false set, rheological and calorimetry tests) are also developed for identifying the incompatibility of concrete materials. Among these existing test methods, some of them are too simple to be accurate and some of them require expensive equipment, complex testing procedures, and/or extensive time, thus are not suitable for field application. The abnormal cement hydration resulting from "incompatibility" of concrete materials has resulted in erratic set and strength gain behavior and associated finishing, curing, and early-age cracking. Influences of construction and environmental conditions, such as cold and hot weather, often aggravate these problems. However, the existing guidance is lacking on proper test methods for identifying these problems.

Cement hydration liberates heat. Research has shown that the heat evolution process is strongly influenced by the chemical and physical properties of portland cement (PC), SCMs, chemical admixtures, concrete mix proportions, construction procedures, and curing conditions of concrete. As a result, deviations in the quantities and characteristics of the concrete constituents as well as effects of construction conditions can be detected and concrete performance can be predicted by monitoring the heat of cement hydration (1, 2). Recently, the advancements in the use of thermal measurements of the early heat development of concrete mixtures in the laboratory have demonstrated that calorimetry tests have a high potential for detecting concrete incompatibility problems, predicting fresh concrete properties (such as setting time), and assessing hardened concrete performance (such as strength gain and thermal cracking) under various climatic conditions (3,4).

The objective of this research project is to identify, develop, and evaluate a simple, economical, and reliable calorimetry device and a test method for monitoring heat evolution of pavement concrete.

1.2 Research Approach and Scope

This research project consists of three phases:

Phase I: Identifying user needs for calorimeter tests, potential applications of calorimeter test results, and a potential calorimeter device for the phase II study (completed in December 2005)

Phase II: Developing test procedures and methods for interpreting the test results (completed in December 2007)

Phase III: Verifying the test procedures and the potential applications of calorimetry in the field

1.3 Summary of Phase I and II Study

In the phase I study, a literature search and a survey of participating agencies and others in the portland cement concrete (PCC) paving community were conducted to gather information on the users' needs for a simple, rapid calorimeter test and the potential applications of calorimeter test results. The phase I study also included investigations on the existing test procedures for measuring the heat of hydration of concrete using calorimetry and other methods as well as the test device. It is concluded that in conjunction with another technology, such as HIgh PERformance concrete PAVing (HIPERPAV), the heat evolution test results can be used for the following:

- Flagging changes in cementitious materials
- Prescreening materials and/or mix design
- Identifying incompatibility of cementitious materials
- Verifying mix proportions
- Forecasting setting time
- Estimating sawing and finishing time
- Assessing concrete maturity and strength
- Predicting risk of thermal cracking

After confirming the specific needs of the pavement industry on the calorimetry tests and having a clear vision on the practical applications of the calorimeter tests, the research team proposed a focused, systematical study for phase II.

In phase II, two available calorimeter devices, a semi-isothermal calorimeter manufactured by Thermometric Inc. (approximately $8,000) and a semi-adiabatic calorimeter device, AdiaCal, (approximately $3,000) were utilized. These devices were selected because they would likely have a fair cost and produce results that could differentiate the heat signatures of various concrete materials in a short time span. A wide range of paste and mortar mixtures (over 150 mixes) were tested to evaluate the effects of the concrete materials (ingredients, sources, and proportions), equipment, and environmental conditions on the calorimetry test results. Some known incompatible mixes were specially selected and tested. The interpretation methods of the test results, using the heat evolution indexes that were developed from the derivatives of and the areas under the heat evolution curves were explored. The relationship between the thermal set time derived from the calorimetry test results and the ASTM C403 set time test results of concrete set time and the relationship between the area under the calorimetry curve and the concrete strength were investigated. A draft of isothermal test specification was developed.

In addition, two field trial tests at New York and South Dakota ware also conducted using the AdiaCal calorimeter. The research team members at Transtec Group, Inc. also investigated the potential for predicting concrete performance using results from the calorimetry tests together with the HIPERPAV computer program. However, due to the limited time and funding, the phase II study did not include sufficient field tests and HIPERPAV analyses. The phase III study was then proposed for completing the overall goal of the heat of evolution project.
The following findings were drawn from the phase II study:

- The test method developed for the selected isothermal calorimeter device is easy to apply and repeatable.
- The calorimeter test can be used to differentiate the heat evolution of mortars made with different materials and subjected to different curing conditions.
- The calorimeter test can be used to identify material incompatibility and to flag cementitious changes.
- The heat indexes, related to the first derivative of the calorimeter curve and the area under the curve, are able to characterize the features of mortar. They can also be used to predict the mortar set time and early-age strength (up to two days).
- The selected semi-adiabatic calorimeter test device (AdiaCal) is also easy to use, and the test results provide a very good prediction of the set time of field concrete.
- The AdiaCal calorimeter or similar equipment can be modified to compute temperature losses and can inexpensively replicate the results of semi-adiabatic testing in the field.
- Used with HIPERPAV, semi-adiabatic testing of concrete in the field is the recommended procedure for prediction of pavement performance characteristics, including set times, strength gain, and thermal cracking risk.

1.4 Description of Phase III Study

The focus of this report is on the phase III study, which includes three major parts:

1. Field tests

Three field sites, US 71 (Atlantic, Iowa), Highway 95 (Alma Center, Wisconsin), and US 63 bypass (Ottumwa, Iowa) were selected, and calorimetry tests were conducted at these field sites using different calorimeters: a simple isothermal calorimeter, as identified in the phase II study, and two semi-adiabatic calorimeter (AdiaCal and IQ drum). The set times of the field concrete were also measured according to ASTM C403, and general properties of the concrete and pavement (such as concrete slump, air content, unit weight, water/cement ratio [w/c]), placement temperature, and pavement subbase temperature and sawing time) were also recorded.

2. Lab tests for the field materials

Robust tests were conducted in lab for these field concrete materials. Nine robust mixes, with 50% decrease/increase of water reducer (WR) and/or fly ash (FA) dosages were developed based on the mix proportion actually used in field for each field project. AdiaCal tests were performed for each robust mix, and isothermal calorimeter tests were performed for each robust mix at four different temperatures. Selected IQ drum tests and ASTM C403 set time tests were also performed in lab so as to compare the lab results with the field test results. A statistical analysis was conducted to analyze these test data.

3. Implementation of calorimetry into HIPERPAV prediction

Currently, the HIPERPAV program uses predicted heat evolution results based on cement characteristics and concrete mix design. Heat evolution information is a fundamental input to HIPERPAV for the prediction of the pavement strength and risk of thermal cracking during the early age. This study is to use the calorimeter test results (or heat evolution indexes) as input data for the HIPERPAV program analysis, thus improving reliability of the HIPERPAV analysis. The results from the HIPERPAV analysis can be used for concrete quality control, optimization of pavement designs, and prediction of pavement performance, and can help contractors in managing the temperature of concrete based on the concrete mix designs and specific climate and project conditions.

The detailed information on the phase III research activities and results are presented in the following sections.

2. FIELD SITE SELECTION AND DESCRIPTION

2.1 Field Site Selection

Three field sites (two in Iowa and one in Wisconsin) were selected for the phase III study. The location and brief description of each field project are presented in the following sections.

2.1.1 US 71 (Atlantic, Iowa)

Figure 1 shows a PCC overlay project on US HWY 71 between US 83 and US 34 at Atlantic, Iowa. The overlay was 10.56 miles long and constructed using conventional slipform paving equipment. The 8-in. thick new concrete overlay was placed on top of the partially milled old asphalt pavement.

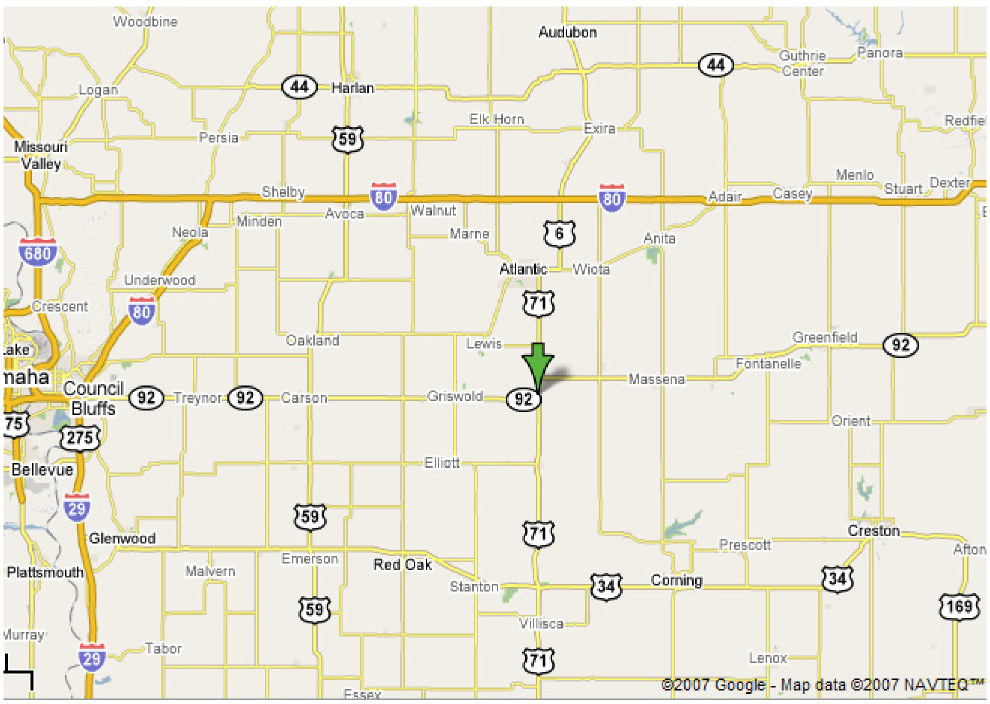


Figure 1. Location of the Atlantic project

2.1.2 HW 95 (Alma Center, Wisconsin)

This project is on south HW 95, from I-94 to Alma Center, Wisconsin. The old pavement was torn up and the new pavement was placed on the old subbase.

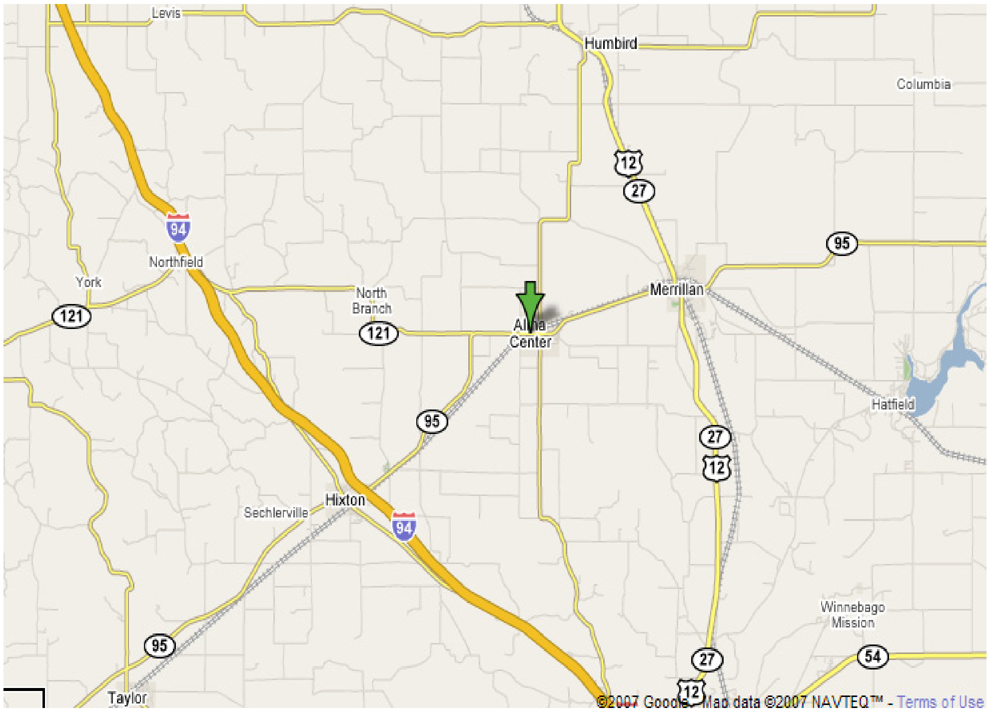


Figure 2. Location of the Alma Center project

2.1.3 US 63 bypass (Ottumwa, Iowa)

This project was a new bypass located at Ottumwa, Wapello County, Iowa, from US 63/ IA 149 south to Steller Avenue. The total length of the new pavement is about 17 miles.

Figure 3. Location of the Ottumwa project

2.2 Mix Proportions

2.2.1 US 71 (Atlantic, Iowa)

Table 1 shows the mix design for the Atlantic project. The cement used in the project was Type IP (F) from Ash Grove with a specific gravity of 2.95. The Class C FA was from Headwaters Inc. with a specific gravity of 2.64. Three types of aggregates (coarse, intermediate, and fine) were used in this project. The coarse and intermediate aggregate were from Hallet Lakeview, Iowa. Both of them have specific gravity of 2.70. The fine aggregate was from Hallet Exira, Iowa. It has a specific gravity of 2.66. The designed air content is 6%. The designed maximum w/c is 0.45.

Table 1. Mix design for Atlantic project

Materials	SSD weight (lbs/cy)	Absolute volume (cy)
Cement	442	0.089
Fly ash	110	0.025
Water	221	0.131
Fine aggregate	1309	0.292
Intermediate aggregate	273	0.060
Coarse aggregate	1560	0.343

2.2.2 HW 95 (Alma Center, Wisconsin)

The mix design of Alma Center is listed in Table 3. The cement used in this project is from Holcim with low alkali. FA is Type C. The moisture was assumed to be 2.5% for sand and 1% for coarse aggregate during the whole project.

Table 2. Mix design for Alma Center project

Materials	SSD weight (lbs/cy)
Cement	446.0
Fly ash	113.0
Water	252.0
Fine aggregate	1370.0
Coarse aggregate	1825.0
AEA-Daravair	5.5 oz
WR-WRDA 82	18.0 oz

2.2.3 US63 Bypass (Ottumwa, Iowa)

The mix design was shown in Table 5. The designed air content was 6% and slump was 2 in. The cement used in this project was Lafarge Type ISM cement. The FA was Type C FA from ISG Resources Inc. Chillicothe with a specific gravity of 2.73. The coarse aggregate was from Ollie, Iowa with a specific gravity of 2.66. The fine aggregate was from Eldon, Iowa with a specific gravity of 2.67. The fineness modulus for the sand was 2.93.

Table 3. Mix design for Ottumwa project

Materials	SSD weight (lbs/cy)	Absolute volume (cy)
Cement	443.0	0.085
Fly ash	111.0	0.024
Water	222.0	0.132
Fine aggregate	1291.0	0.287
Coarse aggregate	1846.0	0.412
Air-entraining agent	49.1 ml	
Water reducer	654.8 ml	

2.3 Material Properties

The chemical properties of cement and FA used in three projects are summarized in Table 4 and Table 5, respectively:

Table 4. Chemical properties of cement

Sample name	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	Fe_2O_3	SrO	Mn_2O_3	LOI
US 71 (Atlantic, IA)	0.30	3.08	8.20	29.64	0.10	3.30	0.73	49.34	0.51	3.31	0.12	0.07	1.29
HW 95 (Alma Center, WI)	0.07	2.35	4.74	20.78	0.08	2.75	0.78	63.09	0.24	3.15	0.11	0.07	1.78
US 63 bypass (Ottumwa, IA)	0.16	4.30	5.22	23.72	0.10	2.95	0.56	58.79	0.38	2.77	0.04	0.49	0.51

Table 5. Chemical properties of fly ash

Sample name	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	Fe_2O_3	SrO	Mn_2O_3	LOI
US 71 (Atlantic, IA)	1.72	4.63	20.1	34.9	1.01	2.27	0.42	26.2	1.64	5.78	0.42	0.05	0.38
HW 95 (Alma Center, WI)	1.83	5.29	19.1	36.3	1.03	1.93	0.47	25.6	1.53	5.26	0.44	0.03	0.36
US 63 bypass (Ottumwa, IA)	3.21	6.81	16.2	31.6	1.02	3.13	0.32	28.8	1.24	6.03	0.51	0.02	0.30

Relativity density (specific gravity) and absorptions of the aggregate used in three projects were tested, and the results are shown in Table 6.

Table 6. Aggregate specific gravity and absorption

Sample name		Type	G_b	$G_{b,SSD}$	G_a	Abs., %
US 71 (Atlantic, IA)	Fine aggregate	Riversand	2.58	2.62	2.69	1.55
	Intermediate aggregate	Gravel	2.63	2.67	2.75	1.68
	Coarse aggregate	Gravel	2.67	2.70	2.76	1.20
HW 95 (Alma Center, WI)	Fine aggregate	Riversand	2.61	2.65	2.72	1.60
	Coarse aggregate	Quartzite	2.87	2.87	2.89	0.33
US 63 by pass (Ottumwa, IA)	Fine aggregate	Riversand	2.59	2.62	2.68	1.32
	Coarse aggregate	Limestone	2.41	2.50	2.64	3.69

3. FIELD TESTS AND RESULTS

3.1 Tests and Methods

For each field site, the following tests and information were conducted and recorded:

- Concrete mixing time, dumping time, truck number, subbase temperature
- Pavement paving, finishing, curing, and sawing time
- Air content, slump, and unit weight
- Setting time
- Microwave w/c ratio
- AdiaCal calorimetry test.
- Isothermal calorimetry test
- IQ drum test
- Maturity-strength test

The Concrete Mobile Lab from the Center of Concrete Pavement Technology (CP Tech Center), Iowa State University (ISU), was brought to three field sites to assist in the field tests.

Concrete mixing time is the time that is shown on the batch ticket. Just before the concrete was dumped on the ground, the subbase temperature was measured at two positions: the surface of subbase using the infrared temperature thermometer and about one in. below the surface using the temperature probe. During the pavement construction, one person stayed in the field and recorded the paving, finishing, and curing time for the site where concrete was sampled. The sawing time was recorded by the saw crew when they cut the marked joint.

Concrete was sampled in front of the paver and sent back to the mobile lab to conduct the rest tests. The air content was conducted following ASTM C231 “Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method.” The unit weight test followed ASTM C138 “Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete.” The slump test was based on ASTM C143 “Standard Test Method for Slump of Hydraulic-Cement Concrete.” A maturity and strength test followed ASTM C1074 “Standard Practice for Estimating Concrete Strength by the Maturity Method.” The 4 in. by 8 in. cylinders were stored in the curing tank of the mobile lab for the first couple days and then transferred to the curing room at Iowa State University until the testing time. Only one Ibutton was put in the middle of the concrete sample to record concrete temperature. The cylinders were broken at 1, 3, 7, 14, and 28 days according to ASTM C39 “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.”

Setting time was performed following ASTM C403 “Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance.” The mortar samples were sieved from concrete first. Two tests were conducted on the same concrete for Alma Center and the Ottumwa project and only one test were performed for the Atlantic project.

The sieved mortar was used for the microwave w/c ratio test. About 1500 g of mortar were placed in a glass bowl and then put in the microwave oven. After being heated for five minutes, the sample was taken out and weighed and then put back into the microwave oven for another two minutes. After that the sample was weighed again. If the weight difference between two tests is less than 0.1 g, the test will stop. Otherwise, the sample was put back into the microwave oven and heated for two more minutes until the weight difference was less than 0.1 g. The w/c ratio was calculated based on the data and concrete properties.

The 4 in. by 8 in. cylinders were used for the AdiaCal calorimetry test. The calorimeter was programmed and keep closed before the concrete samples were prepared. Immediately after the 4 in. by 8 in. samples were loaded into the calorimeter, the lid was closed and the program started to record concrete temperature. The temperature was recorded every minute by the sensor, which is located just below the bottom of the sample holder. When the test was finished, the program was stopped and the data was retrieved from the data logger. For each concrete sample, at least two cylinders were tested. The thermal set times were determined from each temperature curve as described below. The average value was used for the data analysis.

Isothermal calorimetry tests were performed for both sieved mortar and concrete samples at each field site. The test procedures described in the draft of the specification developed in phase II (Appendix E) were followed closely. However, in the field, the mortar samples were sieved from the field concrete instead of mixed. Four sieved mortar and concrete samples were tested for each batch of concrete collected in front of the paver. The mortar sample was about 100 g and the concrete sample was around 300 g. The tests were done inside the mobile lab and the testing temperature was maintained at 30°C at all times. The calorimeter was programmed before the test. The mortar and concrete were put into the plastic container and weighed to the desired amount. Immediately after the sample was ready, it was loaded into the sample holder of the isothermal calorimeter. After that the lid was closed, and the test was started. Then the program recorded the data for every 30 s. When the test was done, the data was retrieved and calibrated.

The cement heat signature test was conducted using the semi-adiabatic calorimeter (IQ drum, as shown in Figure 3.1) manufactured by Digital Site Systems, Inc., Pittsburgh, Pennsylvania. The IQ drum consists of (1) a 6 in. by 12 in. cylinder chamber for concrete specimens or a 2 in. by 4 in. cylinder chamber for mortar specimens in the center, (2) a 6 in. layer of insulation materials outside the chamber, (3) a thermal sensor, and (4) a data logger mounted on the outside wall. During the test, the thermal sensor is inserted into the concrete/mortar specimen to record the test data. The semiadiabatic calorimeter allows a certain amount of heat loss during the test period. The thermal loss can be calculated from the test data and from the calibration factor, which is determined from a calibration test.

Before each test, the mixing proportion and physical properties of the raw materials were input into the software, which provided the desired test results regarding the thermal history and the heat evolution process of the concrete. The concrete obtained from the field was placed into the 6 in. by 12 in. cylinder in three layers and rodded 25 times for each layer. Then, the sample was weighed and put into the drum along with an inserted sensor. The IQ drum was sealed promptly after the sample was added. The test data were recorded every 15 minutes with the aid of a computer program. The entire test took about seven days under room conditions. The same procedure was applied for the mortar sample. But the test for the mortar sample only took three days.

Tests 1–6 were conducted three rounds each day for the Atlantic project and four rounds for the Ottumwa and Alma Center project. The isothermal calorimetery test was conducted once each day because the test has to run for around 24 hours. The maturity-strength test was performed once for each project. Weather data was recorded for all three projects. However, the data was lost for the Ottumwa project due to an equipment issue. The IQ drum test was performed once for each project site on both concrete and mortar samples. The batch ticket for each tested mix was also collected. For the Atlantic project, it was not able to track the exact mixing time for each testing sample. The mixing time was estimated. Therefore, the batch ticket obtained could be different from the testing concrete.

3.2 Test Results

3.2.1 US 71 (Atlantic Project)

3.2.1.1 Batch Ticket

All batch tickets are listed in Appendix A. As mentioned before, these batch tickets may not be the real batch tickets for the tested samples. However, these tickets still show that the concrete mix is very consistent from time to time. Figure 4 shows the variation of the w/c ratio of all mixes. There was little variation from mix to mix. The w/c ratio ranged from 0.389 to 0.436. The mean value was 0.410 and the standard deviation was 0.016. One noticeable change of the mixing tickets is the moisture content of aggregates. For the first two days, the moisture content was 5.0%, 0.7%, and 1.5% for the fine, coarse, and intermediate aggregates, respectively. On the last two days the moisture content for fine aggregate dropped to 0.6% and 0.2%. But the moisture content for coarse aggregate increased to 4.9% and 4.2%. The value for the intermediate aggregate was relatively constant, which was 1.4% and 1.0%. This means that the moisture of aggregates changed during the project; it is every important to adjust the water used in concrete mixture to get consistent concrete mix.

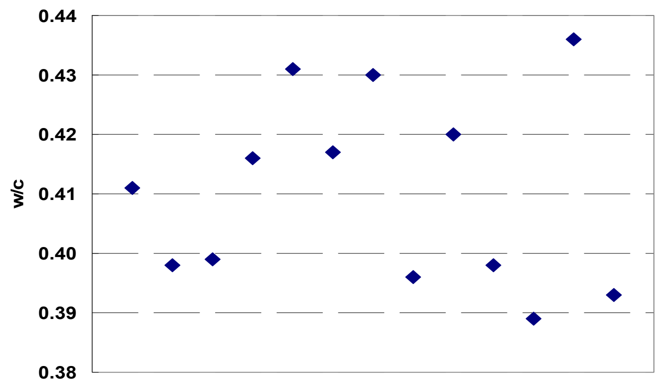


Figure 4. Water to cement ratio for the mixes of US 71 (Atlantic project)

3.2.1.2 Concrete and Pavement Information

The concrete properties and pavement construction information are listed in Table 2. The subbase temperature was tested at two locations. The results show that the temperature below the surface is much lower than the temperature on the surface. The high temperature on the surface could be caused by the radiation of the sun. The difference between the two subbase temperature measurements ranges from a couple degrees to over 20°F. Therefore, it is important to put the temperature at the right place when this value is used for the modeling purpose. Concrete temperature was varied from 78°F to 87°F. At noon, it was slightly higher than in the morning and afternoon.

In the pavement construction, the paving was processed right after the concrete was placed in the field, and it was followed by finishing and curing. There were only a couple minutes between the finishing and curing. Since the construction process was very consistent for this project, the finishing and curing times were only recorded for a couple days. For the rest of construction, we assumed that the finishing and curing times were the same as before. The sawing time was around 11 hours despite the paving time except for the last two tests on July, 20, 2007, which were 8.4 and 8.7 hours from the mixing time. The air content of concrete ranged from 6% to 7.5%, which is in the range of the designed value. The slump was from 1.25 in. to 2.25 in. The variation is only 1 in. The unit weight of concrete is between 140 and 150 lb/ft^3.

Table 7. Concrete and pavement information for US 71 (Atlantic project)

Date	Mixing time	Subbase temp.		Concrete temp. (°F)	Dump time	Paving time	Finishing time	Curing time	Sawing time		Air %	Slump in.	Unit weight (lb/ft^3)	Set time (ASTM)	
		Infrared (°F)	Probe (°F)						Time	hr				Initial (hr)	Final (hr)
6/27/07	12:38 p.m.	121.2	97.9	86.7	1:02 p.m.	1:14 p.m.	1:16 p.m.	2:12 p.m.	10:57 p.m.	10.32	6.00	1.75	145	8.09	10.57
6/27/07	2:35 p.m.	103.1	89.1	85.1	3:00 p.m.	3:04 p.m.	3:06 p.m.	3:51 p.m.	2:05 a.m.	11.50	6.80	1.75	142	8.75	12.38
6/28/07	9:22 a.m.	89.9	79.2	81.7	9:47 a.m.	9:59 a.m.	10:01 a.m.	10:34 a.m.	9:10 p.m.	11.80	7.50	0.75	143	8.14	10.65
6/28/07	11:16 a.m.	94.5	83.5	80.1	11:41 a.m.	11:47 a.m.	11:49 a.m.	12:23 p.m.	10:03 p.m.	10.78	7.00	1.75	144	8.04	10.24
6/28/07	1:40 p.m.	95.5	92.0	82.6	2:05 p.m.	2:08 p.m.	2:11 p.m.	2:54 p.m.	2:59 a.m.	13.32	7.25	1.75	143	7.43	10.09
6/29/07	9:11 a.m.	93.6	75.6	78.1	9:31 a.m.	9:36 a.m.	9:39 a.m.	10:17 a.m.	-	-	7.50	1.63	144	7.80	10.50
6/29/07	10:59 a.m.	88.0	80.0	81.4	11:19 a.m.	11:26 a.m.	11:29 a.m.	12:10 p.m.	-	-	7.50	1.50	145	7.40	9.80
6/29/07	2:57 p.m.	103.5	90.0	81.0	3:17 p.m.	-	-	-	2:10 a.m.	11.22	7.00	1.50	145	7.30	9.40
6/30/07	8:52 a.m.	85.5	76.4	78.1	9:12 a.m.	-	-	-	7:30 p.m.	10.63	7.00	1.38	146	8.30	10.40
6/30/07	11:45 a.m.	109.5	95.2	80.4	12:05 p.m.	-	-	-	11:00 p.m.	11.25	7.60	1.50	148	7.00	10.00
6/30/07	1:23 p.m.	99.5	89.0	81.0	1:43 p.m.	-	-	-	12:49 p.m.	11.43	6.80	2.25	143	8.40	11.20
7/2/07	9:08 a.m.	89.5	82.4	80.2	9:28 a.m.	-	-	-	8:15 p.m.	11.12	7.60	1.50	145	8.90	11.60
7/2/07	10:34 a.m.	100.2	84.2	82.4	10:54 a.m.	-	-	-	9:00 p.m.	8.43	7.00	1.25	145	8.10	9.70
7/2/07	12:40 p.m.	116.0	102.0	86.5	1:02 p.m.	-	-	-	9:23 p.m.	8.72	6.80	1.38	146	6.50	8.70

3.2.1.3 AdiaCal Calorimeter Results

The ASTM C403 was performed for each test sample for initial and final set. In addition to the ASTM method, the AdiaCal (Figure 5), which is a semi-adiabatic calorimeter, was also used to test concrete temperature development history and set times. In order to differentiate the set times from these two methods, the set times from AdiaCal is called AdiaCal thermal set time. In phase II an AdiaCal calorimeter with 3 in. by 6 in. concrete cylinders was employed. After the phase II study, WR Grace developed a better AdiaCal calorimeter, which uses 4 in. by 8 in. concrete cylinders. In the phase III study, this new AdiaCal was used to monitor concrete temperature and determine thermal set.

Figure 6 shows one typical test result from the AdiaCal. The calorimeter recorded concrete temperature with time. There are two methods to determine the thermal set: derivatives and fraction methods (*5*). In phase III, the fraction method was applied since it is more robust than the derivatives method. The fraction number has to be calibrated from the ASTM set time tests and kept constant for each mix. To run a calibration test, both the AdiaCal and ASTM tests use the same mix. The setting times are determined from the ASTM C403 tests first. The fraction numbers for AdiaCal tests are then determined based on the fact that the set times determined from both methods should be equal. In this project, the first set of ASTM C43 and AdiaCal were used to calibrate the fraction number. For the rest of the tests, the fraction numbers were kept constant.

Figure 5. AdiaCal calorimeter

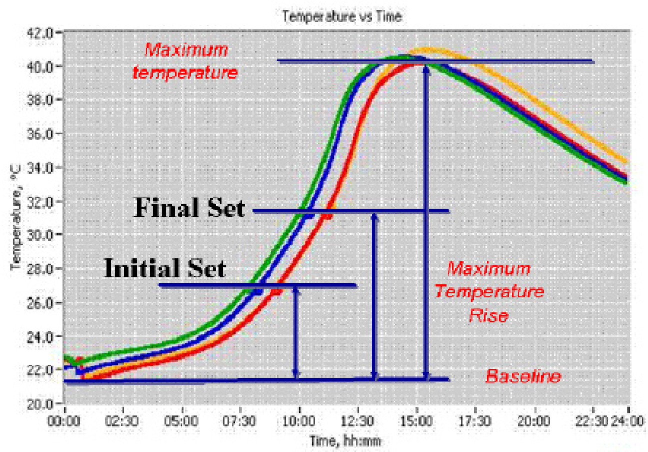
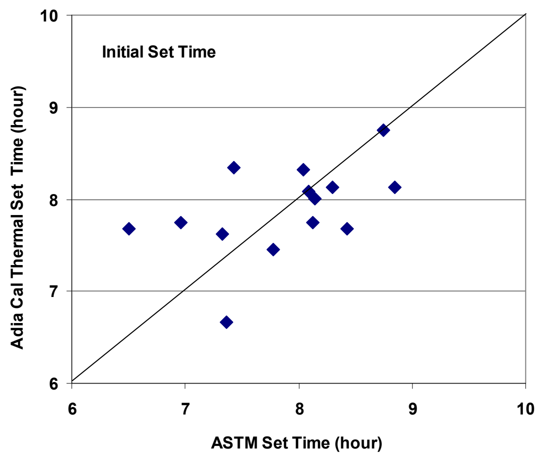


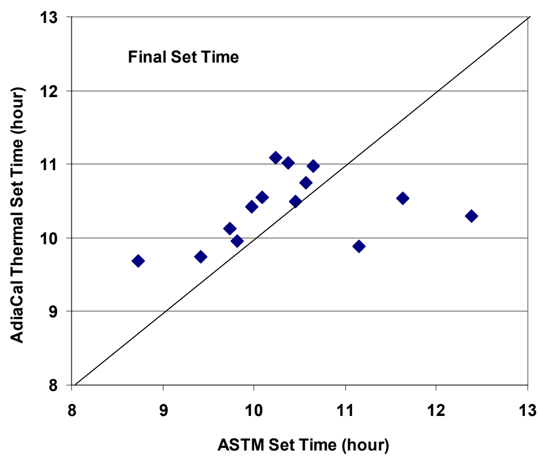
Figure 6. AdiaCal test results and determination of the set times

Figure 7 shows the relationship between the ASTM set times and AdaiCal thermal set times. The results from these two methods are not equal but all test points are all around the equality line. The difference between these two methods is less than one hour except one point. The average variation is 0.47 hours for initial set and 0.66 hours for final set. For the final set, there is one point with a large difference of 2.08 hours. The variation could be from two aspects: error from the ASTM test or testing error from the AdiaCal test. As stated in ASTM C403, the single-operator coefficient of variation on each of three batches made on different days is 7.1% and 4.7% for the initial and final setting time, respectively. Therefore, the range of results obtained on three separate batches by the same operator with the same apparatus, using the same materials and temperature conditions, on three different days should not exceed 23% of their average for initial set time and 16% for final set time. The difference between these two tests was less than 23% percent of ASTM test for initial set. The highest difference is 10.2% and the average is 6.3%. For the final set time, the difference is less than 16% except one point. The highest difference is 16.8% and the average is 6.2%.

Like the other test, the AdiaCal tests conducted in this field project also showed quite large variation as shown in Figure 7. The variation could come from at least three sources: (1) variation due to the equipment and test procedure, (2) variation in the environmental temperature, which was different for the tests done at different times, and (3) the variation due to the fraction selected for thermal set time prediction. In this project, the fraction number was determined only based on one set of field tests because of the busy field test schedule. Much smaller variations in the relationship between the AdiaCal thermal set times and ASTM set times were found in the tests of the other two field projects (Alma Center, WI and Ottumwa, IA).



(a) Initial set



(b) Final set

Figure 7. ASTM set time vs. AdiaCal thermal set time from US 71 (Atlantic, IA) field study (Initial thermal set—17% and 14% fraction for two AdiaCal, respectively; Final thermal set—50% fraction for both AdiaCal)

3.2.1.4 Isothermal Calorimeter Results

The isothermal calorimeter, which was studied in phase II, was carried to the field. For each day, one test was performed due to the duration of the testing time. In phase II only mortar samples were tested. In the field both concrete and mortar samples were tested. For each test, four mortar samples and four concrete samples were tested. Figures 8 and 9 show the isothermal calorimetry results from different days using mortar and concrete samples.

During the first couple hours, the rate of heat evolution was negative. This was caused by sample stabilization. Since sample temperature was lower than the temperature of calorimetry, the samples absorbed heat from the calorimeters. Therefore the rate of heat evolution was negative. The unit of heat evolution was calculated in term of per gram cementitious materials.

Figures 8 and 9 show that all the hydration curves have similar shapes with two hydration peaks. There is little variation in the values of the second peak. The time for the peak value was slightly delayed for the test on July 2nd. Compared with the mortar sample, concrete has lower peak values. This could be caused by the sieving and the size of concrete sample. When the mortar was sieved from concrete, part of the mortar was left with coarse aggregate. The sieved mortar could be slightly different from the original mortar in concrete. Also, the concrete samples were only 300 g; it was hard to get a representative concrete sample. It was easy to get more aggregate or paste in the sample compared with the designed value. All these factors could cause the difference between the mortar and concrete sample.

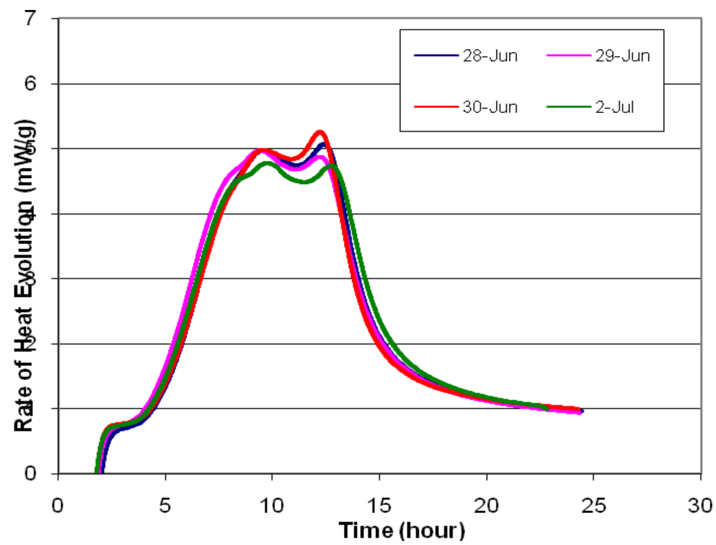


Figure 8. Isothermal calorimetry results for US 71 (Atlantic, IA) field mortar samples

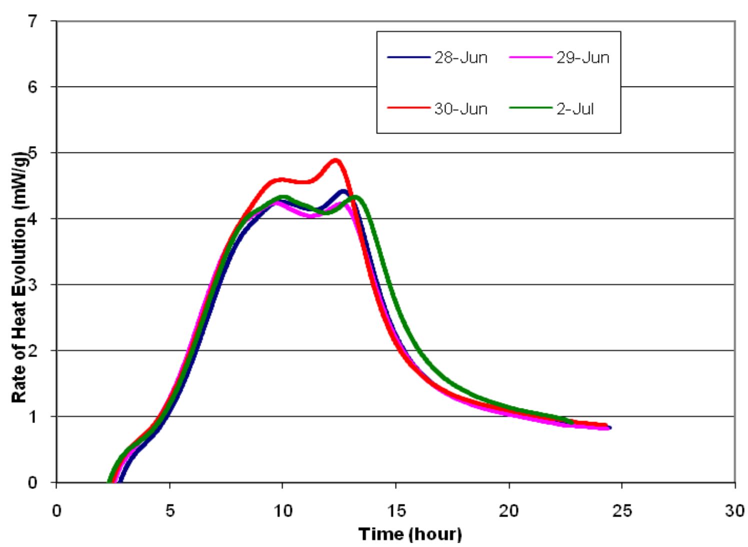
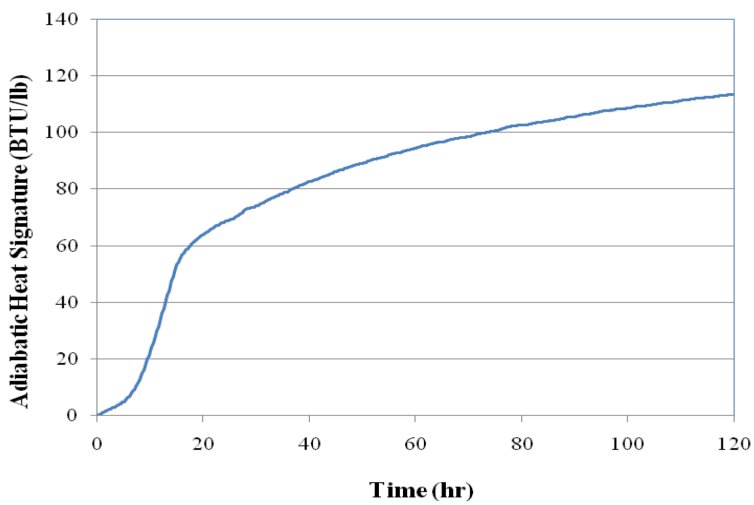


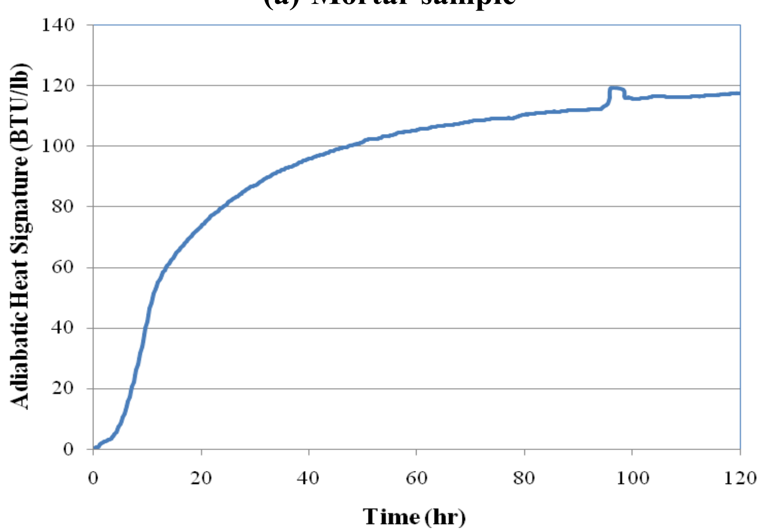
Figure 9. Isothermal calorimetry results for US 71 (Atlantic, IA) field concrete samples

3.2.1.5 Semi-Adiabatic Calorimetry (IQ Drum) Test

Figure 13 shows the results from the semi-adiabatic calorimetry test. The main purpose of this test is to provide the data for HIPERPAV analysis. After 120 hours, the generated heat was about 120 BTU/g cementitious materials. At the very beginning the heat evolution was slow. After a couple hours, the generated heat started to increase quickly until 15 hours–20 hours. After that the heat evolution increased much slower. Concrete hydrated slightly faster than mortar samples. This could be caused by the higher temperature of concrete. The higher the temperature, the faster the hydration occurred.



(a) Mortar sample



(b) Concrete sample

Figure 10. Heat evolution with time for US 71 (Atlantic, IA) field test

3.2.1.6 Maturity-Strength Results

Maturity and strength were tested for concrete samples until 28 days. The 4 in. by 8 in. cylinder samples were casted and put into the curing tank inside the mobile lab. After getting back to ISU, the samples were transferred into the curing room and cured until the test date. The temperature of the curing tank inside the mobile lab was set at 70°F. One Ibutton was placed in the middle of the sample to monitor concrete temperature. Maturity and strength were plotted in Figure 10. There was a strong linear relationship between strength and maturity. The R-square value is 0.99. The 28-day strength is almost 5000 psi.

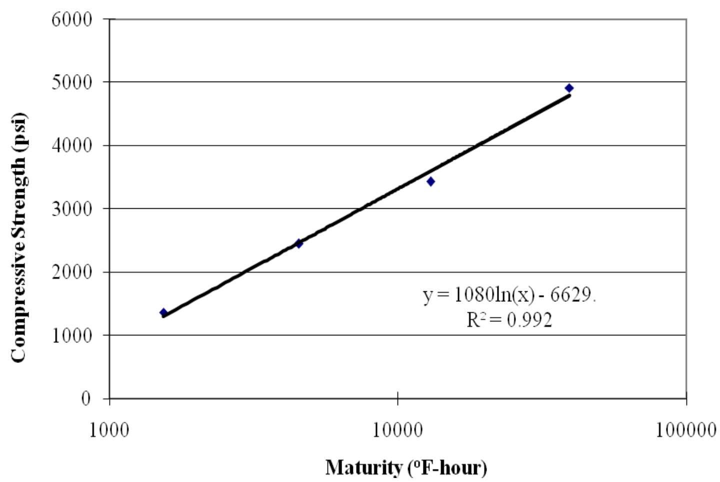
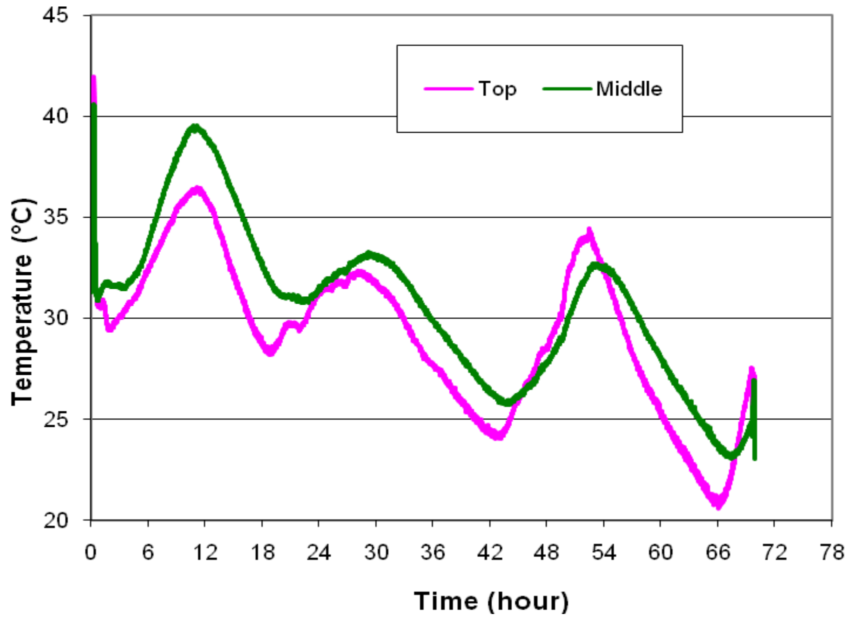


Figure 11. Maturity-strength relationship for US 71 (Atlantic, IA) samples

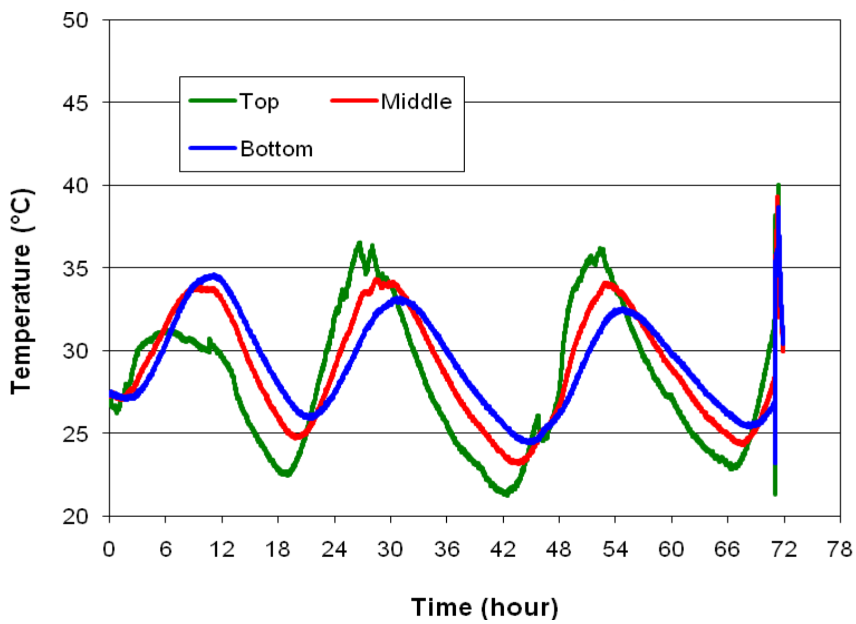
3.2.1.7 Pavement Temperature

During the pavement construction, several Ibuttons were put inside the slab after measuring concrete temperature development. On June 27th and 30th, a stick with three Ibuttons was inserted into the pavement. The first Ibutton was one inch below the surface, the second one was in the middle, and the third one was one inch above the bottom. The stick was placed one foot from the edge of the pavement to avoid the edge effect due to heat exchange between slab and environment. The temperature profiles were shown in Figure 11. For both tests, the top temperature was more affected by the environment since it was close to the surface. It was higher at day time and lower at night time. In Figure 11(a) the bottom temperature was missing due to an equipment issue. The first peak of middle pavement temperature on July 27th was about 5°C higher than that of July 30th. This could be caused by the higher concrete placement temperature, which will accelerate cement hydration.

Figure 12 shows the temperature in the middle of the pavement tested at different days. The difference among these results should be caused by the environment conditions, the time of placement, and cement hydrations.



(a) Temperature measured on July 27th



(b) Temperature measured on July 30th

Figure 12. Pavement temperature from US 71 (Atlantic, IA) field tests

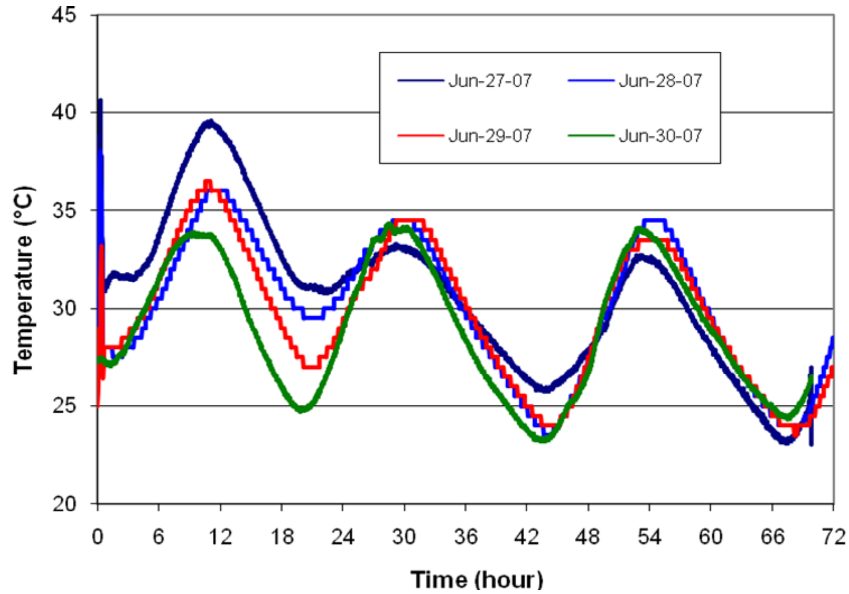


Figure 13. Pavement temperature from US 71 (Atlantic, IA) measured at the middle on different date

3.2.2 HW 95 (Alma Center Project)

3.2.2.1 Batch Ticket

All 12 batch tickets are listed in Appendix B. The w/c ratios are consistent and close to the designed value for all mixes expect one mixed at 10:51 a.m., July 17th, which had higher cement content and a lower w/c of 0.392. The purpose of this mix was to provide high early-age strength because the slab that was paved in the afternoon had to be opened to traffic the next day. The results of other tests clearly showed the difference between this mix and others. The rest of the w/c ratios were plotted in Figure 14. All w/c ratios were between 0.44 and 0.44. The average value was 0.45. The standard deviation was 0.004.

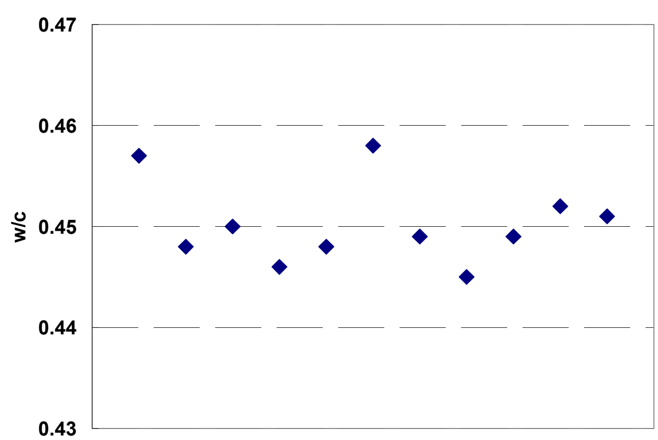


Figure 14. Water to cement ratio for the mixes of HW 95 (Alma Center, WI) project

3.2.2.2 Concrete and Pavement Information

For the Alma Center project, only three day tests were conducted. There were four round tests for each, two in the morning and two in the afternoon. The concrete and construction information are listed in Table 4. Again the subbase temperature measured by two methods was different. The temperature measured by the probe underneath the surface was a couple degrees lower. The surface temperature ranges from 76°F to 115°F. Even in the same day the temperature difference could be as much as 28°F. The concrete temperature was controlled around 75°F. The highest temperature was 79.2°F and the lowest was 72.5°F. Concrete normally will be dumped in front of the paver less than 10 minutes after mixing. The paving was carried out right after the dumping. Then the finishing was applied. However, the curing for this project was delayed. It was applied about 1 1/2 to 3 hours after the finishing. The slab was cut about 10 to 12 hours after the mixing time, except for the last test. The sawing time for the last test was 16.8 hours: much longer than the rest of the tests. This was caused by the environmental temperature, which was between 40°F and 50°F during the night. The low temperature delays the strength development, which in turn affects the saw cutting time. The properties of fresh concrete were close for all different tests except the second test on the first day. This test showed low air content, w/c ratio, slump, and setting time, but high unit weight. The air content ranged from 5.8% to 7.8%. The slump was from 1 in. to 2.75 in. The unit weight was from 148 lb/ft^3 to 154 lb/ft^3. The initial set happens after seven and before 10 hours. The final set times were from nine to 12 1/2 hours. The w/c ratio was also determined from the microwave method. The determined w/c ratio ranges from 0.4 to 0.47, which is close to the real w/c ratio.

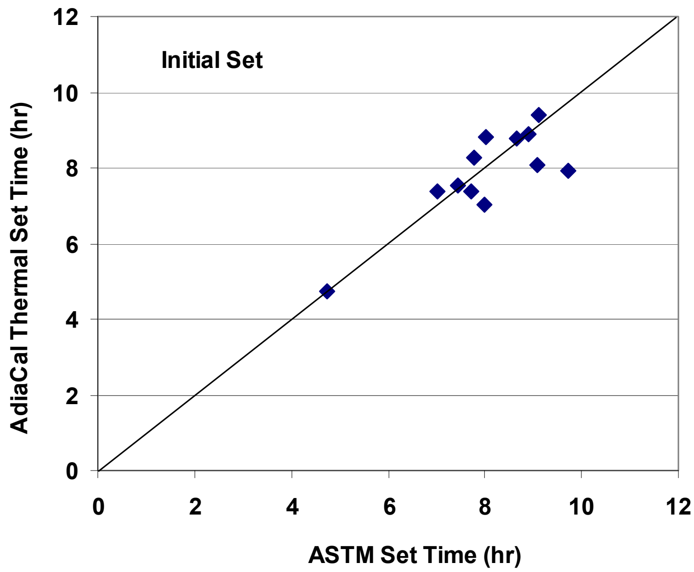
Table 8. Concrete and pavement information for HW 95 (Alma Center, WI) project

Date	Mixing time	Subbase temp. Infrared (°F)	Subbase temp. Probe (°F)	Con. temp. (°F)	Dump time	Paving time	Finishing time	Curing time	Sawing time: Time	Sawing time: Hr	Air (%)	Slump (inch)	Unit weight (lb/ft^3)	Set time (ASTM): Initial (hr)	Set time (ASTM): Final (hr)	Microwave w/c
7/17/07	8:32 a.m.	76.1	75.2	73.1	8:42 a.m.	8:50 a.m.	8:53 a.m.	10:31 a.m.	8:05 p.m.	11.38	5.8	2.00	150	8.89	11.36	0.47
7/17/07	10:52 a.m.	91.2	88.0	73.9	11:00 a.m.	11:10 a.m.	11:12 a.m.	12:36 p.m.	10:30 p.m.	11.63	4.0	0.75	154	4.74	5.91	0.39
7/17/07	1:28 p.m.	92.0	88.3	75.0	1:32 p.m.	1:37 p.m.	1:40 p.m.	4:30 p.m.	1:40 a.m.	12.20	7.0	1.00	154	7.45	9.61	0.44
7/17/07	2:59 p.m.	100.0	96.4	79.2	3:02 p.m.	3:07 p.m.	3:09 p.m.	4:47 p.m.	3:00 a.m.	11.98	6.5	1.75	150	7.01	9.05	0.41
7/18/07	9:23 a.m.	88.7	82.6	74.7	9:27 a.m.	9:31 a.m.	9:33 a.m.	12:11 a.m.	7:40 p.m.	10.28	7.5	2.75	148	7.98	10.31	0.45
7/18/07	10:47 a.m.	103.9	98.6	75.0	10:52 a.m.	10:59 a.m.	11:01 a.m.	12:20 a.m.	9:15 p.m.	10.47	5.8	1.25	153	7.72	10.00	0.46
7/18/07	2:07 p.m.	105.6	103.1	77.7	2:11 p.m.	2:15 p.m.	2:17 p.m.	3:40 p.m.	1:25 a.m.	11.30	7.8	2.25	148	7.79	10.23	0.38
7/18/07	3:08 p.m.	-	-	-	-	-	-	-	2:30 a.m.	11.37	7.3	1.50	150	8.01	10.70	0.41
7/19/07	8:59 a.m.	87.0	81.9	72.5	9:08 a.m.	9:19 a.m.	9:23 a.m.	10:33 a.m.	8:20 p.m.	11.52	6.0	1.50	151	9.11	11.48	0.41
7/19/07	10:31 a.m.	92.8	92.7	73.2	10:37 a.m.	10:42 a.m.	10:44 a.m.	12:25 p.m.	9:20 p.m.	10.82	6.0	1.50	151	8.65	11.18	0.40
7/19/07	11:54 a.m.	104.3		73.2	12:04 p.m.	-	-	-	11:50 p.m.	11.93	6.5	2.00	150	9.71	12.39	0.42
7/19/07	1:55 p.m.	114.9	105.3	74.7	2:05 p.m.	-	-	-	6:45 a.m.	16.83	7.5	1.25	152	9.08	12.06	0.40

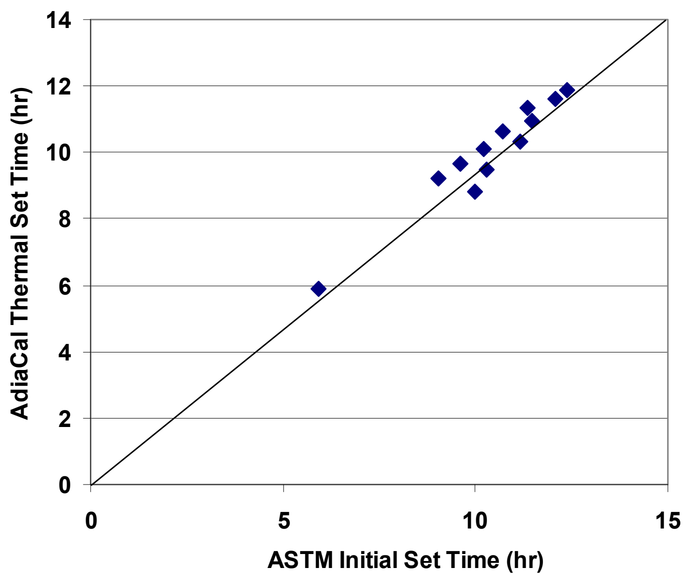
3.2.2.4 AdiaCal Calorimetry Results

AdiCal calorimeter was also used to determine the thermal set time in this project. As stated in the Atlantic project, the ASTM set time method will have variation even for the same operator and materials. In order to reduce the error caused by the operation,in this project, two tests were conducted for each testing concrete. The average value was used to compare with the results from the AdiaCal test. Figure 15 shows the setting times determined from the ASTM and AdiaCal methods. Most of the pints are on or very close to the equality line. The largest difference is 1.8 hours for the initial set and 1.2 hours for the final set. The average differences are 0.5 hours and 0.4 hours for the initial and final set time, respectively. The difference was less than 23% of the ASTM test for initial set. The highest difference is 18.2% and the average is 6.1%. For the final set time, the difference is less than 16% except one point. The highest difference is only 8.1% and the average is 3.7%.The results indicate the AdiaCal calorimeter is able to estimate the set time for the field concrete. Like the Atlantic project, the fraction numbers were determined from the first set of ASTM and AdiaCal tests. And the values were kept the same for the rest of the tests.

One of the other purposes of the AdiaCal test is to check if this equipment could be used to identify the changes of concrete mix or construction. Figure 16 shows the temperature curves from four different tests conducted in the same day. Each test had two samples. A total of eight samples were tested. It can be seen that the concrete samples from different batches had different temperature histories. Even for the two tests from the same batch, the temperature could have some difference. The temperature will be influenced by the initial temperature and also the environment. Therefore, it is hard to use concrete temperature from AdiaCal tests as daily quality control tools.



(a) Initial set time



(b) Final set time

Figure 15. ASTM set time vs. AdiaCal thermal set for HW 95 (Alma Center, WI) project, 18% fraction for initial thermal set and 41% for final thermal set

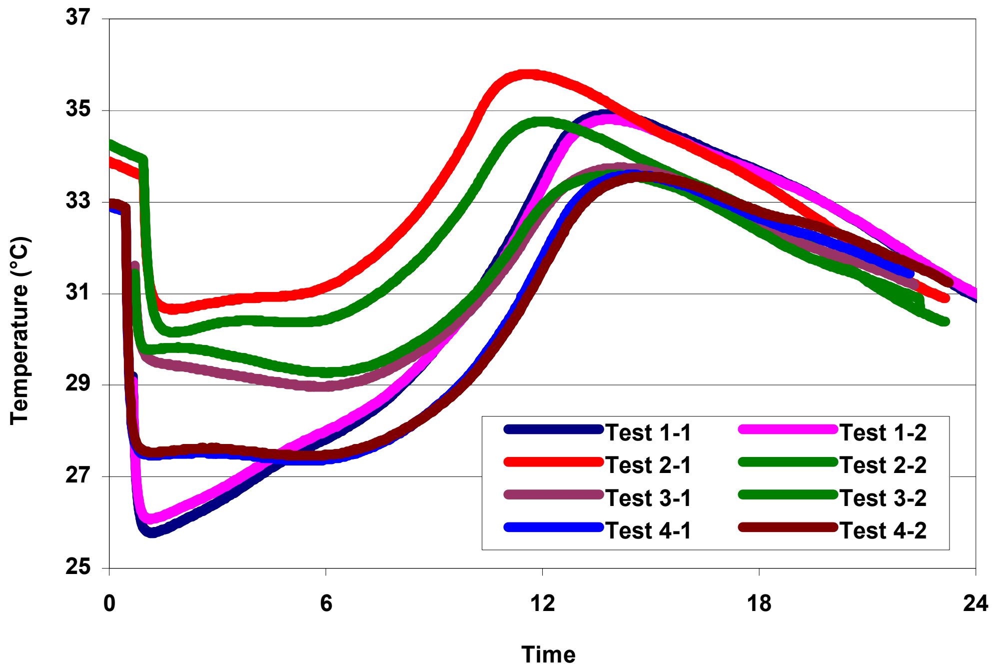
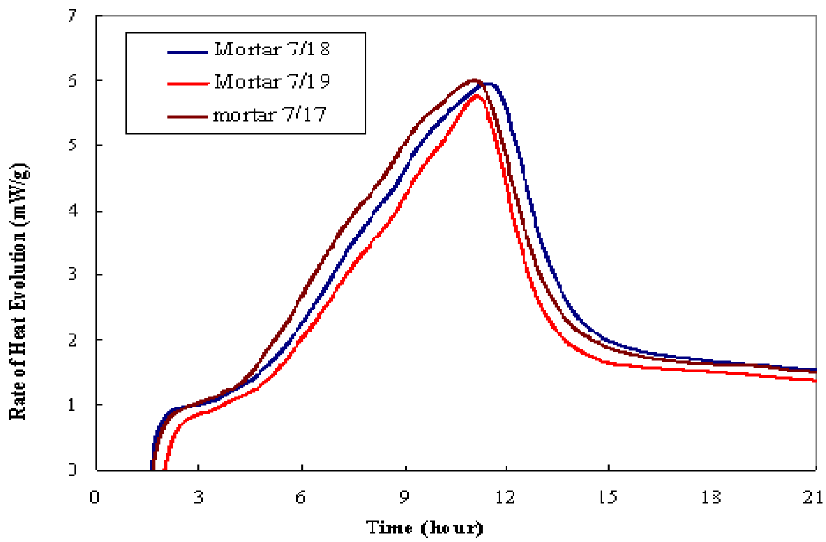


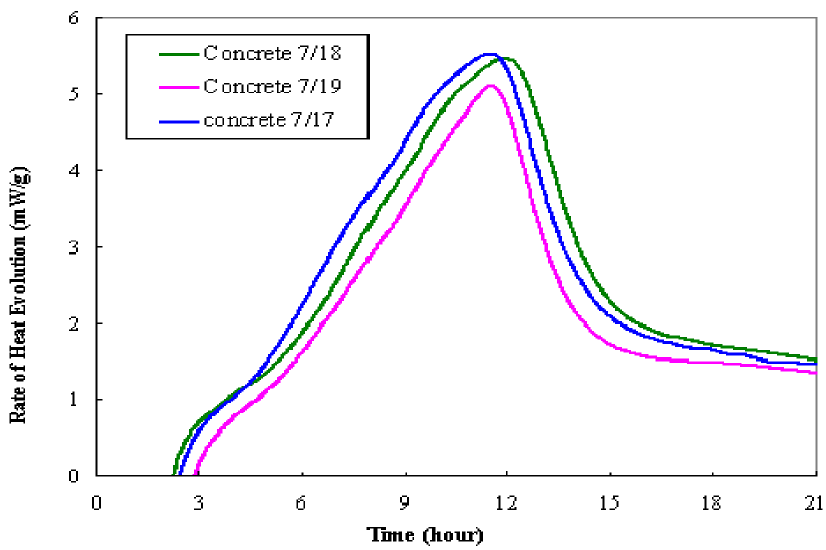
Figure 16. Temperature from AdiaCal tests (tests were performed on HW 95, July 18th)

3.2.2.5 Isothermal Calorimetry Results

Three isothermal calorimetry tests were performed on mortar and concrete for this project. The heat evolution curves have the similar trend for both mortar and concrete samples. The test on July 19th had the lowest value and the test on July 17th had the highest values for both mortar and concrete samples. Tests on July 17th and 18th had very similar peak values. But the peak time for the 18th test was slightly longer. The difference is less than one hour. Compared with the results from mortar samples, concrete samples have lower values. Despite these differences, the results show that for the similar field concrete, the calorimetry results are similar. Therefore, it is possible to use this simple isothermal calorimeter for daily quality control.



(a) mortar sample

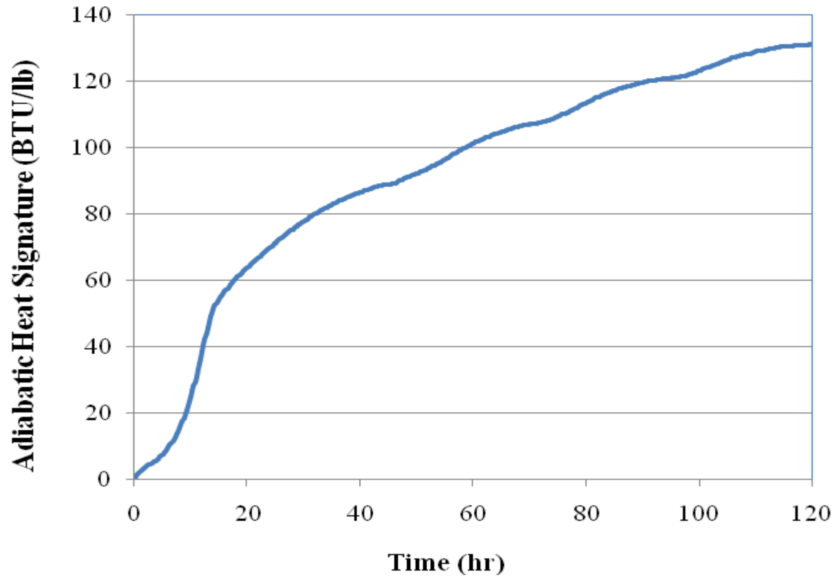


(b) concrete sample

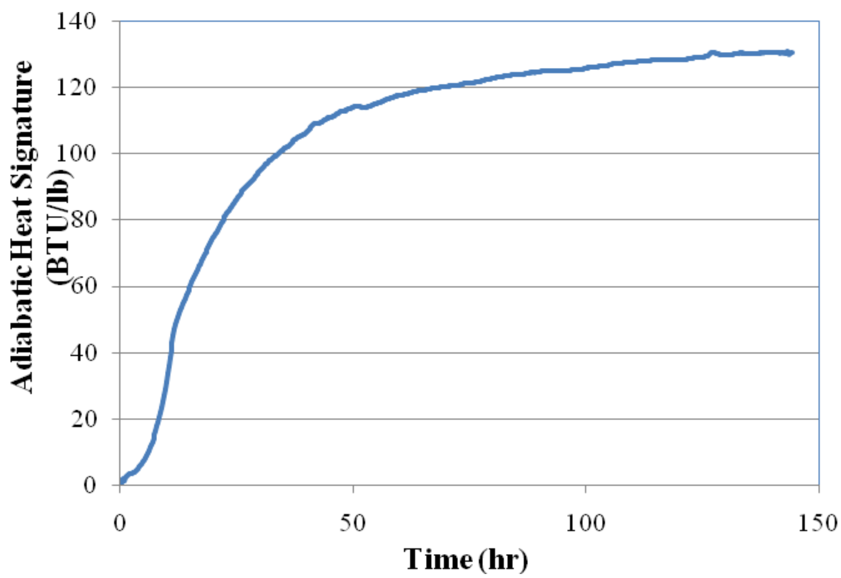
Figure 17. Isothermal calorimetry results from HW 95 (Alma Center, WI) field study

3.2.2.6 Semi-Adiabatic Calorimetry (IQ Drum) Test

Figure 20 shows the IQ drum test results for mortar and concrete samples. The generated heat was about 130 BTU/lb after 150 hours of hydration. For concrete sample, the rate of heat evolution was reduced after about 50 hours. Compared with mortar sample, concrete generated more heat at an early age.



(a) Mortar sample



(b) Concrete sample

Figure 18. Heat evolution with time for HW 95 (Alma Center, WI) project field test

3.2.2.7 Maturity-Strength Results

The compressive strength was tested at 1, 3, 7, 14 and 28 days. One Ibutton was placed in the middle of one concrete sample. However, the Ibutton was broken. The temperature data was not available for this project. Since all the samples were cured in the curing tank inside the mobile lab and also the curing room, it is assumed that the temperature of samples was constant. The 28-day compressive strength is a little bit lower than 5000 psi.

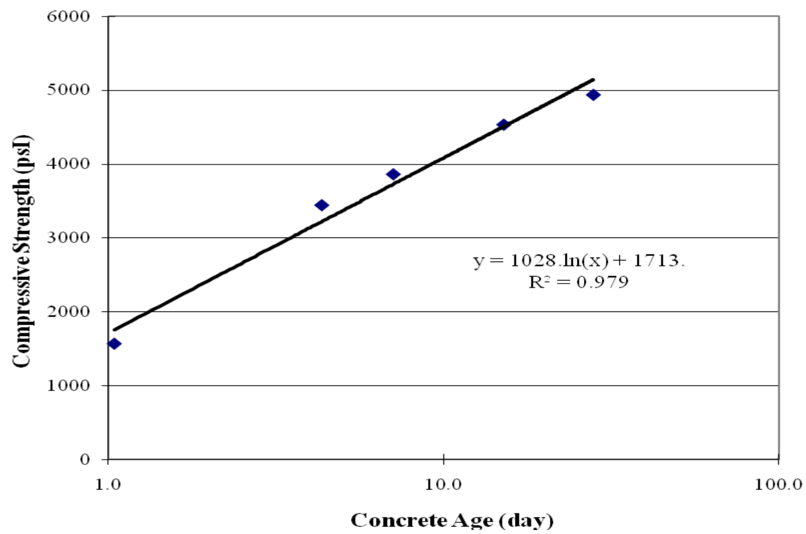
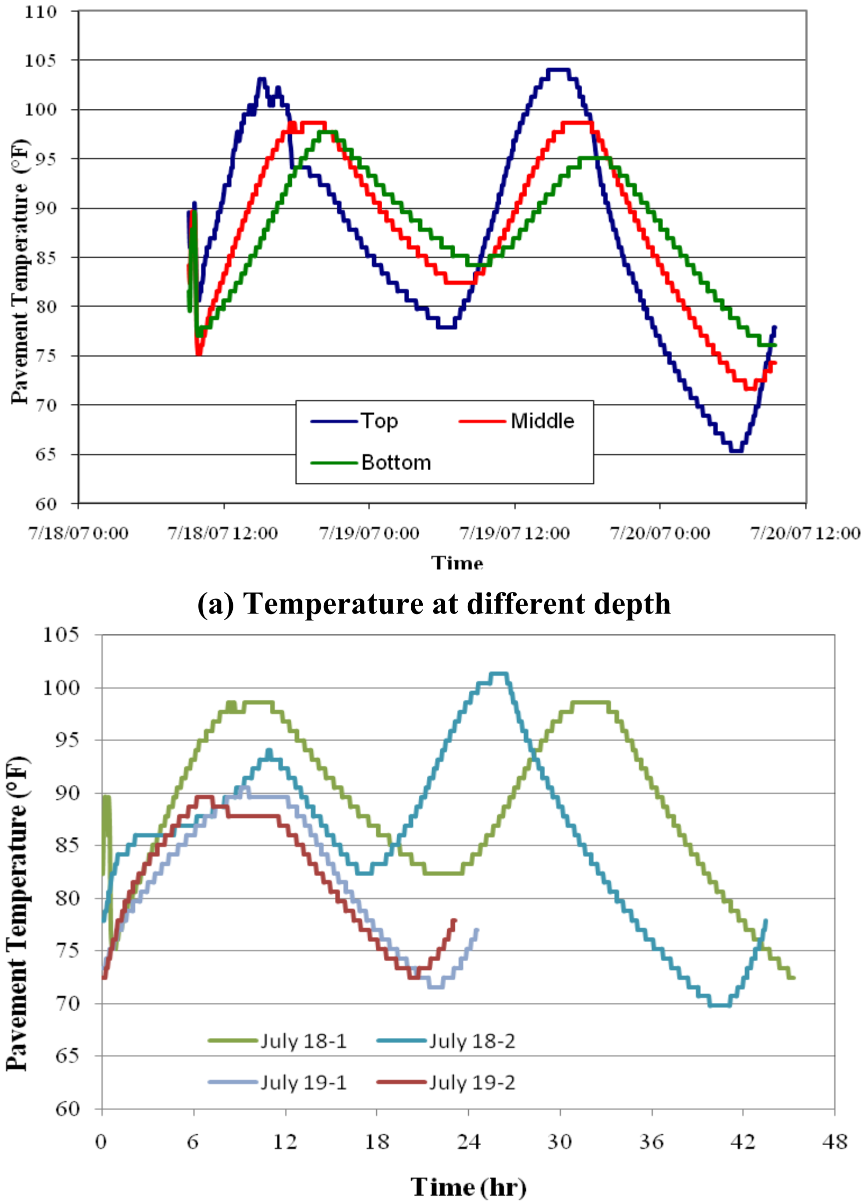


Figure 19. Maturity-strength relationship for HW 95 (Alma Center, WI) samples

3.2.2.7 Pavement Temperature

The pavement temperature was measured at two locations each day on July 18th and 19th. The top, middle, and bottom temperature was only measured in the morning July 18th. For the rest of the tests, only the middle temperature was monitored. Figure 19 shows the results. The variation of the top temperature was larger than middle and bottom due to the influence of the environmental temperature. It was about 5°F higher at peak than the bottom temperature. For the middle temperature, the highest was 100°F. Concrete casted on July 19th had lower temperature compared with concrete on July 18th. The concrete casted in the morning of July 18th had the highest first peak value.



(a) Temperature at different depth

(b) Middle temperature measured at different date

Figure 20. Pavement temperature for HW 95 (Alma Center, WI) project

3.2.3 Ottumwa Project

3.2.3.2 Batch Ticket

All batch tickets were listed in Appendix 1. There were two tickets missing for July 24th tests due to the printer problem. As shown in Figure 21, all mixes had a w/c ratio from 0.35 to 0.39, which was a little bit lower than the designed value, 0.40. The average w/c ratio was 0.37. The standard deviation was 0.01.The batch tickets show that the mixes at different times were consistent.

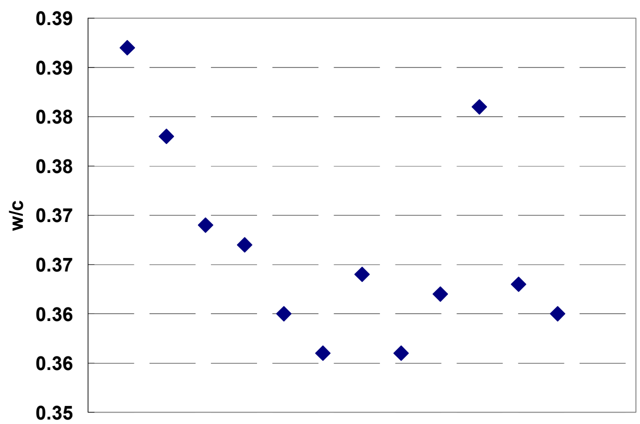


Figure 21. Water to cement ratio for the mixes of US 63 bypass (Ottumwa, IA) project

3.2.3.3 Concrete and Pavement Information

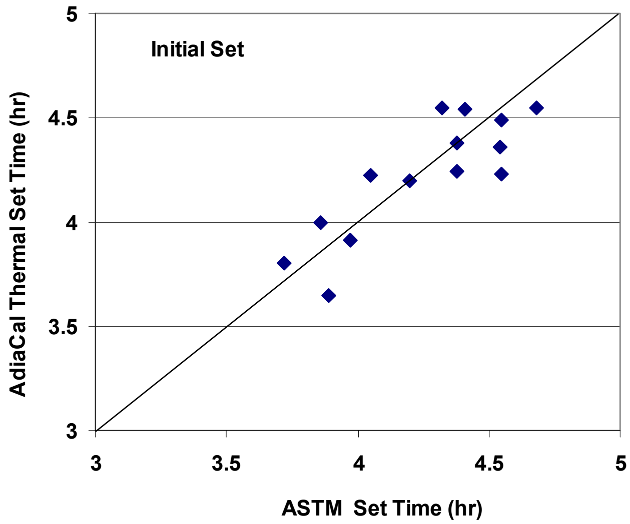
The concrete and pavement information were summarized in Table 6. Pavement was cured about 30 min to one hour after finishing. The sawing time was shorter than the other two projects. It was from 6.8 hours to 10 hours. The air content was from 5.8% to 7%, which was close to the designed value of 6%. The slump was lower than the 2 in. designed values. The slump was from 1.0 in. to 1.5 in. Concrete unit weight was from 140 lb/ft^3 to 146 lb/ft^3. The setting times were also shorter than the other projects. The initial setting time was around 4 hours and final setting time was about 6 hours. The setting times are much shorter than for the other two projects. The microwave w/c ratio was lower than the values from the batch tickets.

Table 9. Concrete and pavement information for US 63 bypass (Ottumwa, IA) project

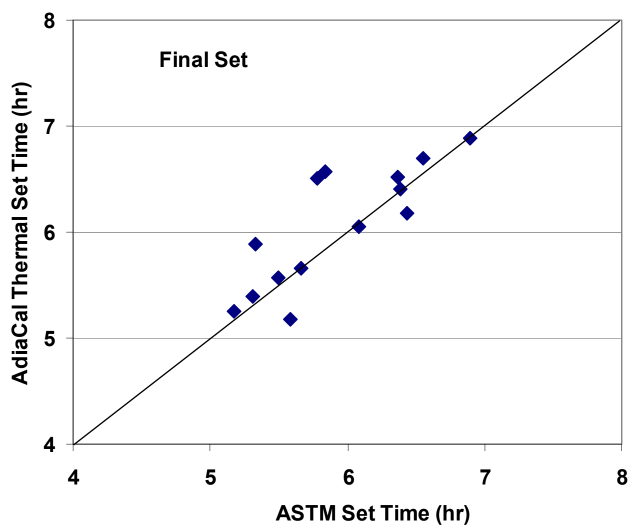
Date	Mix time	Subbase temp.		Con. temp (°F)	Dump time	Paving time	Finish time	Curing time	Sawing time		Air (%)	Slump (inch)	Unit weight (lb/ft^3)	Set time (ASTM)		Microwave w/c
		infrared (°F)	probe (°F)						Time	hr				Initial (hr)	Final (hr)	
7/24/07	8:30 a.m.	80.0	74.3	80.6	8:34 a.m.	8:43 a.m.	8:51 a.m.	9:45 a.m.	4:00 p.m.	7.50	6.00	1.00	144.1	4.38	6.89	0.363
7/24/07	10:13 a.m.	88.8	82.9	84.2	10:20 a.m.	10:26 a.m.	10:33 am	11:24 a.m.	5:00 p.m.	6.78	7.00	1.00	143.6	4.20	5.66	0.359
7/24/07	12:40 p.m.	90.6	91.3	87.6	12:48 p.m	1:02 p.m	1:09 p.m	1:34 p.m	9:05 p.m.	8.42	7.00	1.00	140.9	3.89	5.58	0.331
7/24/07	2:26 p.m	91.9	95	88.0	2:33 p.m	2:39 p.m	2:50 p.m	3:19 p.m	10:30 p.m.	8.07	6.75	1.00	140.6	3.97	5.50	0.309
7/25/07	8:33 a.m.	79.8	75.2	82.6	8:42 a.m.	8:48 a.m.	8:59 a.m.	9:25 a.m.	5:05 p.m	8.53	5.75	1.00	146.3	4.41	5.78	0.385
7/25/07	9:58 a.m.	90.1	84.9	83.5	10:03 a.m.	-	-	-	6:38 p.m	8.67	6.75	1.00	144.2	4.05	5.33	0.378
7/25/07	12:30 p.m	96.1	93.7	88.5	12:39 p.m	12:46 p.m	12:55 p.m	1:31 p.m	9:38 p.m	9.13	7.00	1.25	144.5	3.86	5.31	0.34
7/25/07	1:56 p.m	101.5	98.2	88.5	2:05 p.m	-	-	-	12:00 p.m	10.07	7.10	1.00	144.0	3.72	5.17	0.376
7/30/07	8:16 a.m.	79.2	75.9	83.1	8:25 a.m.	-	-	-	-	-	6.75	1.00	143.7	4.68	6.55	0.35
7/30/07	9:32 a.m.	90.3	81.7	81.3	9:47 a.m.	-	-	-	-	-	7.75	1.50	141.0	4.55	6.37	0.318
7/30/07	1:37 p.m	97.3	91.6	85.5	1:50 p.m	-	-	-	-	-	7.50	1.25	142.2	4.54	6.39	0.319
7/30/07	3:15 p.m	101.9	96.3	88.2	3:23 p.m	-	-	-	-	-	6.75	1.00	144.7	4.55	6.44	0.356
7/31/07	8:47 a.m.	84.2	77.5	82.4	8:57 a.m.	-	-	-	-	-	6.00	1.00	145.4	4.32	5.84	0.367
7/31/07	10:51 a.m.	94.3	81	84.6	11:01 a.m.	-	-	-	-	-	-	-	145.4	4.38	6.08	0.356

3.2.3.4 AdiaCal Calorimetry Results

Fourteen AdiaCal tests were performed. The fraction numbers are 13% and 49% for initial and final thermal set, respectively. These fraction numbers were determined from the first set test. Similar to the other two projects, the setting time determined from these two methods is very close. The largest difference is only 0.72 hours for both initial and final setting time. The average difference between the ASTM and AdiaCal is 0.13 hours and 0.23 hours for the initial and final setting times, respectively.



(a) Initial set time

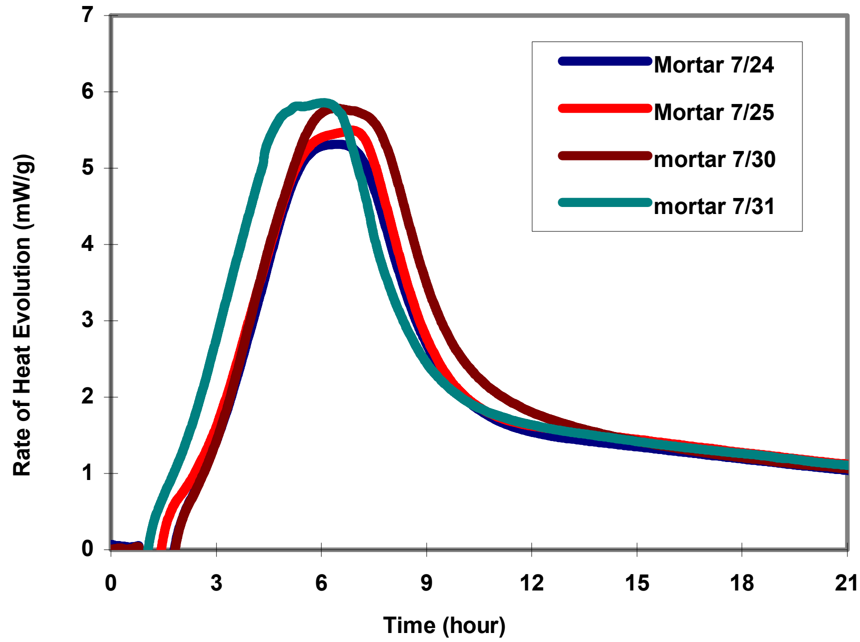


(b) Final set time

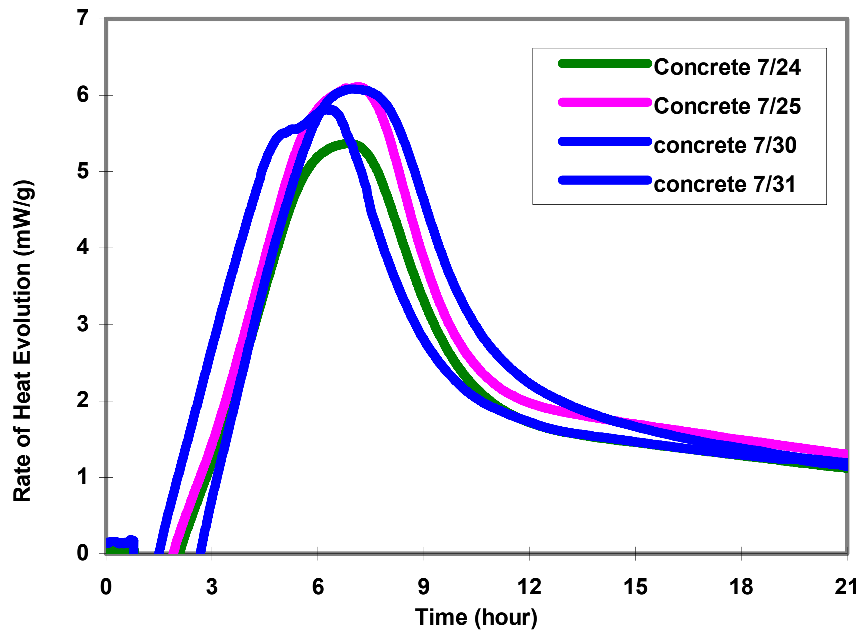
Figure 22. ASTM set time vs. AdiaCal thermal set for US 63 bypass (Ottumwa, IA) project—13% fraction for initial thermal set and 49% for final thermal set

3.2.3.5 Isothermal Calorimetry Results

Figure 23 shows the isothermal calorimetry results. The test on July 31st shows earlier hydration than other tests. The peak is about one hour earlier. The other three tests had almost the same rate of hydration at the early time. However, the peak values were different for these tests. Both concrete and mortar have the similar trend.



(a) Mortar sample

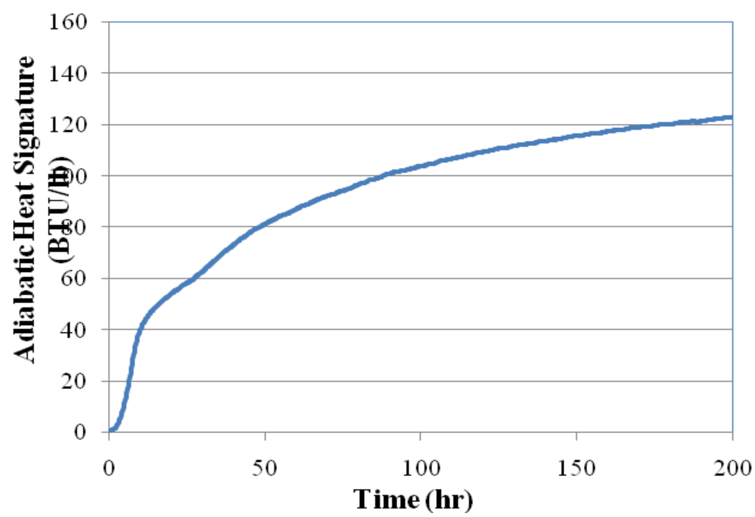


(b) Concrete sample

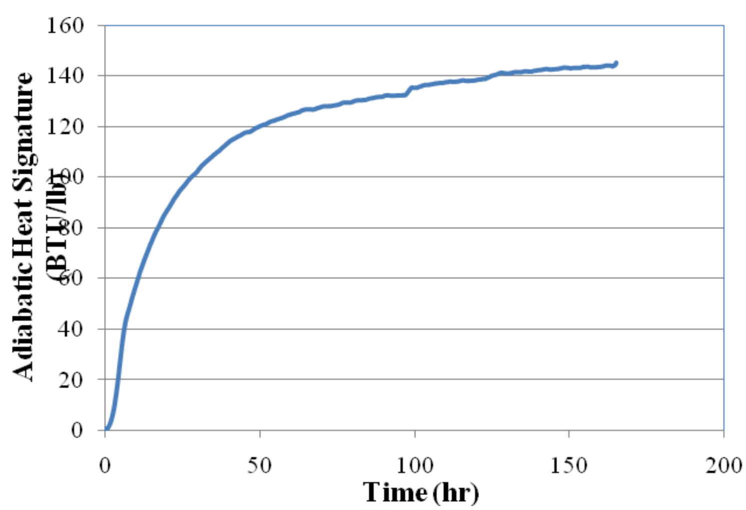
Figure 23. Isothermal calorimetry results for US 63 bypass (Ottumwa, IA) project

3.2.3.6 Semi-Adiabatic Calorimetry (IQ Drum) Test

Figure 25 shows the IQ drum test results. The concrete sample hydrated faster at early age due to the higher temperature. The highest concrete temperature during the test was 113.7°F. For mortar sample, the highest temperature was only 86.4°F. The difference was almost 30°F. The generated heat was about 140 BTU/lb at 150 hours for concrete sample and 120 BTU/lb for mortar samples at 200 hours. After about 40 hours, the hydration of concrete samples slowed down.



(a) Mortar sample

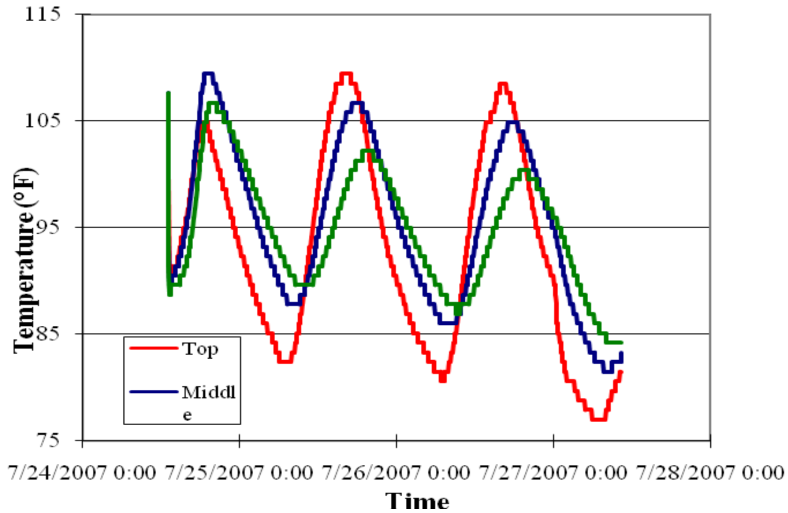


(b) Concrete sample

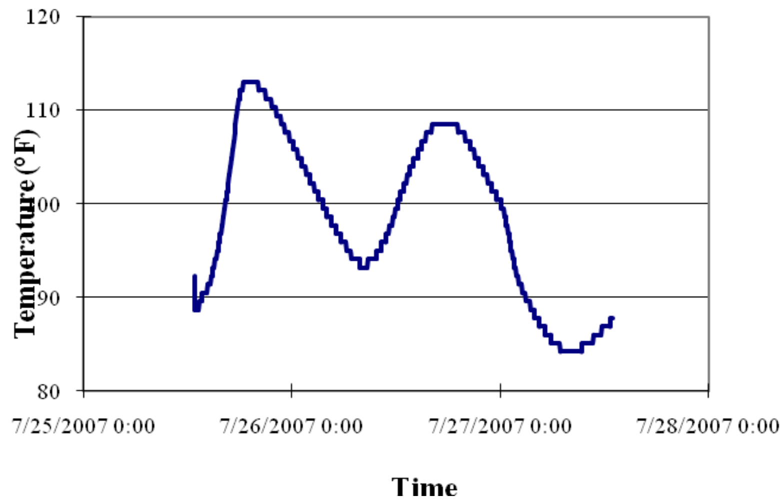
Figure 24. Heat evolution with time for US 63 bypass (Alma Center, WI) project

3.2.3.7 Pavement Temperature

Figure 24 shows the pavement temperature tested on two different days. The Ibuttons were put into the pavement around noon. The temperature difference inside pavement is about 7°F at peak time. On the first day, the middle layer had the highest temperature due to cement hydration and less heat loss. The first peak value was reached around 6 p.m..



(a) Temperature at different depth



(b) Middle temperature measured on July 25th

Figure 25. Pavement temperature for US 63 bypass (Ottumwa, IA) project

3.3 Comparison of Field Test Results from Different Projects

3.3.1 AdiaCal Calorimeter

As shown in each project, the thermal set time determined from the AdiaCal calorimeter was close to the ASTM setting time. The data for all three projects are plotted in Figures 26 and 27. The initial ASTM setting time for different mixes ranges from 4 hours to 10 hours. The maximum difference between these two methods is only 1.77 hours, which is about 18.2% of ASTM result. But the average variation is only 0.37 hours and the standard deviation is 0.40. The variation is relatively larger for samples with long initial set time.

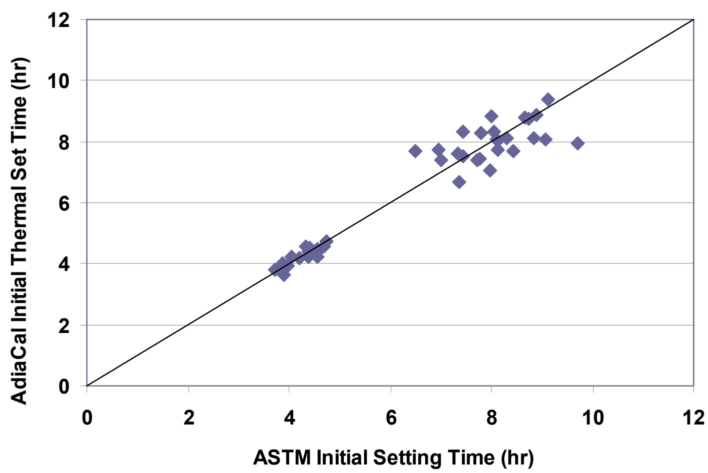


Figure 26. ASTM set time vs. AdiaCal thermal set time—initial set

Figure 27 shows the results of final setting time, it ranges from 5 to 13 hours. All the points are distributed around the equality line. The maximum difference between these two methods is only 2.08 hours, which is about 16.8% of ASTM result. But the average variation is only 0.43 hours and the standard deviation is 0.45.

Since the tested initial and final setting times cover a large range and tests were performed for different concrete mixes at different times, it can be concluded from the results that the AdiaCal calorimeter could be used in the field to estimate concrete setting time. Compared with ASTM test, the AdiaCal method is less labor-intensive especially for samples with long setting times and could reduce the errors caused by operators.

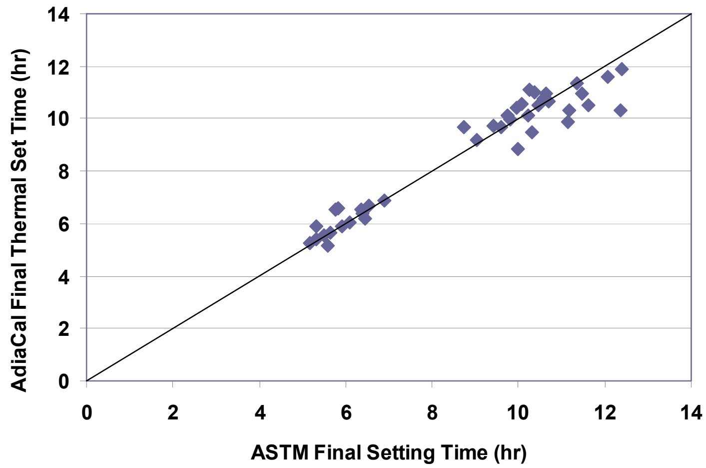


Figure 27. ASTM set time vs. AdiaCal thermal set time—final set

As shown in Figure 16, samples casted in the same day had different temperature history. Both the peak value and time to reach the peak could be different. More figures are listed in the appendix. One of the reasons for the difference is the placement temperature. The variation could be 5°C for the same project. This in turn will affect the hydration process of cementitious materials. Another reason for the difference could be the environmental temperature change. Even the samples were stored in a mobile lab where there is still some room temperature variation. Also, AdiaCal is a simple semi-adiabatic calorimeter with a relatively large coefficient of heat loss. All these factors can significantly affect sample temperature history. At this stage, the concrete temperature is recommended for daily quality control. However, if the placement and environmental temperature could be controlled, this could be a possible method for quality control.

3.3.2 Isothermal Calorimeter

Figure 28 summarizes the isothermal calorimeter test results. The average value of each project is used. It indicates that the results for mortar and concrete samples are not identical. Concrete samples have lower peak values for the Atlantic and Alma Center project but higher values for the Ottumwa project. As explained before, this could be caused by the sampling issues. The peak time is slightly delayed for concrete samples. This is possibly caused by the size of the sample. The concrete sample is about 300 g and the mortar sample is only 100 g. For the concrete sample, the generated heat may take a little longer to dissipate to the heat sink. It could delay the hydration curve.

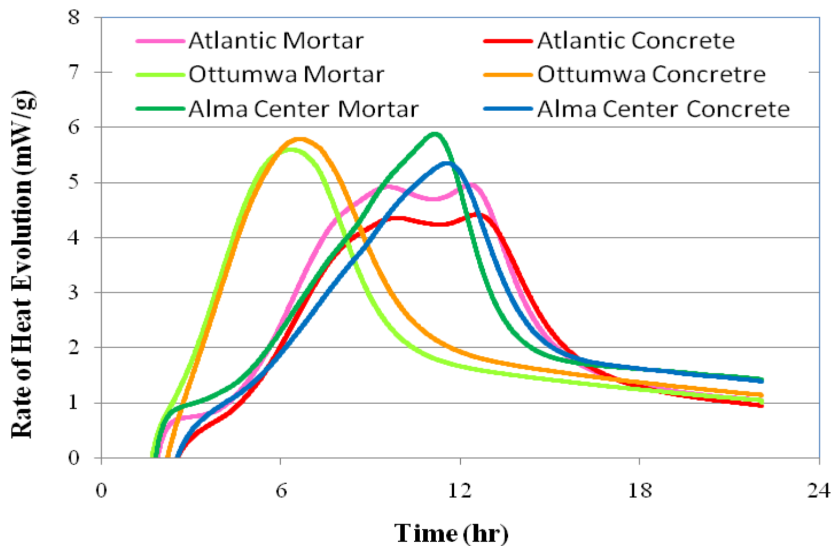


Figure 28. Summary of isothermal field calorimetry results

As shown in Figures 8, 17, and 23, for each project, the isothermal calorimeter results are consistent for samples in different days. But, in order to use the simple isothermal calorimeter for daily quality control,the calorimeter should also be able to detect the difference when there is change in materials or other factors. Figure 28 shows the ability of the isothermal calorimeter to detect the difference caused by materials and other factors. In the figure, the three curves are different in terms of the shape and value. The Ottumwa and Atlantic project had similar mix proportions but different cementitious materials. The two calorimetry curves for these two projects are totally different. Therefore, it is possible for the calorimeter to discover the change when the field mix is changed.

3.3.3 Pavement Sawing Time

Figure 29 shows the pavement sawing time and AdiaCal final thermal set time. Most concrete sawing times were between 6 and 14 hours after mixing. There is no clear relationship between these two parameters. The sawing times are normally longer than the set times. But some of them are every close.

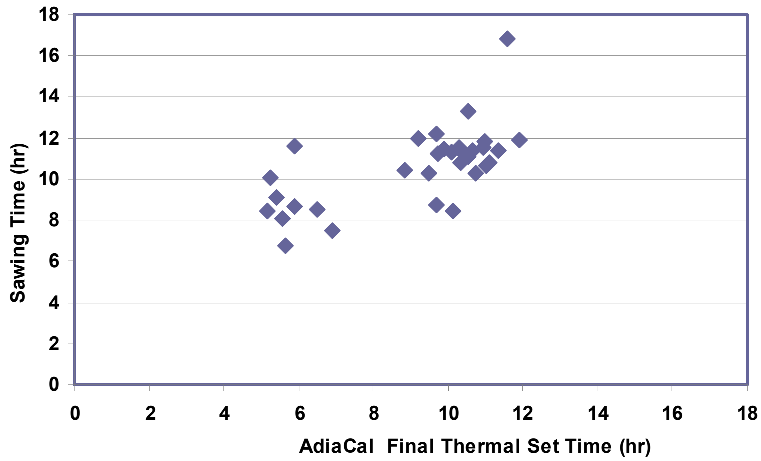


Figure 29. Pavement sawing time vs. AdiaCal thermal final set time

4. LAB TESTS FOR FIELD CONCRETE MATERIALS

Robust tests were conducted in lab for the concrete materials collected from the above-mentioned three field sites: (1) US 71 PCC overlay, Atlantic, Cass County, Iowa, (2) Highway 95, Alma Center, Jackson Country, Wisconsin, and (3) US 63 bypass, Ottumwa, Wapello County, Iowa. Nine robust mixes, with 50% decrease/increase of WR and/or FA dosages were developed based on the mix proportion actually used in field for each field project. By changing the amount of FA and WR at a 50% level, robust tests are used to simulate possible concrete mix proportion error that sometimes occurs in field construction. The specific objectives of the robust tests are the following:

- To study the potential effects of over-doses or under-doses of WR and/or FA on heat generation of concrete
- To find out whether or not the mixtures are acceptable or may have incompatibility problems, the over- or under-dosed materials were used.
- To provide field engineers with acceptable boundaries to evaluate their calorimetry test results, thus, calorimetry technology may be easily used as a tool for field concrete quality control

AdiaCal tests were performed for each robust mix, and isothermal calorimeter tests were performed for each robust mix at four different temperatures. Selected IQ drum tests and ASTM C403 set time tests were also performed in lab so as to compare the lab results with the field test results.

4.1 Tests and Methods

The following tests were conducted for materials and robust mixes of each field site:

1. Specific gravity and absorption of aggregates
2. AdiaCal calorimetry tests
3. Simple isothermal calorimetry test at 10^{o}C (5^{o}C for Alma Center, WI, mixes), 20^{o}C, 30^{o}C, and 40^{o}C
4. IQ Drum calorimetry tests
5. ASTM set time robust tests (for US 63 bypass, Ottumwa, IA, mixes only)

The aggregates of all three field projects were tested for specific gravity and absorption according to ASTM C127 “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate” and C128 “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate.”

The nine robust mixtures prepared using the materials from each field project are the following:
Mix 1: A reference mix made with the same proportion as used in the field project
Mix 2: Mix 1 with over-dosed WR (50% more than that used in Mix 1)
Mix 3: Mix 1 with under-dosed WR (50% less than that used in Mix 1)
Mix 4: Mix 1 with over-dosed FA (50% more than that used in Mix 1)
Mix 5: Mix 1 with under-dosed FA (50% less than that used in Mix 1)

Mix 6: Mix 1 with over-dosed WR and FA (both WR and FA are 50% more than those used in Mix 1)
Mix 7: Mix 1 with over-dosed WR (50% more than that used in Mix 1) and under-dosed FA (50% less than those used in Mix 1)
Mix 8: Mix 1 with under-dosed WR (50% less than that used in Mix 1) and over-dosed FA (50% more than that used in Mix 1)
Mix 9: Mix 1 with under-dosed WR and FA (both WR and FA are 50% less than those used in Mix 1)

The robust mixture proportions of the three projects studied are presented in Tables 10–12. The concrete (Mix 1) of all three field projects contained WR and 20% FA replacement.

Table 10. Concrete mix proportions for US 71 project (Atlantic, IA)

Mix	Cement (pcy)	Fly ash (pcy)	C. Agg. (pcy)	Int. Agg. (pcy)	Sand (pcy)	Water (pcy)	AEA (fl oz/cwt)	WR (fl oz/cwt)
1	442	110	1560	273	1309	221	0.3	4.0
2	442	110	1560	273	1309	221	0.3	6.0
3	442	110	1560	273	1309	221	0.3	2.0
4	383	170	1560	273	1309	221	0.3	4.0
5	497	55	1560	273	1309	221	0.3	4.0
6	387	165	1560	273	1309	221	0.3	6.0
7	497	55	1560	273	1309	221	0.3	6.0
8	387	165	1560	273	1309	221	0.3	2.0
9	497	55	1560	273	1309	221	0.3	2.0

Table 11. Concrete mix proportions for the HW95 project (Alma Center, WI)

Mix	Cement (pcy)	Fly ash (pcy)	C. Agg. (pcy)	Int. Agg. (pcy)	Sand (pcy)	Water (pcy)	AEA (fl oz/cwt)	WR (fl oz/cwt)
1	446	113	1825	0	1370	252	1.0	3.2
2	446	113	1825	0	1370	252	1.0	4.8
3	446	113	1825	0	1370	252	1.0	1.6
4	390	170	1825	0	1370	252	1.0	3.2
5	503	57	1825	0	1370	252	1.0	3.2
6	390	170	1825	0	1370	252	1.0	4.8
7	503	57	1825	0	1370	252	1.0	4.8
8	390	170	1825	0	1370	252	1.0	1.6
9	503	57	1825	0	1370	252	1.0	1.6

Table 12. Concrete mix proportions for US 63 bypass project (Ottumwa. IA)

Mix	Cement (pcy)	Fly ash (pcy)	C. Agg. (pcy)	Int. Agg. (pcy)	Sand (pcy)	Water (pcy)	AEA (fl oz/cwt)	WR (fl oz/cwt)
1	443	111	1846	0	1291	222	0.3	4.0
2	443	111	1846	0	1291	222	0.3	6.0
3	443	111	1846	0	1291	222	0.3	2.0
4	385	170	1846	0	1291	222	0.3	4.0
5	499	56	1846	0	1291	222	0.3	4.0
6	388	167	1846	0	1291	222	0.3	6.0
7	499	56	1846	0	1291	222	0.3	6.0
8	388	167	1846	0	1291	222	0.3	2.0
9	499	56	1846	0	1291	222	0.3	2.0

4 in. by 8 in. concrete cylinder samples were used for AdiaCal calorimetry tests. In the test, all concrete mixtures were mixed according to ASTM C192 "Practice for Making and Curing Concrete Test Specimens in the Laboratory." The cylinder samples were then prepared according to ASTM C192, and placed into the AdiaCal calorimeter right after casting. After the samples were placed into the calorimeter, the pre-programmed calorimeter started recording the concrete temperature immediately. The concrete temperature was recorded every 1/2 min by the sensor located below the bottom of the sample holder; the data was retrieved from the data logger through the program after 48 hours. The average values from at least two samples of each mix were used for analysis. A total of 27 mixes were tested with AdiaCal calorimeter.

The isothermal calorimetry tests were done according to the procedures described in the draft of the specification developed in phase II (Appendix E). Mortar samples were used in the tests. Four different placement and test temperatures (10^{o}C [or 5^{o}C], 20^{o}C, 30^{o}C, and 40^{o}C) were selected for the tests. To control the concrete placement temperature, the raw concrete materials from the three projects were first stored in a refrigerator, oven, or room prior to mixing. Mortars were then mixed according to ASTM C305 "Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars for Plastic Consistency." Four samples, with weights of 100$\pm$2 g each, were placed into standard plastic containers and then loaded into the calorimeter immediately after samples were ready. After the samples were placed into the calorimeter, the pre-programmed calorimeter started taking readings immediately. The readings were taken every 1/2 min for 72, 48, or 24 hours, depending upon the testing temperature. The rates of heat evolution per g of cement were then calculated from the mix design of mortar, and the average values from four samples of each mix were used for analysis. A total of 108 mixtures were tested with isothermal calorimeter at four different temperatures.
Semi-adiabatic calorimetry tests were conducted using IQ Drum for 6 in. by 12 in. concrete cylinders. Only the reference mixes (Mix 1 in Tables 10–12) of each field project were tested. The concrete was mixed according to ASTM C192 "Practice for Making and Curing Concrete Test Specimens in the Laboratory." The cylinder samples were prepared according to ASTM C192, and placed into the calorimeter immediately after casting. After the samples were placed into the calorimeter, the pre-programmed

calorimeter started taking readings immediately. The concrete mix proportion and physical properties of the raw materials were input into the program, which provided the desired results including the thermal history and heat evolution process of concrete. The readings were taken every 15 min through the program, and the entire test took approximately 7 days.

In phase II of the present project, investigators demonstrated that there was a close relationship between the thermal setting values obtained from calorimetry tests and those from the ASTM set time tests. In order to compare the concrete set times measured from the two different methods, standard ASTM set time tests were also performed in the phase III study in addition to the calorimetry tests. The standard ASTM tests were done based on ASTM C403 "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance." Only nine mortar mixes of the US 63 bypass (Ottumwa, IA) project (Table 12) were selected and tested. The mortars were mixed according to ASTM C305 "Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars for Plastic Consistency." The samples were placed and tested at room temperature until final set were achieved.

4.2 Results and Discussion

4.2.1 US 71 Atlantic (IA) Project Mixes

4.2.1.1 AdiaCal Tests

Based on research from phase II, heat indexes were established to help engineers interpret the calorimeter results, and predict concrete performance so as to be used for concrete quality control. The heat indexes include thermal initial set and final set times, which are determined from the first derivative of the temperature curves. The initial thermal set time is defined as the time when the first derivative curve reaches its highest value, at which point the increase in the sample temperature is the fastest. After the initial set time, the first derivative values start to decrease. The final thermal set time is defined as the time when the first derivative becomes zero, which corresponds to the time when the highest sample temperature is achieved in the original temperature curve. In addition to the thermal set times, the areas under the temperature curve during different test periods are used (see Appendix E, Areas A, B, C, D, X, and Y represent the heat generated during the first–sixth hours, sixth–12th hours, 12th–18th hours, 18th–24th hours, first–24th hours [first day], and first–48th hours [first two days], respectively.) The data of the first hour was not used in consideration that the calorimeter system needed a certain time to reach its equilibrium status after samples were placed.

The temperature curves of concrete made with materials collected from the US 71, Atlantic, IA, project and with nine different mix proportions (as shown in Table 10) are shown in Figure 30. All calorimetry curves, from the mixtures with different WR dosages and FA replacement levels and under different temperatures, displayed major peaks that cover a certain area under the peaks, which indicates that there is no incompatibility problem in the concrete mixtures in the ranges of WR and FA applied.

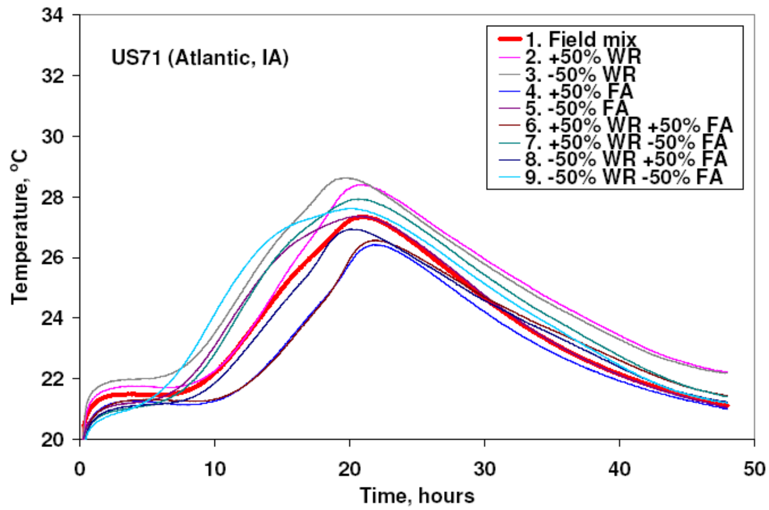


Figure 30. AdiaCal robust test results of US 71 (Atlantic, IA) concrete mixes

The initial and final thermal set times from the original field mix (as shown in the columns in the figure) and the maximum and minimum set times from the mixes with different levels of WR and FA (as shown in the error bars in the figure) obtained from the AdiaCal curves were summarized in Figure 31. The detailed thermal set times and areas under heat generated curves at different periods of all nine mixes are listed in Table B.1.. The results showed that the initial thermal set times of the nine concrete mixtures tested were between 9.5 hours and 19.7 hours, while the final thermal set times of the mixtures were between 19.6 hours and 21.8 hours. The figure also shows that the variation of initial thermal set time is larger than that of final thermal set time. In other words, the amount of WR and/or FA has more impact on the initial set than on the final set of the mixtures.

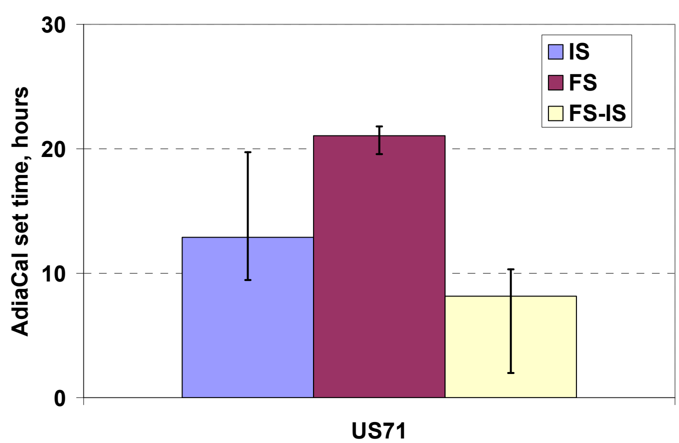


Figure 31. Estimated set time from US 71 (Atlantic, IA) AdiaCal robust test

The areas under the temperature-time curves within different time periods were also analyzed and the results (with the columns referring to the value from original field mixes and the error bars referring to the maximum and minimum values from mixes with different levels of WR and FA) are shown in Figure 32. The figure illustrates that the areas under the calorimeter curves increased within the first 24 hours, which indicated that more heat is generated through time in this period. Approximately the same amount of heat was generated in the first and second day.

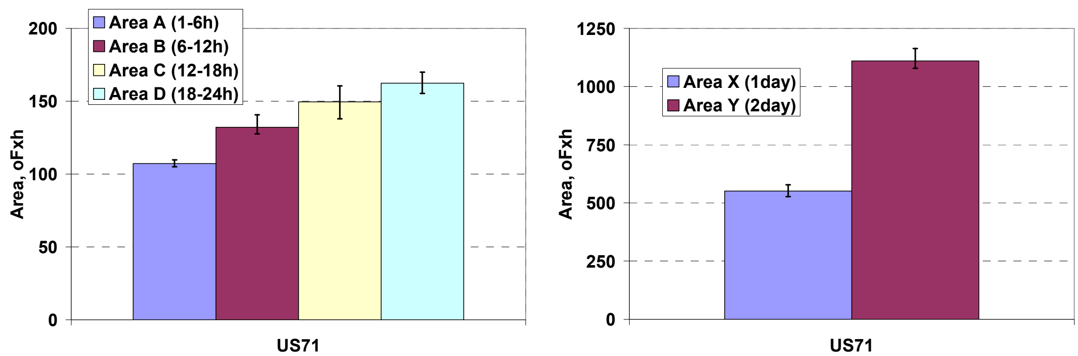


Figure 32. Areas under AdiaCal test curves of US 71 (Atlantic, IA) project during different test period

Statistical analysis was performed to study the effect of the amount of WR and FA replacement on the initial and final thermal set time, the mortar setting window (FS-IS), and peak temperature of AdiaCal tests. Least square fit was performed in the analysis of these calorimeter test values. As shown in Figure 33, initial and final thermal set time both increased with the level of WR and FA replacement. However, the effects of FA replacements on these thermal parameters are more significant than that of WR. The figure also suggests that the setting window (from initial setting to final setting time) reduced with the increased FA replacement levels. The peak temperature from the AdiaCal test reduced with the FA replacement; however, no obvious changes were found with different water reducer dosage.

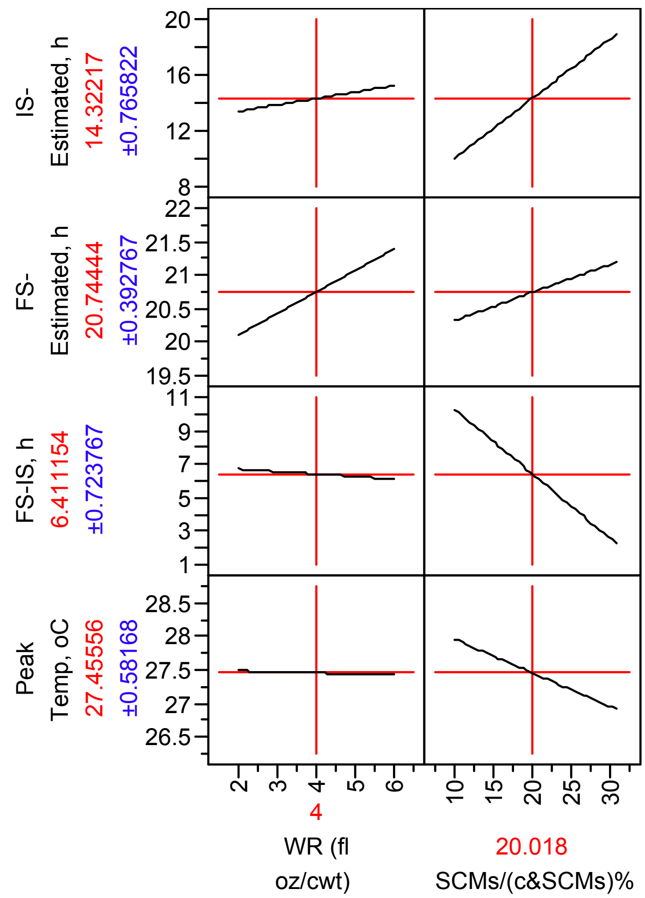


Figure 33. Statistical analysis from US 71 (Atlantic, IA) AdiaCal robust test

4.2.1.2 Isothermal Calorimetry Test Results

The heat evolution curves of the mortar used in the field concrete but tested at four different temperatures (10°C, 20°C, 30°C, and 40°C) are shown in Figure 34. As seen in the figure, similar to the results from the field isothermal calorimetry tests, all the heat generation curves had two major peaks, which reflect FA replacement in the concrete mixtures. These second peaks were not observed from the AdiaCal calorimetry test. With increase in the testing temperature, the maximum rate of heat generation and the area under the major peaks increases, while the times to reach this maximum rate also decrease. This indicates that high curing temperature is favorable to the concrete strength development, and extended curing time is needed for the concrete to gain a specific strength value when concrete is under a low temperature environmental condition.

The initial thermal set time increased from 6.4 hours to 20.3 hours when the temperature changed from 40°C to 10°C, while the final thermal set time increased from 9.3 hours to 29.4 hours when the temperature decreased from 40°C to 10°C.

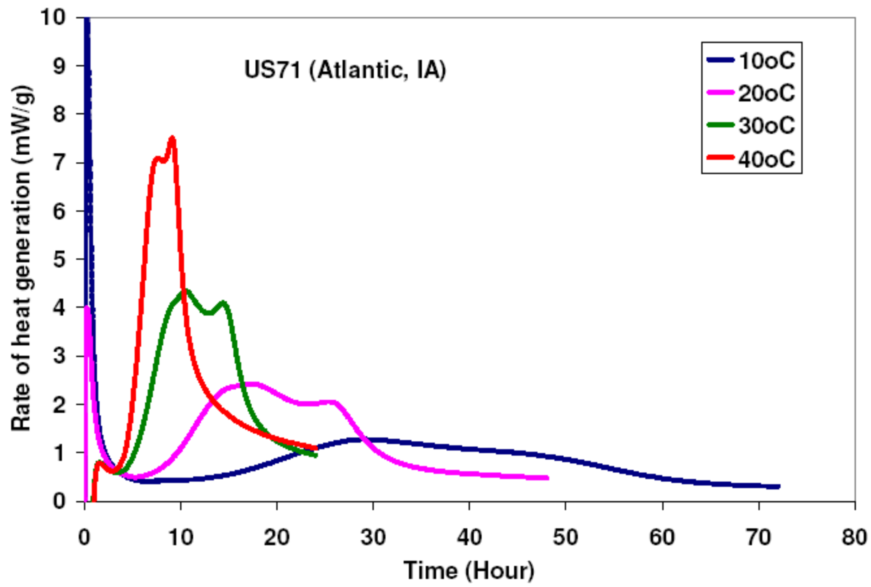
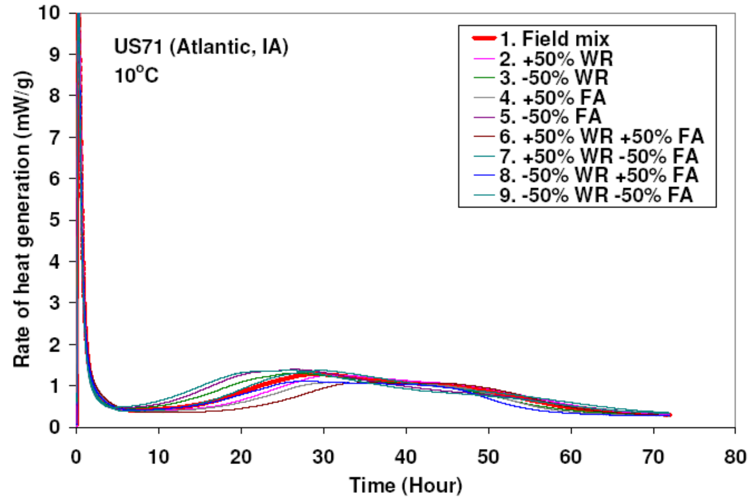
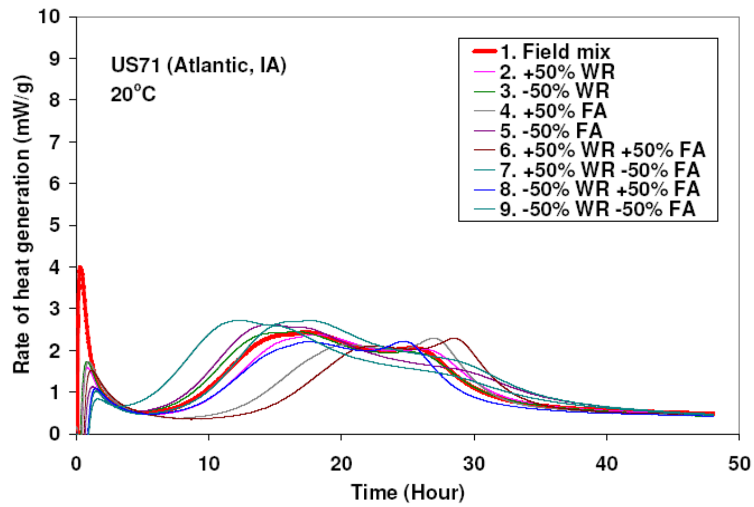


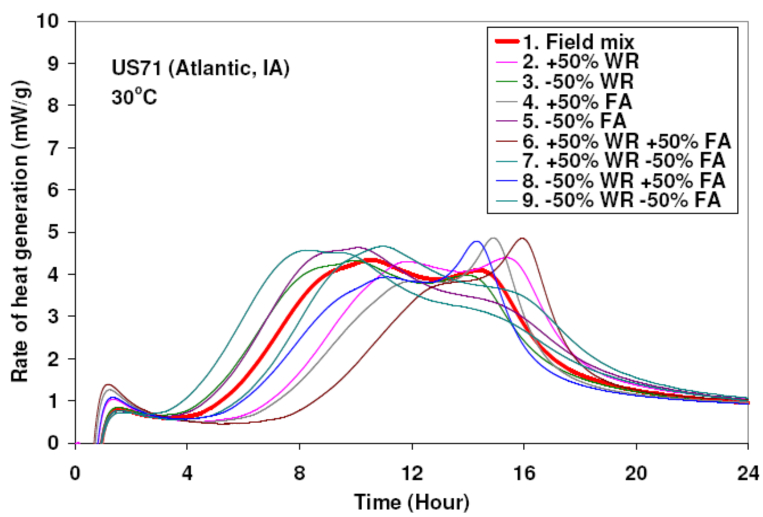
Figure 34. Isothermal test results of US 71 (Atlantic, IA) Mix 1 at four temperatures

The heat generation curves of all nine different mixes for the US 71 Atlantic, Iowa, project at four different temperatures (10°C, 20°C, 30°C, and 40°C) are shown in Figure 35. All calorimetry curves, from the mixtures with different WR dosages and FA replacement levels and under different temperatures, displayed two major peaks that cover a certain area under the peaks, which is related to FA effect. The similar shape of the heat generation curves indicates that there is no incompatibility problem in the concrete mixtures in the ranges of WR and FA applied.

The results showed that the initial thermal set times of the US 71 Atlantic, Iowa, mixtures were between 20.3 hours and 28.8 hours at 10°C, between 12.2 hours and 19.5 hours at 20°C, between 7.2 hours and 15.5 hours at 30°C, and between 6.4 hours and 7.3 hours at 40°C. The final thermal set times were between 29.4 hours and 35.1 hours at 10°C, between 17.5 hours and 28.6 hours at 20°C, between 10.7 hours and 16.1 hours at 30°C, and between 9.3 hours and 10.0 hours at 40°C.


US71 (Atlantic, IA)
10°C
1. Field mix
2. +50% WR
3. -50% WR
4. +50% FA
5. -50% FA
6. +50% WR +50% FA
7. +50% WR -50% FA
8. -50% WR +50% FA
9. -50% WR -50% FA
Rate of heat generation (mW/g)
Time (Hour)


US71 (Atlantic, IA)
20°C
1. Field mix
2. +50% WR
3. -50% WR
4. +50% FA
5. -50% FA
6. +50% WR +50% FA
7. +50% WR -50% FA
8. -50% WR +50% FA
9. -50% WR -50% FA
Rate of heat generation (mW/g)
Time (Hour)


US71 (Atlantic, IA)
30°C
1. Field mix
2. +50% WR
3. -50% WR
4. +50% FA
5. -50% FA
6. +50% WR +50% FA
7. +50% WR -50% FA
8. -50% WR +50% FA
9. -50% WR -50% FA
Rate of heat generation (mW/g)
Time (Hour)

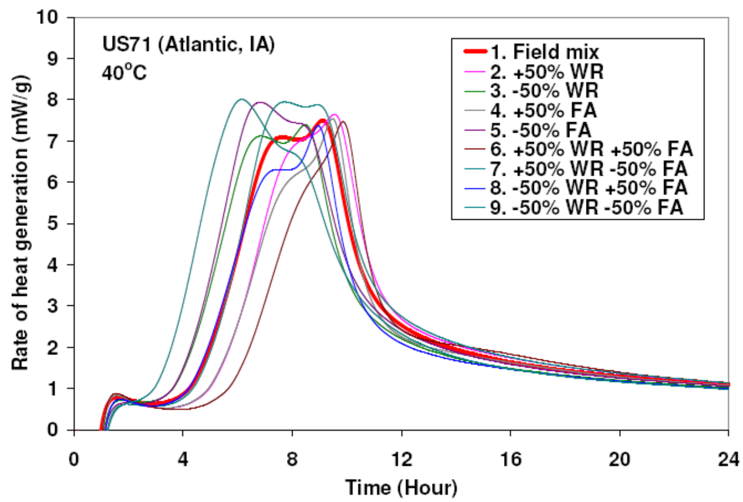


Figure 35. Isothermal robust test results of US 71 (Atlantic, IA) mortar mixes at different temperatures

The boundaries of initial and final thermal set time from the isothermal robust tests were summarized in Figure 36. Similar to AdiaCal thermometry results, the columns refer to the value from original field mixes and the error bars refer to the maximum and minimum values from mixes with different levels of water reducer and fly ash. Results showed that the initial and final thermal set times and the setting time window all increase with the decrease of the environmental temperature. Also, the variations of the thermal set time increase while the environmental temperature decrease. Unlike the AdiaCal test results, the variation of the initial thermal set time appeared not clearly different from that of the final thermal set times. The detailed thermal set times and the area under heat generation curves at different time periods of each mixes can be found in Table C.1.–26.

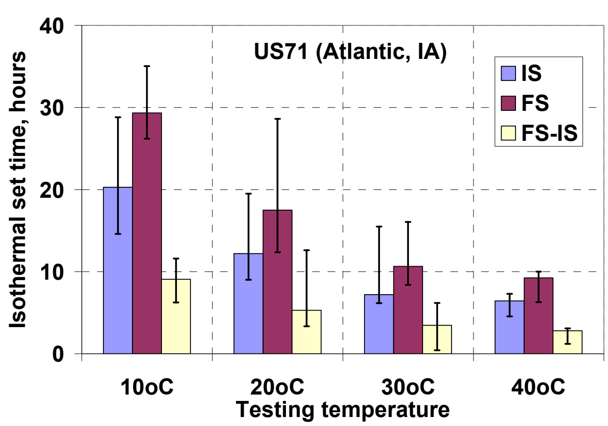


Figure 36. Estimated set time from isothermal robust test on US 71 (Atlantic, IA) mixes

The areas under the heat generation time curves within different time periods were also analyzed. Results in Figure 37 show that more heat was generated when the environmental temperature was higher. At low temperature (10^oC), the area increased with the time elapse within the first 24 hours, which indicated more heat was generated. The heat generation within 24 hours to 48 hours is higher than the first 24 hours after cement makes contact with water. However, the heat generation will slow down after 48 hours. The larger area of the first hour to 6 hours might be caused by the stabilization time of the sample, which will usually have a relatively high temperature compared to the environmental temperature. With the increase of the environmental temperature, larger amounts of heat were observed at an earlier period. The heat generation reaches the peak at 6 hours to 12 hours, but slows down after 12 hours or 24 hours at 30^oC and 40^oC. Results indicated high strength development at early ages when the environmental temperature is higher.

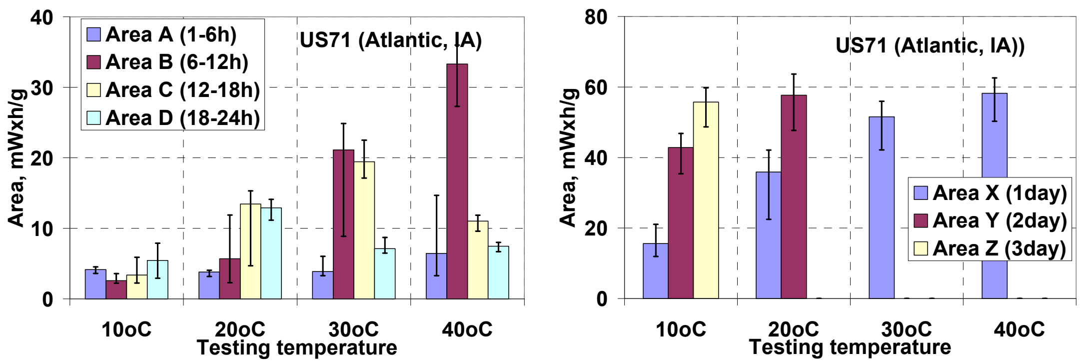


Figure 37. Heat generation from isothermal robust test mixes at different times US 71 (Atlantic, IA) mixes

Similar to the AdiaCal thermometry study, statistical analyses were performed in order to study the effect of the amount of WR, FA replacement and environmental temperature on the initial and final thermal set times and the peak heat generation rate in isothermal tests. Least squares fit was performed on the prediction of initial thermal set (IS) and final thermal set (FS), time between the final and initial sets, or set time window, (FS-IS), and peak temperature from isothermal test using the parameters of WR dosage, FA replacement % and environmental temperature. According to the results as shown in Figure 38, both initial and final thermal set times decrease when the environmental temperature goes up, the set time window (FS-IS) reduced with the increase of environmental temperature. The initial setting and final setting time both increase with the amount of WR used and the percent replacement of the FA. Environmental temperature has most the significant effect on the initial setting and final thermal set times and the peak heat generation rate. The set time window does not have obvious changes with the increase of percentage replacement of FA and WR. FA replacement and WR dosage do not have obvious effects on peak heat generation rate from the isothermal test.

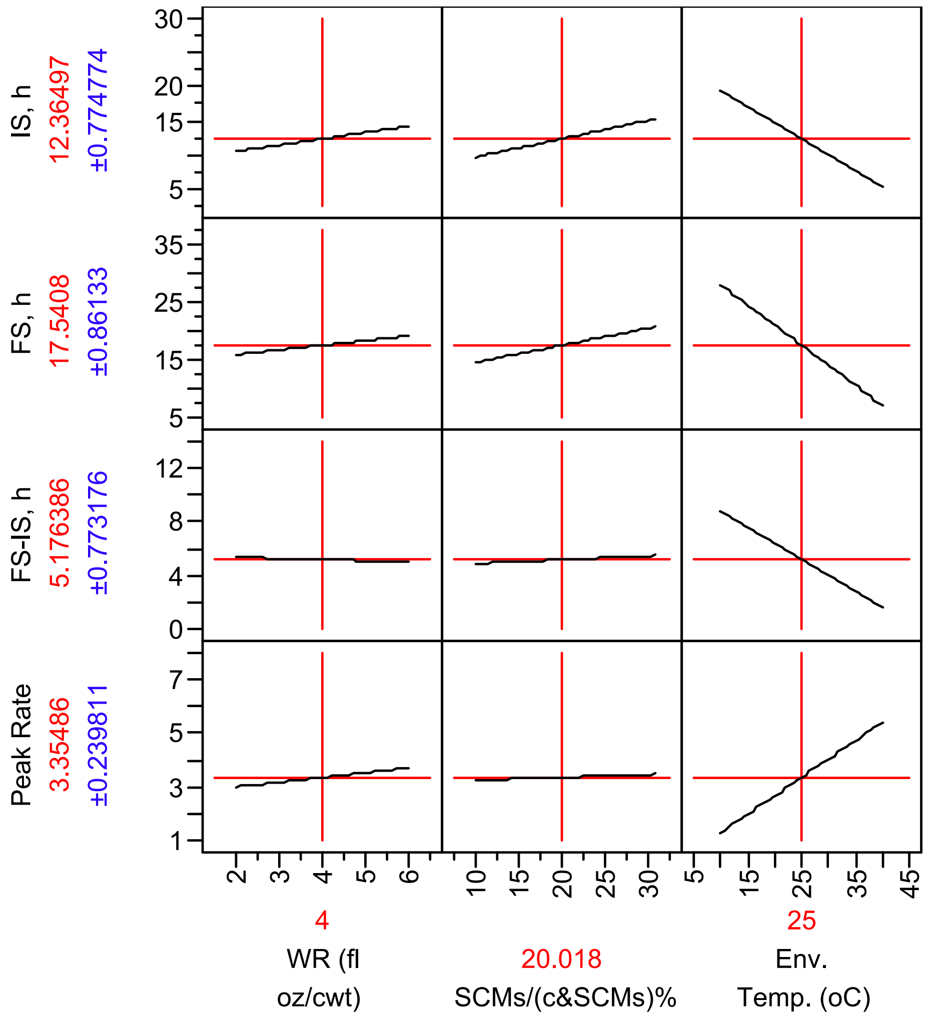


Figure 38. Effect of mix design and temperature on IS and FS from isothermal robust test US 71 (Atlantic, IA mixes)

4.2.1.3 IQ Drum test results

The semi-adiabatic calorimetry (IQ Drum) test of the field mix was also performed in the laboratory; the results of the heat generation curves will be used for the calculation of the concrete performance with HIPERPAV program. Results obtained from the IQ Drum test are shown in Figure 39. The results show that the heat evolution was slow at the first 5 hours, but it increased rapidly during 5 hours–20 hours and gradually became stable after 20 hours. The heat generated was about 120 BTU/gram cementitious materials at the time of 150 hours, which was similar to that of the field IQ Drum test. This indicated a very good consistency of the IQ Drum tests in the mobile lab and a conventional concrete lab.

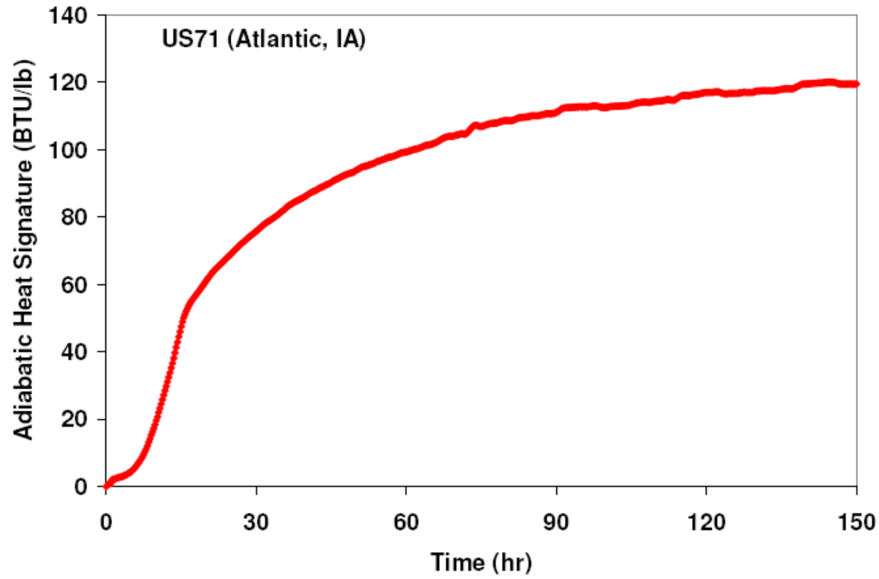


Figure 39. IQ drum test result of US 71 (Atlantic, IA) Mix 1

4.2.2 Alma Center (WI) Mixes

4.2.2.1 AdiaCal Test Results

AdiaCal calorimetry curves from all nine Alma Center (WI) mixes are shown in Figure 40. The thermal set times and the parameters related to the shape of the temperature curves of each mix are given in Table 21.

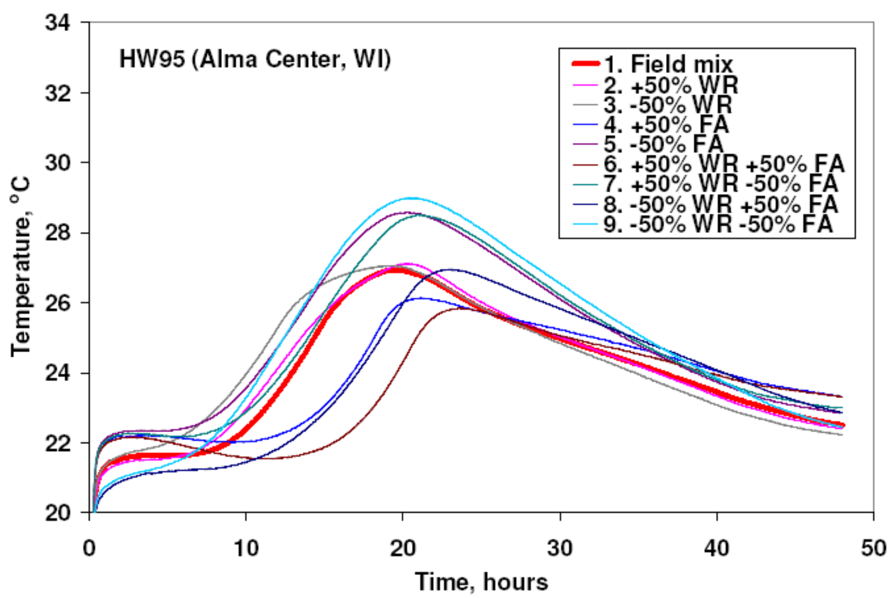


Figure 40. AdiaCal robust test results of HW 95 (Alma Center, WI) mortar mixes

Similar to the US 71 (Atlantic, IA) project, all calorimetry curves, from the mixtures with different WR dosages and FA replacement levels and under different temperatures, displayed major peaks that cover a certain area under the peaks, which indicates that there is no incompatibility problem in the concrete mixtures in the ranges of WR and FA applied.

The results illustrate that the initial thermal set times are between 11.8 hours and 20.5 hours, while the final setting thermal set times are between 19.6 hours and 23.6 hours. The initial and final thermal set times from the original field mix and the maximum and minimum set times from the mixes with different levels of WR and FA obtained from the AdiaCal curves were summarized in Figure 41. Similar to what observed in the US 71 Atlantic (IA) project, the variation of the initial thermal set times of these mixtures from the AdiaCal tests is much larger than the variation of the final thermal set times. In other words, the amount of WR and/or FA has more impact on the initial set than on the final set of the mixtures.

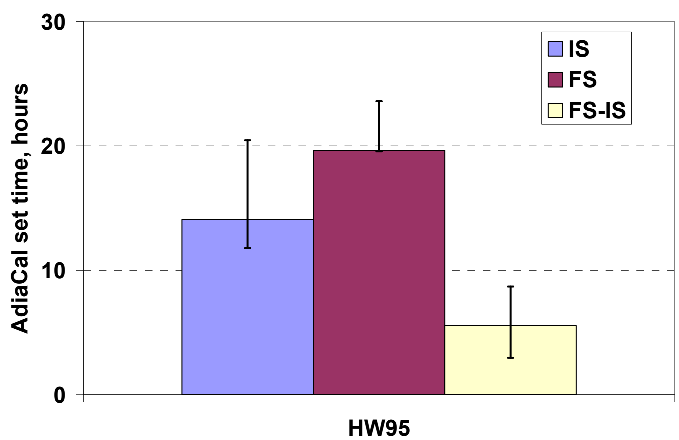


Figure 41. Estimated set time from HW 95 (Alma Center, WI) AdiaCal robust test

The areas under the temperature-time curves within different time periods were also analyzed and the results are shown in Figure 42. The figure illustrates that similar to the results found in the US 71 project, the areas under the calorimeter curves increased within the first 24 hours, which indicated that more heat is generated through time. Also, approximately the same amount of heat was generated in the first and second day.

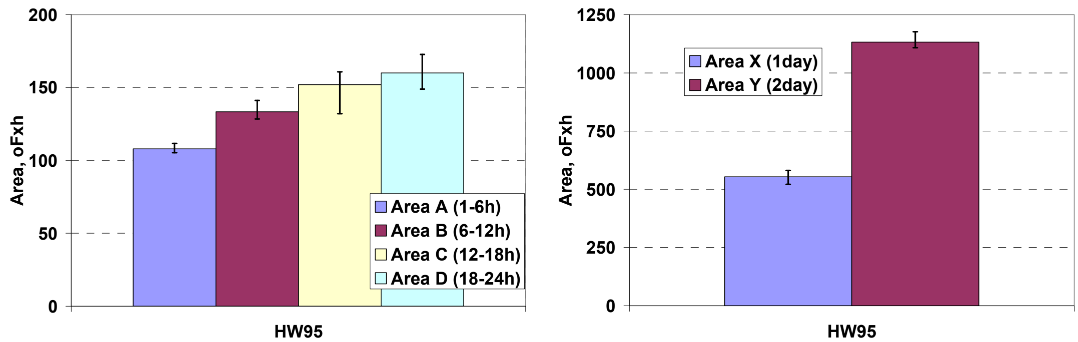


Figure 42. Areas under HW 95 (Alma Center, WI) AdiaCal test curves during different test period

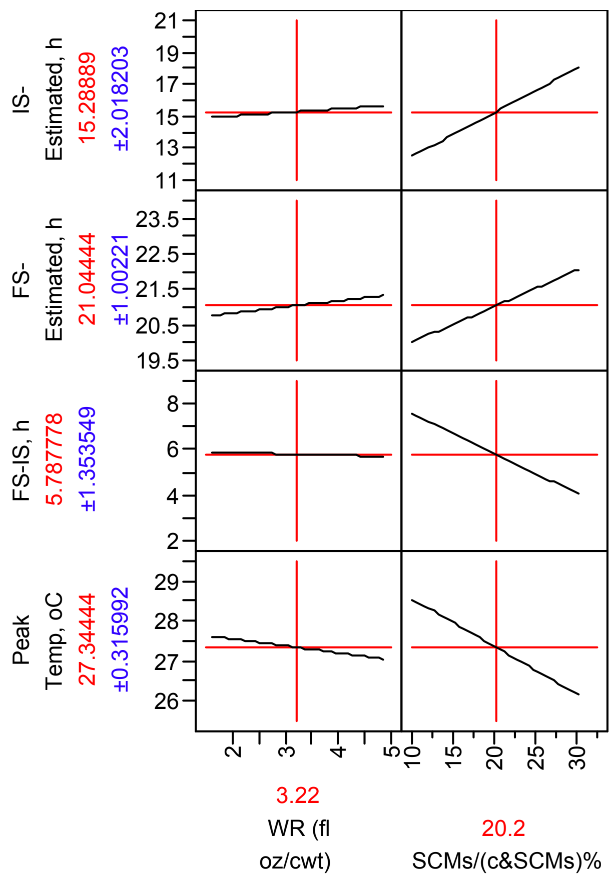


Figure 43. Statistical analysis from the HW 95 (Alma Center, WI) AdiaCal robust test

Statistical analyses were also performed to study the effect of the amount of WR and FA replacement on the initial and final thermal set time, the mortar setting window (FS-IS), and peak temperature of AdiaCal tests. As shown in Figure 43, initial and final thermal set time both increase with the level of WR and FA replacement. The peak temperature from the AdiaCal test reduced with the FA replacement and WR dosage. However, the effects of FA replacements on these thermal parameters are more significant than that of WR. The figure also suggests that the setting window reduced with the increased FA replacement levels, while no obvious effects from WR were found. The peak temperature from the AdiaCal test reduced with the FA replacement and WR dosage.

4.2.2.4 Isothermal Calorimetry Test

Isothermal calorimetry tests were performed at four different temperatures (5°C, 20°C, 30°C, and 40°C), where 5°C instead of 10°C was used in the study of Alma Center (WI) mixes due to the weather conditions of the project location. Similar to what was used for the US 71 Atlantic (IA) project, the rate of heat generation of the mortar was tested for 72 hours at the testing temperature of 5°C, 48 hours at the testing temperature of 20°C, and 24 hours at the testing temperatures of 30°C and 40°C. Figure 44 shows that the initial thermal set times increased from 7.2 hours to 25.1 hours, while the final thermal set times increased from 9.3 hours to 34.5 hours when the testing temperature dropped from 40°C to 5°C.

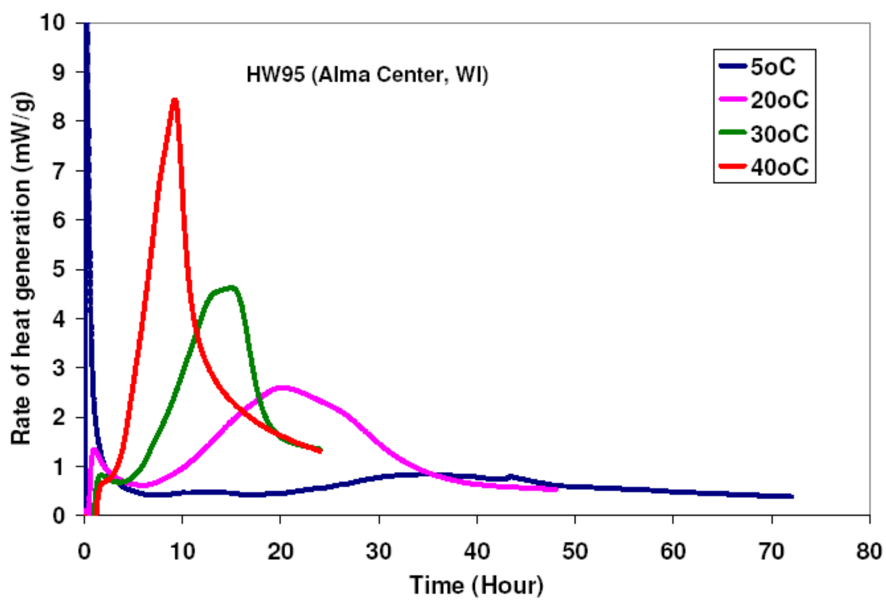
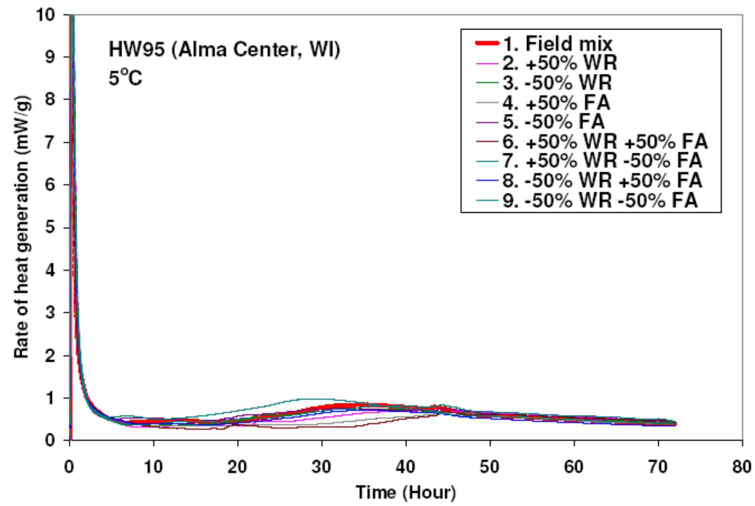
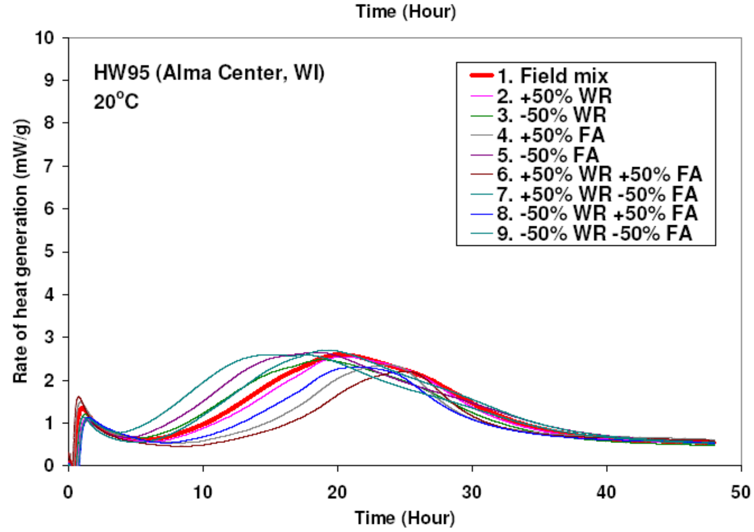


Figure 44. Isothermal test results of HW 95 (Alma Center, WI) mortar mix 1 at different temperatures

At the test temperature 20°C and above, all calorimetry curves, from the mixtures with different WR dosages and FA replacement levels, displayed a regular calorimetry curve shape and possess a certain peak height and width, which indicates that there is no incompatibility problem in the concrete mixtures in the ranges of WR and FA applied. However, the low heat generation at 5°C testing temperature might indicate prolonged set time and potential construction problems.

The heat generation curves of all nine mixes of the Alma Center (WI) project tested at four different temperatures (5°C, 20°C, 30°C, and 40°C) are shown in Figure 45. The thermal set time and the area under heat generation curves at different time periods of each mix are presented in Tables 27–30.





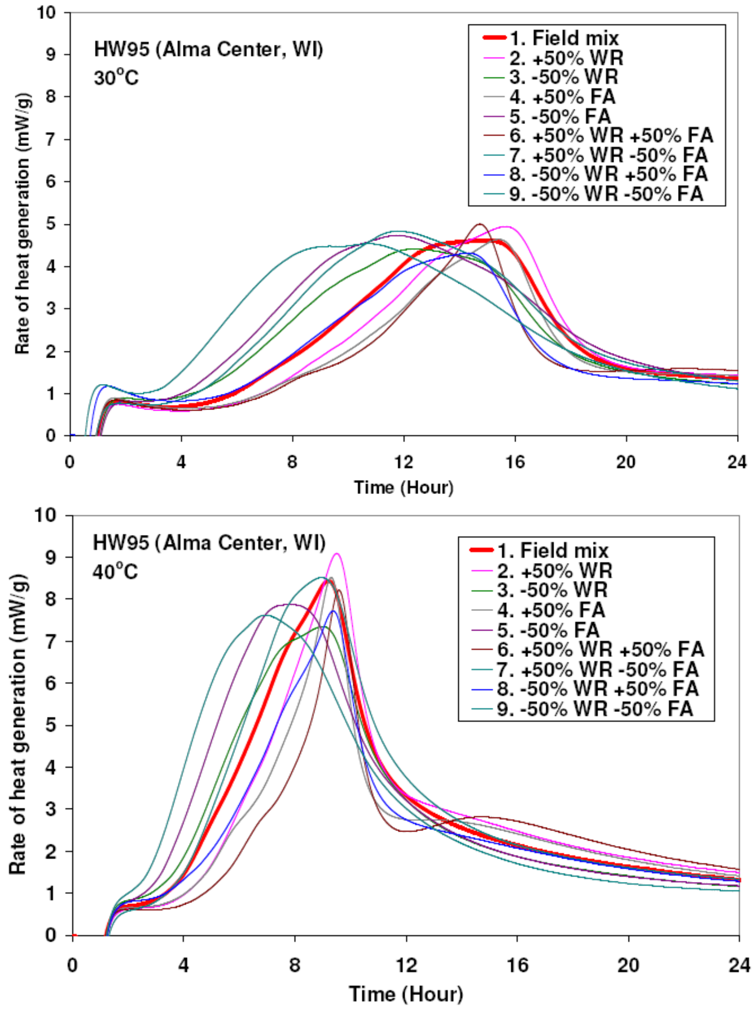


Figure 45. Isothermal test results of HW 95 (Alma Center, WI) mortar mixes different temperatures

The results show that the initial thermal set times of the Alma Center (WI) mixtures are between 25.1 hours and 35.3 hours at 5°C, between 13.7 hours and 19.4 hours at 20°C, between 11.8 hours and 14.2 hours at 30°C, and between 7.2 hours and 9.3 hours at 40°C. The final thermal set times are between 34.5 hours and 45.0 hours at 5°C, between 20.5 hours and 25.1 hours at 20°C, between 15.0 hours and 15.8 hours at 30°C, and between 9.3 hours and 9.7 hours at 40°C. It is noted that at the low temperature (5°C), the initial thermal set took place at approximately 24 hours, while the final thermal set can take place at almost 40 hours. There is a little strength development of the mixture during the first 72 hours after cast and cured at 5°C.

The boundaries of initial and final set from the isothermal robust tests were summarized in Figure 46. Similar to the US 71 (Atlantic, IA) project, the initial and final thermal set times and the setting time window all increased with the decrease of the environmental temperature. The variation of the thermal set time values generally decreased with the increased testing temperature. Also, unlike the AdiaCal test results, the variation of the initial thermal set time appeared not clearly different from that of the final thermal set times.

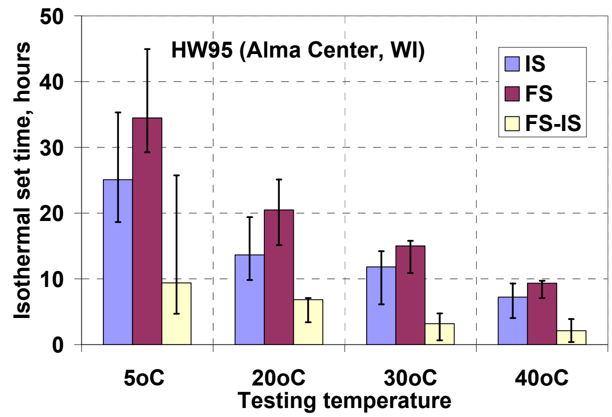


Figure 46. Estimated set time from isothermal robust test on HW 95 (Alma Center, WI) mixes

The areas under the heat-generation time curves within different time periods were also analyzed, and results are shown in Figure 47. Similar to the US 71 project, more heat was generated when the environmental temperature was higher. At low temperature (5^{o}C), the area increased with the time elapse within the first 24 hours, which indicated more heat was generated. The heat generation within 24 to 48 hours is higher than the first 24 hours after cement make contact with water. However, the heat generation will slow down after 48 hours. The larger area of the first 1–6 hours might be caused by the stabilization time of the sample, which will usually have relatively high temperature compared to the environmental temperature. With the increase of the environmental temperature, larger amounts of heat were generated at an earlier period. Heat generation reaches the peak at 6 hours–12 hours, but slows down after 12 hours or 24 hours at 40^{o}C. Results indicated high strength development at early ages when the environmental temperature is higher.

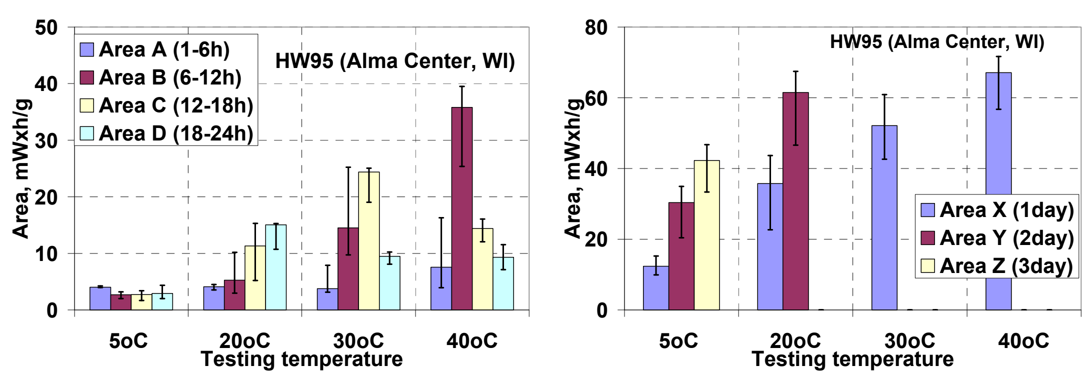


Figure 47. Heat generation from isothermal robust test mixes at different times HW95 (Alma Center, WI) mixes

Similar to the US 71 project, least squares fit was performed on the prediction of initial thermal set (IS) and final thermal set (FS), setting time window (FS-IS) and peak temperature from isothermal test using the parameters of WR dosage, FA replacement percent, and environmental temperature. According to the results as shown in Figure 48, both initial setting and final thermal set times decrease when the environmental temperature goes up, and the setting time window (from initial setting to final setting time) reduces with the increase of environmental temperature. The initial setting and final setting time both increase with the amount of WR used and the percent replacement of the FA. Environmental temperature has significant effect on the initial and final thermal set times and the peak heat generation rate. FA replacement and WR dosage do not have obvious effects on thermal set times and peak heat generation rate from the isothermal tests on HW 95 (Alma Center, WI) mixes.

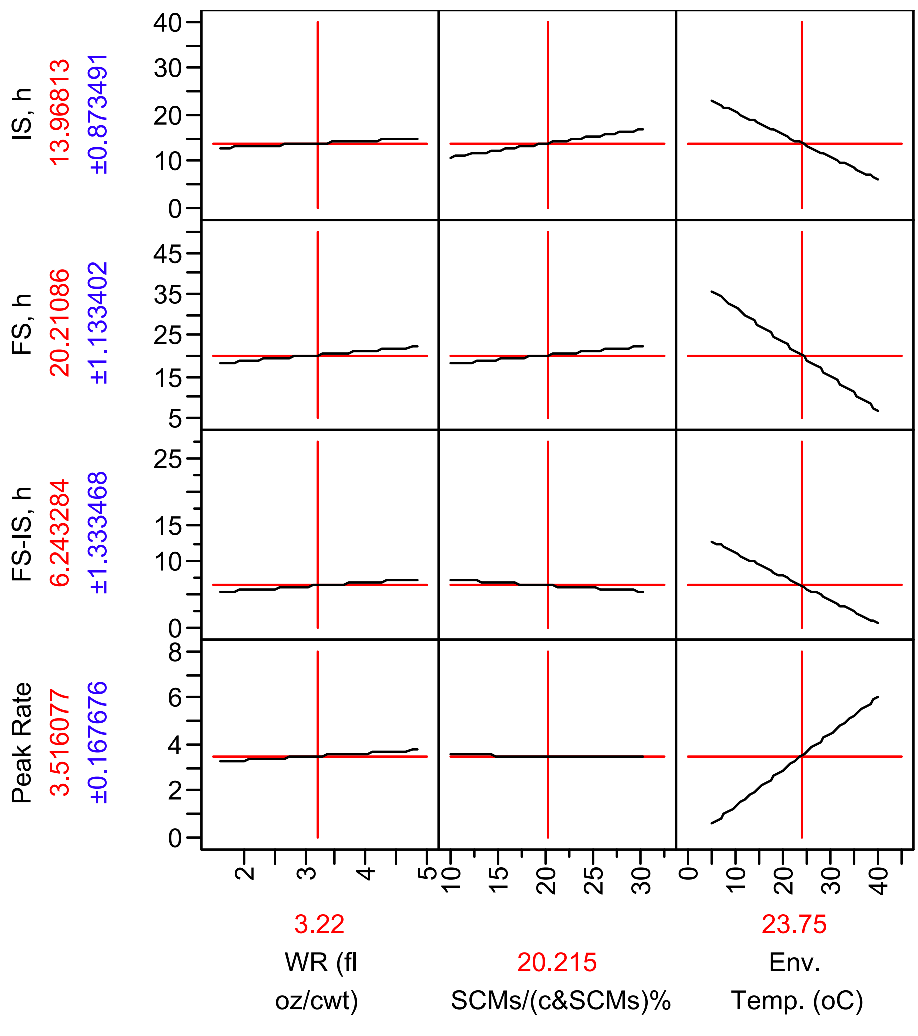


Figure 48. Effect of mix design and temperature on IS and FS from isothermal robust test HW 95 (Alma Center, WI) mixes

In addition to the above-mentioned robust tests, where a fixed low w/c of 0.45 was used, a mortar sample with a w/c of 0.30 and over-dosed air entraining agent (AEA) and WR approximately 6 times the original mixes were also studied using the isothermal calorimeter at 30°C. A potential incompatibility problem was found with this mixture (Figure 14, w/c=0.30) although it was not found in the previous robust tests (w/c=0.45). As seen in Figure 49, the first major peak of heat generation rate was delayed from approximately 12 hours to 24 hours when the w/c of the mixture decreased from 0.45 to 0.3 (with over-dosed AEA and WR). Another major hydration peak appeared at approximately 60 hours after testing, thus considerably elongating the final set time and strength development of the mixture.

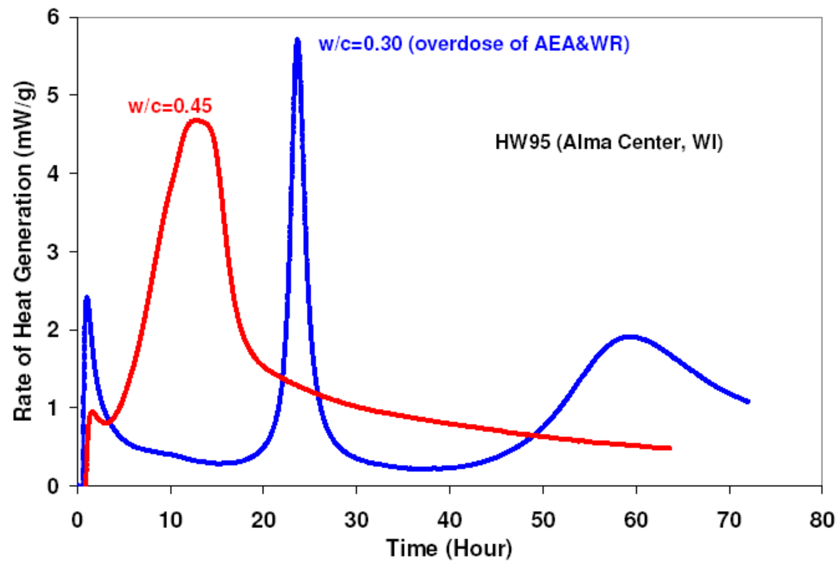


Figure 49. Isothermal test results of mortar with normal and overdosed chemical admixtures

4.2.2.5 IQ Drum Test Results

The semi-adiabatic calorimetry test results of the original Alma Center (WI) mix can be found from the IQ Drum results as shown in Figure 50. Similar to the Atlantic (IA) mix, results showed that the heat evolution was slow during the first couple hours; however, the generated heat started to increase quickly after that until about 20 hours. The heat generation rate was more stable after 20 hours. The generated heat was about 130 BTU/g cementitious materials at 150 hours, which was quite similar to the results from the field test. This indicated a very good consistency of the IQ Drum test.

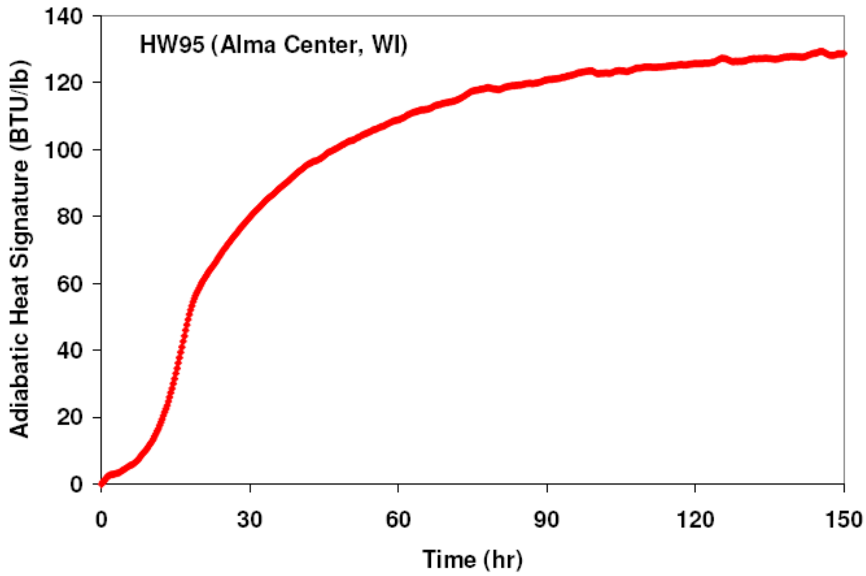


Figure 50. IQ Drum test result of the HW 95 (Alma Center, WI) concrete (Mix 1)

4.2.3 Ottumwa (IA) Mixes

4.2.3.1 AdiaCal test results

AdiaCal calorimeter was used to determine the thermal set time with the robust mix design from the materials collected from Ottumwa (IA). The temperature curves from all nine different mixes are shown in Figure 51, while the detailed information on the AdiaCal thermal set time and the areas under the temperature curves of each mix can be found in Table B.3..

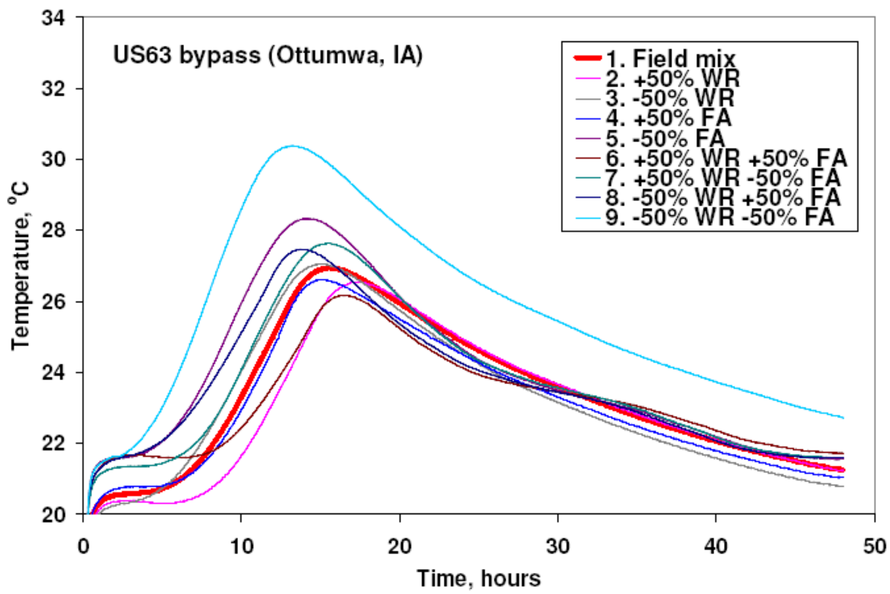


Figure 51. AdiaCal robust test results of US 63 bypass (Ottumwa, IA) concrete mixes

Similar US 71 (Atlantic, IA) and HW 95 (Alma Center, WI) projects, all calorimetry curves, from the mixtures with different WR dosages and FA replacement levels and under different temperatures, displayed major peaks that cover a certain area under the peaks, which indicate that there is no incompatibility problem in the concrete mixtures in the ranges of WR and FA applied. Results showed that the initial thermal set times are between 8.3 hours and 14.3 hours, while the final thermal set times are between 13.2 hours and 17.5 hours. The initial and final thermal set times from the original field mix and the maximum and minimum set times from the mixes with different levels of WR and FA obtained from the AdiaCal curves were summarized in Figure 52. The figure also shows that the variation of initial thermal set time is larger than that of final thermal set time. In other words, the amount of WR and/or FA has more impact on the initial set than on the final set of the mixtures.

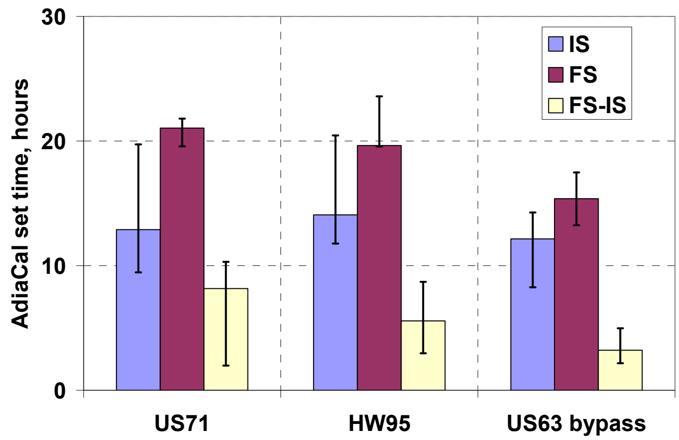
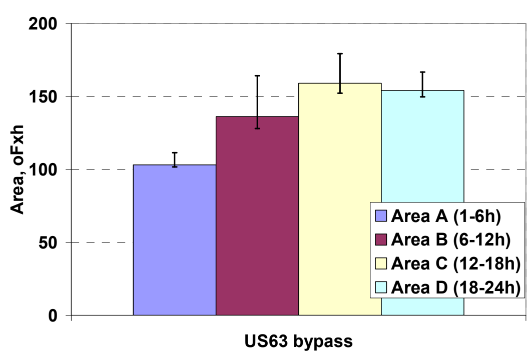


Figure 52. Estimated set time from US 63 bypass (Ottumwa, IA) AdiaCal robust test

It can be observed in the figure that concrete made with US 63 bypass (Ottumwa, IA) mix proportion and materials has early final setting time compared to concrete made with the other two field mix designs and materials; however, there is no obvious difference on the initial setting within three projects. As a result, the window of setting time (time between initial and final setting) is narrower with the materials from US 63 bypass (Ottumwa, IA).

The areas under the temperature-time curves within different time periods were also analyzed and the results (with the columns referring to the value from original field mixes and the error bars referring to the maximum and minimum values from mixes with different levels of WR and FA) are shown in Figure 53. The figure illustrates that the area under the calorimeter curves from three projects had similar trends in the first 24 hours. However, in the Ottumwa (IA) Mix 1, area D (18 hours–24 hours) reduced when compared with area C (12 hours–18 hours). This implies that the heat generation slowed down after 18 hours.



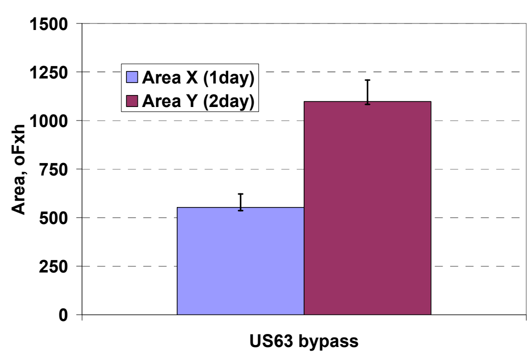


Figure 53. Areas under AdiaCal test curves of US 63 bypass (Ottumwa, IA) projects during different test period

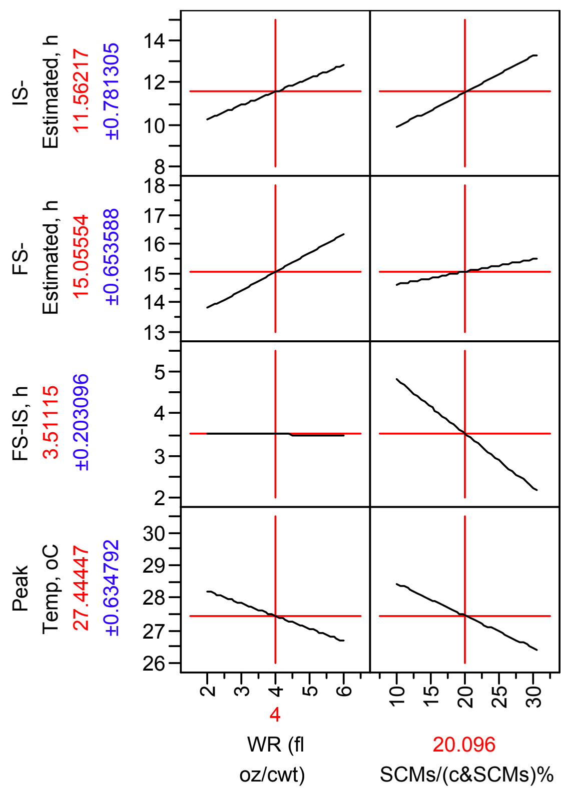


Figure 54. Statistical analysis from the US 63 bypass (Ottumwa, IA) AdiaCal robust test

Statistical analyses were performed to study the effect of the amount of WR and FA replacement on the initial and final thermal set time, the mortar setting window (FS-IS), and peak temperature of AdiaCal tests. Least square fit was performed in the analysis of these calorimeter test values. Different from US 71 and HW 95 projects, as shown in Figure 54, the effects of FA replacements and WR on the initial and final thermal set time in US 63 bypass mixes are significant. The figure also suggests that the setting window reduced with the increased FA replacement levels; however, no significant changes on the setting window were found with the changes in amount of WR. The peak temperature from the AdiaCal test reduced with the FA replacement and WR dosage.

4.2.3.2 Isothermal Robust Test Results

Similar to US 71 (Atlantic, IA) and HW 95 (Alma Center, WI) mix, the isothermal tests were performed for 72 hours at the testing temperature of 10^{o}C, 48 hours at the testing temperature of 20^{o}C, and 24 hours at the testing temperature of 30^{o}C and 40^{o}C. Figure 55 shows that with the increase of the testing temperature, the maximum rate of heat generation increases, while the time to reach this maximum rate decreases. The initial thermal set times increased from 4.1 hours to 18.5 hours when the temperature dropped from 40^{o}C to 10^{o}C. The final thermal set time increased from 5.8 hours to 25.7 hours when the temperature dropped from 40^{o}C to 10^{o}C.

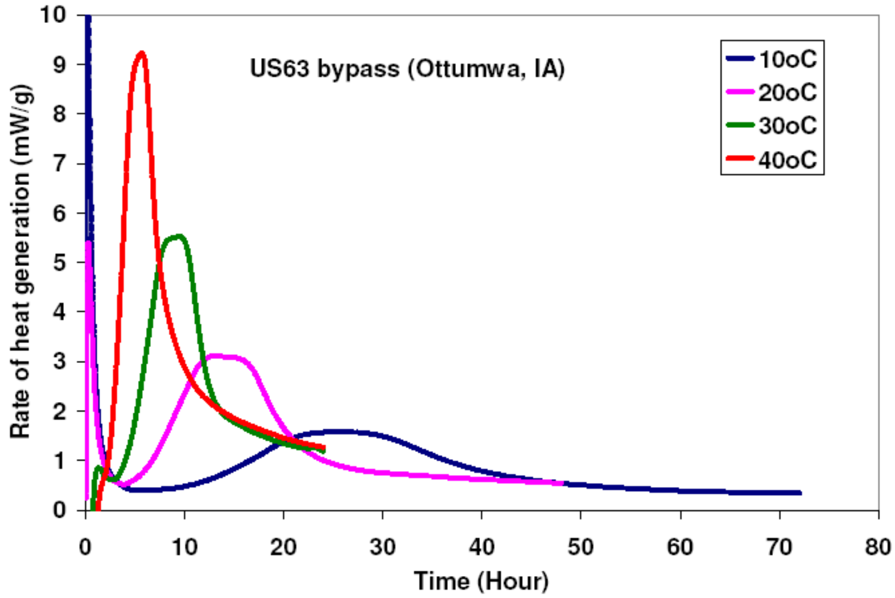


Figure 55. Isothermal test results for US 63 bypass (Ottumwa, IA) mix 1 at different temperatures

Isothermal calorimeter test results from the robust tests are shown in Figure 56. The detailed information on the thermal set time and the area under the heat generation curves during different time periods for each mix can be found in
Table C.9.–34.

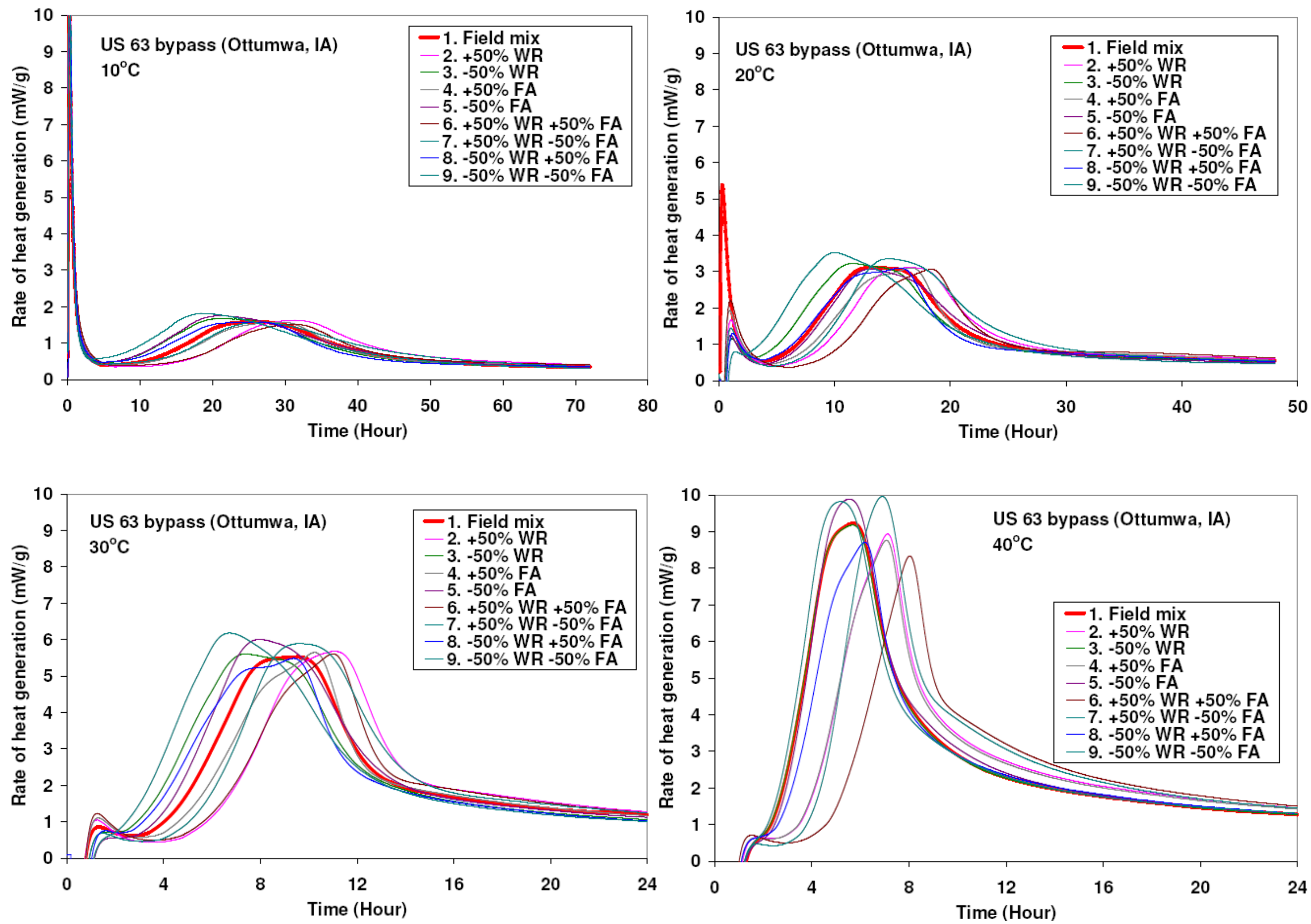


Figure 56. Isothermal robust test results of US 63 (Ottumwa, IA) mortar mixes at different temperatures

All calorimetry curves, from the mixtures with different WR dosages and FA replacement levels, displayed a regular calorimetry curve shape and possessed a certain peak height and width, which indicates that there is no incompatibility problem in the concrete mixtures in the ranges of WR and FA applied. Results showed that the initial thermal set time of Ottumwa (IA) mixes are between 18.5 hours and 22.4 hours at the test temperature of 10^{o}C, between 8.6 hours and 12.9 hours at the test temperature of 20^{o}C, between 6.9 hours and 8.2 hours at the test temperature of 30^{o}C, and between 4.1 hours and 6.9 hours at the test temperature of 40^{o}C. The final thermal set times are between 25.7 hours and 31.4 hours at the test temperature of 10^{o}C, between 13.2 hours and 18.5 hours at the test temperature of 20^{o}C, between 9.7 hours and 11.2 hours at the test temperature of 30^{o}C, and between 5.8 hours and 8.2 hours at the test temperature of 40^{o}C.

The boundaries of the initial and final thermal setting times from the isothermal robust tests were summarized in Figure 57. Results showed that the initial and final thermal set times and the setting time window all increase with the decrease of the environmental temperature. Again, the variation of the thermal set time is generally increased with the testing temperature. Similar to the US 71 (Atlantic, IA) and HW 95 (Alma Center, WI) projects, the variation of the thermal set time values generally decreased with the increased testing temperature. Also, unlike the AdiaCal test results, the variation of the initial thermal set time was not clearly different from that of the final thermal set times.

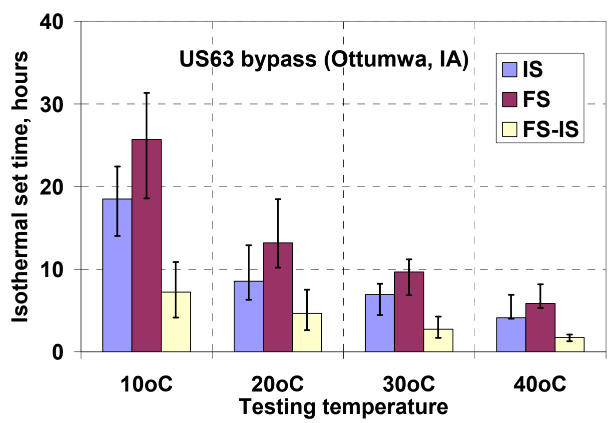


Figure 57. Estimated set time from isothermal robust test on US 63 bypass (Ottumwa, IA) mixes

The areas under the heat-generation time curves within different time periods were also analyzed. Results in Figure 58 showed that the curves from three projects showed similar trends in the first 24 hours. Generally, more heat was generated when the environmental temperature was higher. At low temperature (10^{o}C), the area increased with the time elapse within the first 24 hours, which indicated more heat was generated. However, the heat generation within 24 hours to 48 hours is higher than the first 24 hours after cement made contact with water. The heat generation was found to be earlier and higher compared to the other two projects. The heat generation slowed down after 12 hours at 30^{o}C and 40^{o}C.

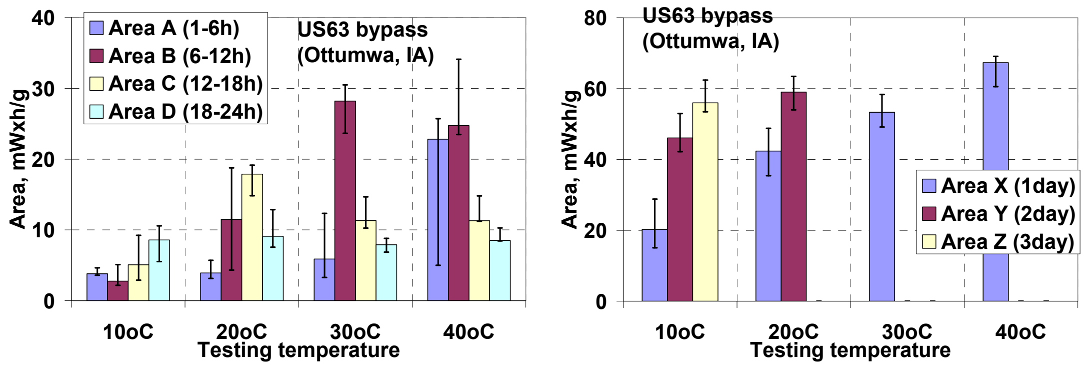


Figure 58. Heat generation from isothermal robust test mixes at different times US 63 bypass (Ottumwa, IA) mixes

Least squares fit was performed on the prediction of thermal initial set (IS) and final set (FS) time, setting time window (FS-IS) and peak heat generation from isothermal test using the parameters of WR dosage, FA replacement percentage and environmental temperature. According to the results as shown in Figure 59, similar to the finding from the other two fields, the environmental temperature has the most significant effect on the initial and final thermal set times and the peak heat generation rate. Both initial and final thermal set times decrease when the environmental temperature goes up, setting time window (from initial setting to final setting time) also reduces with the increase of environmental temperature. The initial setting and final setting time both increase with the amount of WR used and the percent replacement of the FA. The setting time window can be reduced, increased or no obvious change with the increase of percentage replacement of FA and WR, depending on the change on initial and final thermal set times. FA replacement and WR dosage do not have obvious effects on peak heat generation rate from the isothermal test.

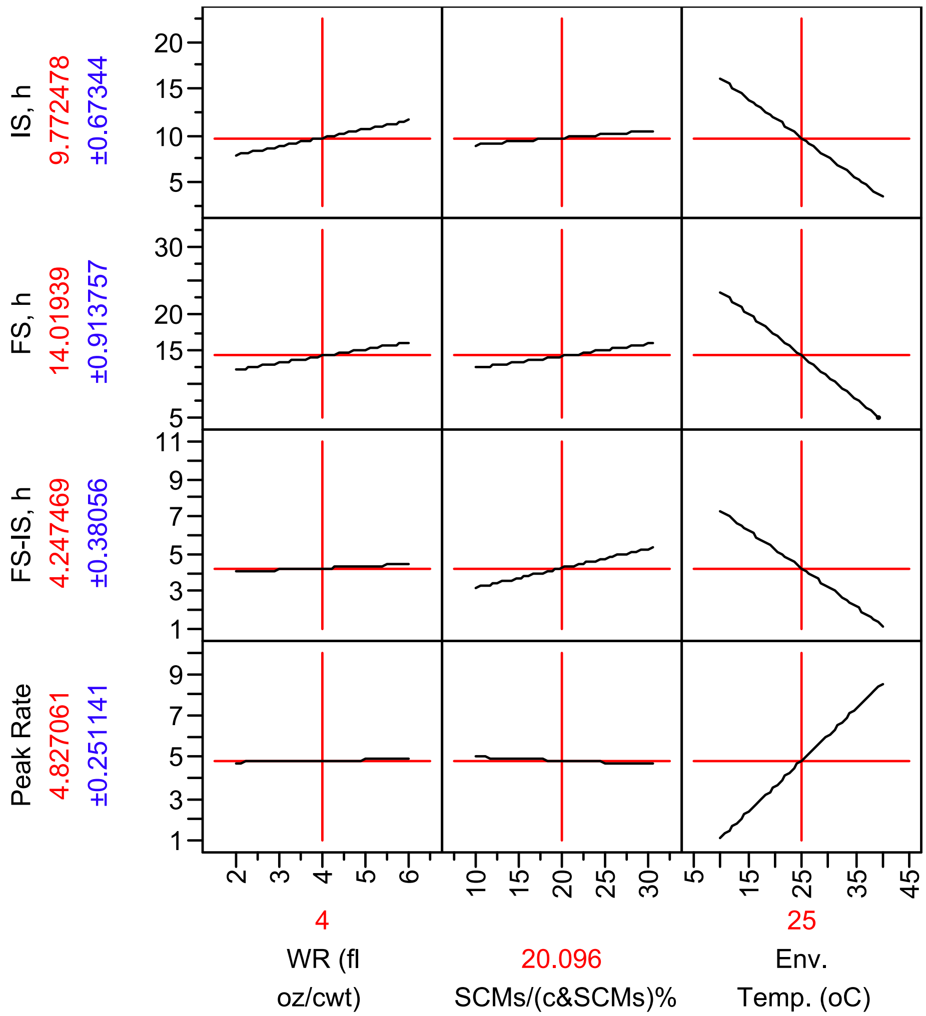


Figure 59. Effect of mix design and temperature on IS and FS from isothermal robust test (US63 bypass (Ottumwa, IA) mixes)

4.2.3.2 IQ Drum Test Results

The semi-adiabatic calorimetry test result is shown in Figure 56. The generated heat was about 130 BTU/g cementitious materials at 150 hours, which was quite similar to the result from the field test. This indicated a very good consistency of the IQ Drum test.

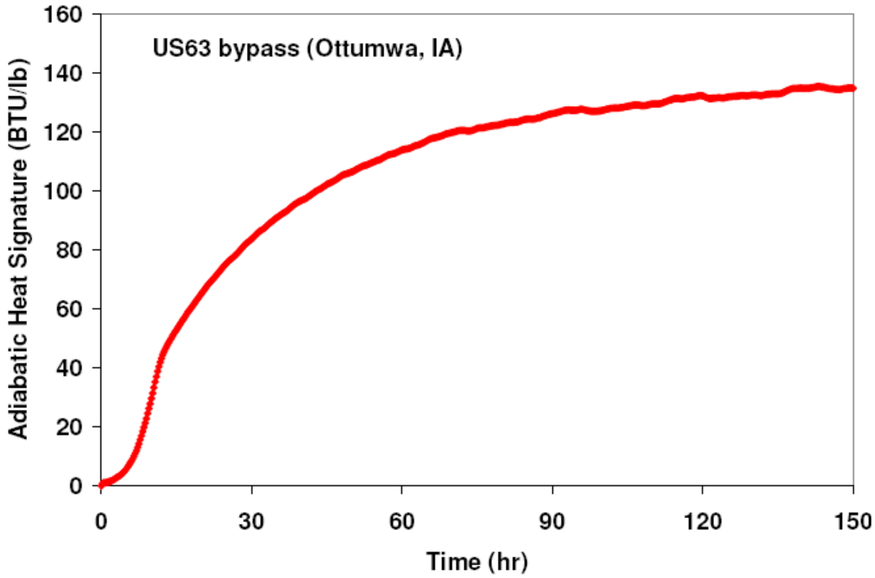


Figure 60. IQ Drum test result of US 63 bypass (Ottumwa, IA) Mix 1

4.2.3.3 ASTM C403 Set Time Test Results

The relationships between thermal set times and ASTM C403 set times have been studied previously. Here is another verification of the relationships. Only the materials collected from Ottumwa (IA) were tested using the ASTM C403 method. The initial and final set times of the nine mixes used for the isothermal robust tests were tested and the results are shown in Table 13.

Table 13. ASTM set time result from robust test (US 63 (Ottumwa, IA) mixes)

Robust mix number	1	2	3	4	5	6	7	8	9
ASTM initial setting (hr)	7.8	9.3	6.5	8.3	6.7	9.3	8.3	8.4	5.8
ASTM final setting (hr)	10.1	11.7	8.8	10.9	8.9	14.6	11.0	10.6	8.2

The results show that the initial set time of the mixes is between 5.8 hours and 9.3 hours, while the final set times are between 8.2 hours and 14.6 hours. Statistical analysis was performed in order to study the effect of the amount of WR and FA replacement on the ASTM initial and final setting. According to the results as shown in Figure 61, the initial setting and final setting time increase with the amount of WR used and the percent replacement of the FA. Also, the setting time window (from initial setting to final setting time) increased with the increase of percentage replacement of FA and WR.

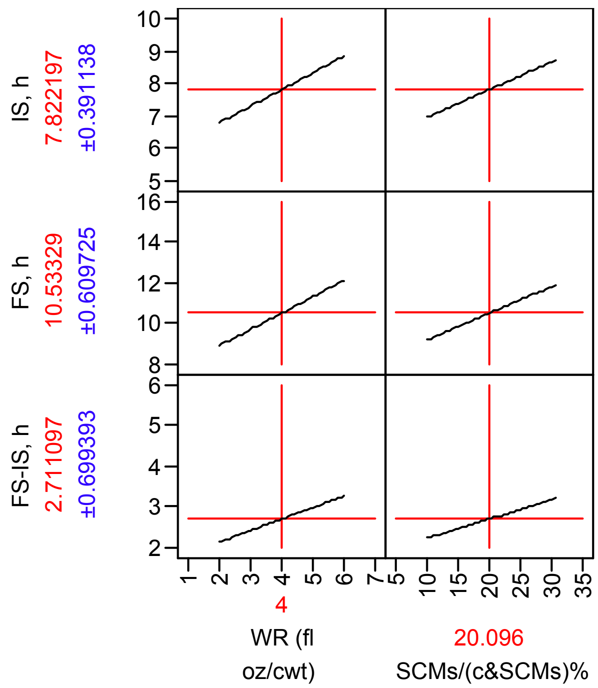


Figure 61. Effect of mix design on ASTM setting time US63 bypass (Ottumwa, IA) mixes

4.3 Comparison of Lab Test Results from Different Projects

4.3.1 AdiaCal Tests

As mentioned previously, AdiaCal semi-adiabatic calorimetry tests were performed with materials collected from all three projects at room temperature. The results from Mix 1 (the original field concrete mix proportion) tests of the three projects are summarized in Figure 62. Similar to the results from field site tests, concrete samples made with Ottumwa (IA) materials reach peak temperature earlier than samples made with Atlantic (IA) and Alma Center (WI) materials. However, the differences in the peak temperatures of these three mixes are not significant.

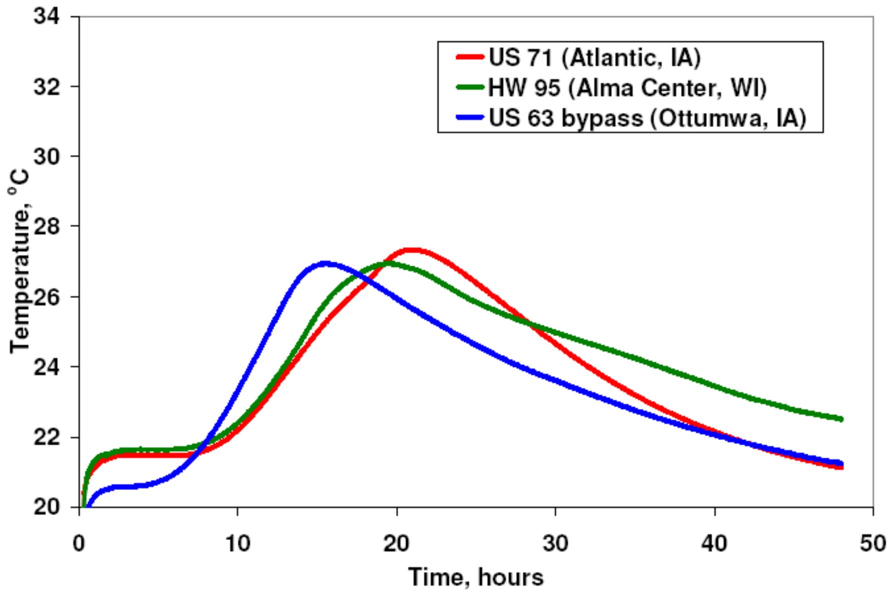


Figure 62. AdiaCal calorimetry results from different projects (Mix 1)

4.3.2 Isothermal Tests

Isothermal robust calorimetry tests were performed with materials collected from all three projects at four different temperatures. The rate of heat generation curves of samples with three original mix designs are summarized in Figure 63. It is found that similar shapes of heat generation curves were presented at all different temperatures. Similar to the results from the field test, samples made with Ottumwa (IA) materials reached peak heat of generation rate earlier than samples made with Atlantic (IA) and Alma Center (WI) materials. Also, the peak rate of heat generation is slightly higher. The results are consistent with the finding from AdiaCal tests.

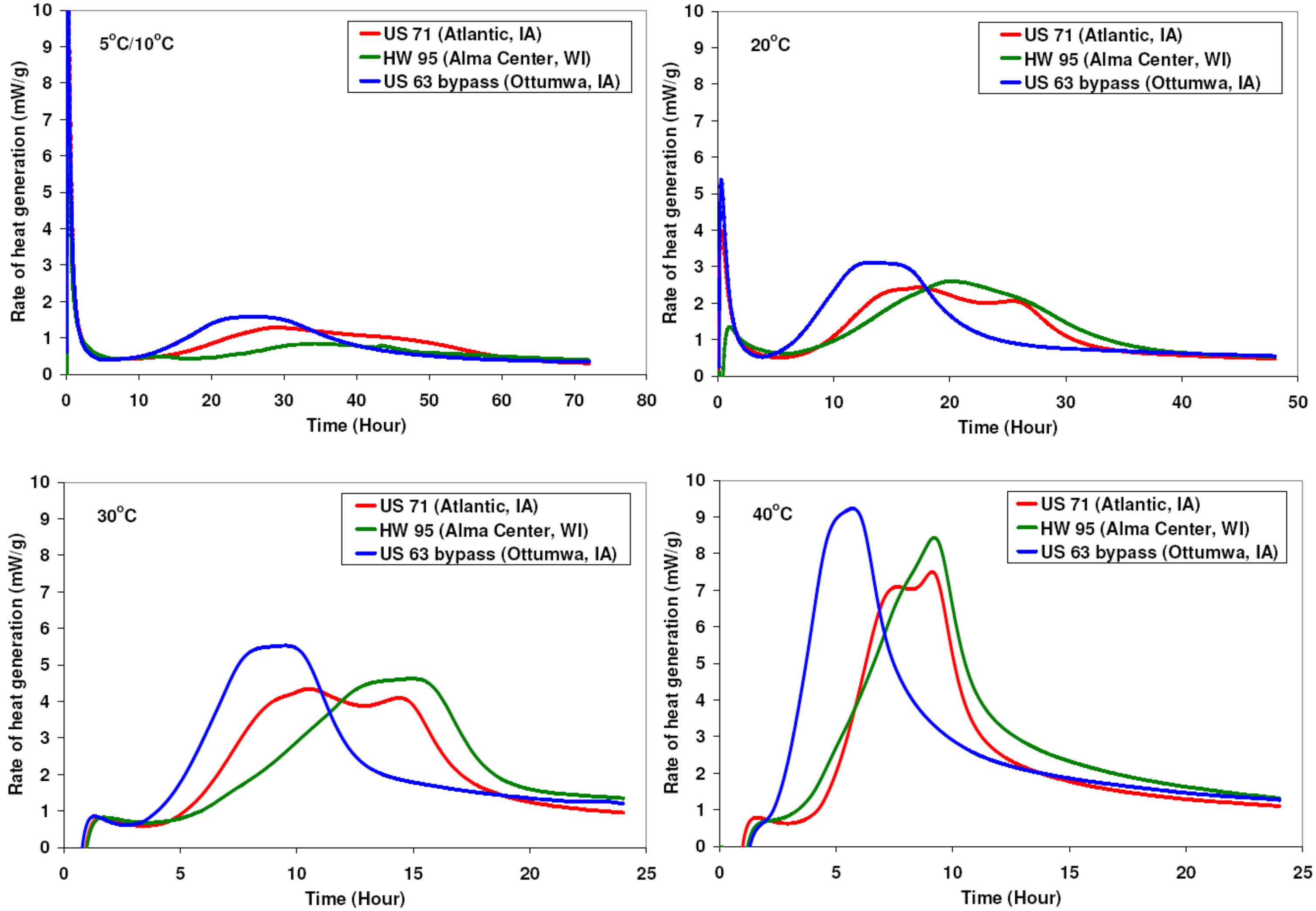


Figure 63. Isothermal test results of mortar mix 1 of three projects at different temperatures

4.3.3 Set Time Results Comparison

Thermal set time from the AdiaCal thermometry test and isothermal thermometry at 20°C was compared. As shown in Figure 64, thermal set time from both tests are generally in agreement. Similar results were found from the thermal set time from the AdiaCal and isothermal calorimetry tests. The thermal set times from nine Ottumwa mixes were also compared with ASTM 403 set times. As shown in Figure 65, results from both tests are generally in agreement with the ASTM test results. However, the relationship is not as good as it was found to be from the field test. The relative big variation may be caused by the difference of concrete and mortar mixing and the bigger variation of the WR dosage and the FA replacement.

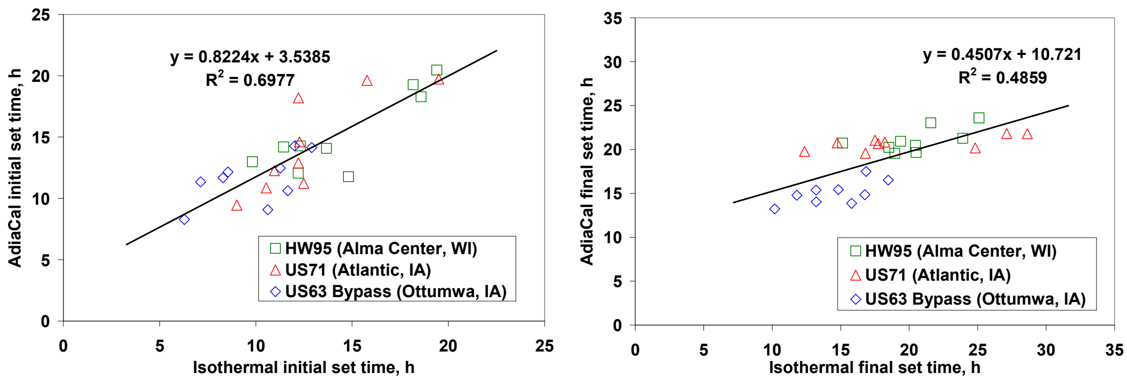


Figure 64. Comparison of isothermal and AdiaCal set time results

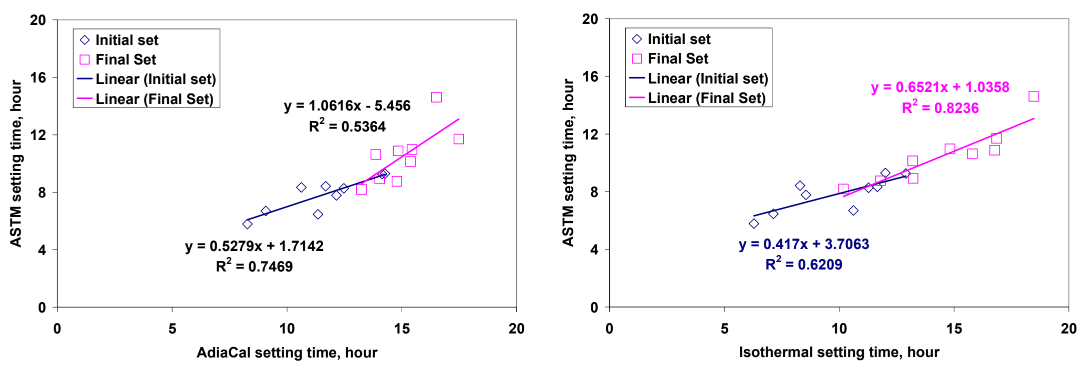


Figure 65. Comparison of ASTM and thermal set time results

5. HIPERPAV PREDICTION OF CONCRETE PERFORMANCE

In this section, a procedure for characterizing the hydration curve from both isothermal and semi-adiabatic test data is presented. As a result of the procedure, heat of hydration parameters for a mixture can be ascertained and used as inputs in the HIPERPAV software to predict performance of concrete containing the same mixture.

5.1 Introduction

Under adverse environmental conditions, concrete pavements may be affected by large temperature differentials and moisture loss resulting in premature cracking. HIPERPAV is a software product developed for the Federal Highway Administration (FHWA) to serve as a tool in the identification and control of the numerous factors affecting concrete pavement behavior at early ages. HIPERPAV assesses concrete behavior within the first 72 hours based on materials used for the mix, design parameters, weather conditions, and curing techniques. HIPERPAV directly considers the effects of: temperature development in concrete, creep, relaxation, drying, thermal, and autogenous shrinkage. A detailed description of HIPERPAV can be found elsewhere (5,6,7,8).

HIPERPAV predicts the temperature and moisture development in concrete pavements as a function of hydration and climatic conditions. Temperature and moisture changes result in stress development in the slab and are related to the development of strength. If stresses are higher than strength, cracking is likely to occur.

The results from the HIPERPAV analysis can be used for concrete quality control, optimization of pavement designs, prediction of pavement performance, and to help contractors manage the temperature of concrete based on the concrete mixture designs and specific climate and project conditions. The proposed study will facilitate applications of both the HIPERPAV program as well as calorimeter tests in the concrete pavement industry.

Currently, the HIPERPAV program predicts the concrete temperature development (heat evolution) based on materials' properties including cement characteristics (from a database of the chemical compositions of cements and cementitious materials), type of admixtures used, aggregate thermal properties, and concrete mixture proportions. In HIPERPAV, concrete heat evolution is fundamental for the prediction of the pavement concrete set time, strength, and stress development during the early age. In this project, a method to characterize heat evolution from calorimetry test data was evaluated and the HIPERPAV program was modified to use this information as an alternate method to improve reliability of the HIPERPAV analysis. (That is, in this project, the HIPERPAV program was modified to include the inputs for characterization of the heat evolution of concrete mixtures. Thus, users will have the ability to directly enter heat evolution parameters obtained from a calorimetry test for the concrete strength and stress analysis.)

To understand the evaluation of the method to characterize heat evolution and how it is incorporated into HIPERPAV, it is important to first understand the basics of activation energy.

5.2 Activation Energy

Activation energy (E_a) is the minimum amount of energy required for a material to undergo a chemical reaction. A cement's E_a is a critical material parameter in evaluating its hydration characteristics. Therefore, it is computed in this section and will be utilized in the hydration study presented later.

5.2.1 Method to Determine Activation Energy

Different methods for computing E_a include ASTM C1074 from strength testing—both an incremental method and a linear approximation method (*10*)—and it can also be derived from the Arrhenius equation. For the purpose of this research project, E_a was computed based on the Arrhenius equation and isothermal test results as follows (*11*).

Step 1: Locate a maximum rate of heat evolution $P_{\max}$ (W/g) for each test temperature (T_1, T_2, T_3, and T_4) from the isothermal test results, as shown in Figure 66. It is regarded that $P_{\max}$ would happen at the same heat state Q (J/g) for different test temperatures of the same material (*12*), and thus these peak points are utilized for computing E_a .

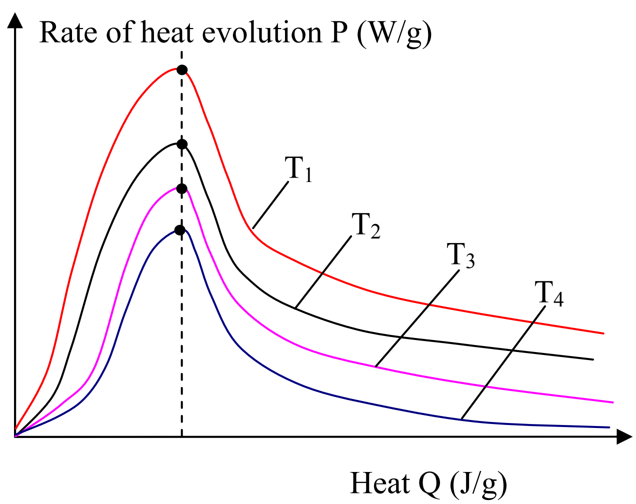


Figure 66. Locate maximum hydration rate

Step 2: Determine a liner relationship between the natural-logarithmic-scaled $P_{\max}$ and the inverse of temperature (K). The Arrhenius equation, a formula accounting for the rate of temperature-dependent chemical reaction (here it is referred to as the rate of heat evolution), is defined as follows:

$$P(T) = Ae^{-\frac{E_a}{RT}} \quad (5\text{-}1)$$

where A = the pre-exponential factor
T = temperature (K)
R = gas constant (8.3144 J/mol/°C)

The natural-logarithmic scale is applied to both sides of equation 5-1:

$$Ln[P(T)] = Ln(A) - \left(\frac{E_a}{R}\right)\frac{1}{T} \quad (5\text{-}2)$$

Equation 5-2 shows that the *Ln*(*P(T))* follows a linear function with *1/T*.

Therefore, the activation energy can be determined from the slope of this linear function:

$$E_a = RT \cdot Log\frac{A}{P} \quad (5\text{-}3)$$

The slope of the linear relationship $\frac{-E_a}{R}$ can be achieved from the isothermal test results of P versus T, as shown in Figure 67 (at least two temperature points are needed to determine a slope).

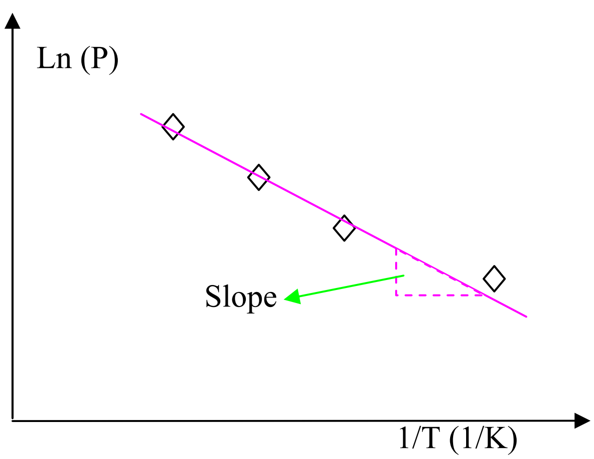


Figure 67. Determine a linear relationship

5.2.2 Results of Activation Energy

The isothermal test results at four temperatures of cement mortar from three sites (Alma Center, Atlantic, and Ottumwa) were utilized to compute E_a. The natural-logarithmic-scaled *P* values versus *1/T* values are presented in Figures 68–70. The values indicate a linear function. Subsequently, E_a is calculated using the slope of those linear functions based on the method described in section 5.1.1, and the results are reported in Table 14 and Figure 71.

These calculated E_a using this approach range from 41,581 J/mol to 52,664 J/mol, which are close to those values reported by other researchers. E_a ranges from 30,000 J/mol to 62,000 J/mol based on the strength testing (*13*). E_a ranges from 33,500 J/mol to 41,000 J/mol (*12*).

The results show mixtures used at the Alma Center have the highest E_a, then Atlantic and Ottumwa. The addition of a WR improves E_a (sample 2 compared to 1), and vice versa (sample 3 compared to sample 1). Adding FA (reducing cement) slightly increases the E_a (sample 4 compared to sample 1). Sample 9 has the lowest E_a (Sample 1–50% WR, 50%–FA).

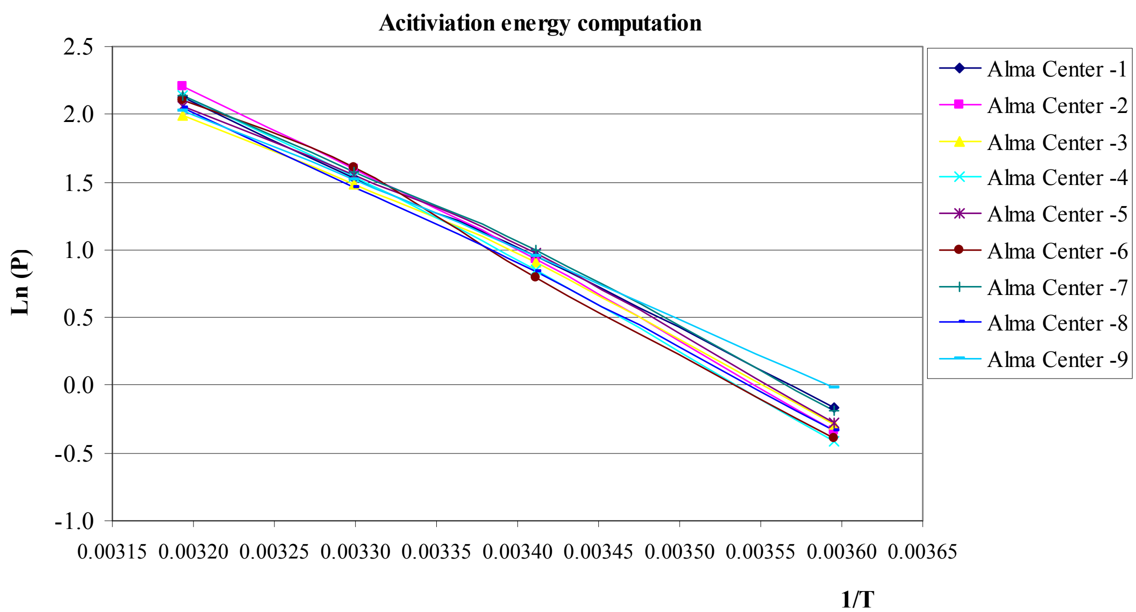


Figure 68. Activation energy calculation for AlmaCenter site (nine mixes, at four temperatures: 5 °C, 20 °C, 30 °C, and 40°C; P unit: mW/g; T unit: K).

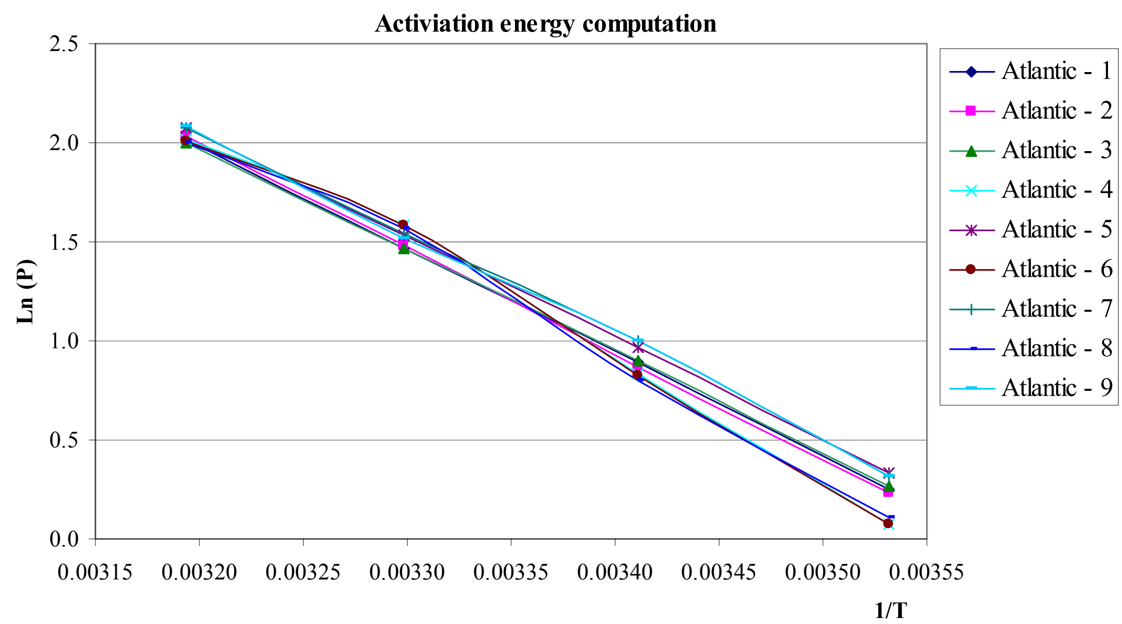


Figure 69. Activation energy calculation for Atlantic site (nine mixes, at four temperatures: 10 °C, 20 °C, 30 °C, and 40°C; P unit: mW/g; T unit: K).

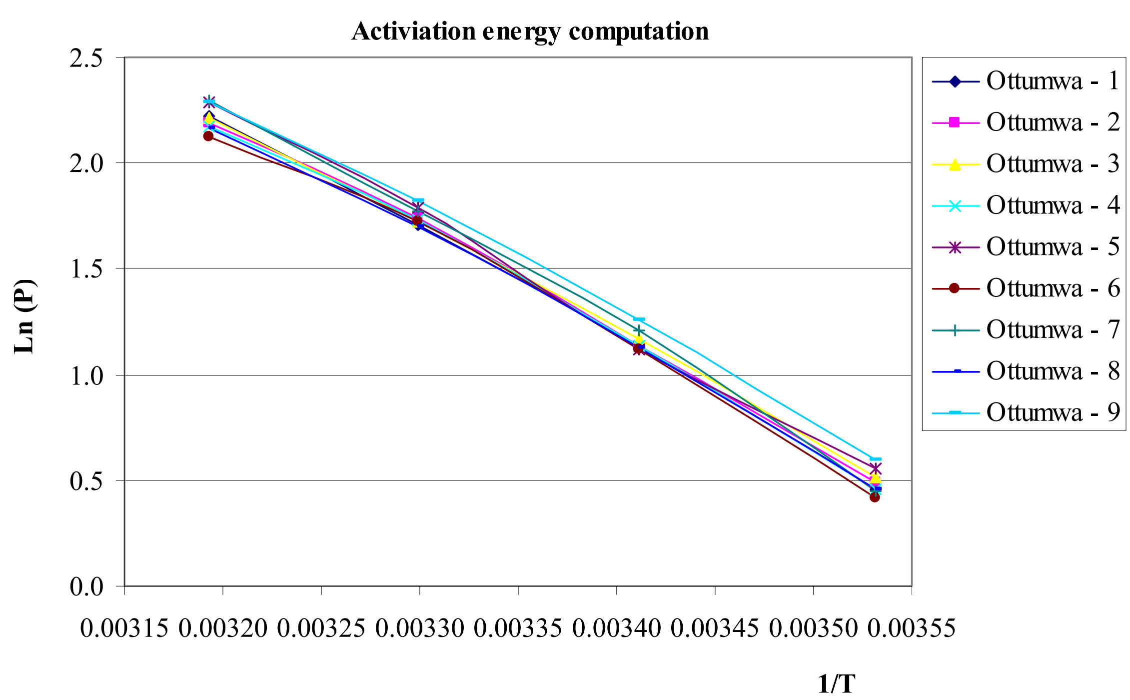


Figure 70. Activation energy calculation for Ottumwa site (nine mixes, at four temperatures: 10 °C, 20 °C, 30 °C, and 40°C; P unit: mW/g; T unit: K)

Table 14. Calculated activation energy (Unit: J/mol).

Sample site	1	2	3	4	5	6	7	8	9
Ottumwa	43227	42160	41805	42414	43250	42212	45072	42021	41581
AlmaCenter	47386	52664	47285	52930	48640	52599	48015	49288	42429
Atlantic	43344	44378	42587	48643	42643	48467	42842	47527	42794

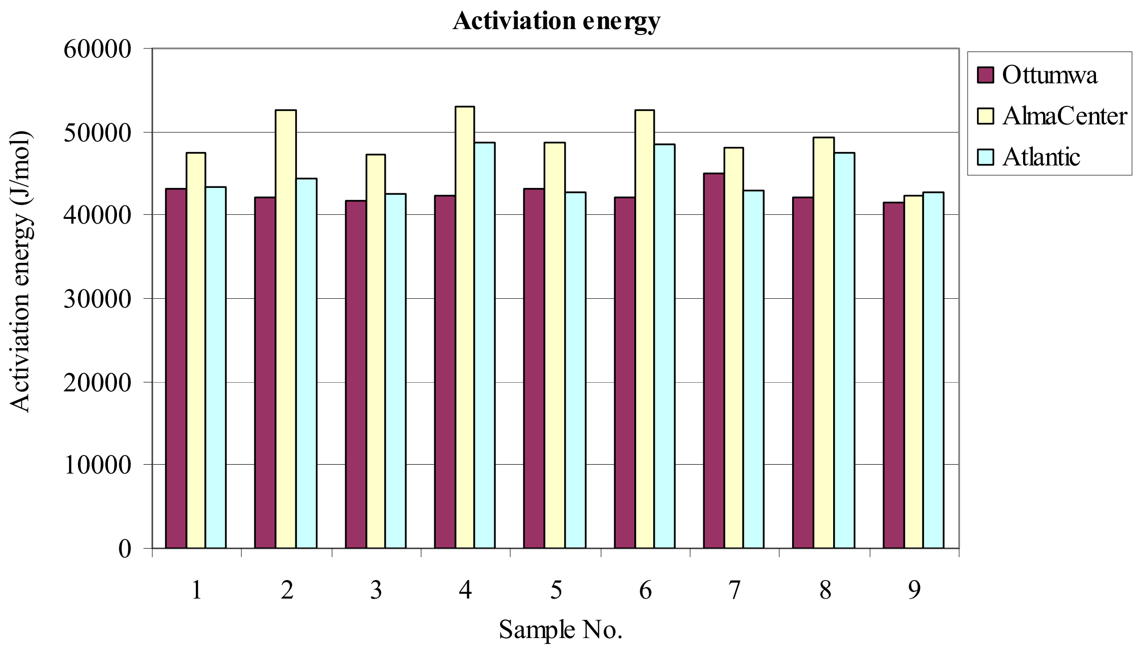


Figure 71. Calculated activation energies for nine mixes at three sites based on the isothermal test results

5.3 Hydration Curve Parameters Based on Isothermal Test

The rate of heat evolved during cement hydration is called degree of hydration (DOH). The hydration curve parameters are used to characterize DOH and compute the heat evolution of cementitious materials. In this section, the hydration curve parameters of cement mortar are computed based on the isothermal test results, as detailed in the following.

5.3.1 Computation Approach

The degree of hydration can be determined according to the generated heat and total heat at a specific point in time (*12*):

$$\alpha(t) = \frac{Q(t)}{H_u} \tag{5-4}$$

where $Q(t)$ is the accumulated heat evolved at the time t during the hydration procedure and H_u is the total heat of the specific cementitious material.

$H(u)$ is determined using the following equation (*7*):

$$H(u) = H_{cem} \cdot p_{cem} + 461 \cdot p_{slag} + 1800 \cdot p_{FA-Cao} \cdot p_{FA} \tag{5-5}$$

The time t is usually converted to an equivalent age that expresses the maturity of cementitious material during the hardening procedure. The well-known equivalent age formula (9) is adopted in this research:

$$\Delta t_e(T_r) = e^{-\frac{E_a}{R} \cdot \left(\frac{1}{T_c} - \frac{1}{T_r}\right)} \cdot \Delta t \tag{5-6}$$

Where, T_c = the temperature (K),
T_r = the reference temperature,
E_a = activation energy that is computed in section 5.2.

The following equation to characterize cement hydration is utilized (*9*):

$$\alpha(t_e) = \alpha_u \cdot \exp\left(-\left[\frac{\tau}{t_e}\right]^{\beta}\right) \tag{5-7}$$

Where,
$\alpha(t_e)$ = degree of hydration at equivalent age, t_e,
t_e = equivalent age at reference temperature (21.1°C), (hrs),
α_u = ultimate degree of hydration,
τ = hydration time parameter (hrs), and
β = hydration shape parameter.

A larger α_u indicates a higher DOH (Figure 72), and a larger τ implies a larger delay of hydration (Figure 73). The slope of the major linear part of the hydration shape is represented by β; a larger β implies a higher hydration rate (Figure 74).

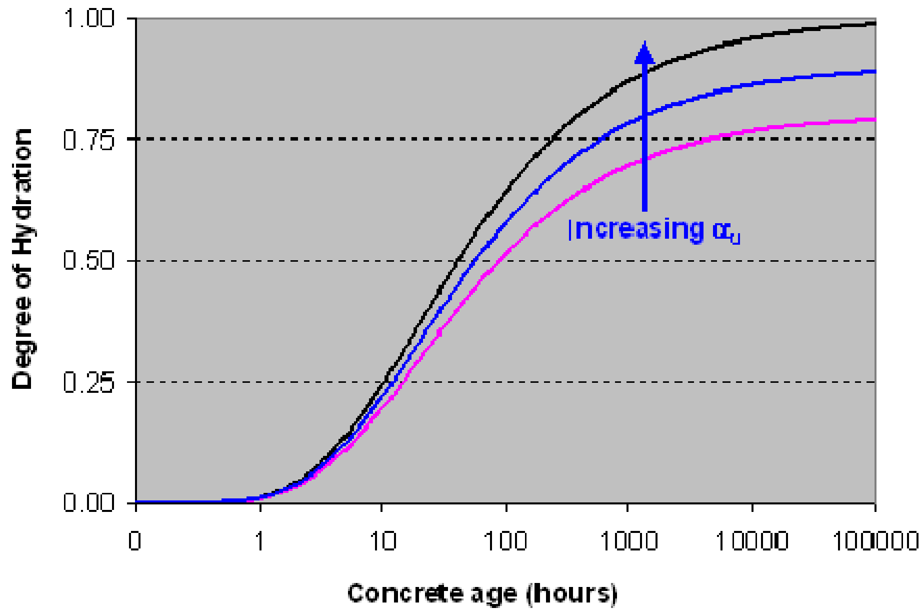


Figure 72. Influence of hydration curve parameter α_u on degree of hydration

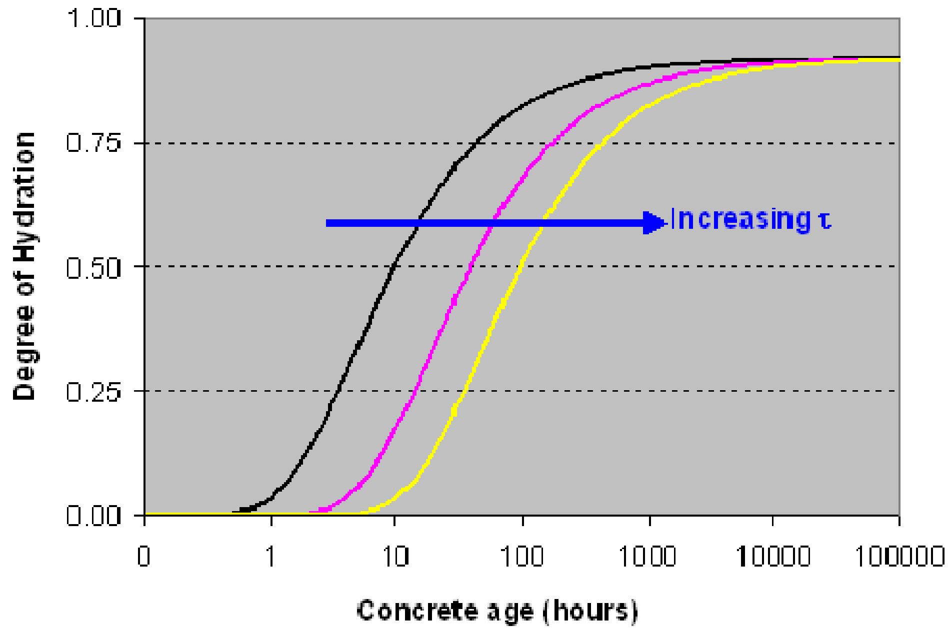


Figure 73. Influence of hydration curve parameter β on degree of hydration

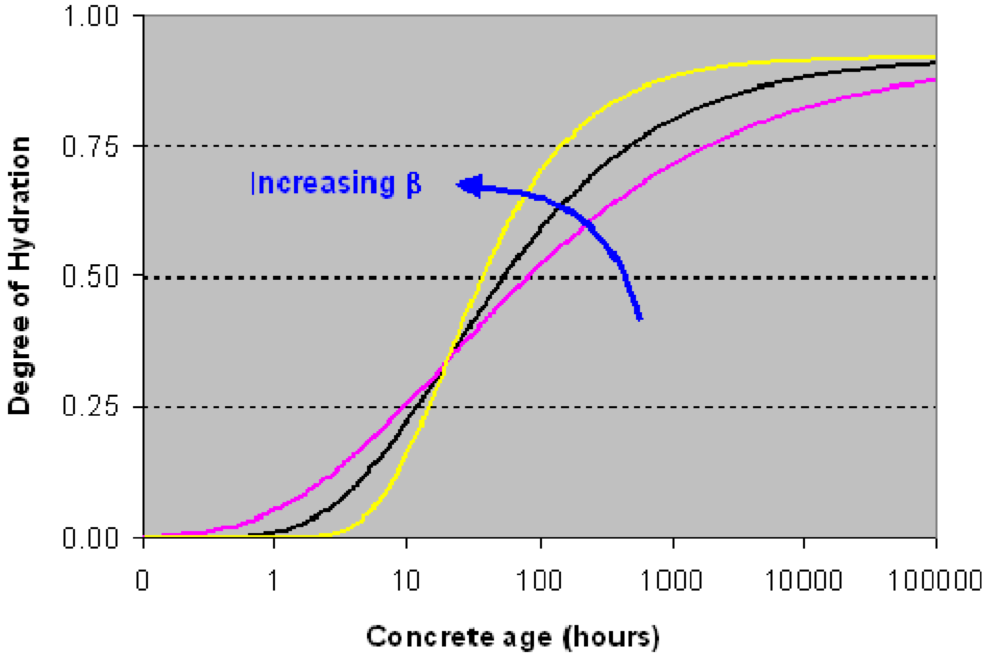


Figure 74. Influence of hydration curve parameter τ on degree of hydration

The natural-logarithmic scale is applied to Equation 5-7:

$$Ln[\alpha(t_e)] = Ln(\alpha_u) - \left[\frac{\tau}{t_e}\right]^{\beta} \qquad (5\text{-}8)$$

$$Log\{Ln(\alpha_u) - Ln[\alpha(t_e)]\} = \beta \log \tau - \beta \log t_e \qquad (5\text{-}9)$$

Equations 5–9 show $\log\{\log(\alpha_u) - \log[\alpha(t_e)]\}$ has a linear relationship to $\log t_e$, thus, the parameter of β can be determined from the slope; and τ can be achieved from the intersection point of this linear function.

The degree of hydration is computed using Equation 5-4 at different equivalent ages, and then compared with the theoretical results using equation 5-5. Curve fitting and back-calculation are performed to achieve these hydration curve parameters, which are realized using the optimization method through the Solver function embedded in Microsoft Excel 2003. The computation procedure with the sample-5 at the Alma Center is detailed in the following paragraph.

First, the rates of heat evolution results from isothermal test data are pre-processed. There exists a peak area at the initial stage due to temperature equilibrium at the test set-up as shown in Figure 75. This peak area is relatively small and difficult to be accurately accounted for; thus, it is removed for the heat computation. A straight line is used to connect the start points and the valley points after those peak areas (Figure 75).

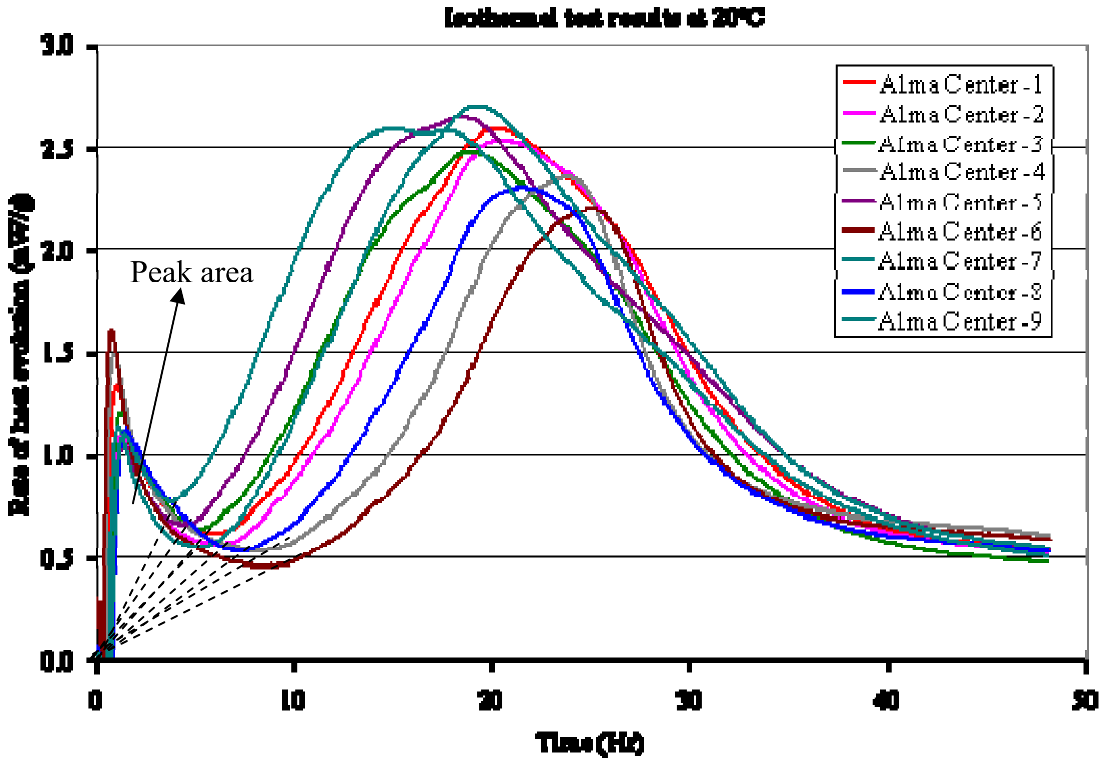


Figure 75. Pre-process the data of rate of heat evolution from isothermal tests

Subsequently, the generated heat from time t_i to time t_{i+1} is calculated using the trapezoidal method as shown in Figure 76. The heat *Q(t)* is calculated as follows:

$$\Delta Q(t) = \frac{[P(t_i) + P(t_{i+1})] \times (t_{i+1} - t_i)}{2} = \frac{[P(t_i) + P(t_{i+1})] \times \Delta t}{2} \qquad (5\text{-}10)$$

Therefore, the accumulated heat at each time point can be calculated as follows:

$$Q(t_{i+1}) = Q(t_i) + \Delta Q \qquad (5\text{-}11)$$

Equation 5-9 is substituted into Equation 5-4 to determine the DOH. (Note: These DOH values will be called as "measured values" in order to compare with the predicted ones from Equation 5-7).

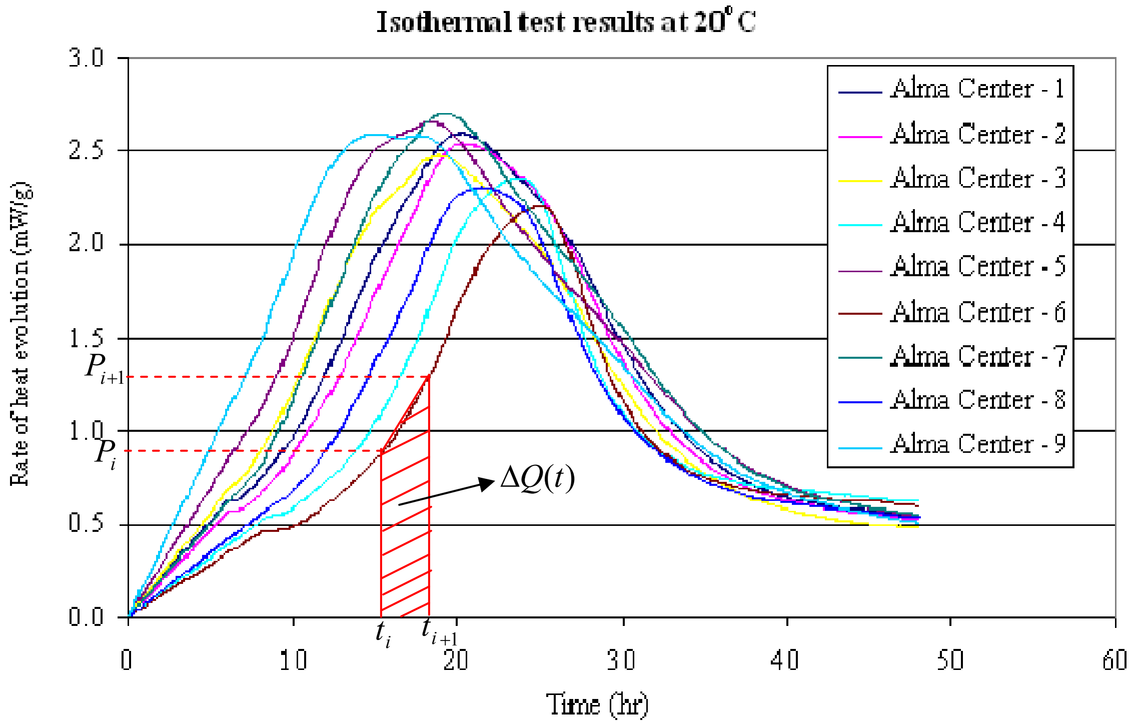


Figure 76. Heat computation based on the trapezoidal method

The determined DOH, α, is compared with the theoretical calculated results using a group of seed values of hydration curve parameters based on Equation 5-7, and the curve fitting and optimization method are utilized to achieve the hydration curve parameters (α_u, τ, and β). As an example, the curve fitting results at four temperatures of sample-5 at Alma Center are presented in Figures 77–80. The calculation is performed at each temperature for each mix at each site.

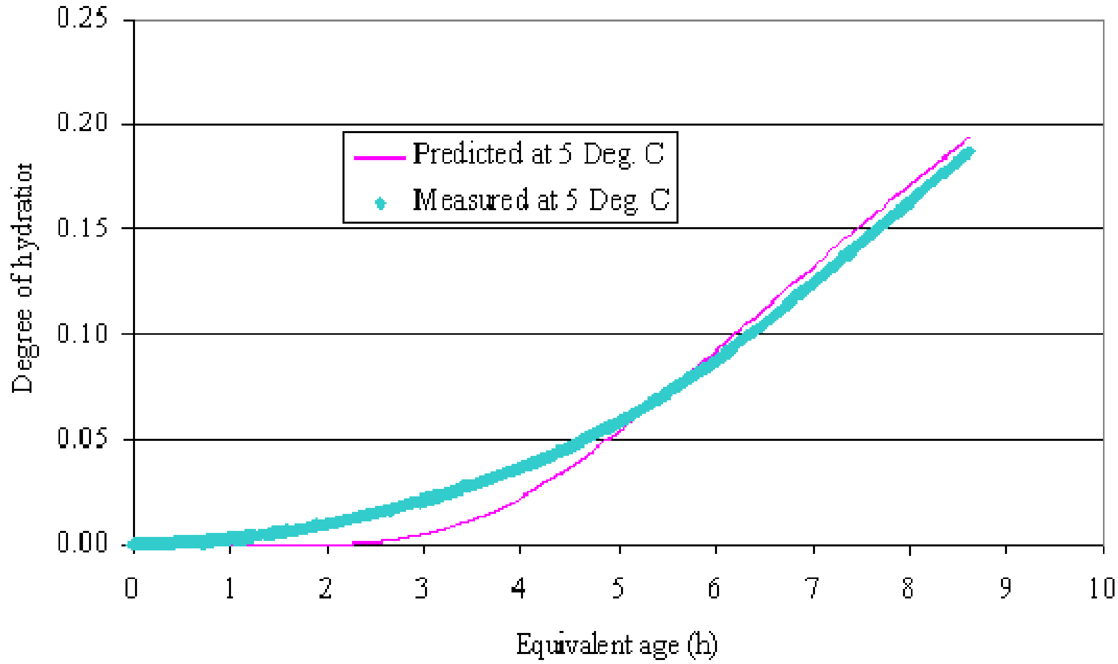


Figure 77. Predicted degree of hydration vs. measurements at 5 °C (Sample 5, Alma Center)

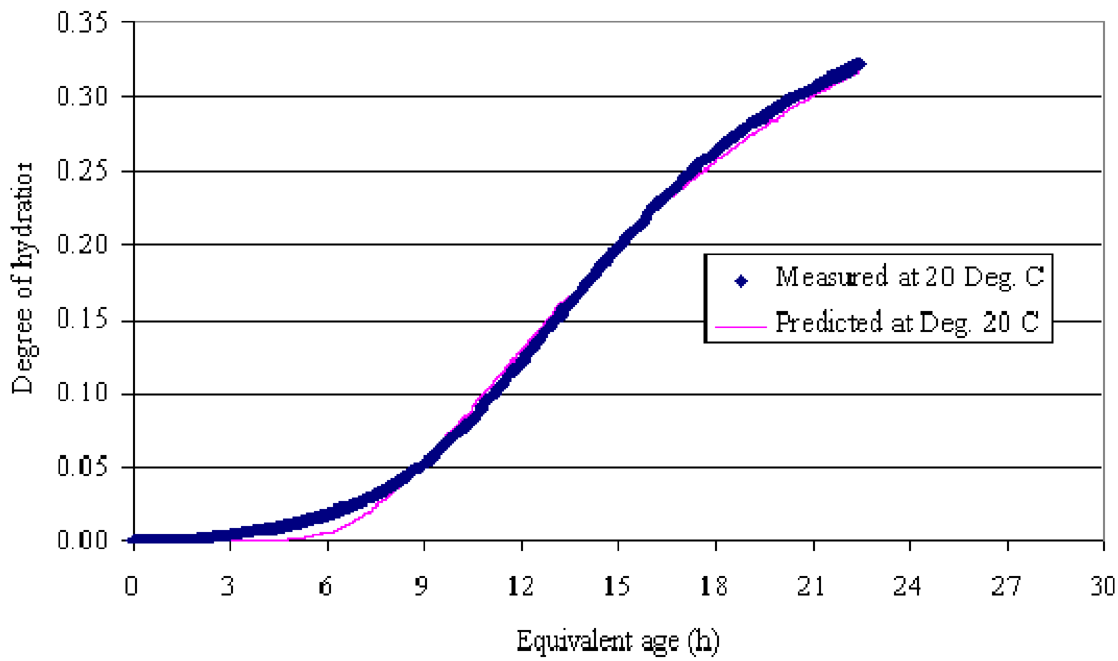


Figure 78. Theoretical degree of hydration vs. measurements at 20 °C (Sample 5, Alma Center)

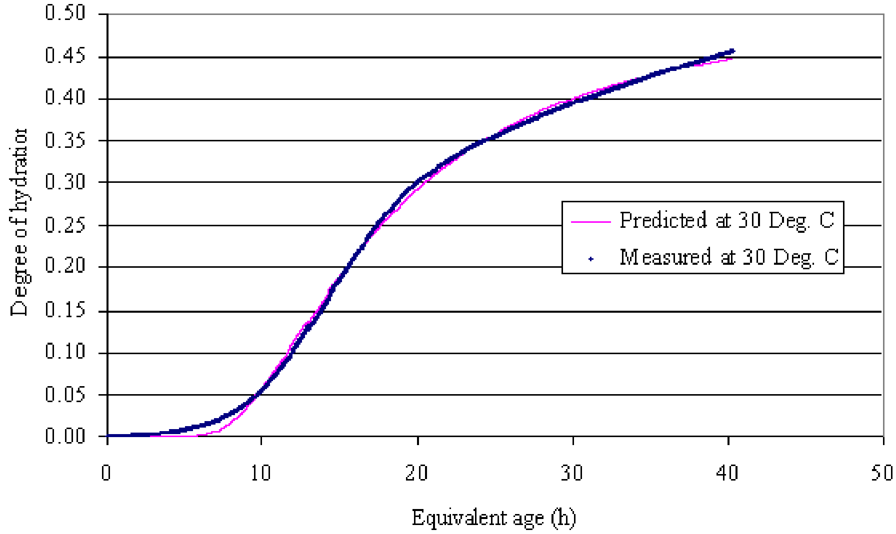


Figure 79. Predicted degree of hydration vs. measurements at 30 °C (Sample 5, Alma Center)

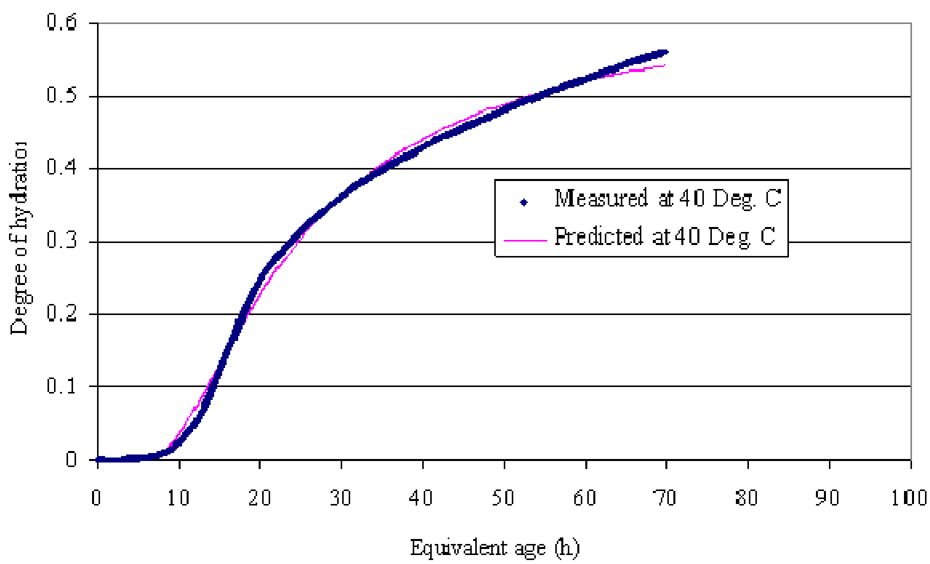


Figure 80. Predicted degree of hydration vs. measurements at 40 °C for (Sample 5, Alma Center)

5.3.2 Calculation Results

The back-calculated hydration curve parameters for all mixes at three sites are presented in Tables 15–17. The mean values of hydration curve parameters at 20 °C, 30 °C, and 40°C (Alma Center and Atlantic), and 30 °C and 40°C (Ottumwa) are also presented since they will be utilized in the pavement temperature computation as discussed later. The back-calculation is performed considering three temperatures (20 °C, 30 °C, and 40°C) at the same step. It should be noted that at 5 °C, the back-calculated α_u is sometimes larger than one; thus it is controlled to be less than one during the optimization procedure. The results of the back calculation show adding WR would increase the hydration rate while increasing FA content reduces the hydration rate, and τ increases with increasing temperature.

Table 15. Hydration curve parameters calculated based on isothermal test results (Alma Center, WI)

Sample no.	Parameters	5°C	20°C	30°C	40°C	20 °C–40°C[1]	Average 20 °C,30 °C,40°C
1	α_u	0.9900	0.6108	0.6252	0.5959	0.5586	0.6106
	β	0.7035	1.6408	1.7508	1.9374	1.8504	1.7763
	τ	29.3885	20.2465	25.9669	29.4758	22.8392	25.2297
2	α_u	0.7162	0.6212	0.6618	0.6592	0.7155	0.6474
	β	1.9342	1.7294	1.8644	1.9366	1.9342	1.8435
	τ	20.1814	20.0513	29.1004	36.7210	20.1814	28.6242
3	α_u	0.9579	0.5905	0.6044	0.5761	0.4749	0.5903
	β	0.7035	1.6408	1.7508	1.9374	2.1456	1.7763
	τ	29.3885	20.2465	25.9669	29.4758	31.8346	25.2297
4	α_u	0.9900	0.5935	0.7216	0.6600	0.6216	0.6785
	β	0.6940	1.7758	1.6676	1.6379	1.6936	1.6937
	τ	31.3042	21.7487	30.3611	34.4732	28.8627	28.8611
5	α_u	0.9900	0.6992	0.7216	0.6051	0.5717	0.6753
	β	0.6881	1.3610	1.4878	1.8616	1.8107	1.5701
	τ	28.8024	19.7491	24.5006	26.9429	20.0933	23.7309
6	α_u	0.9900	0.4688	0.4988	0.6068	0.4129	0.5248
	β	0.7971	2.0843	1.7205	1.4647	1.9857	1.7565
	τ	36.6549	22.6095	29.2576	45.8113	24.9138	32.5595
7	α_u	0.9900	0.6476	0.6638	0.6097	0.5810	0.6404
	β	0.7503	1.5567	1.6415	2.0698	1.8125	1.7560
	τ	30.0142	20.0987	23.7024	29.1781	21.4137	24.3264
8	α_u	0.6751	0.5376	0.6052	0.6196	0.5416	0.5875
	β	0.8907	1.8083	1.7062	1.7566	1.7717	1.7570
	τ	19.8322	20.3703	24.8406	32.6339	22.9035	25.9483
9	α_u	0.5684	0.7181	0.6961	0.6093	0.6101	0.6745
	β	1.0399	1.2447	1.3566	1.7380	1.5778	1.4464
	τ	16.2371	18.9216	20.2745	21.6115	18.2808	20.2692

Note: [1] back-calculation considering three temperatures at the same step

Table 16. Hydration curve parameters back-calculated based on isothermal test results (Atlantic, IA)

Sample no.	Parameters	5°C	20°C	30°C	40°C	20 °C–40°C	Average 20 °C,30 °C,40°C
1	α_u	0.9900	0.6060	0.5801	0.5371	0.5066	0.5744
	β	0.9277	1.6992	1.9421	2.2421	2.1927	1.9611
	τ	26.6044	18.3391	20.8226	27.2633	19.2624	22.1417
2	α_u	0.9140	0.5866	0.5433	0.5154	0.4882	0.5484
	β	1.0957	1.7944	2.2946	2.4197	2.4049	2.1696
	τ	24.5420	19.1539	22.5632	27.8291	20.7546	23.1821
3	α_u	0.7909	0.6224	0.6010	0.5324	0.5152	0.5853
	β	1.1247	1.6220	1.7726	2.0871	2.1575	1.8272
	τ	20.2132	18.0107	18.9814	22.5658	17.7784	19.8526
4	α_u	0.8611	0.5415	0.5187	0.5402	0.4880	0.5335
	β	1.1201	2.2463	2.4873	2.3114	2.5121	2.3483
	τ	21.0165	20.5071	22.9329	30.2924	22.0432	24.5775
5	α_u	0.7828	0.6538	0.6811	0.6034	0.5080	0.6461
	β	1.0529	1.4173	1.7726	2.0871	2.0441	1.7590
	τ	14.6331	19.1543	20.4121	26.2018	18.1415	21.9227
6	α_u	0.9308	0.5255	0.5085	0.5287	0.4604	0.5209
	β	1.1511	2.3990	2.6702	2.3426	2.7631	2.4706
	τ	25.1907	22.1607	25.1194	32.8242	23.6658	26.7014
7	α_u	0.7630	0.6304	0.5698	0.5097	0.4991	0.5700
	β	1.1755	1.6402	1.9223	2.3287	2.2734	1.9637
	τ	21.9671	19.5463	21.3133	24.7369	19.6538	21.8655
8	α_u	0.7248	0.5791	0.5573	0.5433	0.5032	0.5599
	β	1.2721	1.8846	2.1994	2.2006	2.3164	2.0949
	τ	17.8805	18.1573	21.1945	27.0361	19.8111	22.1293
9	α_u	0.7868	0.7255	0.6719	0.5575	0.5617	0.6516
	β	1.0066	1.1372	1.3372	1.7853	1.6398	1.4199
	τ	20.0718	17.8486	19.6514	20.5597	16.7853	19.3532

Table 17. Hydration curve parameters back-calculated based on isothermal test results (Ottumwa, IA)

Sample no.	Parameters	5°C	20°C	30°C	40°C	20 °C–40°C	Average 30 °C,40°C
1	α_u	0.5598	0.5295	0.4905	0.6312	0.5798	0.6312
	β	1.4649	1.6057	1.9539	1.4170	1.4467	1.4170
	τ	9.3784	14.2056	16.6248	20.4194	17.6295	20.4194
2	α_u	0.5878	0.5012	0.4618	0.6254	0.5470	0.6254
	β	1.5765	1.9010	2.3930	1.5472	1.7191	1.5472
	τ	12.1947	16.0293	18.3387	25.2515	19.4279	25.2515
3	α_u	0.5637	0.5517	0.5342	0.6072	0.5898	0.6072
	β	1.4340	1.4857	1.6847	1.8907	1.3580	1.8907
	τ	9.1983	12.9745	14.3461	25.0715	16.0093	25.0715
4	α_u	0.5381	0.4997	0.4615	0.6152	0.5587	0.6152
	β	1.4980	1.6355	2.0229	1.5335	1.4637	1.5335
	τ	10.6448	15.4495	16.8088	25.1642	18.9353	25.1642
5	α_u	0.6140	0.5061	0.5177	0.6390	0.5882	0.6390
	β	1.3743	1.7233	1.9534	1.4710	1.4826	1.4710
	τ	9.5829	14.3867	15.0166	20.4169	16.7574	20.4169
6	α_u	0.5618	0.4712	0.4525	0.5916	0.5882	0.5916
	β	1.4423	1.8693	2.1951	1.7298	1.4826	1.7298
	τ	12.0907	17.4293	18.3742	29.3694	16.7576	29.3694
7	α_u	0.6316	0.5354	0.4866	0.6348	0.5680	0.6348
	β	1.3625	1.9418	2.3196	1.7158	1.7611	1.7158
	τ	11.6373	15.6103	17.1054	24.8943	18.4770	24.8943
8	α_u	0.5404	0.5193	0.5039	0.6174	0.5425	0.6174
	β	1.4114	1.5082	1.7221	1.3677	1.4599	1.3677
	τ	9.4450	14.0397	14.7238	22.4863	15.9444	22.4863
9	α_u	0.6319	0.6032	0.5634	0.6469	0.5856	0.6469
	β	1.2789	1.3351	1.5969	1.3721	1.4361	1.3721
	τ	8.9879	11.6651	13.2458	19.8030	13.5333	19.8030

It is also noted that the total heat H_u would affect the hydration curve parameters, requiring that sensitivity analysis be performed. H_u ranges from 370 J/g to 513 J/g based on the 21 mixes (*15*). In this study, *Hu* ranging from 250 to 467 J/g is utilized for the sensitivity analysis. These results shown in Table 18 indicate that α_u increases, while β and τ decrease as H_u decreases.

Table 18. Sensitivity of hydration curve parameters to total heat

(1) H_u: 467 J/g

	5°C	20°C	30°C	40°C	20 °C–40 °C	Average 20 °C,30 °C,40°C
α_u	0.9900	0.6108	0.6252	0.5959	0.5586	0.6107
β	0.7035	1.6408	1.7508	1.9374	1.8504	1.7764
τ	29.3885	20.2465	25.9669	29.4758	22.8392	25.2297

(2) H_u: 414 J/g

	5oC	20oC	30oC	40oC	20 °C–40 oC	Average 20 °C,30 °C,40°C
α_u	0.9900	0.6886	0.7048	0.6718	0.6298	0.6884
β	0.7559	1.6408	1.7508	1.9374	1.8504	1.7763
τ	25.2348	20.2466	25.9669	29.4760	22.8392	25.2298

(3) H_u: 250 J/g

	5oC	20oC	30oC	40oC	20 °C–40 °C	Average 20 °C,30 °C,40°C
α_u	0.9900	0.9900	0.9900	0.9900	0.9900	0.9900
β	1.1033	2.0642	2.1479	2.4760	2.0287	2.2294
τ	14.4082	18.5720	23.5986	27.7870	22.1826	23.3192

5.4 Hydration curve parameters based on the semi-adiabatic test and HIPERPAV II model

In this section the hydration curve parameters are back-calculated using the Semi-adiabatic test results. The rate of heat evolution is calculated as follows (6,7,8):

$$P(t_e) = H_u \cdot C_p \left[\frac{\tau}{t_e}\right]^{\beta} \cdot \left[\frac{\beta}{t_e}\right] \cdot \alpha(t_e) \cdot \exp\left(\frac{E_a}{R}\left(\frac{1}{273.15+T_r} - \frac{1}{273.15+T_c}\right)\right) \quad (5\text{-}12)$$

where, P(t_e) = rate of heat liberation at equivalent age, t_e, (W/m^3),
H_u = Total heat of hydration (J/kg)
C_p = the specific heat of cemetious material.
E = activation energy (J/mol),
R = universal gas constant (8.3144 J/mol/°C),

The theoretical hydration curve is calculated from using seed values of the hydration time and shape parameters with the theoretical maximum temperature increase from the hydration reaction estimated for that test. The time and shape parameters are then back-calculated by minimizing the log of errors (differences) at every time step from the actual hydration curve to the theoretical hydration curve. Afterwards, the effects of heat on the developed stress and strain of pavement and material strengths are accounted for (HIPERPAV II).

For concrete samples, the total heat of hydration is calculated by relating the mass and specific heat of the concrete with the total temperature increase observed. The formula for the total heat of hydration is given below in Equation 5-13.

$$H_u = \frac{m_{concrete}}{m_{cement}} \bullet C_p \bullet \Delta T \tag{5-13}$$

Where,

$m_{concrete}$	=	mass of concrete (kg)
m_{cement}	=	mass of cementitious material (kg)
C_p	=	specific heat of concrete (J/g·°C)
ΔT	=	total change in temperature (°C)

Subsequently, the temperature rise at the adiabatic condition can be determined as follows:

$$\Delta T = \frac{P(t) \times (t_{i+1} - t_i)}{C_c} \tag{5-14}$$

Thus, the temperature at any point in time is determined as follows:

$$T_{i+1} = T_i + \Delta T = T_i + \frac{P(t) \times (t_{i+1} - t_i)}{C_c} \tag{5-15}$$

The theoretical computed temperature is compared with the measured adiabatic temperature at all time points, and curve fitting is performed through the optimization method using the Solver function embedded in Microsoft Excel 2003 to achieve the hydration curve parameters. The calculated temperatures versus measurements of four concrete mixtures are presented in Figure 81. The calculated results of hydration curve parameters are presented in Table 19.

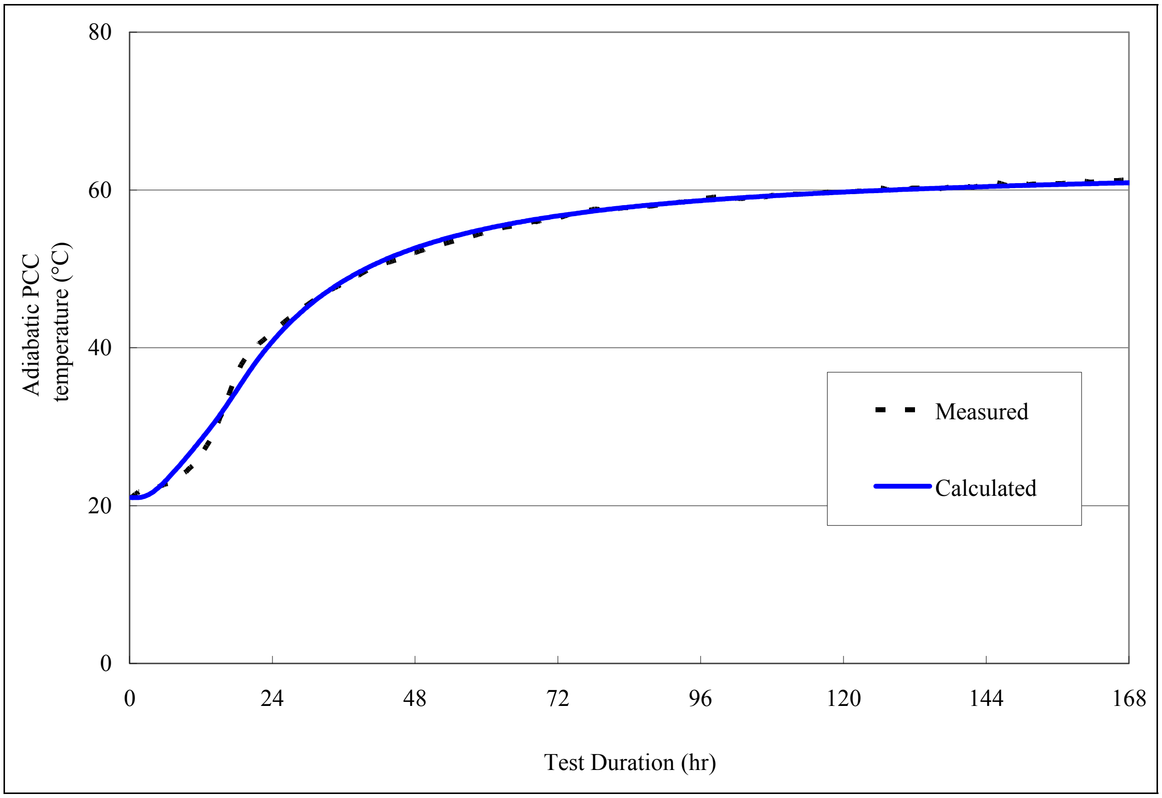


Figure 81. Alma Center field concrete

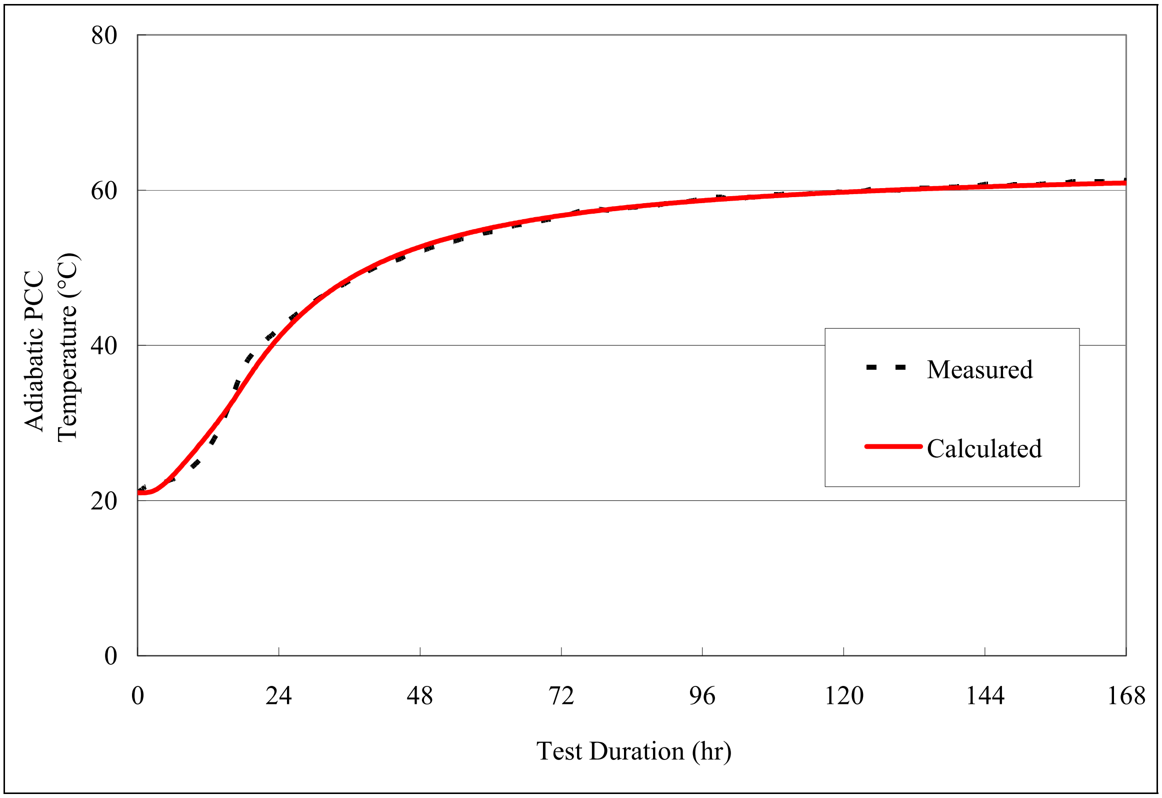


Figure 82. Alma Center lab concrete

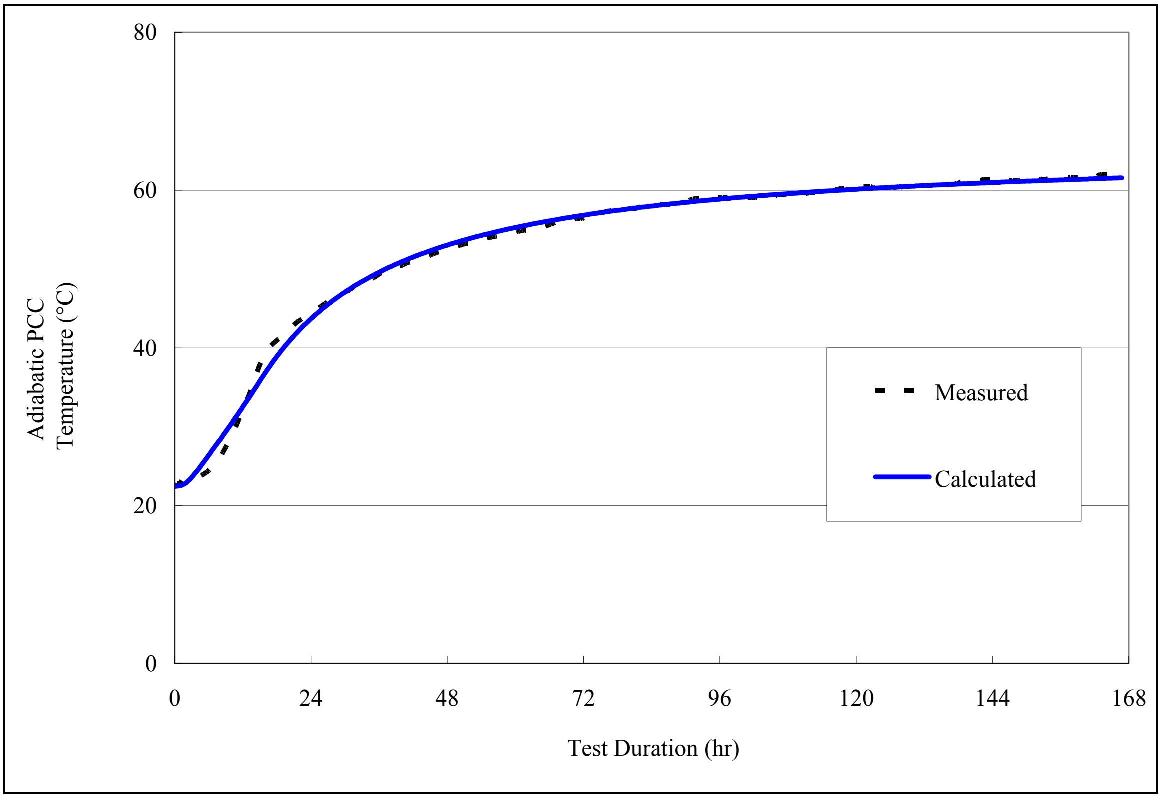


Figure 83. Atlantic Field concrete

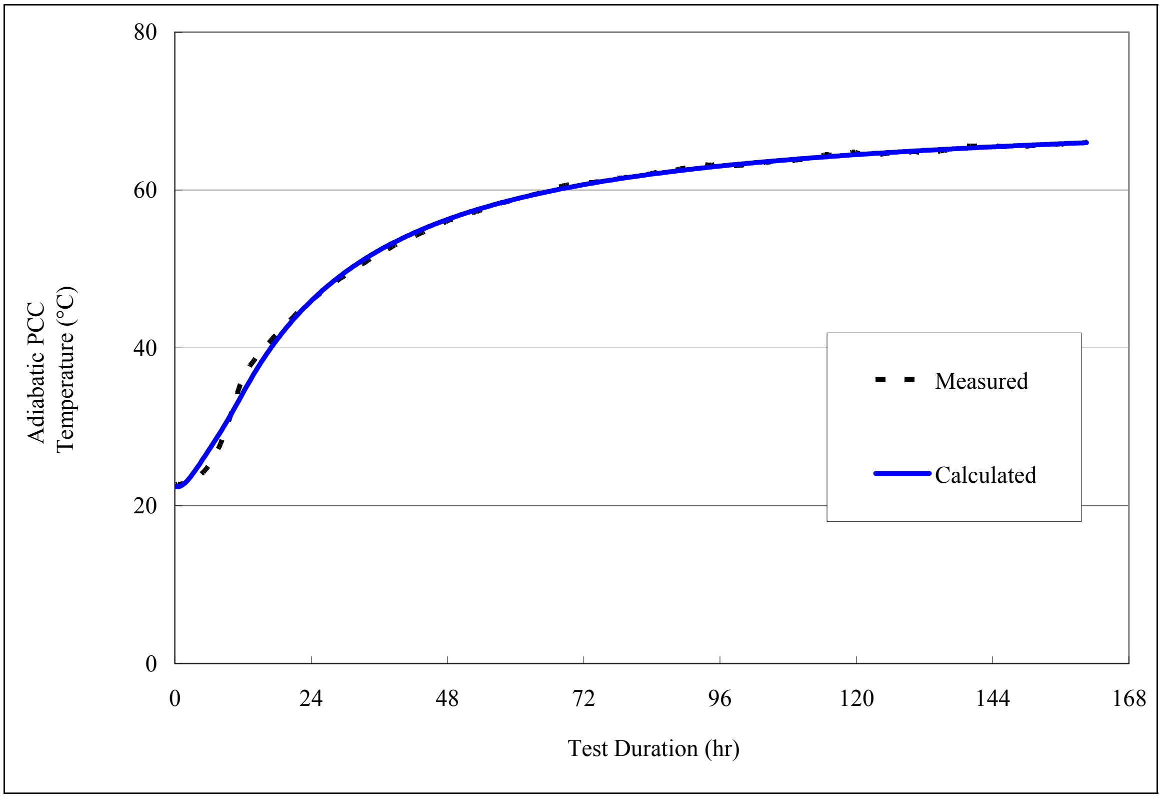


Figure 84. Ottumwa Field Concrete

Table 19. Back-calculated hydration curve parameters based on Semi-adiabatic test

	Alma Center field concrete	Alma Center lab concrete	Atlantic field concrete	Ottumwa field concrete
α_u	0.633	0.646	0.655	0.805
β	0.705	0.699	0.604	0.556
τ	33.292	33.022	32.502	35.380

Results seem to indicate the following: the calculated hydration curve parameter β, based on the isothermal test data, is larger than that calculated using semi-adiabatic test data. β values based on the semi-adiabatic tests are closer to the values reported by other researchers (Schindler 2002) using the chemical-based empirical equation; and the hydration curve parameter τ based on the isothermal test data seems to be smaller than that of the semi-adiabatic test data. In order to evaluate these two groups of hydration curve parameters, the HIPERPAV II software was used to predict the in situ pavement temperatures.

5.5 Conversion from Isothermal to Semi-Adiabatic Calorimetry

Based on the limited tests, it would be meaningful to convert between the isothermal and semi-adiabatic or full-adiabatic tests. However, there are very few studies presented on this topic based on the authors' literature review. Wadsö (*12*) developed a statistical model, and Hatzitheodorou et al. (*16*) developed a model and computation procedure based on the maturity to convert from the isothermal test to semi-adiabatic and full-adiabatic for cement and cement mortar, respectively. In this research a mathematical model and computation approach to convert the isothermal calorimetry of cement mortar to semi-adiabatic calorimetry of cement concrete are developed, which has extended from the basic methodology (*12*). The Visual Basic Application (VBA) program is utilized to realize the computational procedure using finite difference method on the Microsoft Excel 2003 platform. The model and computation procedure are detailed as follows with an example of Alma Center:

Step 1: Pre-process the data of isothermal tests. The peak area at the initial early stage due to temperature equilibrium is removed as discussed previously (Figure 75). At least two tests at two temperatures are needed for this computation (e.g., in this project four temperatures are used).

Step 2: Calculate the generated heat at each point in time. The trapezoidal method is used to approximate the accumulated heat as shown in Equation 5-9 and Figure 76.

Step 3: *P* versus *Q*. The measured *P(t)* (W/g) vs. *Q* (J/g) are plotted as shown in Figure 85. Thus, at each Q point, the P points at different temperatures can be achieved. Since the tests at different temperatures have different Q points, linear interpolation is utilized to achieve the P points at any Q point. This method has good accuracy because the time interval of recorded test data is very small (e.g., 0.01 hour).

$$P(t) = P_i + (t - t_i) \times \frac{(P_{i+1} - P_i)}{(t_{i+1} - t_i)} \tag{5-16}$$

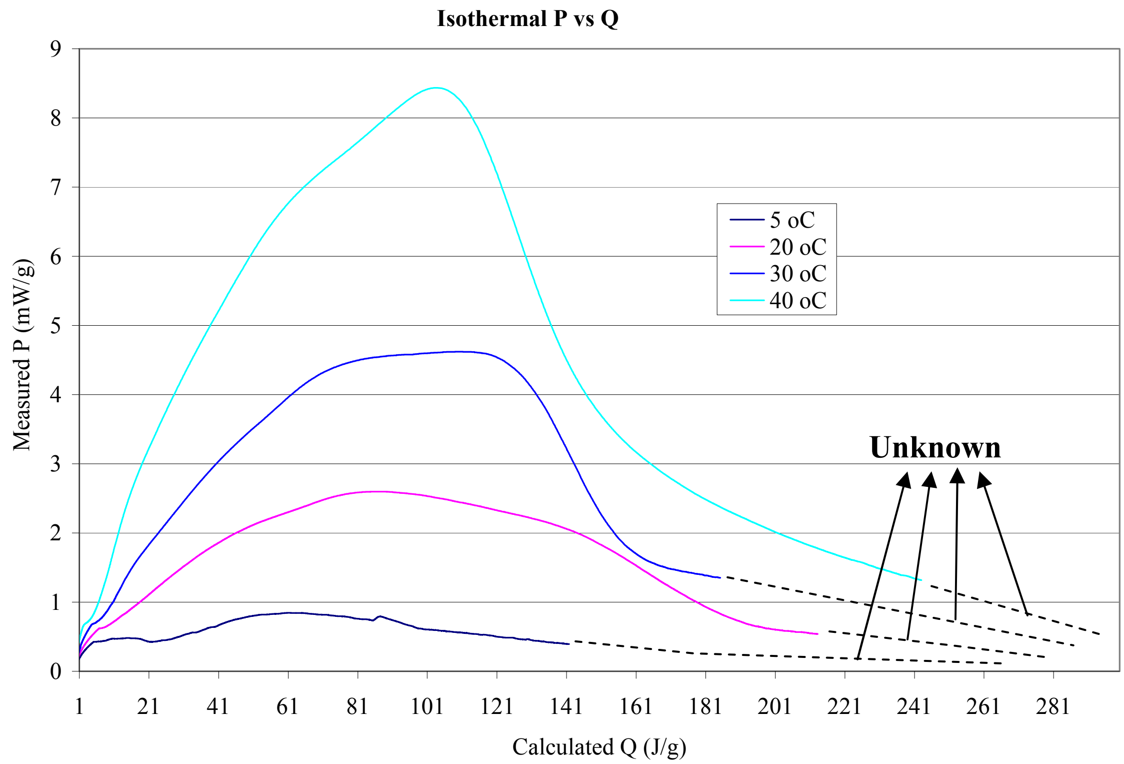


Figure 85. P vs. Q

However, the test results might not provide a complete list of P vs. Q since the test may stop before it reaches the maximum heat state H_u, as shown in Figure 85. Therefore, a statistical regression is utilized to predict the trend of P vs. Q points at a longer time period during hydration, and it shows that the exponential function could predict this trend well. For example, the exponential function is used to predict the P vs. Q points for those unknown areas at longer hydration time beyond the test range as illustrated in Figure 86.

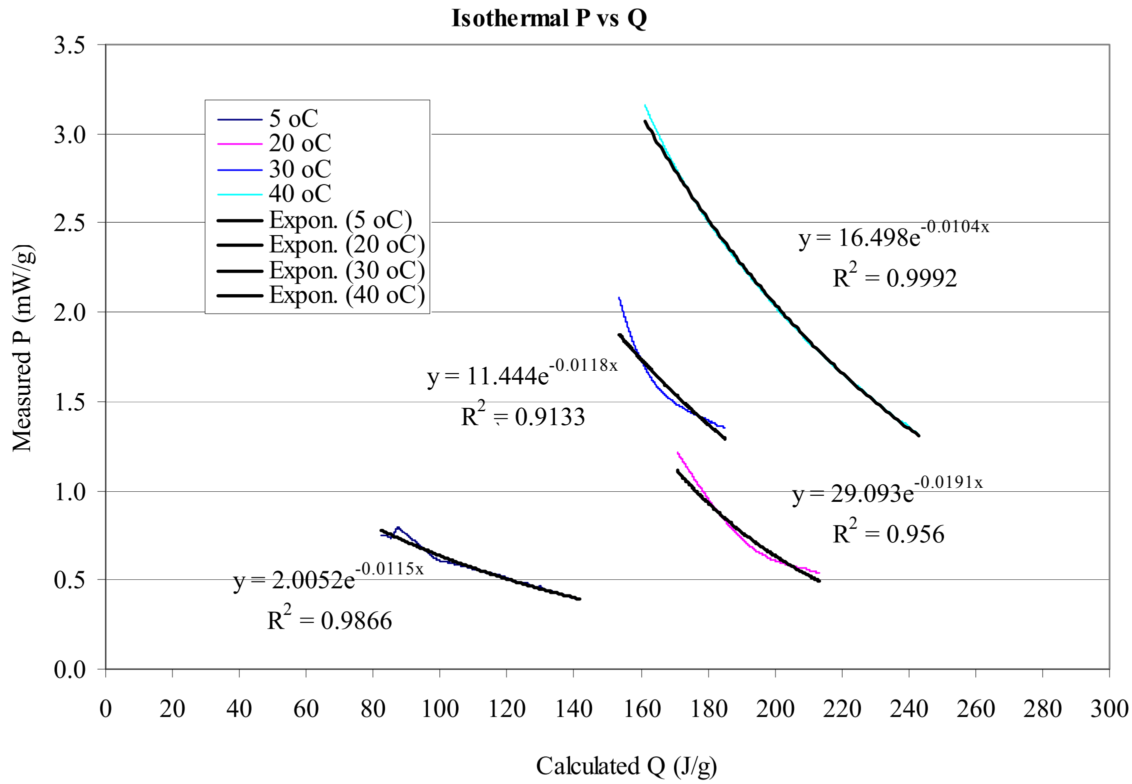


Figure 86. Exponential equations to approximate P vs. Q

Step 4: P vs. T. A key concept to understanding this research is that at the specific heat state (Q) and temperature state (T) for the cementitious material, the rate of heat evolution (P) (hydration rate) is always the same, no matter if it is exposed to isothermal, adiabatic or other testing regimes and environmental conditions. Therefore, the purpose of this step is to achieve P vs. T at different Q states. The measured and linearly interpolated P point at each Q point of four temperatures (Figure 87) is extracted to approximate a relationship between *P* and *T*, and a multi-linear model is used to approximate this relationship, as shown in Figure 88.

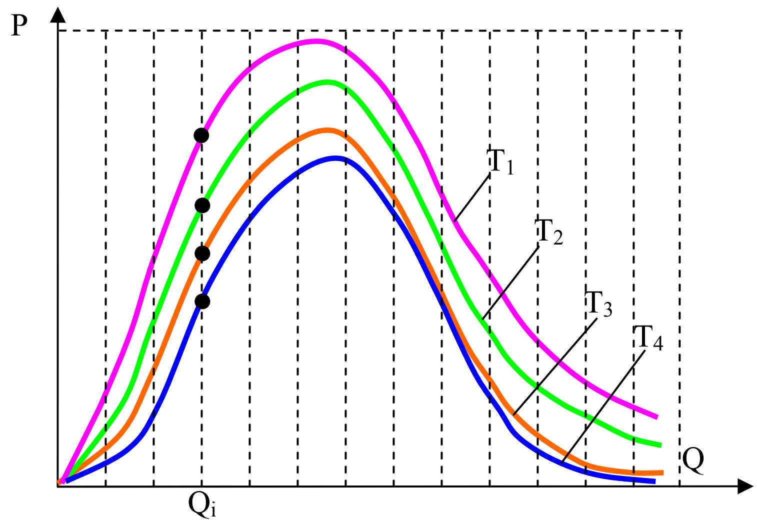


Figure 87. Extract P points at any Q state

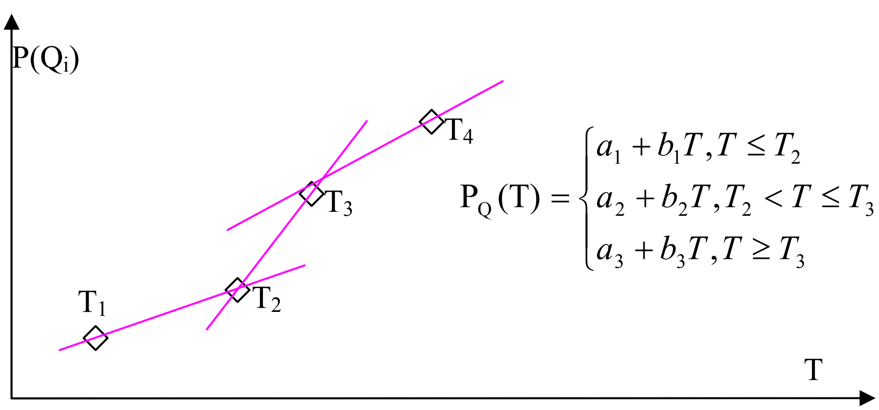


Figure 88. Approximate P vs. T at any heat (Q) state

Step 5: Temperature is lost during the semi-adiabatic test. As shown in Figure 89, the generated heat by cement hydration releases through the calorimeter wall into the immediate environment. The temperature at the surface of the inside wall (T_{in}) is higher than that at the surface of the outside wall T_{out}. According to Fourier's law, the rate of heat conduction within a solid is determined as follows:

$$P = \frac{\Delta Q}{\Delta t} = k \times A \times \frac{T_{in} - T_{out}}{\Delta x} \qquad (5\text{-}17)$$

Where, k = thermal conductivity of calorimeter

A = surface area of calorimeter

Δx = the thickness of calorimeter wall.

T_{in} = temperature at the surface of inside wall

T_{out} = temperature at the surface of outside wall

Therefore, the heat loss of concrete through the release of calorimeter to the surrounding environment at a time step can be calculated as follows:

$$\Delta Q = k \times A \times \frac{T_{in} - T_{out}}{\Delta x} \times \Delta t = \frac{k \times A}{\Delta x} \times \left(T_{in} - T_{out}\right) \times \Delta t \qquad (5\text{-}18)$$

$$\Delta Q_{Cond} = k \times A \times \frac{T_{in} - T_{out}}{\Delta x} \times \Delta t \qquad (5\text{-}19)$$

Accordingly, the temperature loss through calorimeter conduction at a time step is computed as follows:

$$\Delta T_{cond} = \frac{\Delta Q}{C_p} = \left[\frac{k \times A}{C_p \times \Delta x}\right] \times \left(T_{in} - T_{out}\right) \times \Delta t \qquad (5\text{-}20)$$

where, C_p = the heat capacity of concrete (J/kg·°C).

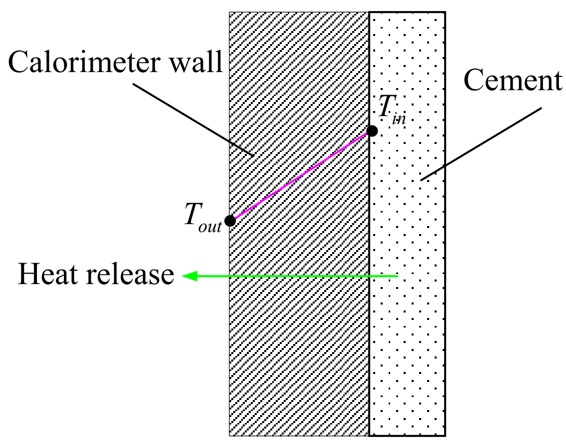


Figure 89. Heat conduction in the calorimeter wall

Heat convection happens between the outside surface of calorimeter and the surrounding air. However, in order to simplify this computation procedure, it is assumed that the T_{out} is the same as the temperature of air, and T_{in} is the same as that of the cement. In this project, the semi-adiabatic tests were performed and the heat (temperature) losses are estimated, thus the $C = \frac{k \times A}{C_{Con} \times \Delta x}$ in Equation 5-20 as a material parameter (W/°C) can be back-calculated.

Step 6: Determine temperature "absorbed" or "released" by the calorimeter. During the temperature rise procedure, the calorimeter "absorbs" a portion of heat and during the procedure of temperature decrease, it "releases" a portion of heat that is generated by cement hydration. This part of heat also contributes to the semi-adiabatic temperature decrease or rise.

The absorbed or released heat by the calorimeter can be calculated as:

$$\Delta Q_{calo} = C_{calo} \times \frac{\Delta T}{2} \times M_{Calo} \qquad (5\text{-}21)$$

where, C_{calo} = the heat capacity of calorimeter (J/kg·°C)
M_{Calo} = the mass of calorimeter (kg)
ΔT = the raised or decreased temperature (°C)

Therefore, the temperature loss or gain of concrete due to calorimeter absorption or release can be determined as follows:

$$\Delta T_{Calo} = \frac{Q_{Calo}}{C_p \times M_{Con}} = \left[0.5 \times \frac{C_{calo}}{C_p} \times \frac{M_{Calo}}{M_{Con}} \right] \times \Delta T \qquad (5\text{-}22)$$

Where, C_p = the heat capacity of concrete (J/kg·°C)
M_{Con} = the mass of concrete (kg)

Let $R = 0.5 \times \frac{C_{calo}}{C_{con}} \times \frac{M_{Calo}}{M_{Con}}$ as a ratio parameter.

Therefore, the total temperature loss due to heat conduction through calorimeter to the surrounding air and heat absorption or release of calorimeter can be calculated in the following equation:

$$\Delta T_{Loss} = \frac{\Delta Q}{C_{con}} = \left[\frac{k \times A}{C_{con} \times \Delta x} \right] \times \left(T_{in} - T_{out} \right) \times \Delta t + \left[0.5 \times \frac{C_{calo}}{C_{con}} \times \frac{M_{Calo}}{M_{Con}} \right] \times \Delta T \qquad (5\text{-}23)$$

The modeled results of temperature loss using Equation 5-23 versus measurements are shown in Figure 90.

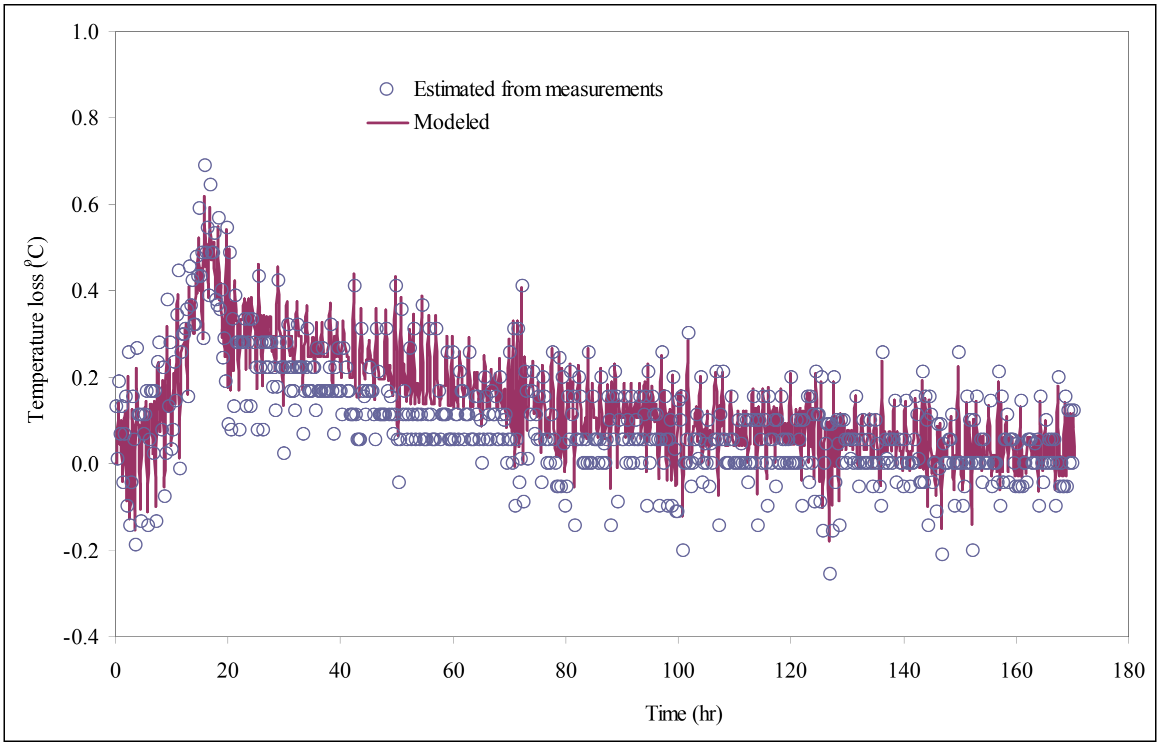


Figure 90. Calculated temperature losses versus measurement estimations

Step 7: Determine the semi-adiabatic temperature. Due to the heat balance at each heat state (time point or temperature state), the total heat generated by the cement hydration includes the one raising the temperature of concrete, the one released to the surrounding environment through calorimeter conduction, and the one absorbed (during temperature rise) or released (during temperature decrease) by the calorimeter. The heat balance at the semi-adiabatic test is expressed as:

$$\Delta Q_{tot} = \Delta Q_T + \Delta Q_{Cond} + \Delta Q_{Calo} \qquad (5\text{-}24)$$

Where Q_{tot} is the total heat, Q_T is the heat in the cement which raises the temperature of the concrete sample in the semi-adiabatic condition. The temperature rise of concrete at a specific step is determined as:

$$\Delta T = \frac{\Delta Q_{tot}}{C_{Con}} - T_{Loss} \qquad (5\text{-}25)$$

It should be noted that the isothermal test data are based on the cement mortar, while the semi-adiabatic tests are based on cement concrete. Thus, generated heat evolution Q (J/g) of cement mortar is converted to that of cement concrete. In this research an assumption is proposed that during the hydration procedure, the temperatures are uniform for all material components including cement paste, aggregates, and sands. Therefore, the potential delay of temperature rise or decrease due to different heat conductivity of material components is ignored. Based on this assumption, the heat evolution procedure is the same for cement mortar (cement paste plus sand) and cement concrete (cement paste, sand and aggregate) except that they have different mass, as illustrated in Figure 91. Therefore, the heat Q (J/g) of concrete can be determined in terms of the test results of cement mortar:

$$Q_{con} = Q_{cem} \times \frac{M_{cem}}{M_{con}} \tag{5-26}$$

where Q_{con} = heat of concrete (J/g)
Q_{cem} = heat of cement (J/g)
M_{con} = mass of concrete (g)
M_{cem} = mass of cement (g)

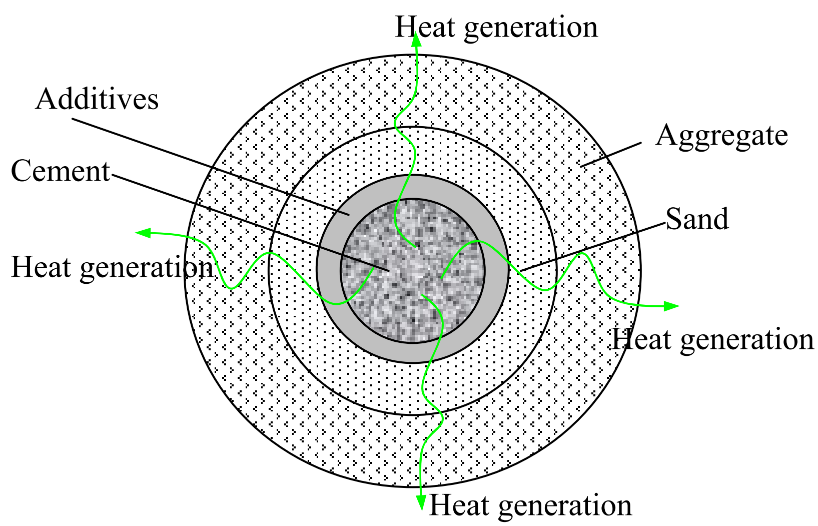


Figure 91. Heat generation of cementitious material

The finite difference (FD) method is used to solve this computer procedure based on a VBA program built on the Microsoft Excel platform. A heat step (ΔT) or time step (Δt) can be used to run this procedure. When using a heat step, the time can be back-calculated from Equation 5-8 as follows:

$$\Delta t = \frac{2Q(t)}{P(t_i) + P(t_{i+1})} \tag{5-27}$$

When using a time step, a small time step such as of 0.01 hour is needed to assure the accuracy of computation. The accumulated temperature at the *jth* time step is denoted by T_j, then the temperature at the next step is determined as follows:

$$T_{j+1} = T_j + \Delta T \tag{5-28}$$

As an example, the forward FD method with regards to time steps (0.01 hour per step) is used to simulate the temperature vs. time at the semi-adiabatic test from the isothermal test results, as shown in Figure 92.

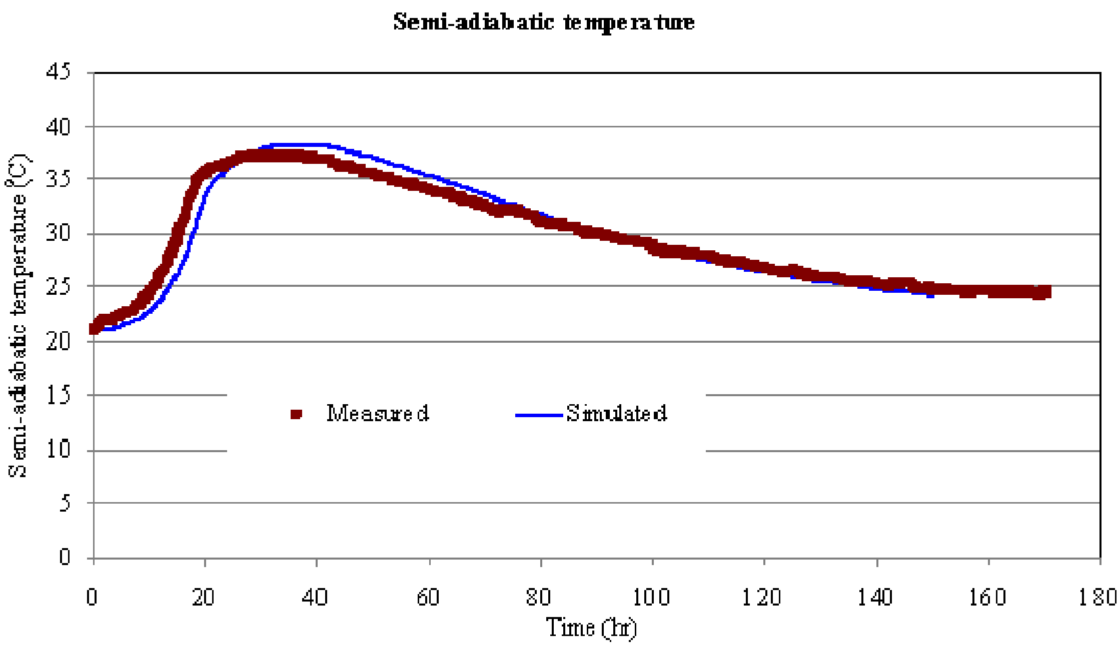


Figure 92. Simulated semi-adiabatic temperature (from isothermal data) vs. measurements

The results show that the simulation from isothermal data has a reasonable agreement with the measurements though there is some small delay at the early age.

The full-adiabatic temperature can also be simulated using this approach if the isothermal test data includes the higher temperature levels necessary to approximate the temperature of a full-adiabatic test condition. Without this high-level temperature, the rate of heat evolution at the high-level temperature range is unknown, and the prediction of trend in that range may induce significant errors.

However, after converting the isothermal calorimetry to the semi-adiabatic calorimetry, the semi-adiabatic calorimetry data can be converted to the full-adiabatic calorimetry data using the method (*17*).

The predicted semi-adiabatic temperatures can be used to back-calculate the hydration curve parameters based on the method described in section 5.3. Subsequently, the pavement temperature, stresses, and strength of concrete materials can be predicted using the HIPERPAV software.

The computational procedure discussed by the previous paragraphs is summarized in Figure 93.

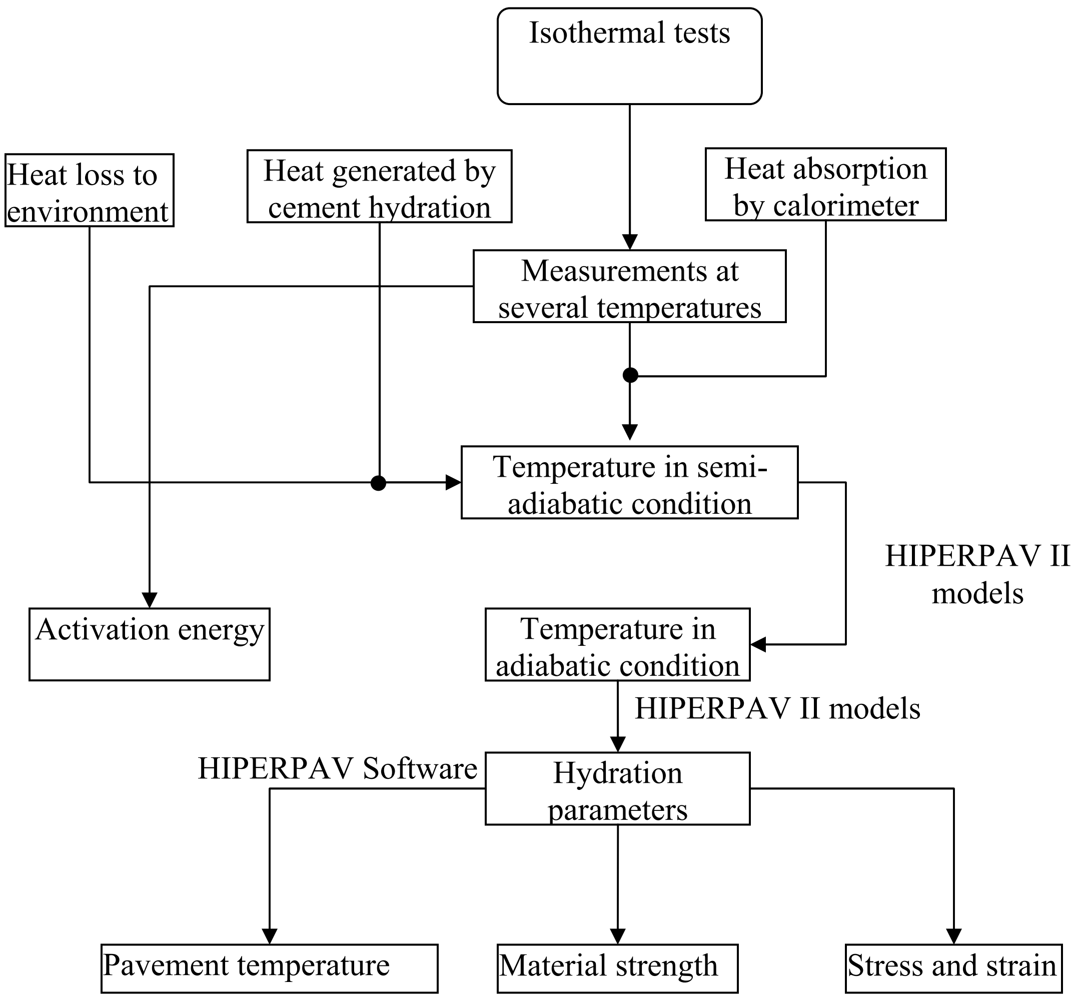


Figure 93. Flow chart of computation procedure

5.6 Modification of HIPERPAV Software

The HIPERPAV software was modified to allow users to define the inputs of hydration curve parameters (α_u, β, and τ). Originally, HIPERPAV computed hydration curve parameters based on linear regression models as a function of cement chemistry (6,7,8). In this modified version, users input values for the hydration curve parameters, as shown in Figure 94. HIPERPAV then predicts hydration and pavement temperatures as a result of these inputs.

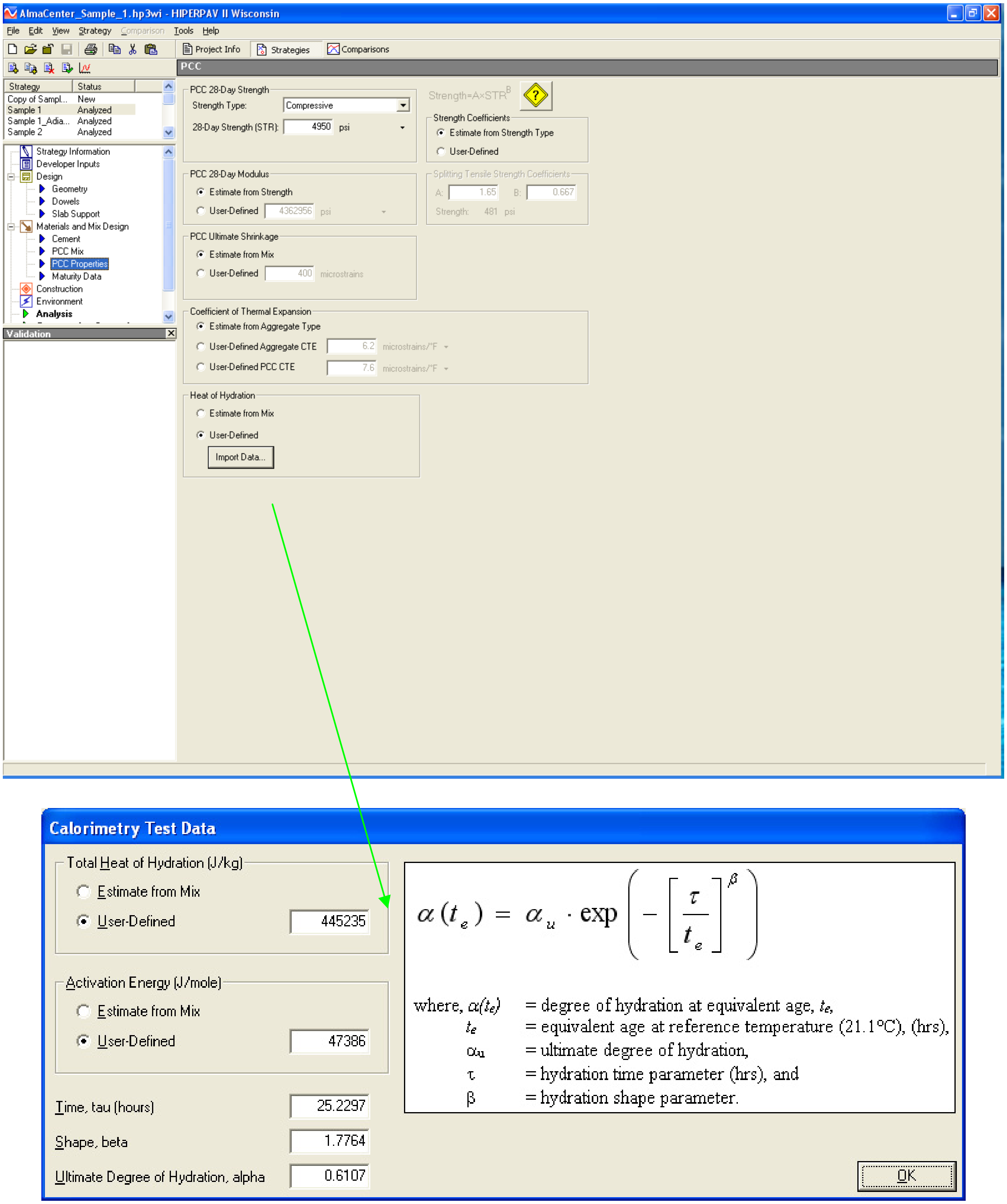


Figure 94. Windows of inputs of hydration curve parameters in the modified HIPERPAV II software.

5.7 Prediction of Pavement Temperatures

The temperatures of in situ pavement at three sites (Alma Center, WI; Atlantic, IA; and Ottumwa, IA) are predicted using the HIPERPAV II software. Increased temperatures due to hydration are very important in calculating developed stresses and material strength in concrete at early ages. The hydration parameters back-calculated from both the isothermal tests and semi-adiabatic tests are used as inputs in HIPERPAV II software, in order to find which one would be more reliable for predicting the pavement temperatures. The analysis and results are presented in the following sections.

5.7.1 Alma Center Pavement Temperature and Prediction

5.7.1.1 Inputs

The weather information for temperature, wind speed, and humidity at the Alma Center in Iowa were downloaded from the Weather Underground website (http://www.wunderground.com/) and are shown in Figure 95–97.

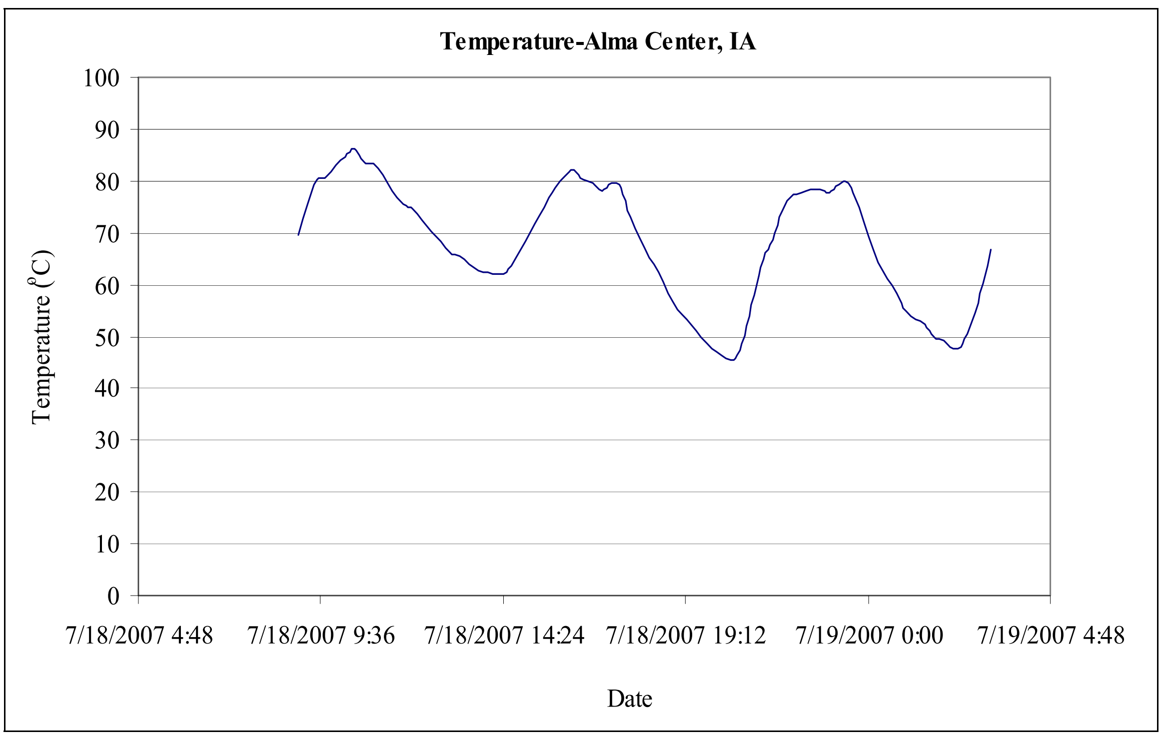


Figure 95. Temperature at the Alma Center, IA

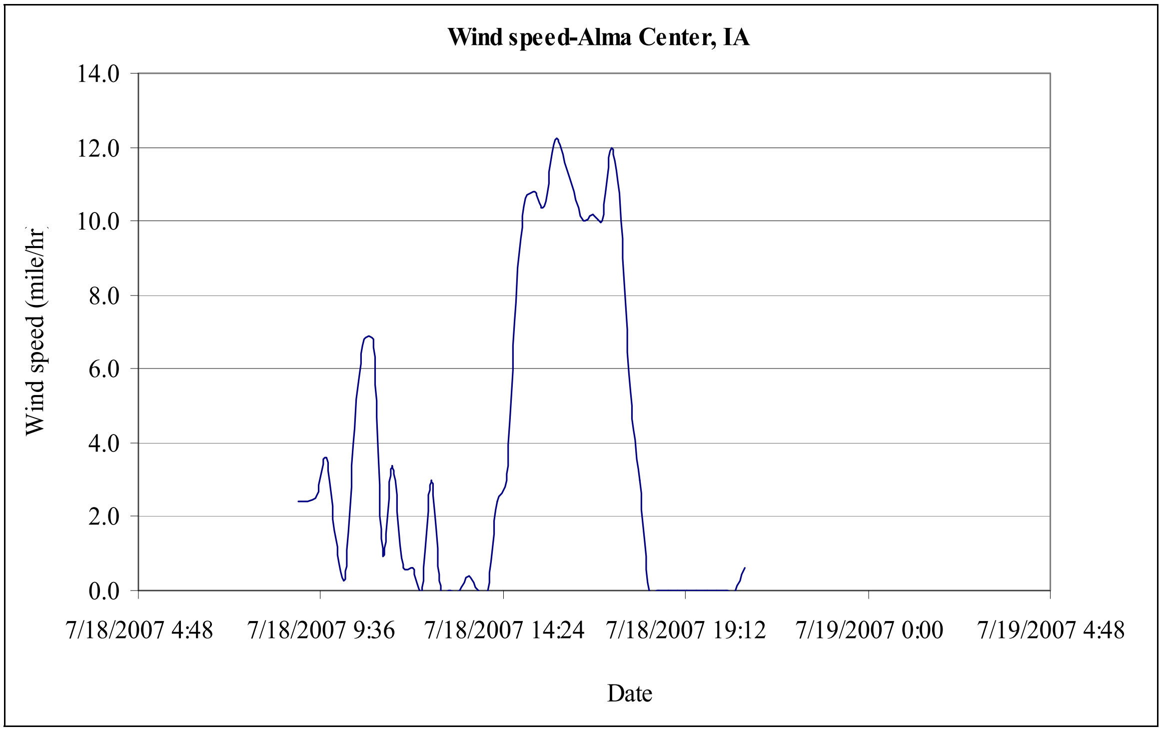


Figure 96. Wind speed at the Alma Center, IA

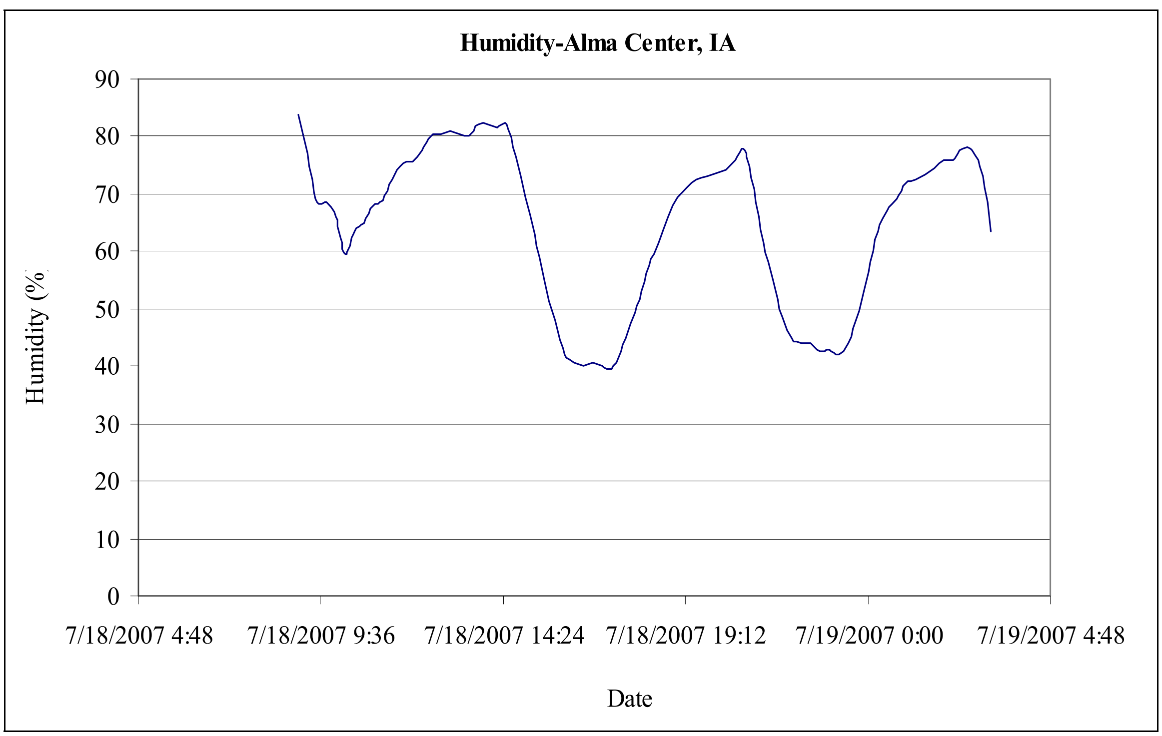


Figure 97. Humidity at the Alma Center, IA

5.7.1.2 Results and Analysis

The predicted temperatures using both the hydration curve parameters back-calculated from isothermal tests and semi-adiabatic tests are presented in Figure 98–100. The figures show hydration curve parameters generated from semi-adiabatic test data better match actual pavement temperatures than the curves generated by the isothermal test data. The temperatures using the hydration curve parameters of isothermal tests have a delay at the first cycle due to a larger τ value. Therefore, results using the semi-adiabatic test data are recommended by this research. It should be noted that the measured pavement temperatures may have errors due to equipment and environmental conditions.

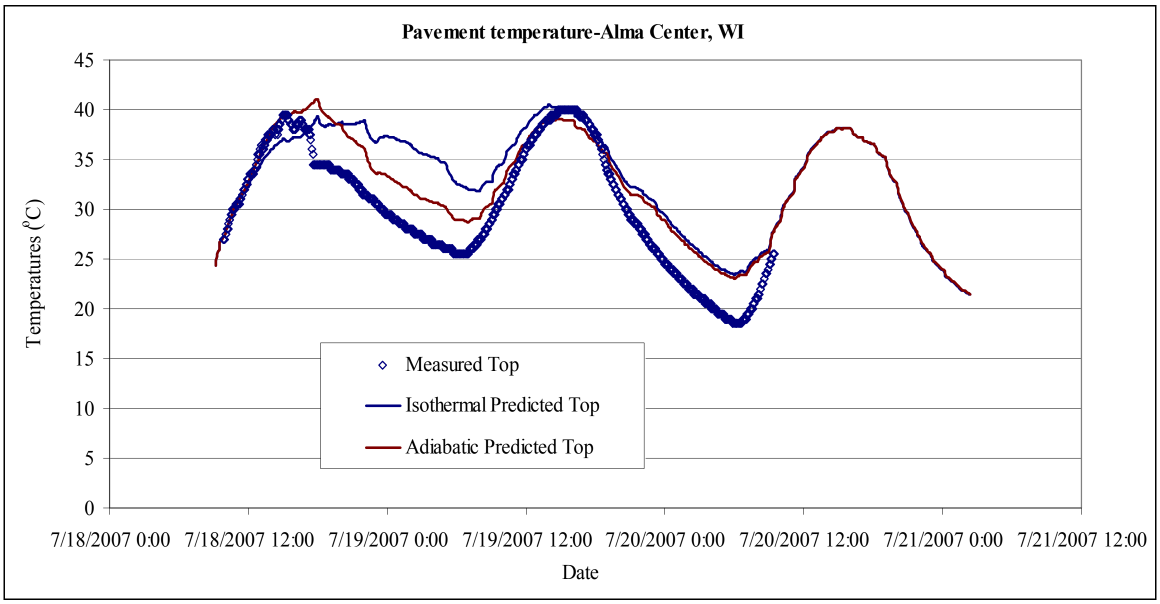


Figure 98. Predicted pavement temperatures versus measurements (pavement top, Alma Center, WI)

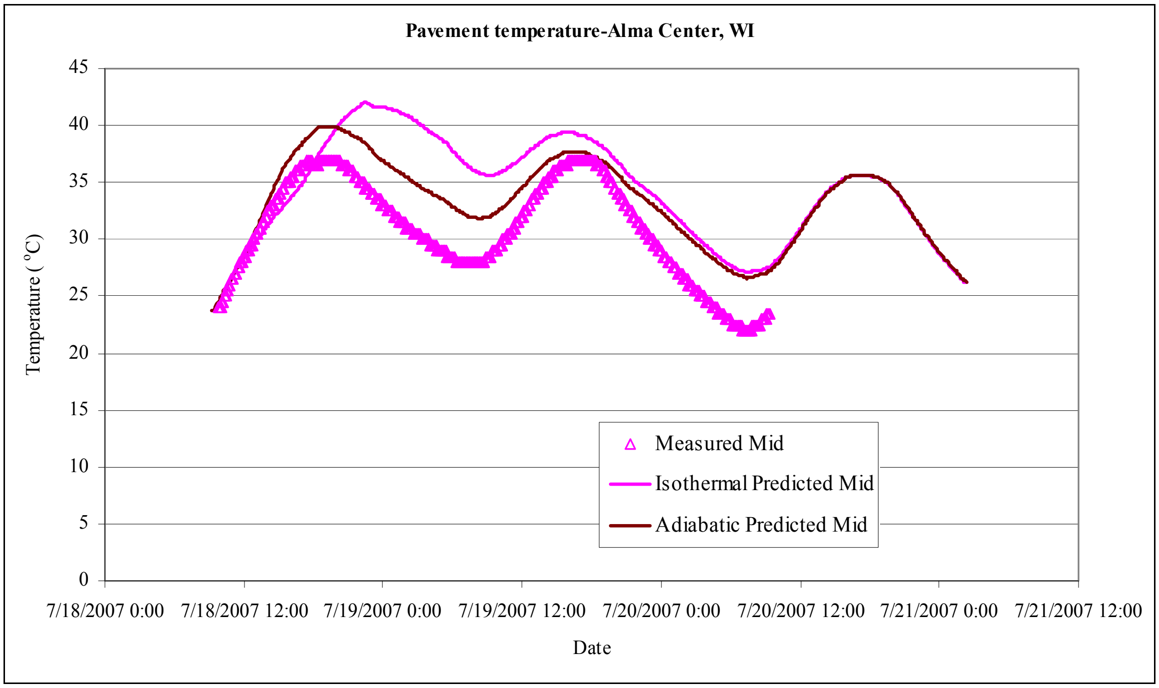


Figure 99. Predicted pavement temperatures versus measurements (pavement mid, Alma Center, WI)

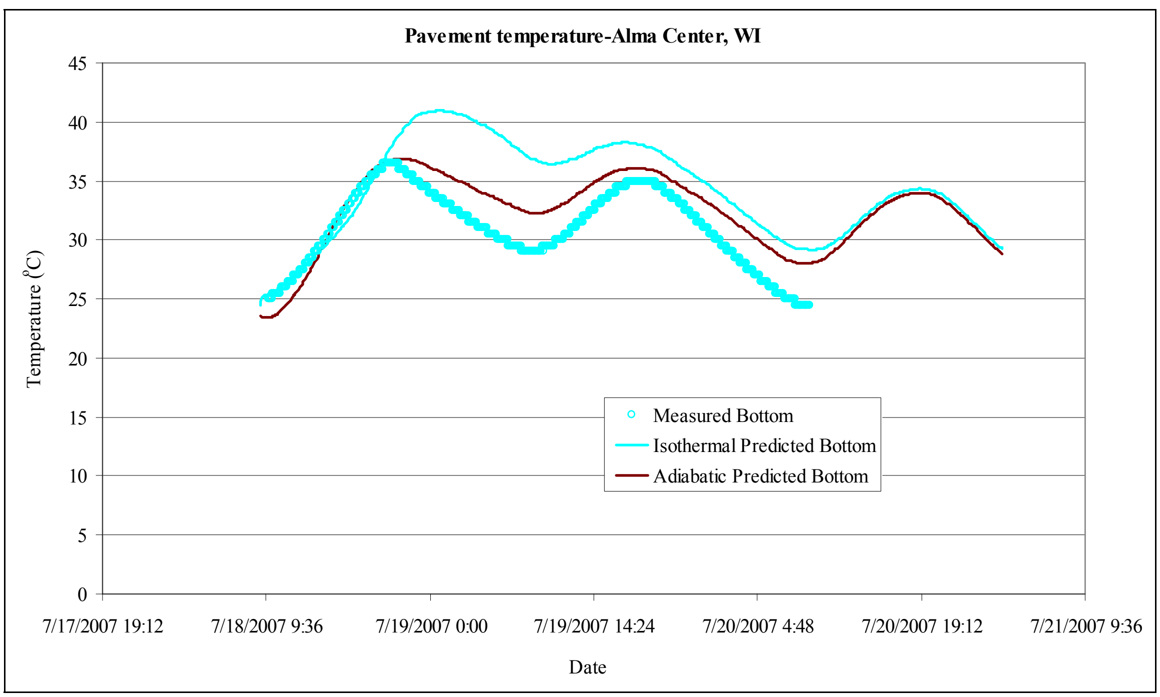


Figure 100. Predicted pavement temperatures versus measurements (pavement bottom, Alma Center, WI)

5.7.2 Atlantic Pavement Temperature and Prediction

5.7.2.1 Inputs

The weather information for temperature, wind speed and humidity in Atlantic, Iowa is plotted in Figure 101–103.

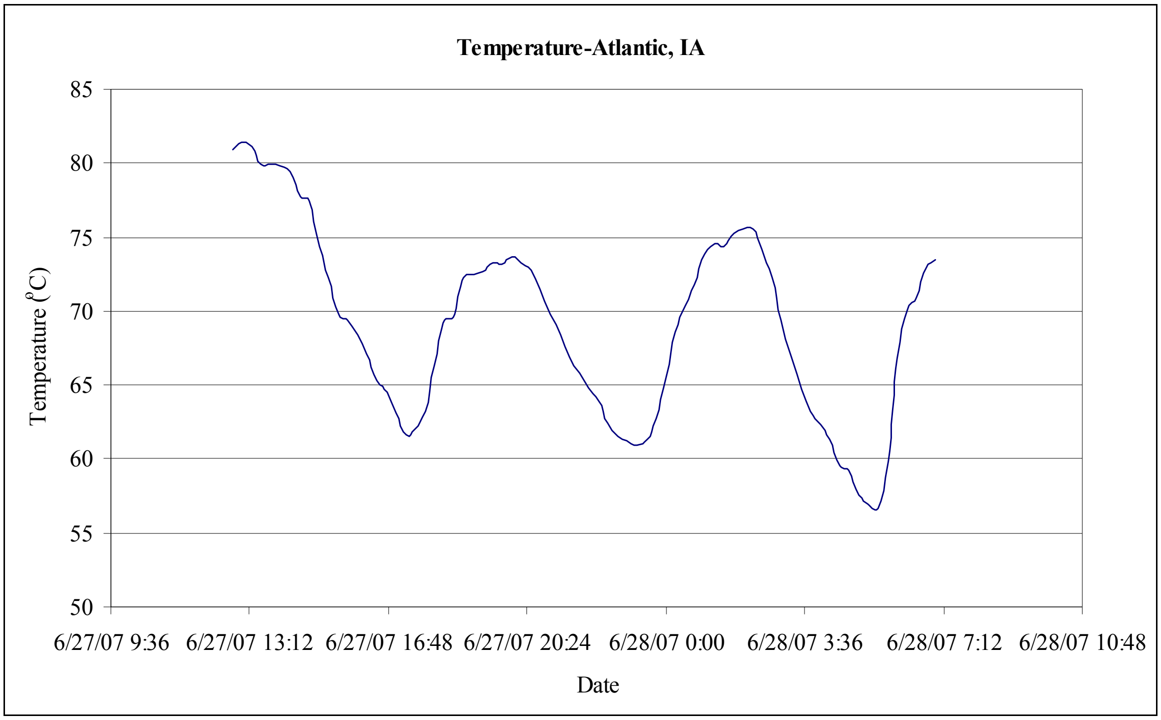


Figure 101. Temperature in Atlantic, IA

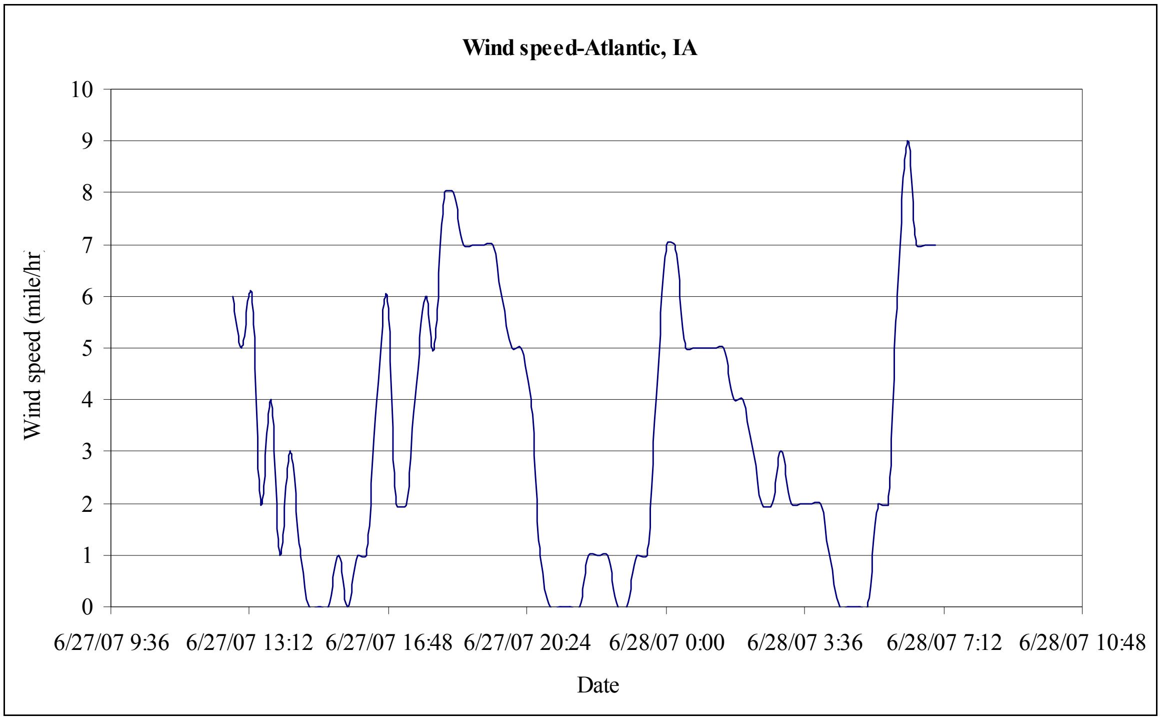


Figure 102. Wind Speed in Atlantic, IA

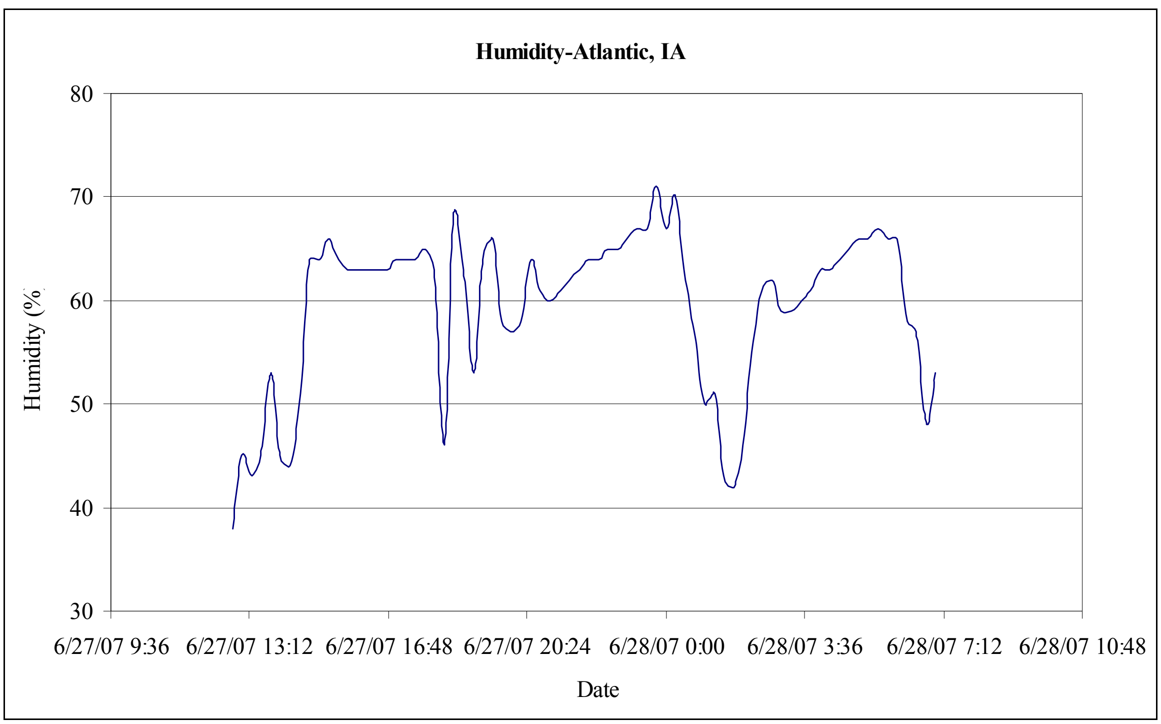


Figure 103. Humidity in Atlantic, IA

5.7.2.2 Results and Analysis

The predicted temperatures of pavement placed in Atlantic, Iowa are presented in Figure 104–106. The results of hydration curve parameters modeled by semi-adiabatic test data match actual pavement temperatures better than the hydration curve parameters resulting from isothermal test data. It is noted that the pavement temperatures for the bottom of the slab experienced a sharp drop which might be attributed to sensor error during that period.

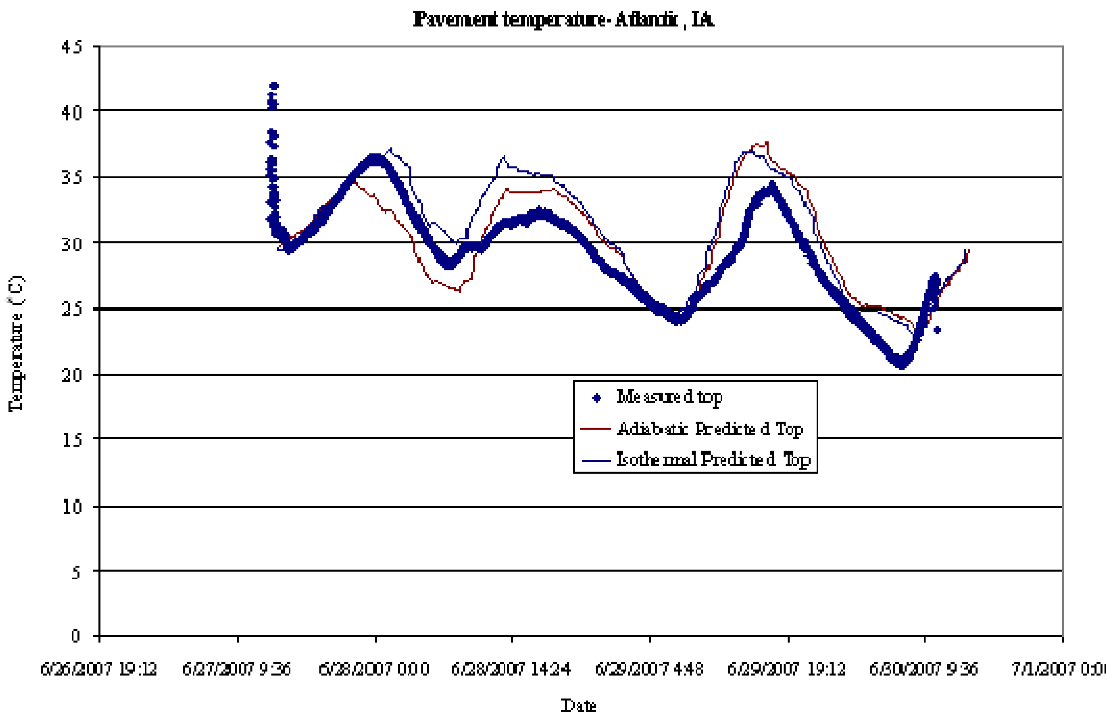


Figure 104. Predicted pavement temperatures versus measurements (pavement top, Atlantic, IA)

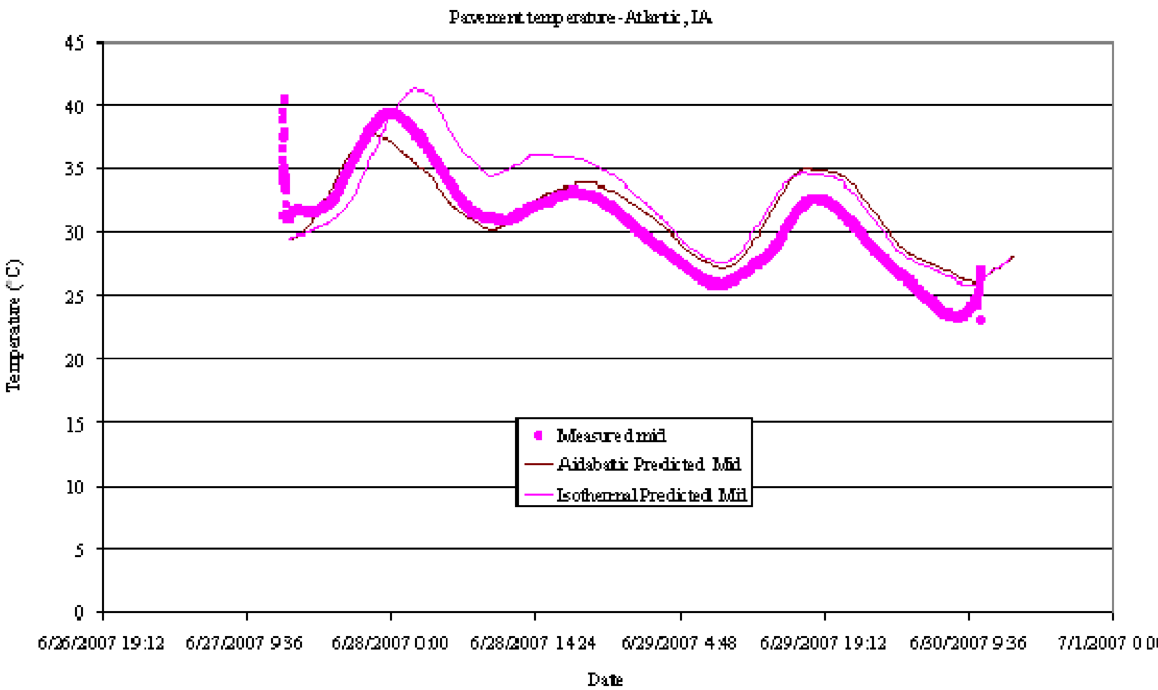


Figure 105. Predicted pavement temperatures versus measurements (pavement mid, Atlantic, IA)

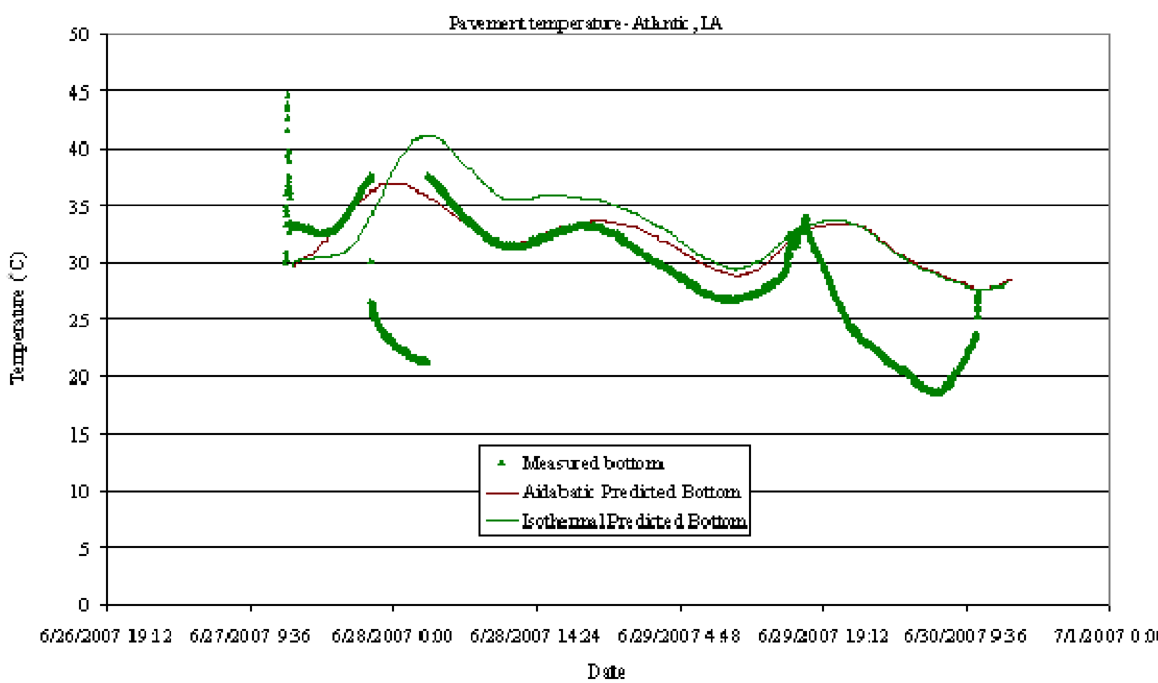


Figure 106. Predicted pavement temperatures versus measurements (pavement mid, Atlantic, IA)

5.7.3 Ottumwa Pavement Temperature and Prediction

5.7.3.1 Inputs

The weather information of temperature, wind speed and humidity in Ottumwa, Iowa were downloaded from the Weather Underground website (http://www.wunderground.com/) and are shown in Figure 107–109.

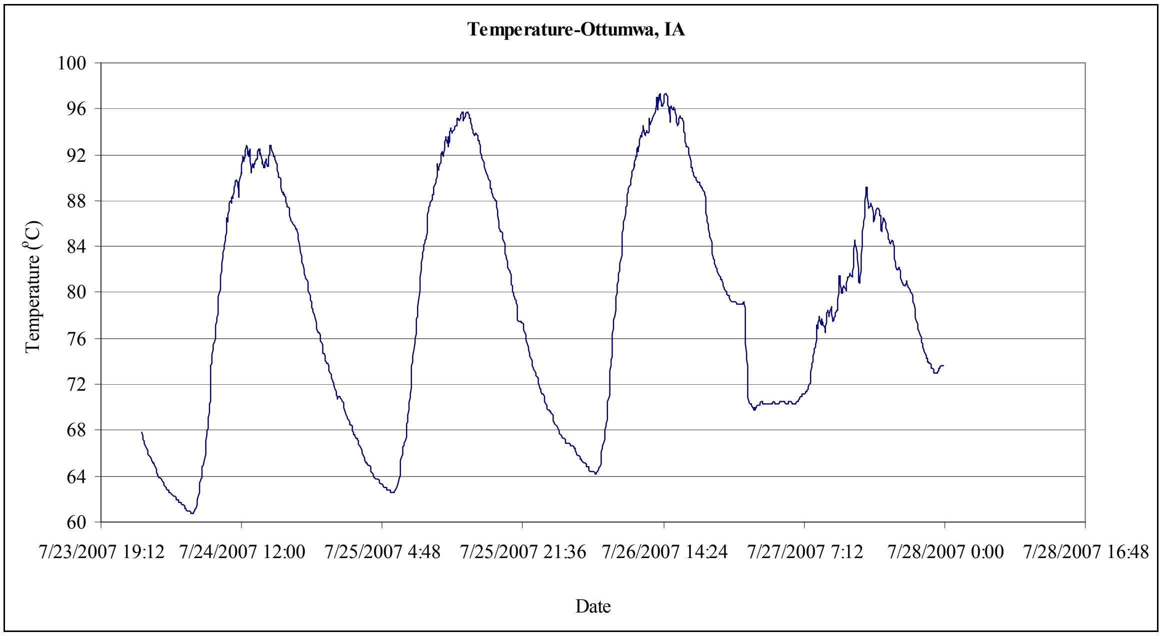


Figure 107. Temperature in Ottumwa, IA

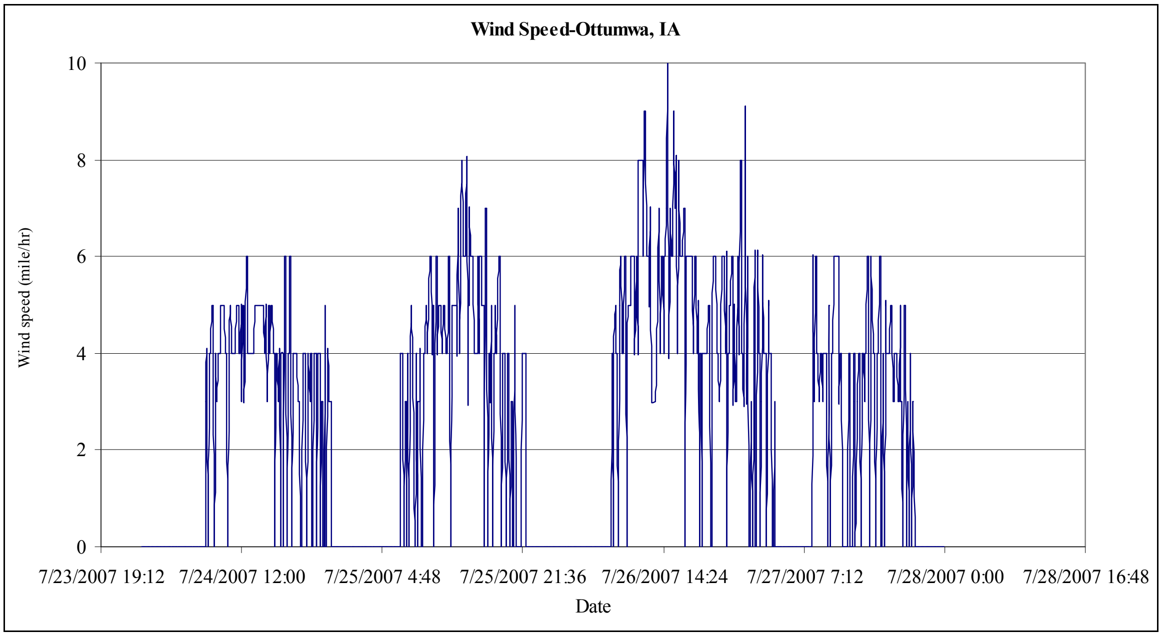


Figure 108. Wind speed in Ottumwa, IA

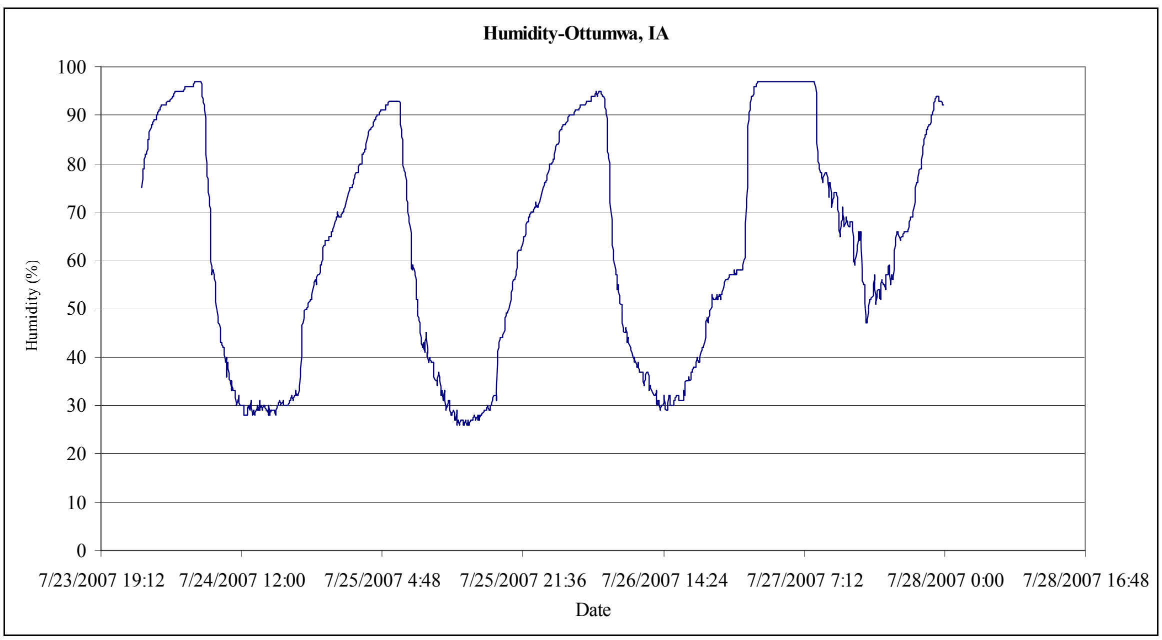


Figure 109. Humidity in Ottumwa, IA

5.7.3.2 Results and Analysis

The predicted temperatures of a pavement in Ottumwa using both the hydration curve parameters back-calculated from the isothermal test and the semi-adiabatic test are presented in Figures 110–112. Like the cases before, the results indicate hydration curve parameters resulting from semi-adiabatic test data (as opposed to isothermal test data) are a better match to actual pavement temperatures. As seen in the previous case, a sharp drop in actual pavement temperatures is recorded for the bottom of the slab. Again, this drop could be attributed to sensor error.

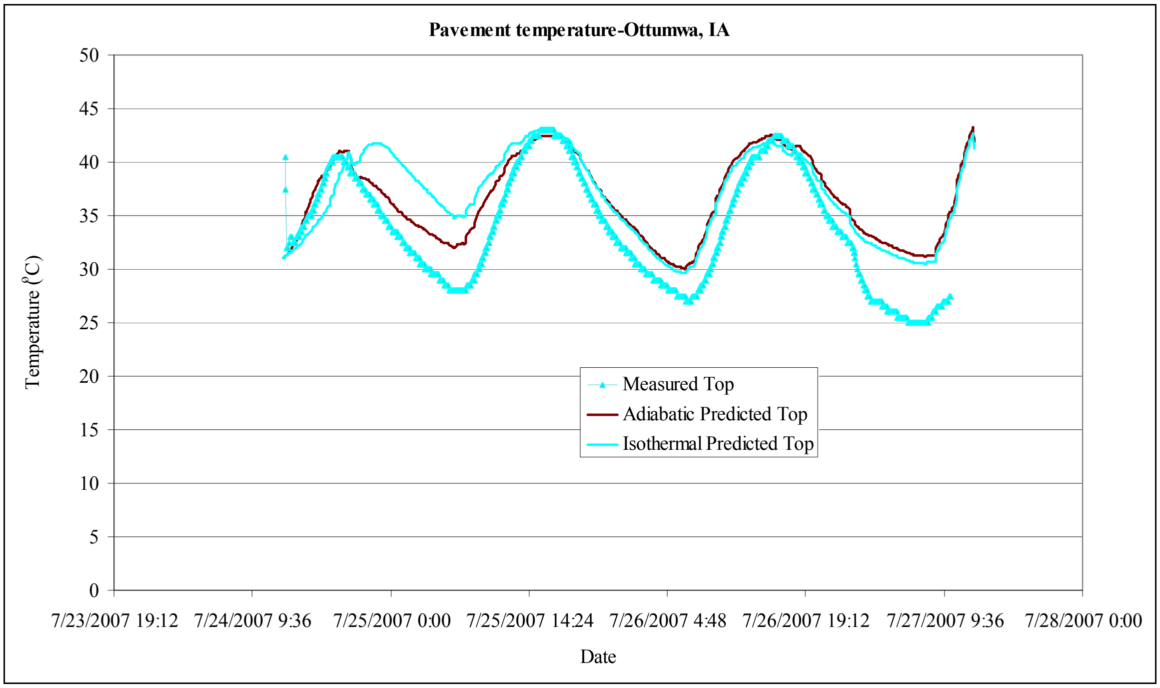


Figure 110. Predicted pavement temperatures versus measurements (pavement top, Ottumwa, IA)

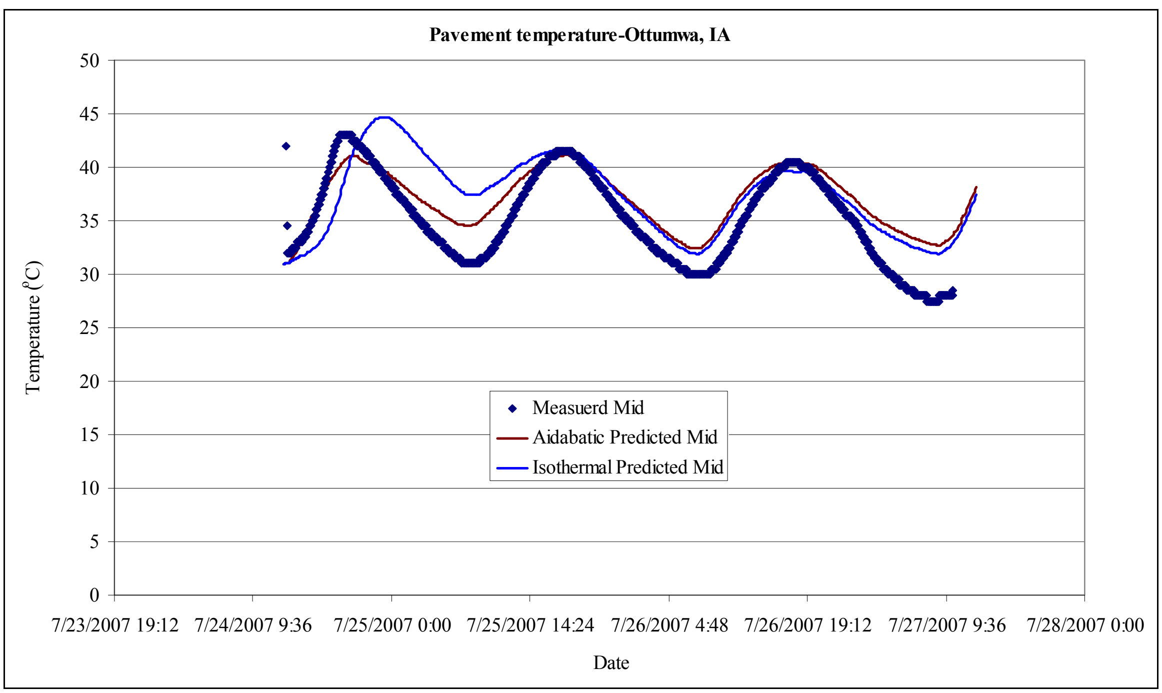


Figure 111. Predicted pavement temperatures versus measurements (pavement mid, Ottumwa, IA)

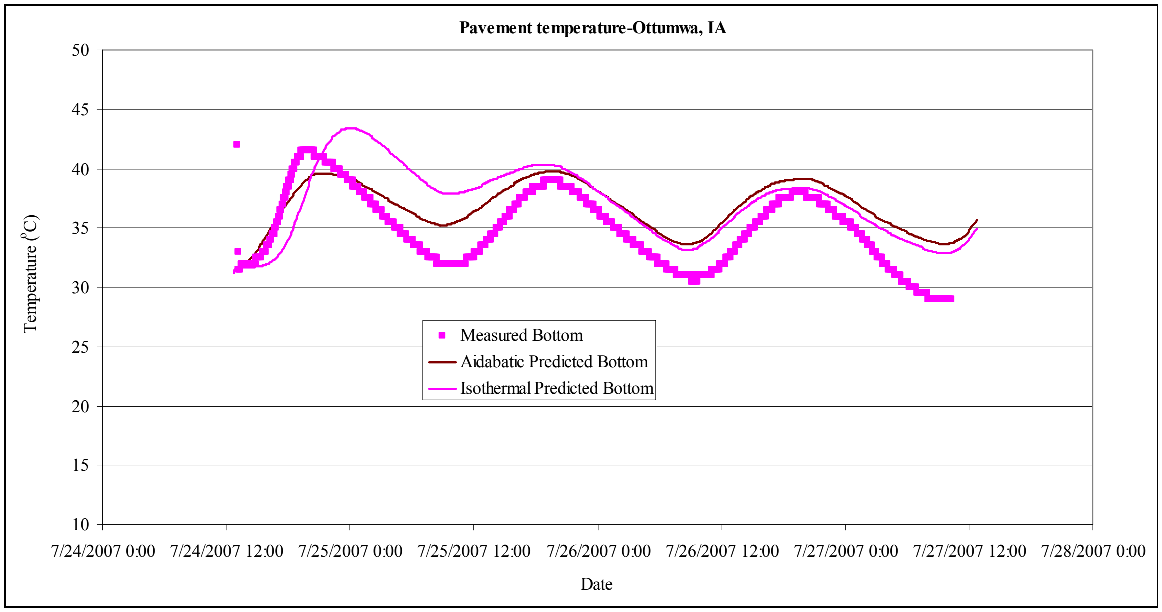


Figure 112. Predicted pavement temperatures versus measurements (pavement bottom, Ottumwa, IA)

5.7.4 Summary

In summary of this section, the predicted pavement temperatures using HIPERPAV software prove to be in agreement with actual measurements. The simulated temperatures using the hydration curve parameters of semi-adiabatic tests were proven to have higher accuracy than those using the hydration curve parameters of isothermal tests. This result could be attributed to at least two reasons: (1) the semi-adiabatic test condition of increased temperature is closer to that of the in situ pavement than that of isothermal test condition of constant temperature; (2) the isothermal test in this project is performed on the cement mortar, while the semi-adiabatic test is performed on concrete as that of in situ pavement. Therefore, the hydration curve parameters of semi-adiabatic tests are recommended for implementation in HIPERPAV software.

5.8 Conclusion

This section presented procedures for ascertaining hydration curve parameters from isothermal and semi-adiabatic calorimetric test data in an effort to create a modified version of Federal Highway's HIPERPAV II software that would predict concrete hydration and pavement temperatures with more accuracy. Several analyses were also performed to establish which set of parameters from laboratory testing (isothermal or semi-adiabatic) offer better accuracy in HIPERPAV analysis of actual field testing sites.

The original HIPERPAV II software uses an embedded, empirical, chemical-based function (6,7,8) to determine hydration curve parameters to develop heat evolution. However, it would be more reliable to use laboratory or field test results to characterize the hydration of cementitious materials. First, the activation energy, a material parameter necessary for determining hydration curve parameters, was computed using the Arrhenius equation. Hydration curve parameters were calculated using both the isothermal and semi-adiabatic test data for the rate of heat evolution. A mathematical model and computation approach to convert the isothermal calorimetry of cement mortar to semi-adiabatic calorimetric of cement concrete was developed and realized using the finite difference method. The HIPERPAV II software was modified to allow user defined inputs for hydration curve parameters. Finally, analyses using the modified software (for both isothermal and semi-adiabatic data inputs) were compared to actual field site conditions and pavement temperatures at three different locations.

As a result of the comparison, it was determined that a higher accuracy could be achieved in HIPERPAV analyses by using hydration curve parameters calculated from semi-adiabatic test data.

It is critical to predict pavement temperature effectively in order to evaluate the development of critical stresses and concrete strengths when using the HIPERPAV software. Therefore, hydration curve parameters based on the semi-adiabatic tests are recommended as inputs to the software for increased accuracy and reliability. Already a powerful tool for the paving community, an even more accurate and reliable HIPERPAV program will give contractors that much more of an edge on predicting early age concrete behavior, preventing unnecessary cracking, and securing their financial investments.

6. SPECIFICATION MODIFICATION

During the phase III study, the isothermal calorimetry tests followed the procedure described in the draft of a specification developed in the phase II study. Minor modifications were made on the test procedure during the phase III field tests. The revised specification for the isothermal calorimeter equipment and test method for mortar and concrete is presented in Appendix E. It is expected that the proposed specification of the present research will serve as a key reference for the future ASTM and/or AASHTO concrete calorimeter specification development.

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7. CONCLUSIONS AND RECOMMENDATIONS

Three field sites, US 71 (Atlantic, Iowa), Highway 95 (Alma Center, Wisconsin), and US 63 bypass (Ottumwa, Iowa) were selected, and calorimetry tests were conducted at these field sites using different calorimeters: a simple isothermal calorimeter, and two semi-adiabatic calorimeters (AdiaCal and IQ drum). The set times of the field concrete were also measured according to ASTM C403, and general properties of the concrete and pavement (such as concrete slump, air content, unit weight, w/c, placement temperature, and pavement subbase temperature and sawing time) were also recorded. The results from the field tests indicate the following:

- AdiaCal semi-adiabactic calorimetry tests, using concrete samples, can provide general information on concrete performance. The test results are very sensitive to the concrete placement temperature. (The temperature curves obtained from the AdiaCal calorimeter tests varied largely in the samples tested in the same day.) Thus, the test results are useable for set time prediction of field concrete but not desirable for accurate quality control.
- Same as the finding drawn in the phase II study, the thermal set times obtained form both AdiaCal and isothermal calorimetry tests are well related to those from the ASTM C403 tests. Compared with the isothermal calorimetry test, the AdiaCal test is easy to operate.
- The simple isothermal calorimetry test results of samples at a given project were consistent. The test results of samples from different projects looked very different, demonstrating the subtle changes in these concrete materials and/or mixture proportions. As a result, the simple isothermal calorimeter could be a good tool for daily concrete quality control.
- In the simple isothermal calorimetry tests, concrete samples showed much larger variations than mortar samples. Therefore, mortar samples sieved from field concrete are recommended for field calorimetry tests.
- The general property tests of field concrete (such as slump, temperature, air content, and unit weight and w/c tests) indicated that field concrete mixes were consistent from day to day. No incompatibility problem was identified in the concrete studied.
- Neither the isothermal calorimeter nor AdiaCal showed good ability to identify changes in w/c ratio of the field concrete. Hence, the microwave method can be used as a supplementary test for such identification.
- Pavement sawing times were close to the final setting time in these three field projects, but no clear relationship was observed between the setting and sawing times.

Robust tests were conducted in lab for the concrete materials obtained from the above mentioned three field sites. Nine robust mixes, with 50% decrease/increase of WR and/or FA dosages were developed based on the mix proportion actually used in field for each field project. AdiaCal tests were performed for each robust mix, and isothermal calorimeter tests were performed for each robust mix at four different temperatures. Selected IQ drum tests and ASTM C403 set time tests were also performed in lab so as to compare the lab results with the field test results. A statistical analysis was conducted to analyze these test data. The results from the lab tests for the field materials suggest the following:

- The results from the lab tests for the field materials are generally consistent with those from the corresponding field tests.
- The simple isothermal tests showed clearly a second peak related to the hydration of fly ash in the concrete mixes tested. Such a heat evolution peak was not generally observed from

AdiaCal or IQ Drum tests.

- The thermal set times obtained from both AdiaCal and isothermal calorimetry tests were closely related to those from the ASTM C403 tests. The effects of WR dosage and FA replacement level on concrete set time could be identified by both calorimetry test methods.
- The simple isothermal test results illustrated that as testing temperature increased, the variation in thermal set time decreased. This implies that potential concrete set time and strength development problems might show in winter construction while fewer problems may be expected in summer construction.
- Testing/curing temperature had a more significant effect on concrete calorimetry parameters (thermal set time and the area under the heat evolution curve) than WR and FA.
- Compared with FA, WR has less effect on thermal set time. However, in a different project, WR affected calorimetry parameters differently.
- The robust tests demonstrated that when the WR and/or FA amounts are 50% higher or lower than the designed dosage, the concrete heat-generation curves looked similar but shifted only to the left or right, depending upon the degree of material variation. There was no incompatibility problem within these mixes tested at the designed testing temperature.
- The robust test method can be used for establishing acceptable heat evolution boundaries. Thus, field engineers can easily evaluate their calorimetry test results and use the calorimetry as a single tool for field concrete quality control.

The computation and theoretical modeling are performed for ascertaining hydration curve parameters from isothermal and semi-adiabatic calorimetric test data, in an effort to create a modified version of Federal Highway's HIPERPAV II software that would predict concrete hydration and pavement temperatures with more accuracy. The original HIPERPAV II software is modified to allow the users to input the laboratory or field-test determined hydration curve parameters. First, the activation energy, a material parameter necessary for determining hydration curve parameters, was computed using the Arrhenius equation. Consequently, hydration curve parameters were calculated using both the isothermal and semi-adiabatic test data. Meanwhile, a mathematical model and computation approach to convert the isothermal calorimetry of cement mortar to semi-adiabatic calorimetry of cement concrete was developed and realized using the finite difference method. Finally, analyses using the modified software (for both isothermal and semi-adiabatic data inputs) were compared to actual field site conditions and pavement temperatures at three different locations (Alma Center, WI; Atlantic, IA; Ottumwa, IA). The primary findings are summarized as the following:

- The computed activation energies of cementitioius materials used in this research from the isothermal test data are close to the values reported by other researchers; adding WR and FA replacement seems to improve activation energy to some extent
- A higher accuracy of predicted pavement temperatures could be achieved in HIPERPAV analyses by using hydration curve parameters calculated from semi-adiabatic test data.
- It is critical to predict pavement temperature effectively in order to evaluate the development of critical stresses and concrete strengths using the HIPERPAV software. Therefore, hydration curve parameters based on the semi-adiabatic tests are recommended as inputs to the software for increased accuracy and reliability.
- The simulated semi-adiabatic temperatures converted from the isothermal heat signatures using the theoretical models seem to have a reasonable agreement with the measurements though there is some small delay at the early stage. Therefore, it is a possibility to use this

model and computation approach for conversion between different calorimetry signatures.

Based on the results of the present study, the following recommendations are proposed:

- Calorimetry tests may be used (1) by concrete mix proportion designers and the cement industry for checking strength development at different temperature condition and the incompatibility of using SCMs and chemical admixtures, (2) by contractors as a quality control tool for flagging material changes and mix proportion errors and for estimation of concrete set time (AdiaCal tests), and (3) by others for prediction concrete pavement temperature development and cracking potential via using the HIPERPAV.program.
- The calorimetry research results shall be disseminated through various workshops, tech notes, newsletters, and websites to increase awareness of advantages of using calorimetry in concrete practice.
- Research should be continued on the specification development for using calorimetry technique in concrete and on the prediction of concrete performance using calorimetry test results in the HIPERPAV program.

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APPENDIX A: INFORMATION OF FIELD PROJECTS

A.1 Information for Atlantic Project

Batch ticket

Date:	June 27, 2007		Time:				12:38:26 p.m.
Batch Size:							8,50 cyds
Material	Indication (lb)	Targets (lb)	% Tol	WatFree (lb)	Moist %		(lb)
FA	11640	11710	-0.06	554.3	5.00	Dry Aggs	26678
CA	13420	13353	0.50	93.3	0.70	Cemes	4695
IA	2300	2355	-2.30	34.0	1.50	Waters	1932
Cement	3760	3757	0.10			Total	33305
Fly Ash	935	935	0.00			w/c	0.411
Water	150 G	153	-2.00	1250.0		Add:	-1G
Air Entr	107 fl.oz	108 fl.oz	-1.70			Temper:	0 G
Reducer	189 fl.oz	188 fl.oz	0.70				

Date:	June 28, 2007		Time:				9:15:18 a.m.
Batch Size:							8,50 cyds
Material	Indication (lb)	Targets (lb)	% Tol	WatFree (lb)	Moist %		(lb)
FA	11680	11710	-0.3	556.2	5.00	Dry Aggs	26657
CA	13340	13353	-0.1	92.7	0.70	Cemes	4685
IA	2320	2355	-1.5	34.3	1.50	Waters	1867
Cement	3750	3757	-0.2			Total	33208
Fly Ash	935	935	0.0			w/c	0.398
Water	125 G	153	-2.3	1041.7		Add:	6 G
Air Entr	108 fl.oz	108 fl.oz	-2.3			Temper:	17 G
Reducer	187 fl.oz	188 fl.oz	-0.4				

Date:	June 28, 2007			Time:			11:20:37 a.m.
Batch Size:							8,50 cyds
Material	Indication (lb)	Targets (lb)	% Tol	WatFree (lb)	Moist %		(lb)
FA	11660	11710	-0.4	555.2	5.00	Dry aggs	26598
CA	13320	13353	-0.2	92.6	0.70	Cemes	4680
IA	2300	2355	-2.3	34.0	1.50	Waters	1865
Cement	3745	3757	-0.3			Total	33143
Fly Ash	935	935	0.0			w/c	0.399
Water	120 G	153	-2.4	1000.0		Add:	6 G
Air Entr	108 fl.oz	108 fl.oz	-2.3			Temper:	22 G
Reducer	187 fl.oz	188 fl.oz	-0.4				

Date:	June 28, 2007			Time:			1:37:34 p.m.
Batch Size:							8,50 cyds
Material	Indication (lb)	Targets (lb)	% Tol	WatFree (lb)	Moist %		(lb)
FA	11680	11710	-0.3	556.2	5.00	Dry Aggs	26577
CA	13260	13353	-0.7	92.2	0.70	Cemes	4685
IA	2320	2355	-1.5	34.3	1.50	Waters	1949
Cement	3760	3757	0.1			Total	33212
Fly Ash	925	935	-1.1			w/c	0.416
Water	141 G	153	-1.4	1175.0		Add:	-4 G
Air Entr	108 fl.oz	108 fl.oz	-2.3			Temper:	11 G
Reducer	187 fl.oz	188 fl.oz	-0.4				

Date:	June 29, 2007			Time:			9:07:03 a.m.
Batch Size:							8,50 cyds
Material	Indication (lb)	Targets (lb)	% Tol	WatFree (lb)	Moist %		(lb)
FA	11700	11710	-0.2	556.2	5.00	Dry Aggs	26531
CA	13260	13353	-0.8	92.7	0.80	Cemes	4660
IA	2280	2355	-3.3	34.3	1.60	Waters	2009
Cement	3725	3757	-0.9			Total	3320
Fly Ash	9935	935	0.0			w/c	0.431
Water	127 G	153	-2.3	1058.3		Add:	-12 G
Air Entr	108 fl.oz	108 fl.oz	-2.3			Temper:	29 G
Reducer	187 fl.oz	188 fl.oz	-0.4				

Date:	June 29, 2007			Time:			10:59:03 a.m.
Batch Size:							8,50 cyds
Material	Indication (lb)	Targets (lb)	% Tol	WatFree (lb)	Moist %		(lb)
FA	11740	11710	0.2	569.7	5.00	Dry Aggs	26845
CA	13280	13353	-0.6	105.4	0.80	Cemes	4670
IA	2540	2355	7.7	40.0	1.60	Waters	1948
Cement	3765	3757	0.2			Total	33463
Fly Ash	905	935	-3.2			w/c	0.417
Water	142 G	153	-2.1	1183.3		Add:	-5 G
Air Entr	108 fl.oz	108 fl.oz	-2.3			Temper:	6 G
Reducer	187 fl.oz	188 fl.oz	-0.4				

Date:	June 29, 2007			Time:			2:59:03 p.m.
Batch Size:							8,50 cyds
Material	Indication (lb)	Targets (lb)	% Tol	WatFree (lb)	Moist %		(lb)
FA	11740	11710	0.2	569.7	5.10	Dry Aggs	26727
CA	13360	13353	0.0	106.0	0.80	Cemes	4670
IA	2340	2355	-0.7	36.9	1.60	Waters	2013
Cement	3735	3757	-0.6			Total	33410
Fly Ash	935	935	0.0			w/c	0.43
Water	137 G	153	-2.1	1141.7		Add:	-12 G
Air Entr	108 fl.oz	108 fl.oz	-2.3			Temper:	19 G
Reducer	187 fl.oz	188 fl.oz	-0.4				

Date:	June 30, 2007			Time:			8:53:51 a.m.
Batch Size:							8,50 cyds
Material	Indication (lb)	Targets (lb)	% Tol	WatFree (lb)	Moist %		(lb)
FA	13380	13340	0.3	79.8	0.6	Dry Aggs	26800
CA	11740	11698	0.4	548.4	4.9	Cemes	4695
IA	2340	2353	-0.6	32.3	1.4	Waters	1860
Cement	3770	3757	0.3			Total	33355
Fly Ash	925	935	-1.1			w/c	0.396
Water	144 G	146 G	-1.4	1200.0		Add:	7 G
Air Entr	110 fl.oz	112 fl.oz	-2.0			Temper:	0 G
Reducer	187 fl.oz	188 fl.oz	-0.4				

Date:	June 30, 2007			Time:			11:45:41 a.m.
Batch Size:							8,50 cyds
Material	Indication (lb)	Targets (lb)	% Tol	WatFree (lb)	Moist %		(lb)
FA	13280	13340	-0.4	79.2	0.60	Dry Aggs	26802
CA	11640	11698	-0.5	543.7	4.90	Cemes	4685
IA	2540	2353	7.9	35.1	1.40	Waters	1966
Cement	3765	3757	0.2			Total	33453
Fly Ash	920	935	-1.6			w/c	0.42
Water	148 G	151 G	-2.0	1233.3		Add:	-6 G
Air Entr	110 fl.oz	112 fl.oz	-2.0			Temper:	9 G
Reducer	187 fl.oz	188 fl.oz	-0.4				

Date:	June 30, 2007			Time:			1:23:31 p.m.
Batch Size:							8,50 cyds
Material	Indication (lb)	Targets (lb)	% Tol	WatFree (lb)	Moist %		(lb)
FA	13400	13340	0.5	79.9	0.60	Dry Aggs	26704
CA	11660	11698	-0.3	544.7	4.90	Cemes	4680
IA	2300	2353	-2.3	31.8	1.40	Waters	2040
Cement	3745	3757	-0.3			Total	33423
Fly Ash	935	935	0.0			w/c	0.436
Water	153 G	146 G	-1.9	1275.0		Add:	-15 G
Air Entr	111 fl.oz	112 fl.oz	-1.1			Temper:	13 G
Reducer	187 fl.oz	188 fl.oz	-0.4				

Date:	July 2, 2007			Time:			9:14:19 a.m.
Batch Size:							8,50 cyds
Material	Indication (lb)	Targets (lb)	% Tol	WatFree (lb)	Moist %		(lb)
FA	13240	13287	-0.4	26.4	0.20	Dry Aggs	26566
CA	11540	11620	-0.7	465.1	4.20	Cemes	4685
IA	2300	2344	-1.9	22.8	1.00	Waters	1864
Cement	3770	3757	0.3			Total	33115
Fly Ash	915	935	-2.1			w/c	0.398
Water	162 G	163 G	-0.6	1350.0		Add:	6 G
Air Entr	111 fl.oz	112 fl.oz	-1.1			Temper:	0 G
Reducer	187 fl.oz	188 fl.oz	-0.4				

Date:		July 2, 2007		Time:			10:55:39 a.m.
Batch Size:							8,50 cyds
Material	Indication (lb)	Targets (lb)	% Tol	WatFree (lb)	Moist %		(lb)
FA	13240	13287	-0.4	26.4	0.20	Dry Aggs	26546
CA	11520	11620	-0.9	464.3	4.20	Cemes	4710
IA	2300	2344	-1.9	22.8	1.00	Waters	1830
Cement	3765	3757	0.2			Total	33087
Fly Ash	945	935	1.1			w/c	0.389
Water	158 G	158 G	0.0	1316.7		Add:	12 G
Air Entr	112 fl.oz	112 fl.oz	-0.2			Temper:	0 G
Reducer	187 fl.oz	188 fl.oz	-0.4				

Date:		July 2, 2007		Time:			12:53:42 p.m.
Batch Size:							8,50 cyds
Material	Indication (lb)	Targets (lb)	% Tol	WatFree (lb)	Moist %		(lb)
FA	13360	13287	0.6	26.7	0.20	Dry Aggs	26819
CA	11720	11620	0.9	472.4	4.20	Cemes	4720
IA	2260	2344	-3.6	22.4	1.00	Waters	1855
Cement	3780	3757	0.6			Total	33393
Fly Ash	940	935	0.5			w/c	0.393
Water	145 G	148 G	-2.0	1208.3		Add:	9 G
Air Entr	113 fl.oz	114 fl.oz	-0.8			Temper:	15 G
Reducer	188 fl.oz	188 fl.oz	0.2				

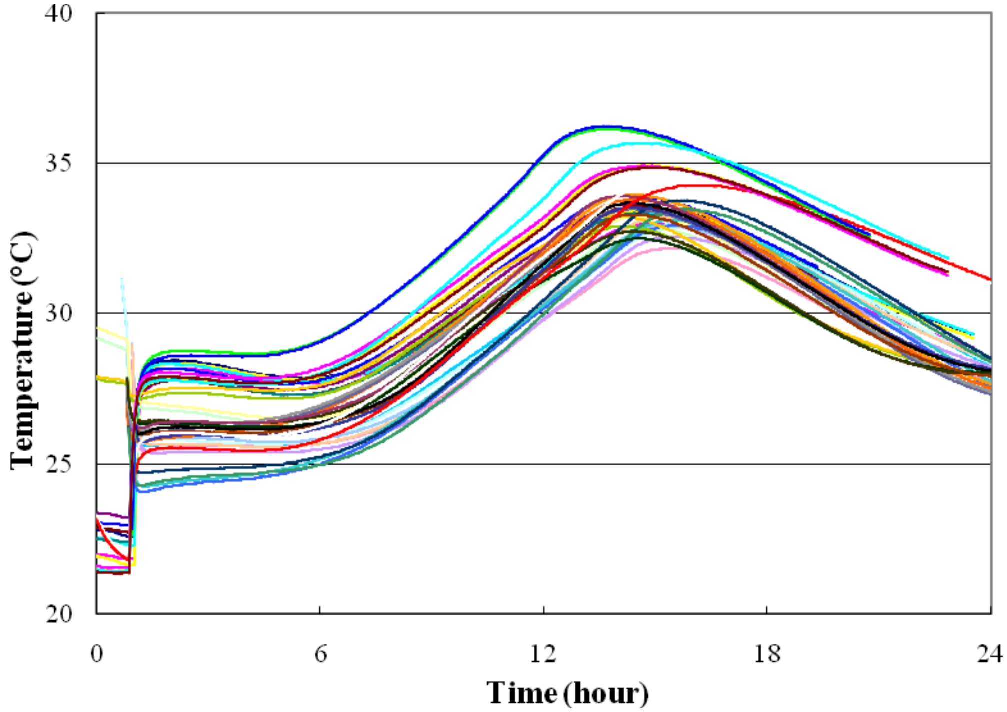


Figure A.1. Concrete temperature for all samples for Atlantic project

A.2 Information for Alma Center Project

Batch Ticket

Date:	July 17, 2007		Time:				08:42:11 a.m.
Ticket No.		13575	Truck no.				
Batch Size:		10.00 cyds	Total Shipped				450.00 cyds
Material	Dsg Qty	Req'd	Bat'd	B/R	Moisture		Actual Water
Sand	1370.00	14043	13940	0.993	2.50%	340.00	40.02
3/4 in.	1210.00	12221	12140	0.993	1.00%	120.20	14.43
1 ½ in.	615.00	6212	6160	0.992	1.00%	60.99	7.32
Cement	446.00	4460	4448	0.997			
Fly Ash	113.00	1130	1105	0.978			
Water	20.00	2041	1999	0.980		1999.19	240.00
Daravair	5.50	55.0	54.0	0.982		3.51	0.42
WRDA 82	18.00	180.00	177.0	0.983		11.52	1.38
Water Trim	916.30 lb	Water Added	0.00		Total Water	2535.42 lb	304.37 gal
w/c	0.457						

Date:	July 17, 2007		Time:				10:51:58 a.m.
Ticket No.		13629	Truck no.				
Batch Size:		10.00 cyds	Total Shipped				10.00 cyds
Material	Dsg Qty	Req'd	Bat'd	B/R	Moisture		Actual Water
Sand	1370.00	14043	13980	0.996	2.50%	340.98	40.93
¾ in.	1210.00	12221	12160	0.995	1.00%	120.40	14.45
1 ½ in.	615.00	6212	6240	1.005	1.00%	61.78	7.42
Cement	750.00	7500	7437	0.992			
Fly Ash	0.00	0	0	0			
Water	25.00	2416	2374	0.983		2374.05	285.00
Daravair	6.75	68	68.0	1.00		4.43	0.53
WRDA 82	22.50	225	222.0	0.987		14.45	1.73
Water Trim	874.65 lb	Water Added	0.00		Total Water	2916.08 lb	350.07 gal
w/c	0.392						

Date:	July 17, 2007			Time:			01:28:35 p.m.
Ticket No.	13689			Truck no.			
Batch Size:	10.00 cyds			Total Shipped			1580.00 cyds
Material	Dsg Qty	Req'd	Bat'd	B/R	Moisture		Actual Water
Sand	1370.00	14043	13960	0.994	2.50%	340.49	40.87
¾ in.	1210.00	12221	12180	0.997	1.00%	120.59	14.48
1 ½ in.	615.00	6212	6140	0.988	1.00%	60.79	7.30
Cement	446.00	4460	4431	0.993			
Fly Ash	113.00	1130	1144	1.012			
Water	20.00	1999	1958	0.979		1957.55	235.00
Daravair	6.50	65	65.0	1.000		4.23	0.51
WRDA 82	18.00	180	177.0	0.983		11.52	1.38
Water Trim	874.65 lb	Water Added	0.00		Total Water	2495.17 lb	299.54 gal
w/c	0.448						

Date:	July 17, 2007			Time:			02:59:25 p.m.
Ticket No.	13725			Truck no.			
Batch Size:	10.00 cyds			Total Shipped			1940.00 cyds
Material	Dsg Qty	Req'd	Bat'd	B/R	Moisture		Actual Water
Sand	1370.00	14043	14120	1.005	2.50%	344.39	41.34
¾ in.	1210.00	12221	12100	0.990	1.00%	119.80	14.38
1 ½ in.	615.00	6212	6240	1.005	1.00%	61.78	7.42
Cement	446.00	4460	4427	0.993			
Fly Ash	113.00	1130	1124	0.995			
Water	20.00	1999	1958	0.979		1957.55	235.00
Daravair	6.00	60.0	60.0	1.000		3.90	0.47
WRDA 82	18.00	180.00	177.0	0.983		11.52	1.38
Water Trim	874.65 lb	Water Added	0.00		Total Water	2498.35 lb	299.99 gal
w/c	0.450						

Date:	July 18, 2007			Time:			09:23:48 a.m.
Ticket No.	13804			Truck no.			
Batch Size:	10.00 cyds			Total Shipped			670.00 cyds
Material	Dsg Qty	Req'd	Bat'd	B/R	Moisture		Actual Water
Sand	1370.00	14043	13940	0.993	2.50%	340.00	40.02
¾ in.	1210.00	12221	12220	1.000	1.00%	120.99	14.52
1 ½ in.	615.00	6212	6100	0.920	1.00%	60.40	7.25
Cement	446.00	4460	4450	0.998			
Fly Ash	113.00	1130	1089	0.964			
Water	20.00	1974	1933	0.979		1932.56	232.00
Daravair	6.50	65.0	65	1.000		4.23	0.51
WRDA 82	18.00	180	177	0.983		11.52	1.38
Water Trim	853.82 lb	Water Added	0.00		Total Water	22469.7lb	296.48 gal
w/c	0.446						

Date:	July 18, 2007			Time:			10:47:14 a.m.
Ticket No.	13840			Truck no.			
Batch Size:	10.00 cyds			Total Shipped			1030.00 cyds
Material	Dsg Qty	Req'd	Bat'd	B/R	Moisture		Actual Water
Sand	1370.00	14043	14060	1.001	2.50%	342.93	41.17
¾ in.	1210.00	12221	12120	0.992	1.00%	120.00	14.41
1 ½ in.	615.00	6212	6260	1.000	1.00%	61.98	7.44
Cement	446.00	4460	4427	0.993			
Fly Ash	113.00	1130	1149	1.017			
Water	20.00	1999	1958	0.979		1957.55	235.00
Daravair	6.50	65	65.0	1.000		4.23	0.51
WRDA 82	18.00	180	177	0.983		11.52	1.38
Water Trim	874.65 lb	Water Added	0.00		Total Water	2498.21 lb	299.90 gal
w/c	0.448						

Date:	July 18, 2007		Time:				2:07:46 p.m.
Ticket No.	13922		Truck no.				
Batch Size:	10.00 cyds		Total Shipped				1850.00 cyds

Material	Dsg Qty	Req'd	Bat'd	B/R	Moisture		Actual Water
Sand	1370.00	14043	13980	0.996	2.50%	340.98	40.93
¾ in.	1210.00	12221	12100	0.990	1.00%	119.80	14.38
1 ½ in.	615.00	6212	6220	1.001	1.00%	61.58	7.39
Cement	446.00	4460	4417	0.990			
Fly Ash	113.00	1130	1126	0.996			
Water	20.00	2041	1999	0.980		1999.19	240.00
Daravair	6.50	65	65	1.000		4.23	0.51
WRDA 82	18.00	180	177	0.983		11.52	1.38
Water Trim	916.30 lb	Water Added	0.00		Total Water	2537.31 lb	304.60 gal
w/c	0.458						

Date:	July 18, 2007		Time:				3:07:51 p.m.
Ticket No.	13943		Truck no.				
Batch Size:	10.00 cyds		Total Shipped				2050.00 cyds

Material	Dsg Qty	Req'd	Bat'd	B/R	Moisture		Actual Water
Sand	1370.00	14043	13980	0.996	2.50%	340.98	40.93
¾ in.	1210.00	12221	12200	0.998	1.00%	120.79	14.50
1 ½ in.	615.00	6212	6100	0.982	1.00%	60.40	7.25
Cement	446.00	4460	4430	0.993			
Fly Ash	113.00	1130	1126	0.996			
Water	20.00	1999	1958	0.979		1957.55	235.00
Daravair	6.50	65	64	0.985		4.17	0.50
WRDA 82	18.00	180	177	0.983		11.52	1.38
Water Trim	874.65 lb	Water Added	0.00		Total Water	2495.40 lb	299.57 gal
w/c	0.449						

Date:	July 19, 2007	Time:		08:59:33 a.m.
Ticket No.	13992	Truck no.		
Batch Size:	10.00 cyds	Total Shipped		490.00 cyds

Material	Dsg Qty	Req'd	Bat'd	B/R	Moisture	Actual Water	
Sand	1370.00	14043	14120	1.005	2.50%	344.39	41.34
¾ in.	1210.00	12221	12160	0.995	1.00%	120.40	14.45
1 ½ in.	615.00	6212	6220	1.001	1.00%	61.58	7.39
Cement	446.00	4460	4417	0.990			
Fly Ash	113.00	1130	1144	1.012			
Water	20.00	2016	1933	0.979		1932.56	232.00
Daravair	6.50	65	60.0	1.000		3.90	0.47
WRDA 82	18.00	180	177	0.983		11.52	1.38
Water Trim	853.83 lb	Water Added	0.00		Total Water	2474.35 lb	297.04 gal
w/c	0.445						

Date:	July 19, 2007	Time:		10:31:07 a.m.
Ticket No.	14030	Truck no.		
Batch Size:	10.00 cyds	Total Shipped		870.00 cyds

Material	Dsg Qty	Req'd	Bat'd	B/R	Moisture	Actual Water	
Sand	1370.00	14043	14000	0.997	2.50%	341.46	40.99
¾ in.	1210.00	12221	12140	0.993	1.00%	120.20	14.43
1 ½ in.	615.00	6212	6220	1.001	1.00%	61.58	7.39
Cement	446.00	4460	4421	0.991			
Fly Ash	113.00	1130	1134	1.004			
Water	20.00	2016	1958	0.979		1957.55	235.00
Daravair	6.50	65	59	0.983		3.54	0.46
WRDA 82	18.00	180	177	0.983		11.52	1.38
Water Trim	874.65 lb	Water Added	0.00		Total Water	2496.15 lb	299.66 gal
w/c	0.449						

Date:	July 19, 2007	Time:	11:54:39 a.m.
Ticket No.	14047	Truck no.	
Batch Size:	10.00 cyds	Total Shipped	1040.00 cyds

Material	Dsg Qty	Req'd	Bat'd	B/R	Moisture	Actual Water	
Sand	1370.00	14043	14000	0.997	2.50%	341.46	40.99
¾ in.	1210.00	12221	12140	0.993	1.00%	12.20	14.43
1 ½ in.	615.00	6212	6240	1.005	1.00%	61.78	7.42
Cement	446.00	4460	4429	0.993			
Fly Ash	113.00	1130	1136	1.005			
Water	20.00	2016	1974	0.979		1974.20	237.00
Daravair	6.50	65	60	1.000		3.90	0.47
WRDA 82	18.00	180	177	0.983		11.52	1.38
Water Trim	895.47 lb	Water Added	0.00		Total Water	2513.08	301.69 gal
w/c	0.452						

Date:	July 19, 2007	Time:	01:55:39 p.m.
Ticket No.	14097	Truck no.	
Batch Size:	10.00 cyds	Total Shipped	1530.00 cyds

Material	Dsg Qty	Req'd	Bat'd	B/R	Moisture	Actual Water	
Sand	1370.00	14043	13960	0.994	2.50%	340.49 lb	40.87 gal
¾ in.	1210.00	12221	12180	0.997	1.00%	120.59	14.48
1 ½ in.	615.00	6212	6300	1.014	1.00%	62.38	7.49
Cement	446.00	4460	4478	1.004			
Fly Ash	113.00	1130	1089	0.964			
Water	20.00	2016	1974	0.979		1974.20	237.00
Daravair	6.50	65	65	1.000		4.23	0.51
WRDA 82	18.00	180	177	0.983		11.52	1.38
Water Trim	895.47 lb	Water Added	0.00		Total Water	2513.42 lb	301.73 gal
w/c	0.451						

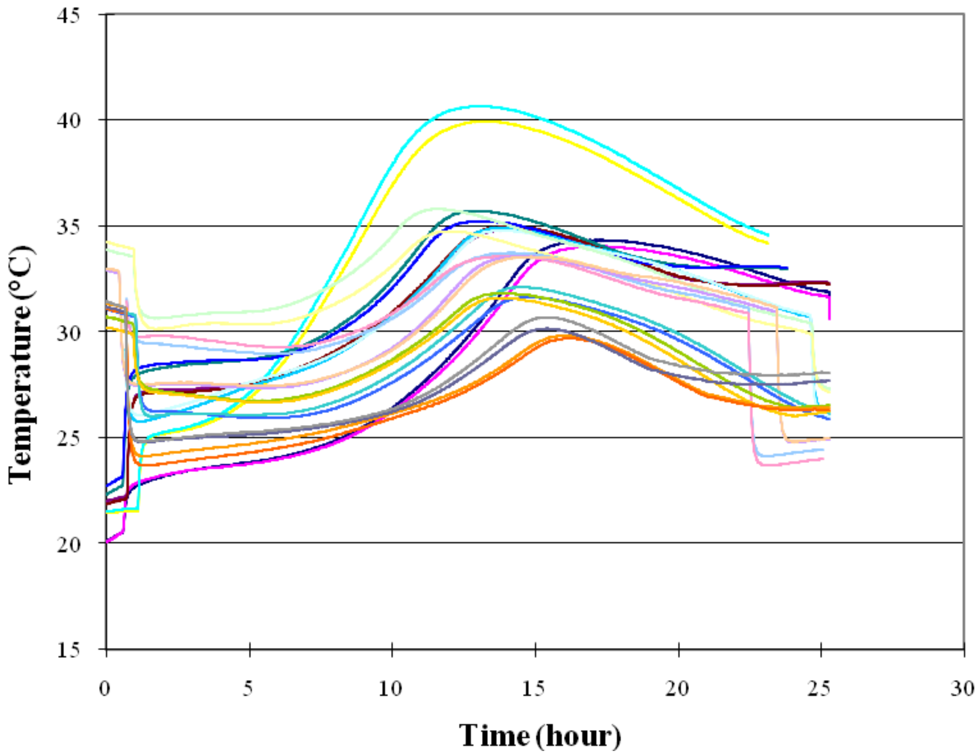


Figure A.2. Concrete temperature for all samples for Alma Center project

A.3 Information for Ottumwa Project

Batch Ticket

Date:	July 24, 2007	Time:		8:30 a.m.
Ticket No.	79	Load:		9 yd
Materials	Qty (lb)	Moisture (%)	Materials	Qty
Rock	14888	0.5	Water	174 (gal)
Sand	12820	3.0	Tempee water	7 (gal)
Cement	4050		Total Water	1956 (lb)
Fly Ash	1005		w/c	0.387
AEA	97 oz			
WR	207 oz			

Date:	July 24, 2007	Time:		10:13 a.m.
Ticket No.	143	Load:		9 yd
Materials	Qty (lb)	Moisture (%)	Materials	Qty
Rock	14940	0.5	Water	175 (gal)
Sand	12820	3.0	Tempee water	0 (gal)
Cement	4055		Total Water	1906 (lb)
Fly Ash	990		w/c	0.378
AEA	95 oz			
WR	204 oz			

Date:	July 25, 2007	Time:		8:33 a.m.
Ticket No.		Load:		9 yd
Materials	Qty (lb)	Moisture (%)	Materials	Qty
Rock	16240	0.2	Water	164 (gal)
Sand	12000	3.2	Tempee water	8 (gal)
Cement	3975		Total Water	1838 (lb)
Fly Ash	1005		w/c	0.369
AEA	79 oz			
WR	201 oz			

Date:	July 25, 2007	Time:		9:58 a.m.
Ticket No.		Load:		9 yd
Materials	Qty (lb)	Moisture (%)	Materials	Qty
Rock	16220	0.5	Water	164 (gal)
Sand	11980	3.0	Tempee water	8 (gal)
Cement	4000		Total Water	1838 (lb)
Fly Ash	1005		w/c	0.367
AEA	79 oz			
WR	201 oz			

Date:	July 25, 2007	Time:		12:30 p.m.
Ticket No.	202	Load:		9 yd
Materials	Qty (lb)	Moisture (%)	Materials	Qty
Rock	16220	0.2	Water	165 (gal)
Sand	11960	3.2	Tempee water	0 (gal)
Cement	3970		Total Water	1785 (lb)
Fly Ash	985		w/c	0.360
AEA	79 oz			
WR	201 oz			

Date:	July 25, 2007	Time:		1:56 p.m.
Ticket No.	242	Load:		9 yd
Materials	Qty (lb)	Moisture (%)	Materials	Qty
Rock	16220	0.5	Water	160 (gal)
Sand	12000	3.0	Tempee water	4 (gal)
Cement	3985		Total Water	1770 (lb)
Fly Ash	987		w/c	0.356
AEA	79 oz			
WR	201 oz			

Date:	July 30, 2007	Time:		8:16 a.m.
Ticket No.	65	Load:		9 yd
Materials	Qty (lb)	Moisture (%)	Materials	Qty
Rock	16280	0.5	Water	155 (gal)
Sand	11940	3.1	Tempee water	8 (gal)
Cement	3965		Total Water	1798 (lb)
Fly Ash	980		w/c	0.364
AEA	97 oz			
WR	198 oz			

Date:	July 30, 2007	Time:		9:32 a.m.
Ticket No.	109	Load:		9 yd
Materials	Qty (lb)	Moisture (%)	Materials	Qty
Rock	16260	0.5	Water	155 (gal)
Sand	11940	3.1	Tempee water	4 (gal)
Cement	3970		Total Water	1764 (lb)
Fly Ash	980		w/c	0.356
AEA	97 oz			
WR	201 oz			

Date:	July 30, 2007	Time:		1:37 p.m.
Ticket No.	195	Load:		9 yd
Materials	Qty (lb)	Moisture (%)	Materials	Qty
Rock	16320	0.5	Water	154 (gal)
Sand	12000	3.1	Tempee water	10 (gal)
Cement	4000		Total Water	1808 (lb)
Fly Ash	1000		w/c	0.362
AEA	97 oz			
WR	201 oz			

Date:	July 30, 2007	Time:		3:15 p.m.
Ticket No.	242	Load:		9 yd
Materials	Qty (lb)	Moisture (%)	Materials	Qty
Rock	16300	0.5	Water	164 (gal)
Sand	11920	3.1	Tempee water	10gal)
Cement	3970		Total Water	1889 (lb)
Fly Ash	990		w/c	0.381
AEA	97 oz			
WR	198 oz			

Date:	July 31, 2007	Time:		8:47 a.m.
Ticket No.	90	Load:		9 yd
Materials	Qty (lb)	Moisture (%)	Materials	Qty
Rock	16360	0.2	Water	159 (gal)
Sand	11940	3.1	Tempee water	10 (gal)
Cement	3985		Total Water	1800 (lb)
Fly Ash	980		w/c	0.363
AEA	79 oz			
WR	198 oz			

Date:	July 31, 2007	Time:		10:51 a.m.
Ticket No.	109	Load:		9 yd
Materials	Qty (lb)	Moisture (%)	Materials	Qty
Rock	16280	0.2	Water	165 (gal)
Sand	11980	3.1	Tempee water	4 (gal)
Cement	3990		Total Water	1800 (lb)
Fly Ash	1010		w/c	0.360
AEA	79 oz			
WR	198 oz			

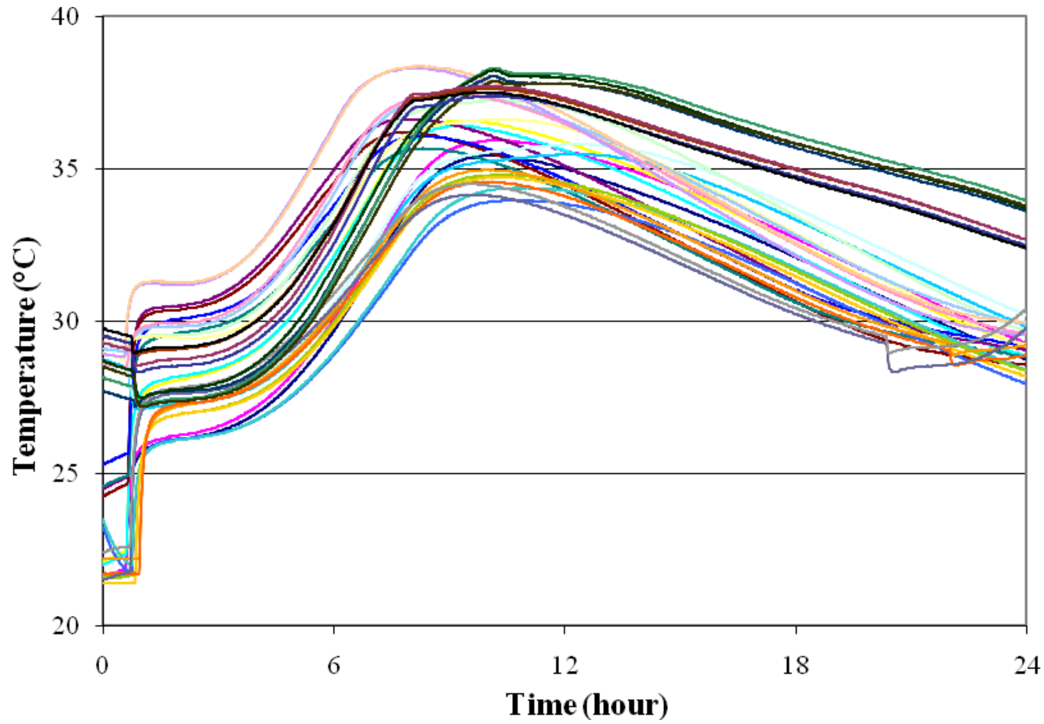


Figure A.3. Concrete temperature for all samples for Ottumwa project

APPENDIX B. ADIACAL MORTAR ROBUST TEST RESULTS SUMMARY

Table B.1. Summary of AdiaCal robust test results of US 71 (Atlantic, IA) mixes

	IS, h	FS, h	FS-IS, h	Peak temp, °C	Peak slope	$A_{1\text{-}6h}$	$A_{6\text{-}12h}$	$A_{12\text{-}18h}$	$A_{18\text{-}24h}$	$A_{1\text{-}24h}$	$A_{24\text{-}48h}$
1	12.90	21.10	8.20	27.30	0.605	107.0	132.00	149.00	162.00	551.00	559.00
2	14.60	20.90	6.20	28.40	0.745	108.0	133.00	151.00	168.00	561.00	589.00
3	12.30	19.60	7.30	28.60	0.726	110.0	139.00	160.00	170.00	578.00	586.00
4	19.60	21.80	2.20	26.40	0.737	106.0	128.00	138.00	155.00	527.00	552.00
5	10.90	20.80	9.90	27.40	0.711	106.0	136.00	156.00	163.00	561.00	560.00
6	19.70	21.80	2.10	26.60	0.839	106.0	128.00	138.00	156.00	528.00	564.00
7	11.20	20.70	9.50	27.90	0.766	105.0	135.00	157.00	166.00	562.00	574.00
8	18.20	20.20	2.00	26.90	0.737	105.0	130.00	147.00	160.00	542.00	560.00
9	9.50	19.80	10.30	27.60	0.786	105.0	141.00	161.00	165.00	571.00	567.00
Max	19.70	21.80	10.32	28.60	0.839	110.0	141.00	161.00	170.00	578.00	589.00
Min	9.50	19.60	1.98	26.40	0.605	105.0	128.00	138.00	155.00	527.00	552.00
Avg.	14.30	20.70	6.40	27.50	0.739	106.0	133.00	151.00	163.00	553.00	568.00
σ	3.90	0.80	3.48	0.80	0.063	1.70	4.50	8.50	5.10	17.90	12.60
σ %	27.51	3.80	54.38	2.78	8.520	1.56	3.38	5.64	3.12	3.24	2.22

Table B.2. Summary of AdiaCal robust test results of HW 95 (Alma Center, WI) mixes

	IS, h	FS, h	FS-IS, h	Peak temp, °C	Peak slope	$A_{1\text{-}6h}$	$A_{6\text{-}12h}$	$A_{12\text{-}18h}$	$A_{18\text{-}24h}$	$A_{1\text{-}24h}$	$A_{24\text{-}48h}$
1	14.10	19.60	5.57	26.90	0.783	108.0	133.00	152.00	160.00	553.00	578.0
2	11.80	20.50	8.70	27.10	0.634	107.0	136.00	154.00	161.00	558.00	578.0
3	12.10	19.60	7.51	27.10	0.729	109.0	141.00	159.00	161.00	569.00	573.0
4	18.30	21.30	2.98	26.10	0.852	111.0	132.00	139.00	155.00	538.00	589.0
5	14.20	20.20	6.04	28.60	0.689	112.0	140.00	160.00	170.00	581.00	596.0
6	20.50	23.60	3.13	25.80	0.822	110.0	130.00	132.00	149.00	521.00	586.0
7	14.30	20.90	6.65	28.50	0.724	111.0	136.00	154.00	170.00	571.00	598.0
8	19.30	23.00	3.78	27.00	0.754	105.0	128.00	138.00	157.00	529.00	595.0
9	13.00	20.70	7.73	29.00	0.771	106.0	137.00	161.00	173.00	576.00	600.0
Max	20.50	23.60	8.70	29.00	0.852	112.0	141.00	161.00	173.00	581.00	600.0
Min	11.80	19.60	2.98	25.80	0.634	105.0	128.00	132.00	149.00	521.00	573.0
Avg.	15.30	21.00	5.79	27.30	0.751	109.0	135.00	150.00	162.00	555.00	588.0
σ	3.20	1.40	2.09	1.10	0.066	2.30	4.20	10.60	7.80	21.60	10.0
σ %	21.14	6.67	36.21	4.03	8.840	2.15	3.14	7.08	4.81	3.89	1.7

Table B.3. Summary of AdiaCal robust test results of US 63 bypass (Ottumwa , IA) mixes

	IS, h	FS, h	FS-IS, h	Peak temp, °C	Peak slope	$A_{1\text{-}6h}$	$A_{6\text{-}12h}$	$A_{12\text{-}18h}$	$A_{18\text{-}24h}$	$A_{1\text{-}24h}$	$A_{24\text{-}48h}$
1	12.15	15.40	3.20	26.90	0.946	103.00	136.00	159.00	154.00	552.00	546.00
2	14.27	17.50	3.20	26.50	0.951	102.00	128.00	152.00	155.00	537.00	547.00
3	11.35	14.80	3.40	27.00	0.909	102.00	140.00	160.00	153.00	555.00	535.00
4	12.48	14.80	2.40	26.60	1.079	104.00	135.00	157.00	151.00	547.00	539.00
5	9.08	14.00	5.00	28.30	1.012	109.00	150.00	168.00	155.00	581.00	547.00
6	14.14	16.50	2.40	26.20	0.830	108.00	133.00	152.00	150.00	543.00	548.00
7	10.63	15.40	4.80	27.60	0.975	107.00	140.00	163.00	154.00	565.00	547.00
8	11.68	13.90	2.20	27.50	0.878	109.00	147.00	162.00	151.00	568.00	545.00
9	8.28	13.20	5.00	30.40	1.256	111.00	164.00	179.00	167.00	621.00	587.00
Max	14.30	17.50	4.97	30.40	1.256	111.00	164.00	179.00	167.00	621.00	587.00
Min	8.30	13.20	2.18	26.20	0.830	102.00	128.00	152.00	150.00	537.00	535.00
Avg.	11.60	15.10	3.50	27.50	0.982	106.00	141.00	161.00	154.00	563.00	549.00
σ	2.00	1.30	1.14	1.30	0.126	3.50	10.90	8.30	5.00	25.80	15.00
σ %	17.59	8.82	32.66	4.64	12.820	3.28	7.68	5.16	3.23	4.580	2.73

APPENDIX C. ISOTHERMAL MORTAR ROBUST TEST RESULTS SUMMARY

Table C.1. Summary of isothermal robust test results of US 71 (Atlantic, IA) mortar mixes at 10°C

	IS, h	FS, h	FS-IS, h	Peak rate	Peak slope	A_{1-6h}	A_{6-12h}	A_{12-18h}	A_{18-24h}	A_{1-24h}	A_{24-48h}	A_{48-72h}
1	20.3	29.4	9.1	1.28	0.07	4.2	2.6	3.4	5.5	15.6	27.2	12.9
2	24.1	31.7	7.6	1.26	0.07	4.3	2.4	2.8	4.3	13.8	27.2	14.1
3	17.6	26.8	9.2	1.30	0.08	3.9	3.0	4.5	6.8	18.2	26.9	11.3
4	25.2	31.6	6.4	1.08	0.07	4.3	2.4	2.7	3.9	13.3	24.4	11.0
5	16.5	26.5	10.0	1.40	0.09	3.6	3.2	5.3	7.7	19.8	26.9	13.1
6	28.8	35.1	6.2	1.08	0.07	4.5	2.2	2.2	2.9	11.9	23.4	13.4
7	19.5	29.5	10.0	1.37	0.09	3.8	2.5	3.5	5.9	15.7	28.1	14.5
8	19.4	28.0	8.6	1.11	0.06	4.2	2.6	3.3	5.0	15.2	24.9	9.8
9	14.6	26.2	11.6	1.38	0.09	3.7	3.6	5.9	7.9	21.0	25.8	12.9
Max	28.8	35.1	11.6	1.40	0.09	4.5	3.6	5.9	7.9	21.0	28.1	14.5
Min	14.6	26.2	6.2	1.08	0.06	3.6	2.2	2.2	2.9	11.9	23.4	9.8
Avg.	20.7	29.4	8.7	1.25	0.08	4.1	2.7	3.7	5.5	16.1	26.1	12.5
σ	4.6	2.9	1.8	0.13	0.01	0.3	0.5	1.2	1.7	3.0	1.6	1.6
σ %	22.0	10.0	20.2	10.34	11.48	8.0	16.6	33.0	30.7	19.0	6.0	12.4

Table C.2. Summary of isothermal robust test results of US 71 (Atlantic, IA) mortar mixes at 20°C

	IS, h	FS, h	FS-IS, h	Peak rate	Peak slope	A_{1-6h}	A_{6-12h}	A_{12-18h}	A_{18-24h}	A_{1-24h}	A_{24-48h}	A_{48-72h}
1	12.2	17.5	5.3	2.43	0.33	3.8	5.7	13.5	12.9	35.9	21.8	NA
2	12.3	18.2	6.0	2.38	0.33	3.5	4.5	12.2	13.0	33.3	22.6	NA
3	11.0	16.8	5.9	2.45	0.35	3.8	6.8	14.2	12.5	37.3	21.1	NA
4	15.8	27.1	11.4	2.30	0.28	4.0	2.6	7.2	12.4	26.2	22.8	NA
5	10.5	14.8	4.2	2.62	0.39	3.5	7.6	15.2	12.6	38.8	23.7	NA
6	19.5	28.6	9.1	2.29	0.27	4.1	2.3	4.7	11.4	22.5	25.2	NA
7	12.5	17.7	5.3	2.72	0.40	3.2	5.5	14.8	14.1	37.5	25.5	NA
8	12.2	24.8	12.6	2.22	0.29	3.4	4.5	11.5	12.4	31.8	19.3	NA
9	9.0	12.4	3.4	2.72	0.40	3.7	11.9	15.3	11.1	42.1	21.6	NA
Max	19.5	28.6	12.6	2.72	0.40	4.1	11.9	15.3	14.1	42.1	25.5	NA
Min	9.0	12.4	3.4	2.22	0.27	3.2	2.3	4.7	11.1	22.5	19.3	NA
Avg.	12.8	19.8	7.0	2.46	0.34	3.7	5.7	12.1	12.5	33.9	22.6	NA
σ	3.1	5.7	3.2	0.19	0.05	0.3	2.9	3.7	0.9	6.3	2.0	NA
σ %	24.4	28.8	46.4	7.59	15.52	8.0	50.6	31.1	7.0	18.5	8.7	NA

Table C.3. Summary of isothermal robust test results of US 71 (Atlantic, IA) mortar mixes at 30^{o}C

	IS, h	FS, h	FS-IS, h	Peak rate	Peak slope	A_{1-6h}	A_{6-12h}	A_{12-18h}	A_{18-24h}	A_{1-24h}	A_{24-48h}	A_{48-72h}
1	7.2	10.7	3.5	4.34	1.02	3.9	21.1	19.5	7.1	51.5	NA	NA
2	9.3	15.5	6.2	4.39	0.96	3.3	15.2	22.5	7.9	48.9	NA	NA
3	6.7	10.1	3.4	4.32	1.08	4.8	22.7	18.2	6.9	52.6	NA	NA
4	14.6	15.0	0.4	4.86	1.16	3.5	13.2	20.2	6.7	43.7	NA	NA
5	6.7	10.2	3.5	4.63	1.17	4.5	23.9	18.8	8.2	55.3	NA	NA
6	15.5	16.1	0.6	4.85	1.02	3.5	8.9	22.3	7.4	42.1	NA	NA
7	8.0	11.1	3.1	4.66	1.14	3.4	20.6	21.1	8.7	53.8	NA	NA
8	13.9	14.4	0.5	4.78	1.08	3.7	17.4	18.9	6.5	46.5	NA	NA
9	6.2	8.4	2.2	4.42	1.17	6.0	24.9	17.1	7.9	55.9	NA	NA
Max	15.5	16.1	6.2	4.86	1.17	6.0	24.9	22.5	8.7	55.9	NA	NA
Min	6.2	8.4	0.4	4.32	0.96	3.3	8.9	17.1	6.5	42.1	NA	NA
Avg.	9.8	12.4	2.6	4.59	1.09	4.1	18.6	19.9	7.5	50.0	NA	NA
σ	3.8	2.8	1.9	0.22	0.08	0.9	5.4	1.9	0.7	5.0	NA	NA
σ %	38.7	22.9	73.0	4.82	7.09	22.1	28.7	9.3	9.9	10.0	NA	NA

Table C.4. Summary of isothermal robust test results of US 71 (Atlantic, IA) mortar mixes at 40^{o}C

	IS, h	FS, h	FS-IS, h	Peak rate	Peak slope	A_{1-6h}	A_{6-12h}	A_{12-18h}	A_{18-24h}	A_{1-24h}	A_{24-48h}	A_{48-72h}
1	6.4	9.3	2.8	5.17	2.74	6.4	33.3	11.0	7.5	58.2	NA	NA
2	6.9	9.7	2.8	6.76	2.72	4.0	32.5	11.7	7.8	56.1	NA	NA
3	5.8	8.6	2.8	3.66	2.38	9.3	31.4	9.9	6.9	57.5	NA	NA
4	6.8	9.6	2.8	5.85	2.36	4.3	29.4	10.6	7.4	51.7	NA	NA
5	5.8	7.0	1.2	4.04	2.82	9.8	33.8	10.7	7.2	61.5	NA	NA
6	7.3	10.0	2.7	7.31	2.17	3.3	27.3	11.7	8.0	50.3	NA	NA
7	6.6	7.9	1.3	5.54	3.30	5.7	36.0	11.9	7.9	61.4	NA	NA
8	6.0	9.1	3.1	4.09	2.25	6.3	29.8	9.6	6.8	52.5	NA	NA
9	4.6	6.3	1.7	3.69	0.57	14.7	31.2	10.0	6.7	62.6	NA	NA
Max	7.3	10.0	3.1	7.31	3.30	14.7	36.0	11.9	8.0	62.6	NA	NA
Min	4.6	6.3	1.2	3.66	0.57	3.3	27.3	9.6	6.7	50.3	NA	NA
Avg.	6.2	8.6	2.4	5.12	2.37	7.1	31.6	10.8	7.4	56.8	NA	NA
σ	0.8	1.3	0.7	1.35	0.76	3.6	2.6	0.8	0.5	4.6	NA	NA
σ %	13.1	15.0	30.9	26.37	32.17	50.8	8.3	7.8	6.6	8.0	NA	NA

Table C.5. Summary of isothermal robust test results of HW 95 (Alma Center, WI) mortar mixes at 5^{o}C

	IS, h	FS, h	FS-IS, h	Peak rate	Peak slope	$A_{1\text{-}6h}$	$A_{6\text{-}12h}$	$A_{12\text{-}18h}$	$A_{18\text{-}24h}$	$A_{1\text{-}24h}$	$A_{24\text{-}48h}$	$A_{48\text{-}72h}$
1	25.1	34.5	9.4	0.84	0.09	4.0	2.7	2.7	2.9	12.4	18.0	11.9
2	22.1	39.9	17.8	0.72	0.11	4.0	2.0	2.2	2.3	10.6	14.8	13.5
3	21.7	34.4	12.7	0.75	0.10	4.0	2.3	2.3	3.1	11.7	16.6	12.6
4	20.2	45.0	24.8	0.66	0.06	4.0	2.2	2.1	2.2	10.5	12.0	11.6
5	19.9	32.9	13.0	0.75	0.07	4.2	3.1	2.8	3.5	13.7	17.2	13.1
6	35.3	44.8	9.5	0.68	0.11	4.1	2.2	1.7	2.0	9.9	10.5	13.0
7	18.6	44.4	25.8	0.83	0.06	4.2	2.4	2.7	3.1	12.3	17.7	14.0
8	27.8	35.3	7.5	0.71	0.03	4.2	2.4	2.3	2.6	11.5	15.3	10.2
9	24.6	29.3	4.7	0.98	0.05	4.2	3.2	3.4	4.4	15.2	19.7	11.8
Max	35.3	45.0	25.8	0.98	0.11	4.2	3.2	3.4	4.4	15.2	19.7	14.0
Min	18.6	29.3	4.7	0.66	0.03	4.0	2.0	1.7	2.0	9.9	10.5	10.2
Avg.	23.9	37.8	13.9	0.77	0.08	4.1	2.5	2.5	2.9	12.0	15.7	12.4
σ	5.2	5.8	7.4	0.10	0.03	0.1	0.4	0.5	0.7	1.7	3.0	1.2
σ %	21.6	15.5	53.5	13.05	37.28	2.5	16.7	20.3	25.7	14.0	18.9	9.4

Table C.6. Summary of isothermal robust test results of HW 95 (Alma Center, WI) mortar mixes at 20^{o}C

	IS, h	FS, h	FS-IS, h	Peak rate	Peak slope	$A_{1\text{-}6h}$	$A_{6\text{-}12h}$	$A_{12\text{-}18h}$	$A_{18\text{-}24h}$	$A_{1\text{-}24h}$	$A_{24\text{-}48h}$	$A_{48\text{-}72h}$
1	13.7	20.5	6.8	2.60	0.23	4.1	5.3	11.3	15.0	35.8	25.7	NA
2	14.8	20.5	5.7	2.54	0.22	3.7	4.7	10.3	14.8	33.5	24.9	NA
3	12.2	19.0	6.8	2.48	0.23	4.1	6.5	12.7	14.0	37.3	22.4	NA
4	18.6	23.9	5.3	2.36	0.26	4.2	3.5	6.5	12.6	26.8	23.6	NA
5	11.4	18.5	7.1	2.65	0.26	3.9	7.9	14.6	14.5	40.9	25.6	NA
6	19.4	25.1	5.7	2.21	0.25	3.8	3.0	5.2	10.7	22.7	23.9	NA
7	12.3	19.4	7.1	2.70	0.25	3.5	6.1	13.2	15.3	38.1	26.6	NA
8	18.2	21.6	3.4	2.31	0.25	4.1	3.9	8.2	13.3	29.5	21.9	NA
9	9.8	15.1	5.3	2.59	0.27	4.5	10.2	15.3	13.7	43.7	23.8	NA
Max	19.4	25.1	7.1	2.70	0.27	4.5	10.2	15.3	15.3	43.7	26.6	NA
Min	9.8	15.1	3.4	2.21	0.22	3.5	3.0	5.2	10.7	22.7	21.9	NA
Avg.	14.5	20.4	5.9	2.49	0.25	4.0	5.7	10.8	13.8	34.3	24.3	NA
σ	3.5	3.0	1.2	0.17	0.02	0.3	2.3	3.6	1.4	6.8	1.6	NA
σ %	23.9	14.5	20.2	6.80	6.52	7.2	40.8	32.9	10.3	19.9	6.4	NA

Table C.7. Summary of isothermal robust test results of HW 95 (Alma Center, WI) mortar mixes at 30°C

	IS, h	FS, h	FS-IS, h	Peak rate	Peak slope	A_{1-6h}	A_{6-12h}	A_{12-18h}	A_{18-24h}	A_{1-24h}	A_{24-48h}	A_{48-72h}
1	11.8	15.0	3.2	4.62	0.65	3.8	14.5	24.4	9.5	52.1	NA	NA
2	12.4	15.8	3.4	4.95	0.74	3.1	11.5	25.1	9.9	49.6	NA	NA
3	8.4	12.5	4.1	4.41	0.66	4.8	19.1	21.7	8.8	54.3	NA	NA
4	12.5	15.5	3.0	4.64	0.71	3.6	10.4	22.1	9.2	45.2	NA	NA
5	7.2	11.9	4.7	4.73	0.77	5.2	22.6	22.7	10.2	60.7	NA	NA
6	14.2	14.9	0.7	5.00	1.04	3.4	9.7	20.1	9.4	42.6	NA	NA
7	7.9	11.9	4.0	4.83	0.77	4.7	21.5	23.0	9.9	59.1	NA	NA
8	11.5	14.4	3.0	4.32	0.60	4.7	14.6	20.2	8.1	47.6	NA	NA
9	6.1	10.9	4.7	4.54	0.80	7.9	25.2	19.0	8.7	60.9	NA	NA
Max	14.2	15.8	4.7	5.00	1.04	7.9	25.2	25.1	10.2	60.9	NA	NA
Min	6.1	10.9	0.7	4.32	0.60	3.1	9.7	19.0	8.1	42.6	NA	NA
Avg.	10.2	13.6	3.4	4.67	0.75	4.6	16.6	22.0	9.3	52.5	NA	NA
σ	2.8	1.8	1.2	0.23	0.13	1.4	5.7	2.0	0.7	6.8	NA	NA
σ %	27.9	13.5	36.3	4.97	17.10	31.5	34.4	9.1	7.4	12.9	NA	NA

Table C.8. Summary of isothermal robust test results of HW 95 (Alma Center, WI) mortar mixes at 40°C

	IS, h	FS, h	FS-IS, h	Peak rate	Peak slope	A_{1-6h}	A_{6-12h}	A_{12-18h}	A_{18-24h}	A_{1-24h}	A_{24-48h}	A_{48-72h}
1	7.2	9.3	2.1	6.49	1.81	7.6	35.8	14.4	9.3	67.1	NA	NA
2	9.1	9.6	0.5	7.66	2.25	5.3	34.3	16.1	10.6	66.2	NA	NA
3	5.2	9.1	3.9	5.92	1.48	9.4	35.0	13.0	8.1	65.5	NA	NA
4	9.1	9.4	0.4	5.45	3.56	5.2	28.3	15.1	10.2	58.9	NA	NA
5	4.9	7.9	3.0	5.33	1.54	12.4	37.0	13.1	8.1	70.5	NA	NA
6	9.3	9.7	0.4	6.58	4.24	3.9	25.4	15.9	11.5	56.7	NA	NA
7	7.2	9.1	1.9	6.97	1.92	7.8	39.5	15.0	9.2	71.6	NA	NA
8	9.1	9.5	0.4	5.90	1.77	6.4	30.1	13.4	9.0	58.9	NA	NA
9	4.1	7.1	3.0	4.86	0.68	16.3	34.9	12.1	7.1	70.4	NA	NA
Max	9.3	9.7	3.9	7.66	4.24	16.3	39.5	16.1	11.5	71.6	NA	NA
Min	4.1	7.1	0.4	4.86	0.68	3.9	25.4	12.1	7.1	56.7	NA	NA
Avg.	7.2	9.0	1.7	6.13	2.14	8.3	33.4	14.2	9.2	65.1	NA	NA
σ	2.1	0.9	1.4	0.88	1.10	3.9	4.5	1.4	1.4	5.6	NA	NA
σ %	28.5	9.9	78.6	14.36	51.43	47.7	13.5	9.9	14.9	8.6	NA	NA

Table C.9. Summary of isothermal robust test results of US 63 bypass (Ottumwa, IA) mortar mixes at 10^{o}C

	IS, h	FS, h	FS-IS, h	Peak rate	Peak slope	$A_{1\text{-}6h}$	$A_{6\text{-}12h}$	$A_{12\text{-}18h}$	$A_{18\text{-}24h}$	$A_{1\text{-}24h}$	$A_{24\text{-}48h}$	$A_{48\text{-}72h}$
1	18.5	25.7	7.2	1.59	0.13	3.8	2.8	5.1	8.6	20.3	25.9	9.9
2	22.4	31.4	8.9	1.63	0.12	4.4	2.2	2.9	5.6	15.0	29.8	12.2
3	14.0	21.0	7.0	1.67	0.12	3.8	3.8	7.3	9.9	24.8	24.2	9.4
4	19.7	29.4	9.7	1.58	0.12	4.5	2.6	4.2	7.5	18.8	25.7	10.6
5	16.3	21.5	5.2	1.75	0.14	3.6	3.9	7.6	10.3	25.4	25.7	10.0
6	20.4	31.3	10.9	1.52	0.11	4.7	2.4	3.1	5.5	15.6	26.6	11.3
7	17.4	26.2	8.8	1.57	0.12	3.9	2.8	4.3	7.8	18.8	28.0	11.4
8	17.3	25.9	8.6	1.58	0.11	4.2	3.5	6.4	9.1	23.2	23.2	9.6
9	14.5	18.6	4.1	1.81	0.16	3.9	5.1	9.2	10.6	28.8	24.1	9.5
Max	22.4	31.4	10.9	1.81	0.16	4.7	5.1	9.2	10.6	28.8	29.8	12.2
Min	14.0	18.6	4.1	1.52	0.11	3.6	2.2	2.9	5.5	15.0	23.2	9.4
Avg.	17.8	25.6	7.8	1.63	0.13	4.1	3.2	5.6	8.3	21.2	25.9	10.4
σ	2.7	4.6	2.2	0.09	0.02	0.4	0.9	2.2	1.9	4.7	2.0	1.0
σ %	15.4	17.8	27.6	5.79	12.07	9.1	28.8	39.5	22.7	22.0	7.9	9.6

Table C.10. Summary of isothermal robust test results of US 63 bypass (Ottumwa, IA) mortar mixes at 20^{o}C

	IS, h	FS, h	FS-IS, h	Peak rate	Peak slope	$A_{1\text{-}6h}$	$A_{6\text{-}12h}$	$A_{12\text{-}18h}$	$A_{18\text{-}24h}$	$A_{1\text{-}24h}$	$A_{24\text{-}48h}$	$A_{48\text{-}72h}$
1	8.6	13.2	4.7	3.12	0.46	3.9	11.5	17.9	9.1	42.4	16.7	NA
2	12.0	16.9	4.8	3.11	0.52	3.5	6.5	17.5	12.2	39.6	18.0	NA
3	7.1	11.8	4.7	3.22	0.48	4.4	15.1	17.4	8.1	44.9	15.6	NA
4	11.3	16.8	5.5	3.10	0.43	3.8	8.4	17.4	8.8	38.5	17.2	NA
5	10.6	13.2	2.6	3.07	0.48	3.2	10.6	17.3	10.0	41.1	15.7	NA
6	12.9	18.5	5.6	3.06	0.48	4.0	4.3	14.8	12.2	35.4	18.6	NA
7	11.7	14.8	3.2	3.35	0.60	3.2	7.7	19.1	12.9	42.9	18.4	NA
8	8.3	15.8	7.5	3.10	0.42	3.9	11.7	17.4	7.6	40.6	16.1	NA
9	6.3	10.2	3.9	3.52	0.54	5.7	18.8	16.3	8.1	48.8	14.6	NA
Max	12.9	18.5	7.5	3.52	0.60	5.7	18.8	19.1	12.9	48.8	18.6	NA
Min	6.3	10.2	2.6	3.06	0.42	3.2	4.3	14.8	7.6	35.4	14.6	NA
Avg.	9.9	14.6	4.7	3.18	0.49	4.0	10.5	17.2	9.9	41.6	16.8	NA
σ	2.3	2.7	1.4	0.16	0.06	0.8	4.4	1.2	2.0	3.8	1.4	NA
σ %	23.8	18.4	30.7	4.89	11.60	19.4	42.3	6.8	20.6	9.3	8.2	NA

Table C.11. Summary of isothermal robust test results of US 63 bypass (Ottumwa, IA) mortar mixes at 30^{o}C

	IS, h	FS, h	FS-IS, h	Peak rate	Peak slope	A_{1-6h}	A_{6-12h}	A_{12-18h}	A_{18-24h}	A_{1-24h}	A_{24-48h}	A_{48-72h}
1	6.9	9.7	2.7	5.44	1.46	5.9	28.2	11.3	7.9	53.3	NA	NA
2	8.2	11.2	3.0	5.68	1.62	3.3	24.5	14.7	8.8	51.3	NA	NA
3	4.9	7.5	2.7	4.79	1.24	9.6	28.5	10.6	7.2	55.9	NA	NA
4	7.4	10.4	3.0	5.65	1.37	4.9	26.0	11.4	8.0	50.3	NA	NA
5	6.4	8.1	1.7	5.30	1.66	6.8	30.5	11.4	7.6	56.3	NA	NA
6	7.9	11.1	3.2	5.61	1.48	3.7	23.7	13.1	8.6	49.1	NA	NA
7	7.7	9.8	2.1	5.88	1.85	3.7	28.4	13.8	8.5	54.3	NA	NA
8	5.3	9.5	4.3	5.00	1.05	8.3	27.2	10.3	7.0	52.8	NA	NA
9	4.5	6.9	2.4	4.25	1.15	12.3	28.9	10.3	6.9	58.3	NA	NA
Max	8.2	11.2	4.3	5.88	1.85	12.3	30.5	14.7	8.8	58.3	NA	NA
Min	4.5	6.9	1.7	4.25	1.05	3.3	23.7	10.3	6.9	49.1	NA	NA
Avg.	6.6	9.3	2.8	5.29	1.43	6.5	27.3	11.9	7.8	53.5	NA	NA
σ	1.4	1.5	0.7	0.52	0.26	3.1	2.2	1.6	0.7	3.0	NA	NA
σ %	21.3	16.5	26.6	9.84	18.19	47.4	8.1	13.4	9.2	5.6	NA	NA

Table C.12. Summary of isothermal robust test results of US 63 bypass (Ottumwa, IA) mortar mixes at 40^{o}C

	IS, h	FS, h	FS-IS, h	Peak rate	Peak slope	A_{1-6h}	A_{6-12h}	A_{12-18h}	A_{18-24h}	A_{1-24h}	A_{24-48h}	A_{48-72h}
1	4.1	5.8	1.7	9.23	4.27	22.8	24.7	11.3	8.5	67.4	NA	NA
2	5.3	7.3	2.0	8.94	3.25	10.9	30.6	13.3	9.8	64.6	NA	NA
3	4.1	5.8	1.7	9.18	4.25	23.0	24.4	11.2	8.4	67.1	NA	NA
4	5.2	7.2	2.0	8.77	3.19	11.1	29.8	13.0	9.6	63.5	NA	NA
5	4.3	5.7	1.4	9.89	4.88	23.1	25.8	11.6	8.6	69.1	NA	NA
6	6.9	8.2	1.3	8.34	2.74	5.0	30.5	14.8	10.3	60.6	NA	NA
7	5.4	7.0	1.6	9.96	4.50	10.2	34.1	14.2	9.8	68.3	NA	NA
8	4.2	6.3	2.1	8.71	3.59	18.4	24.8	11.6	8.7	63.5	NA	NA
9	4.0	5.3	1.3	9.82	4.90	25.7	23.5	11.3	8.6	69.1	NA	NA
Max	6.9	8.2	2.1	9.96	4.90	25.7	34.1	14.8	10.3	69.1	NA	NA
Min	4.0	5.3	1.3	8.34	2.74	5.0	23.5	11.2	8.4	60.6	NA	NA
Avg.	4.8	6.5	1.7	9.20	3.95	16.7	27.6	12.5	9.2	65.9	NA	NA
σ	1.0	0.9	0.3	0.58	0.79	7.5	3.7	1.4	0.7	3.0	NA	NA
σ %	20.0	14.6	18.1	6.29	19.89	44.7	13.5	10.9	7.8	4.5	NA	NA

Table C.13. Summary of robust isothermal test results of US 71 (Atlantic, IA) mixes

	5oC-avg.	5oC-σ	20oC-avg.	20oC-σ	30oC-avg.	30oC-σ	40oC-avg.	40oC-σ
IS, h	20.70	4.60	12.8	3.1	9.8	3.8	6.2	0.8
FS, h	29.40	2.90	19.8	5.7	12.4	2.8	8.6	1.3
FS-IS, h	8.70	1.80	7.0	3.2	2.6	1.9	2.4	0.7
Peak rate	1.25	0.13	2.5	0.2	4.6	0.2	5.1	1.4
Peak slope	0.08	0.01	0.3	0.1	1.1	0.1	2.4	0.8
A_{1-6h}	4.06	0.33	3.7	0.3	4.1	0.9	7.1	3.6
A_{6-12h}	2.72	0.45	5.7	2.9	18.6	5.4	31.6	2.6
A_{12-18h}	3.74	1.23	12.1	3.7	19.9	1.9	10.8	0.8
A_{18-24h}	5.55	1.70	12.5	0.9	7.5	0.7	7.4	0.5
A_{1-24h}	16.06	3.05	33.9	6.3	50.0	5.0	56.8	4.6
A_{24-48h}	26.09	1.56	22.6	2.0	NA	NA	NA	NA
A_{48-72h}	12.54	1.55	NA	NA	NA	NA	NA	NA

Table C.14. Summary of robust isothermal test results of HW 95 (Alma Center, WI) mixes

	5oC-avg.	5oC-σ	20oC-avg.	20oC-σ	30oC-avg.	30oC-σ	40oC-avg.	40oC-σ
IS, h	23.90	5.20	14.5	3.5	10.2	2.8	7.2	2.1
FS, h	37.80	5.80	20.4	3.0	13.6	1.8	9.0	0.9
FS-IS, h	13.90	7.40	5.9	1.2	3.4	1.2	1.7	1.4
Peak rate	0.77	0.10	2.5	0.2	4.7	0.2	6.1	0.9
Peak slope	0.08	0.03	0.2	0.0	0.8	0.1	2.1	1.1
A_{1-6h}	4.12	0.10	4.0	0.3	4.6	1.4	8.3	3.9
A_{6-12h}	2.51	0.42	5.7	2.3	16.6	5.7	33.4	4.5
A_{12-18h}	2.46	0.50	10.8	3.6	22.0	2.0	14.2	1.4
A_{18-24h}	2.89	0.74	13.8	1.4	9.3	0.7	9.2	1.4
A_{1-24h}	11.98	1.68	34.3	6.8	52.5	6.8	65.1	5.6
A_{24-48h}	15.74	2.97	24.3	1.6	NA	NA	NA	NA
A_{48-72h}	12.41	1.16	NA	NA	NA	NA	NA	NA

Table C.15. Summary of robust isothermal test results of US 63 bypass (Ottumwa, IA) mixes

	5oC-avg.	5oC-σ	20oC-avg.	20oC-σ	30oC-avg.	30oC-σ	40oC-avg.	40oC-σ
IS, h	23.90	5.20	14.5	3.5	10.2	2.8	7.2	2.1
FS, h	37.80	5.80	20.4	3.0	13.6	1.8	9.0	0.9
FS-IS, h	13.90	7.40	5.9	1.2	3.4	1.2	1.7	1.4
Peak rate	0.77	0.10	2.5	0.2	4.7	0.2	6.1	0.9
Peak slope	0.08	0.03	0.2	0.0	0.8	0.1	2.1	1.1
$A_{1\text{-}6h}$	4.12	0.10	4.0	0.3	4.6	1.4	8.3	3.9
$A_{6\text{-}12h}$	2.51	0.42	5.7	2.3	16.6	5.7	33.4	4.5
$A_{12\text{-}18h}$	2.46	0.50	10.8	3.6	22.0	2.0	14.2	1.4
$A_{18\text{-}24h}$	2.89	0.74	13.8	1.4	9.3	0.7	9.2	1.4
$A_{1\text{-}24h}$	11.98	1.68	34.3	6.8	52.5	6.8	65.1	5.6
$A_{24\text{-}48h}$	15.74	2.97	24.3	1.6	NA	NA	NA	NA
$A_{48\text{-}72h}$	12.41	1.16	NA	NA	NA	NA	NA	NA

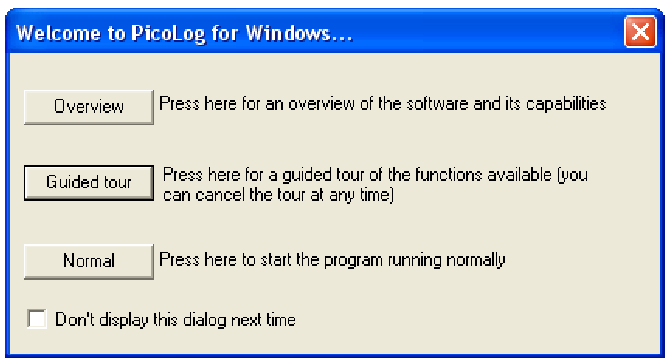
APPENDIX D: CALIBRATION OF THE CALORIMETER

Calibration sample preparation

1. Put 60 grams of epoxy in the plastic cup and wait until the epoxy becomes hard.
2. Put a 50Ω resistor in the middle of the cup and add 120 grams of epoxy.
3. Set the cup still and let the epoxy harden.
4. Connect four calibration cups in series.
5. Connect these two serial sets in parallel.

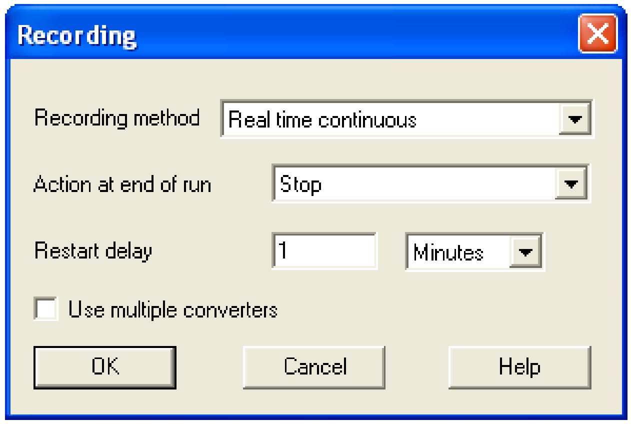
Calibration setting file

1. Open PicoLog Recorder. If a welcome message is displayed as the following, select Normal.

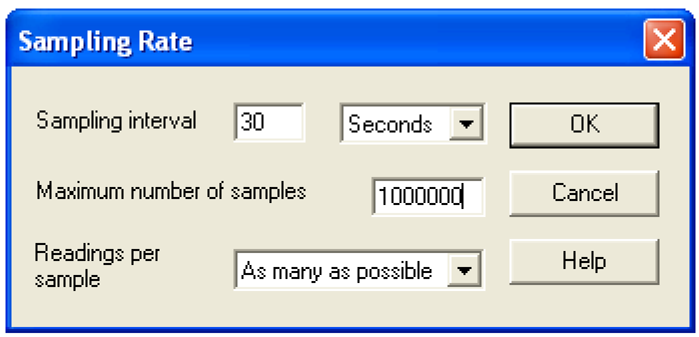


2. The PLW Recorder window is displayed

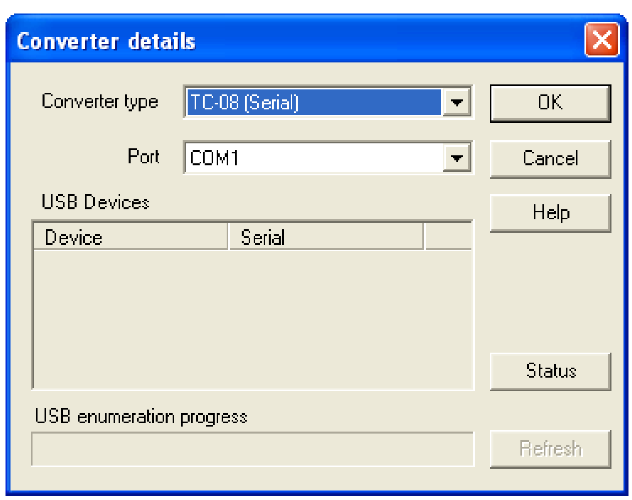
3. Click the New Settings from File dropdown menu, and select. The Recording window appears.



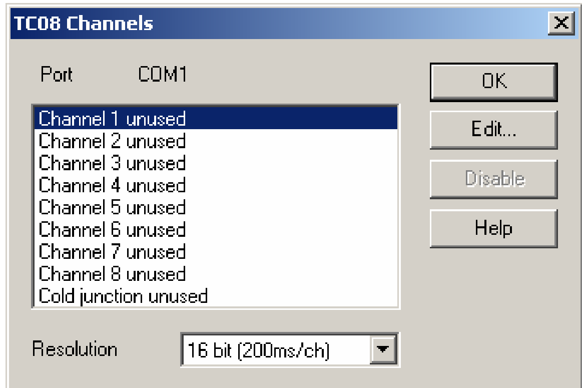
4. Select Real time continuous for Recording method. Define Stop as the Action at end of run and ignore other options, then press OK.
5. The Sampling Rate dialogue box is displayed.
6. Input the Sampling interval and the Maximum number of samples and then click OK.



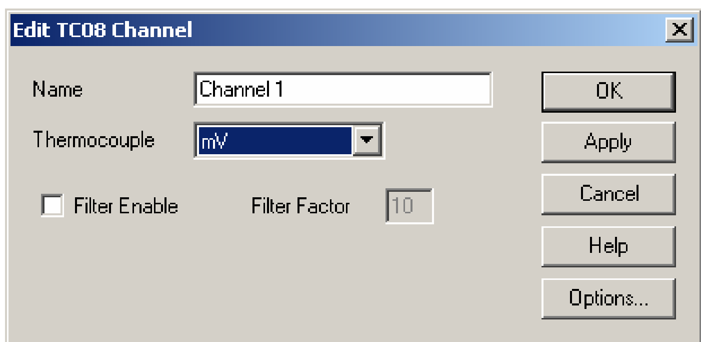
7. The Converter details dialogue box is displayed. Select TC08 (serial) for converter type and COM 1 or the port in use for Port. By clicking on Status, communication between the calorimeter and the PC will be confirmed. Press OK.



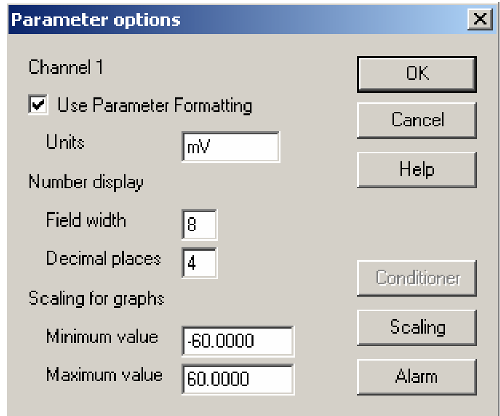
8. The TC08 Channels dialogue box is displayed. Highlight the first channel to be defined. Click on Edit.



9. The Edit TC08 Channel dialogue box is displayed. Accept the default name of Channel 1 in the Name field. Select mV from the dropdown menu for the Thermocouple type. Do not check the Filter Enable box. From the Edit TC08 Channel dialogue box, click on the Options button.



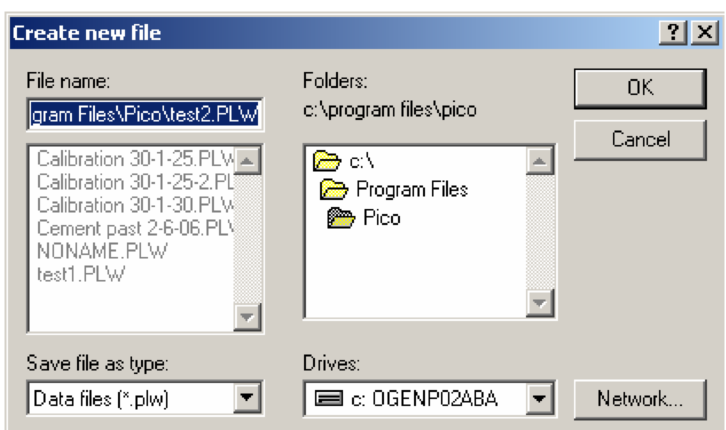
10. The Parameter options dialogue box is displayed. In the Units box, select mV. Input the desired numbers for the Number display and Scaling for graphs. Click OK twice until it goes back to the TC08 Channel dialogue box. Repeat the same procedure for the remaining channels. After defining all eight channels, click OK to accept all channels at the same time.



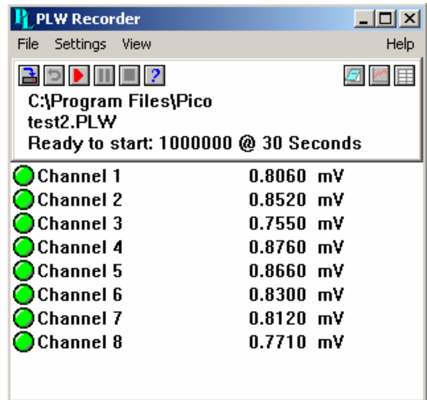
11. The display automatically reverts to PLW Recorder. To save these settings for use later, select Save As from the File dropdown menu. File must be saved with the extension .pls.
12. The parameters for the calibration are now complete.

Calibration process

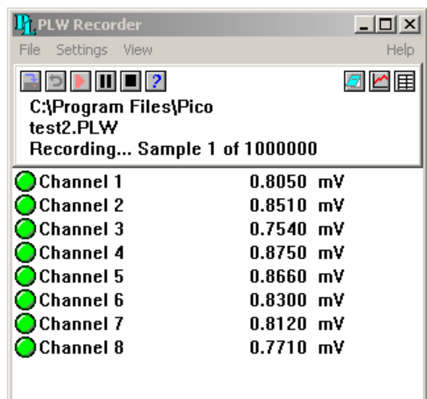
1. Turn on the computer and open the software PicoLog Recorder.
2. Click Open from File dropdown menu. The Open file dialogue box is displayed. Select the setting file created following the above procedures.
3. With the calibration setting file selected, click Open from File dropdown menu.
4. The Create new file dialogue box is displayed. Enter the file name for the experiment. Use a maximum of eight characters to describe all channels at the same time. Then press OK. Make sure the file has the extension **.plw**, which is for data files.



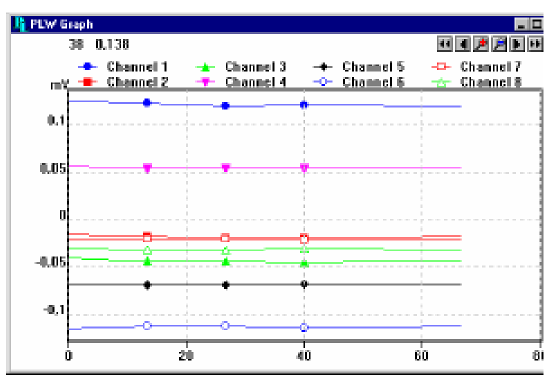
1. The PLW Recorder dialogue box is displayed, showing Ready to Start along with the number of data points to be collected and the frequency of collection. The defined channels are listed below, showing the millivolt values for each channel.



2. To start recording data, click the red START RECORDING button at the left top of the PLW Recorder window. A message in the PLW Recorder dialogue box shows the number of data points collected. The count will continuously update as data samples are collected.



3. A curve of the collected values for each channel can be displayed by clicking the Graph button on the right top of the PLW Recorder dialogue box.



4. When the baseline is stable, allow it to be recorded for 5 minutes ($U_{BL\ before}$).
5. Turn on the voltage generator.
6. Keep the voltage at a constant value until a steady state signal is displayed on the

graph (U_{steady}). The resistors inside the calibration unit are the same. Therefore, the rate of heat evolution for each channel is the same.

7. Shut down the voltage generator and keep the test running.
8. Wait until the signal is stable again and record a baseline for 5 to 10 minutes ($U_{BL\ after}$). Then stop the test.
9. Calculate the calibration factor (ε) for each channel according to the following equations

$$U_{BLmean} = \frac{U_{BLbefore} + U_{BLafter}}{2}$$

$$U_{steady\ state\ adjust} = U_{steady\ state} - U_{BL\ mean}$$

$$\varepsilon = p / U_{steady\ state\ adjust}$$

Where, p is the calculated rate of heat production.

APPENDIX E: PROPOSED SPECIFICATION FOR MONITORING HEAT EVOLUTION OF CEMENTITIOUS MATERIALS USING A SIMPLE ISOTHERMAL CALORIMETRY TECHQUE (VERSION 2)

The following is a test method for monitoring heat evolution of cementitious materials in mortar or concrete using a simple isothermal calorimetry technique.

E.1 Scope

E.1.1

This document describes the test apparatus, procedure, result analysis, and requirements for use of a simple isothermal calorimeter to monitor heat evolution of cement-based materials.

E.1.2

The values stated in SI units shall be regarded as the standard.

E.1.3

This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regularity limitations prior to use.

E.2 Referenced Documents

E.2.1 ASTM Standards

C305 Practice for Mechanical mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency

C403/C 403M Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance

E.3 Summary of Test Method

E.3.1

This method monitors the heat evolution process of paste or mortar samples, with and without admixtures and/or additives, under different curing temperatures. A simple isothermal calorimeter will be used for the test.

E.3.2

The thermal setting times of the tested materials can be estimated from the calorimetry results as described in the section of calculations.

E.4 Significance and Use

E.4.1

The heat evolution process of a cement-based material is strongly influenced by the chemical and physical properties of the cement, supplementary cementitious materials (SCMs), chemical admixtures, mix proportions, construction procedures, and curing conditions. Therefore, deviations in the quantities and characteristics of the material constituents as well as effects of construction conditions can be detected by monitoring the heat evolution of the cementitious material using a simple calorimeter. Research and practice have demonstrated that a calorimetry test has a high potential for characterizing cementitious material features, detecting the concrete incompatibility problems, predicting fresh concrete properties (such as set time), and assessing hardened concrete performance.

E.5 Apparatus

E.5.1 Mixer

The mixer shall comply with practice ASTM C305.

E.5.2 Paddle, Mixing Bowl

Equipment shall comply with practice ASTM C305.

E.5.3 Scraper

The scraper shall consist of a semi-rigid rubber blade attached to a handle about 150 mm long. The blade shall be about 75 mm long, 50 mm wide, and tapered to a thin edge about 2 mm thick.

E.5.4 Supplementary Apparatus

The balances, weights, glass graduates and any other supplementary apparatus used in measuring and preparing the mortar materials prior to mixing shall conform to the respective requirements for such apparatus as specified in the method for the particular test for which the mortar is being prepared

E.5.5 Calorimeter and Acquisition System

The isothermal calorimeter is suitable and calibrated to monitor the heat of hydration of cement paste and mortar in a reproducible fashion. The calorimeter shall be able to provide a testing temperature within 0°C –60°C ±0.5°C. It shall have three or more test units to allow three or more repetitions to be performed at the same time. The variation in the maximum rate of heat evolution between the repeated samples shall be less than 5%. The data acquisition equipment shall be capable of performing continuous logging of the measurement results with a time interval of no more than 60 s.

E.5.6 Environment Chamber

The system shall provide the chamber with a constant temperature in a range of 0°C–60 °C.

E.6 Test Specimens

E.6.1

The test specimens can be paste or mortar. The specimen sizes for paste and mortar are 10 g and 100 g, respectively. A repetition of three samples should be tested for each paste or mortar mix.

E.6.2

The batch size should be sufficient to provide homogeneously mixed samples in the mixer used.

E.7 Procedure

E.7.1

Set the environmental chamber at the desired temperature and let the temperature in the chamber become stabilized.

E.7.2

Program the calorimeter.

E.7.2.1

Click the stop button in the PLW Recorder window to stop the previous test.

E.7.2.2

Click the New Data from File dropdown menu in the PLW Recorder window.

E.7.2.3

Enter the name of the new file and press OK.

E.7.3

Prepare the paste or mortar sample according to the ASTM C305 method. Record the mixing time.

E.7.4

Load the specimen into the calorimeter.

E.7.4.1

Weigh and record the empty mass of the plastic sample cup to be used, or tare the scale to zero with the empty plastic sample cup on the scale.

E.7.4.2

Place the mixed paste or mortar into the plastic sample cup on the scale.

E.7.4.3

Weigh and record the sample to an accuracy of 0.1 g and cover the sample cup with the lid. The mass of the specimen shall be noted.

E.7.4.4

Immediately place the plastic sample cup into the calorimeter.

E.7.5

Click the start button in the PLW Recorder window and start measuring the heat evolution rate.

E.8. Calculations

E.8.1 Post-Processing of Data

The evaluation method consists of the following steps:

1. Remove the baseline:

$$U(t) = U_{raw} - U_{bl}$$

Here Uraw is the signal from the calorimeter and Ubl is the measured baseline of the calorimeter.

2. Apply the calibration coefficient (□) and divide by the mass of cement (mc)

$$P(t) = \frac{\varepsilon \cdot U(t)}{m_c}$$

3. Calculate the results as rate of heat evolution, power (mW) as a function of time and normalize to a unit mass of total cementitious materials (mW/g). The result is the average of the test specimens. The maximum value of each specimen shall not be within 5% of the average value. If it is higher than 5%, this value should be deleted.

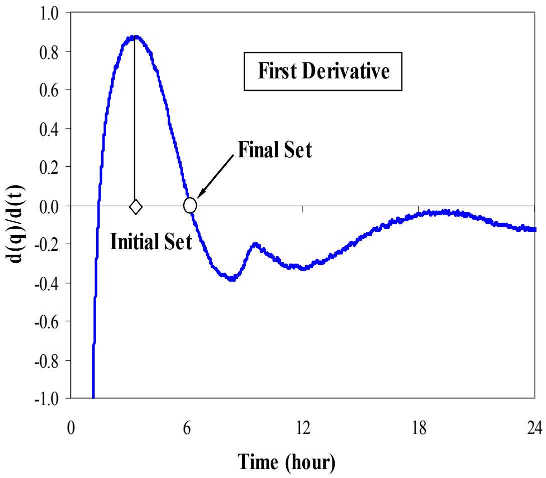
E.8.2 Interpretation of The Results

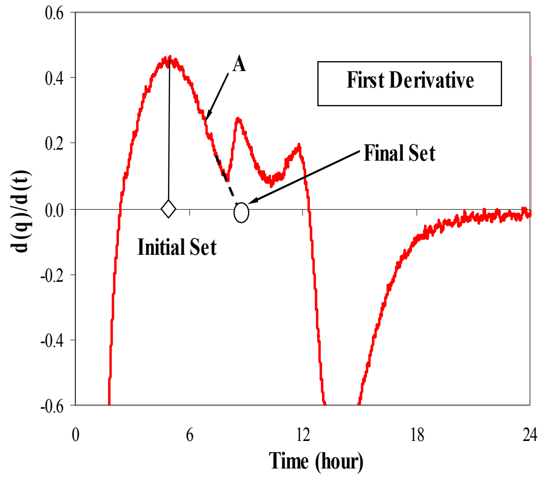
E.8.2.1 Determine the Area underneath the Heat Evolution Curve

The area underneath the curve represents the heat generated during that time. The areas for 1 hour–6 hours, 6 hours–12 hours, 12 hours–18 hours, and 18 hours—24 hours are calculated. The first hour is not counted because the system needs a certain time for stabilization.

E.8.2.2 Determine the Setting Times

In this method, the first derivative, d(q)/d(t), of a calorimetry curve is derived from the original heat evolution test data. The initial set time of the tested mortar is defined as the time when the first derivative curve reaches its highest value. At this point, the increase in the rate of heat generation is the fastest. After the initial set time, the first derivative value starts to decrease. The time when the first derivative drops to zero is defined as the final set of the tested mortar. This point corresponds to the time when the highest rate of hydration is achieved and after this point the rate of hydration will be reduced. For some samples, the heat evolution curve is similar to Figure1b. There are three peaks in the positive sides of the heat revolution curve. The initial set of the tested mortar is still defined as the time at which the first derivative of the heat evolution curve reaches its highest value. Unlike Figure1a, the first derivative of the rate of heat evolution of the mortar with FA starts increasing again before descending to zero. In order to determine the final set under this situation, line A in Figure 1b is extended to cross with the time-axis. This intersecting point is defined as the final set time of the mortar containing FA.





(a) **(b)**

Figure E.1. Determination of set times from heat evolution curve

E.9 Report

E.9.1

The report shall include the following information:

- Source and identity of all materials tested
- Temperature, date, time and duration of test
- Mix proportions
- Any unusual observations, such as early stiffening
- A plotted rate of heat evolution curve
- Calculated area values and setting times

E.10 Precision and Bias

E.10.1 Precision

The variation caused by the equipment and operators shall be less than 5% for the peak value.

E.10.2 Bias

Error of heat evolution test can come from both the testing and data interpreting process. It should be recommended that the operator of the heat evolution test should be able to perform the test in a consistent manner. The time from the mortar/concrete mixing to the time the specimen is place into the testing device should be well-controlled and documented. Also, it is recommended that the original temperature of raw materials before mixing should also be controlled; a difference of the material temperature and testing temperature within 3^{o}C should be required. In low testing temperature, due to the larger difference of test temperature and room temperature, and to the lower rate of heat evolution, a higher level of deviation of heat evolution reading is commonly observed. In order to better interpret the data, a higher degree of smoothing process can be applied; however, excessive smoothing process can generate bias.

Bias for this test method cannot be determined since there is no reference standard available for comparison.