temperature rise of the mixture close to that of the Type V Cement (C9). The replacement of Cement C9 with SCM's FC2 and S1 increases the adiabatic temperature rise by 15°C (27°F).

CONCLUSIONS

The variability of the semi-adiabatic calorimeter test was quantified in this study. These results allow the comparison of results from different mixtures, instruments, and laboratories. Several conclusions may be drawn. First, the calibration method should use a conduction model based on time to reduce the variation between instruments. Second, the accuracy of the calorimeter instrumentation causes bias in the calculated adiabatic temperature rise. However, the precision and accuracy of the lab-made calorimeter was comparable to the calorimeter manufactured by a third party. Finally, for any two test results, a difference of 8.8% for α_u, 20.9% for τ, and 16.9% for β is considered statistically significant at a 95% confidence level.

The change in adiabatic temperature rise associated with w/cm, cement content, aggregate type, placement temperature, cement type, and SCM's was investigated. The following factors were the most important to reduce the adiabatic temperature rise: reduced cement content, use of a lower-heat cement, such as a Type V cement type, reduced aggregate specific heat, and substitution of cement with Class F fly ash. Through the use of heat transfer calculations and a mixture-specific activation energy, the effect that placement temperature has on the rate of hydration can be accounted for to convert semi-adiabatic calorimeter test results into fully adiabatic test results.

ACKNOWLEDGEMENTS

The authors would like to extend their appreciation and gratitude for the financial support provided by the Texas Department of Transportation. The advice and support of Ralph Browne is greatly appreciated.

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Table 1–Chemical and physical properties of cement

	Ty I LA	**Ty I**	**Ty I/II LA**	**Ty III**	**Ty V**	**SCM's**				
Cement	**C1**	**C2**	**C6**	**C8**	**C9**	**FF1**	**FF2**	**FC1**	**FC2**	**S1**
SiO_2 (%)	20.45	19.18	20.77	20.3	21.63	56.63	51.69	37.83	33.31	34.48
Al_2O_3 (%)	5.43	5.34	3.88	4.85	4.04	30.68	24.81	19.83	18.39	11.35
Fe_2O_3 (%)	2.01	2.3	3.73	3.56	5.29	4.94	4.22	6.17	5.40	0.67
CaO (%)	64.51	63.17	64.5	63.94	63.07	0.69	13.12	23.13	28.91	41.73
MgO (%)	1.15	1.09	1.01	0.82	0.77	0.73	2.29	4.62	5.25	7.32
Na_2O (%)	0.14	0.12	0.18	0.07	0.27	0.12	0.18	1.74	1.64	0.14
K_2O (%)	0.56	0.95	0.6	0.66	0.23	2.26	0.84	0.06	0.35	0.38
Na_2O Eq. (%)	0.51	0.75	0.575	0.504	0.42	1.607	0.733	1.778	1.870	0.390
SO_3 (%)	3.35	3.2	2.38	3.44	2.74	0.00	0.46	1.50	2.27	1.88
LOI[*] (%)	1.80	4.1	2.67	1.71	1.55	2.10	0.23	0.67	0.34	0.83
Insoluble Residue (%)	-	0.63	0.25	-	1.43	-	-	-	-	-
Free CaO	1.66	4	2.8	1.89	3.8	-	-	-	-	-
C_3S (%)	58.29	63.11	66.54	58.54	49.85	-	-	-	-	-
C_2S (%)	14.65	7.38	9.35	14.04	24.41	-	-	-	-	-
C_3A (%)	10.99	10.26	3.97	6.83	1.76	-	-	-	-	-
C_4AF (%)	6.12	7.00	11.35	10.83	16.10	-	-	-	-	-
Gypsum	5.70	5.44	4.05	5.85	4.66	-	-	-	-	-
Blaine fineness (m^2/kg)	350.0	390.9	365.4	539.0	409.0	147.3	165.5	348.4	299.9	331.6

[*] LOI = Loss on Ignition

Table 2–Summary Statistics for Semi-Calorimetry Variation

Mix #	No. of Tests	Slope Parameter β			Time Parameter τ			Degree of Hydration α_u		
		Avg.	Std. Dev. (σ)	C.V.	Avg. (hrs)	Std. Dev. (σ)	C.V.	Avg.	Std. Dev. (σ)	C.V.
2*	4	1.126	0.011	1.0%	12.506	0.859	6.9%	0.743	0.030	4.0%
4**	4	1.130	0.061	5.4%	12.349	1.123	9.1%	0.739	0.016	2.2%
10*	5	0.755	0.062	8.3%	11.564	1.057	9.1%	0.635	0.029	4.6%
14*	2	0.745	0.025	3.4%	14.806	0.309	2.1%	0.814	0.005	0.6%
15*	7	0.905	0.070	7.7%	16.633	1.361	8.2%	0.787	0.028	3.5%
18**	3	0.908	0.042	4.7%	24.750	0.697	2.8%	0.798	0.008	1.0%
19**	3	0.461	0.009	1.9%	45.540	2.914	6.4%	0.884	0.027	3.1%
20**	3	0.429	0.005	1.1%	74.740	3.965	5.3%	1.014	0.025	2.5%

*Multiple Batch, Multiple Instrument; **Single Batch, Multiple Instrument

Table 3–Summary of Semi-Adiabatic Test Results

Mix #	Cement	SCM (% Replacement by Mass)			Total Cement. Content	Mix. Temp	w/cm	Chemical Admixture (ASTM)		Coarse Aggregate		H_u	α_u	τ	β	E_a
	ID	Type	%	CaO	kg/m³	°C		Type	% by Mass	Type	$\frac{FA^*}{FA+CA}$	kJ/kg		hrs		J/mol
1	C1	-	-	-	279	18.7	0.42	A&D	0.23	SRG	0.40	513	0.733	13.386	1.084	30,810
2	C1	-	-	-	335	21.1	0.42	A&D	0.23	SRG	0.40	513	0.743	12.506	1.126	30,810
3	C1	-	-	-	396	19.0	0.42	A&D	0.23	SRG	0.40	513	0.673	11.332	1.279	30,810
4	C1	-	-	-	335	13.4	0.42	F	0.31	LS	0.40	513	0.739	12.349	1.130	40,650
5	C1	-	-	-	335	19.0	0.42	F	0.31	LS	0.40	513	0.719	12.426	1.052	40,650
6	C1	-	-	-	335	29.1	0.42	F	0.31	LS	0.40	513	0.759	12.243	0.927	40,650
7	C1	-	-	-	335	21.0	0.32	F	0.50	SRG	0.40	513	0.636	12.013	1.246	40,650
8	C1	-	-	-	335	23.2	0.40	F	0.16	SRG	0.40	513	0.683	12.727	1.063	40,650
9	C1	-	-	-	335	19.3	0.42	F	0.21	SRG	0.40	513	0.740	11.564	1.193	40,650
10	C2	-	-	-	335	22.5	0.44	-	-	SRG	0.44	530	0.635	12.608	0.755	38,725
11	C6	-	-	-	335	23.7	0.44	-	-	SRG	0.44	496	0.702	11.373	0.739	37,165
12	C8	-	-	-	335	23.3	0.44	-	-	SRG	0.44	493	0.697	9.342	0.895	37,344
13	C9	-	-	-	335	23.2	0.44	-	-	SRG	0.44	464	0.635	15.170	0.813	38,597
14	C2	FF1	30	0.7	335	23.9	0.44	-	-	SRG	0.44	374	0.814	14.806	0.745	38,787
15	C1	FF2	30	13.1	335	15.0	0.42	A&D	0.23	SRG	0.40	430	0.788	18.953	0.929	31,975
16	C1	FF2	30	13.1	335	20.7	0.42	A&D	0.23	SRG	0.40	430	0.751	17.631	0.910	31,975
17	C1	FF2	30	13.1	335	28.9	0.42	A&D	0.23	SRG	0.40	430	0.787	16.633	0.905	31,975
18	C1	FC1	30	23.1	335	22.0	0.42	A&D	0.23	SRG	0.40	484	0.798	24.750	0.908	32,864
19	C9	FC2	30	28.9	335	23.0	0.44	-	-	SRG	0.44	481	0.884	45.540	0.461	41,164
20	C9	S1	40	-	335	23.4	0.44	-	-	SRG	0.44	463	1.000	58.143	0.440	45,077

*FA = weight of Fine Aggregate (pcy or kg/m³), CA = weight of Coarse Aggregate (pcy or kg/m³)

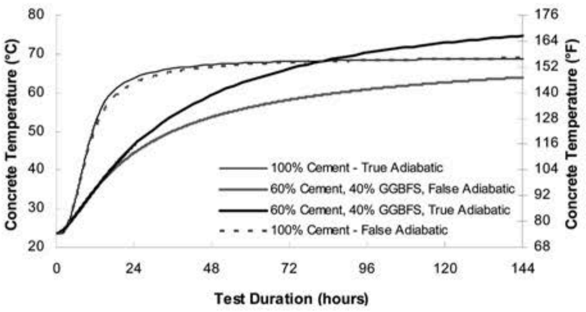

Figure 1—Comparison of adiabatic temperature rise calculations.

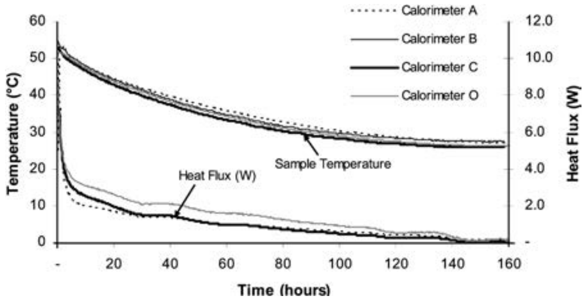

Figure 2—Water calibration results for calorimeters used in study.

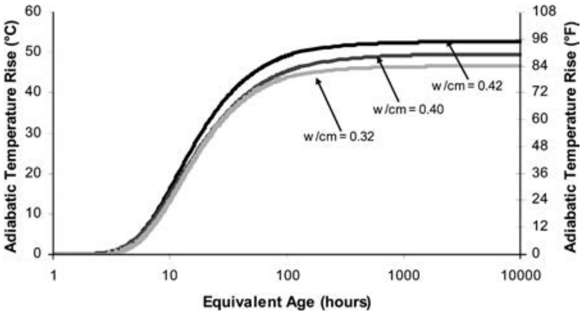

Figure 3—Effects of *w*/*cm* on hydration behavior.

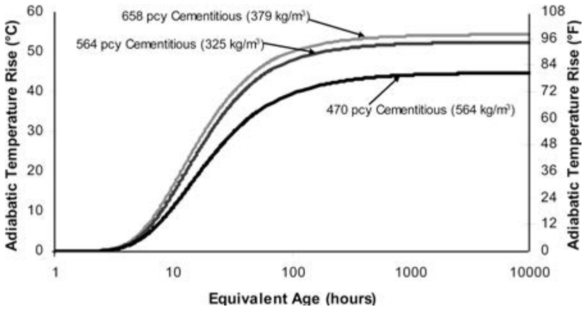

Figure 4—Effects of cementitious content on hydration behavior.

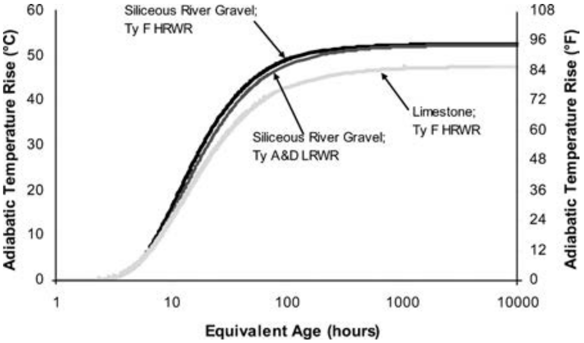

Figure 5—Effects of aggregate type and admixture type on hydration behavior.

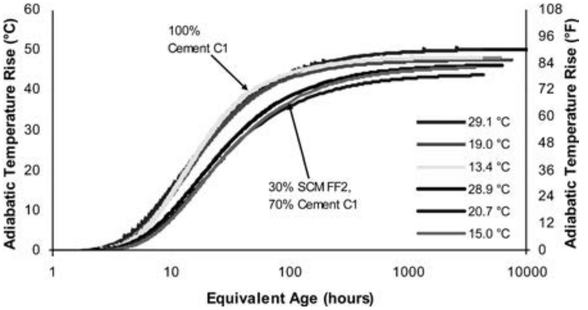

Figure 6—Effects of placement temperature on calculated adiabatic temperature rise for 100% cement C1 (Mixtures 4, 5, and 6) and 30% SCM FF2, 70% cement C1 (Mixtures 15, 16, and 17).

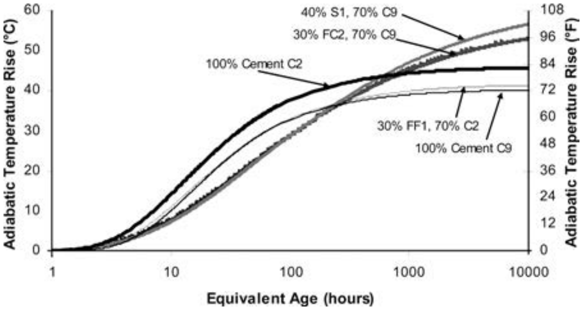

Figure 7—Effects of cement type on adiabatic temperature (Mixtures 9-13).

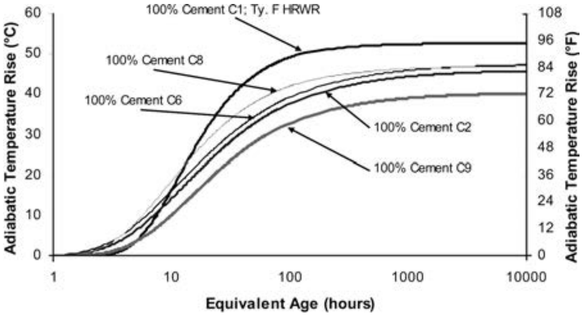

Figure 8—Effects of SCMs' on adiabatic temperature rise (Mixtures 10, 13, 14, 19, and 20).

Characterization of Concrete Paving Mixtures with HIPERPAV

by J.M Ruiz, R.O. Rasmussen, and T.R. Ferragut

Synopsis: Concrete paving mixtures are subjected to varying climatic conditions during the hydration process. The temperature of the concrete is a function of the heat generated by the cement paste and climatic conditions as well as curing procedures applied during construction. Temperature development in the concrete is closely related to the development of concrete properties and also affects the generation of internal stresses in the pavement that if not properly controlled may result in cracking and other distresses.

With the FHWA HIPERPAV software, it is possible to assess the impact on the performance of the pavement that different concrete materials will have by evaluating their heat of hydration properties (heat fingerprint) and their interaction with the environment.

Characterization of concrete mixtures in terms of their heat of hydration allows for a more rational selection of materials as a function of the climatic conditions to which they are exposed. Selected concrete mixtures with this approach can thus provide more confidence in that they will perform satisfactorily under the site-specific conditions to which they are subjected effectively reducing potential excessive stresses in the pavement.

In this paper, the system approach to characterize concrete paving mixtures and its effect under various climatic conditions is presented.

Keywords: calorimetry; concrete pavements; concrete paving; degree of hydration; HIPERPAV; setting time

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BACKGROUND

A concrete paving mixture is typically engineered to adequately develop the properties required during construction and throughout the life of the pavement. Adequate development of early-age properties such as setting time, strength development, and thermal cracking resistance are dependant on the materials and proportions used. They are also dependant on design factors, construction procedures and environmental conditions during placement.

Often times, placement of concrete pavements extends all year long and paving contractors are faced with unfavorable changes in the properties of their concrete mixtures as a result of seasonal climatic changes. Typically, adjustments are made to the type and dose of chemical admixtures used based on experience to accommodate for some of these changes. Also, a common situation is the change in the source of materials that may drastically impact the development of concrete properties.

It is the intent of this paper to demonstrate that with the use of semi-adiabatic calorimetric testing and HIPERPAV, development of early-age properties for concrete paving mixtures can be evaluated as they are subjected to changes in materials source or to different climatic conditions. Furthermore, concrete mixtures with different admixture types and doses can be evaluated during the planning stage provided their heat fingerprint is known from calorimetric testing.

HIPERPAV MODELING AND CALORIMETRY

Sponsored by the U.S. Department of Transportation, Federal Highway Administration, HIPERPAV (HIgh PERformance concrete PAVing) is a software tool capable of predicting the early-age behavior of concrete pavements. HIPERPAV successfully integrates materials, pavement design, climate, and construction operations into an easy to use Windows-based software package. Using a systems approach, primary factors influencing concrete pavements are considered when predicting the strength and stresses during the first 72 hours after construction.

The core of the HIPERPAV system is a robust model for pavement temperature prediction (Figure 1). In addition to temperature, HIPERPAV predicts moisture changes during the first few hours after construction. Development of concrete strength and other properties is closely related to the curing temperature and moisture state in the concrete[1].

In addition, temperature and moisture changes in concrete may lead to significant changes in volume that can, in turn, produce axial movement, curling and warping, and shrinkage. Due to restraint at the slab-subbase interface and the slab own weight, significant stresses are generated. Since concrete is weak in tension, pavement damage may occur if the stresses in the concrete exceed the developing strength.

For jointed concrete pavements, damage may be experienced as uncontrolled cracking or microcracking. By modeling strength and stress development in the pavement with the use of HIPERPAV, users are able to identify potential risks and select alternative concrete mixtures that result in optimum performance. More specific details about the HIPERPAV software can be found elsewhere.

HIPERPAV scenarios

Uncontrolled mid-slab cracking in the early-age jointed plain concrete pavement, or JPCP, is the critical distress which is modeled by the HIPERPAV system. Two possible scenarios of stress-versus-strength development can occur. Figure 2 graphically depicts these scenarios. The first scenario shows the stress maintaining a magnitude which is consistently lower than that of the strength; therefore early-age distress is not expected.

The second scenario shows that stress development is at a much greater rate than strength development. At the point of intersection of these plots, a failure may possibly occur in the form of a crack. Equally important is the setting time of the concrete mix under site-specific environmental conditions that can be identified by HIPERPAV as the point when strength development starts. McCullough and Ruiz et al provide a more detailed description of the software and the theoretical models considered[2,3,4].

Concrete temperature prediction

In the early ages, concrete temperature is a function of climatic conditions and the heat of hydration generated as a result of the exothermic reaction between the cementitious materials and water. A conceptual representation of this interaction is illustrated in figure 3. The heat generated due to hydration results in a temperature rise in the concrete as a function of the thermal properties (i.e. conductivity and specific heat) of the paste and aggregate. On the other hand, climatic conditions such as air temperature, solar radiation, cloud cover, and convection due to windspeed affect the amount of heat lost or gained through the surface of the pavement. This heat loss or gain is transported through the