

Preliminary Optimization of Concrete Paving Mixtures for Sustainability and Performance

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Abstract

Greater sustainability in concrete construction projects generally requires higher replacement of portland cement clinker-based binder materials with byproduct supplementary cementitious materials (SCM's). There may be serious constructability-related performance side effects of such concrete mixtures, however, including delayed setting, slower strength gain, and increased sensitivity of the mixture to changing temperatures. Related impacts for paving applications may include placement and finishing issues, cracking, surface profile and durability concerns, and various other quality and scheduling implications. Mix designs often require more aggressive chemical admixture use and performance side effects are difficult to predict and manage. A protocol is presented for the evaluation of materials and preliminary optimization of proportions that can help maximize practical SCM use in concrete paving mixtures while approximating the performance of traditional mix designs. An approach using simple thermal profile testing of paste mixtures in the lab is presented and used to show how these influences can be understood and managed.

Introduction

Background. Those who design, specify, and construct concrete pavements are increasingly being required to consider and improve the sustainability of such construction. The metrics used to quantify and compare concrete sustainability are evolving, but a principal focus is reduction of the concrete mixture's content of portland cement clinker, which is responsible for much of concrete's embodied energy and associated greenhouse gas emissions. Lowering concrete's "clinker factor" must typically involve greater replacement of ordinary portland cement (OPC) with byproduct supplementary cementitious materials (SCM's). The associated performance side effects, however, may present significant problems for pavement construction.

Challenges of lower clinker factor paving mixtures. As replacement of OPC with byproduct materials is increased without offsetting mixture adjustments, setting time is retarded and early strength development slowed. These effects can become extreme as SCM content exceeds that of traditional, accepted mix designs, and the effects of cooler weather and mix temperatures on these performance attributes become much more pronounced. All of these trends tend to create operational and quality issues for the concrete paving contractor. Finishing characteristics and bleed water rates change, slipped pavement edges may become less stable, both plastic and drying shrinkage cracking become more likely, and the proper timing of finishing operations and joint sawing become variable and less evident. Some agencies have experienced incompatibility issues with high-SCM mixtures, which can cause even more extreme performance deviations. Agencies and contractors who have dealt with such issues may naturally resist taking on such projects again.

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Proposed protocol for optimizing sustainability and mix performance. The challenges posed by lower clinker factor mixtures can usually be addressed and managed and normal mix performance restored through carefully engineered adjustments of proportions and, in some cases, use of certain additional or alternative materials. This process begins with screening of cementitious materials and admixtures, and selection of those with preferred performance attributes. Then the practical limits of OPC replacement must be considered and proportions adjusted with the aid of chemical and mineral admixtures so as to essentially restore the performance of traditional paving mixtures. This process is theoretically possible using laboratory concrete mixtures, but that becomes impractical due to the number of batches required. This paper presents a simple, expedient laboratory method for preliminary evaluation of materials and proportions that can be used in place of most of these concrete lab batches, with minimal commitments of personnel time and resources. The method is used to document proportioning approaches for successful mitigation of problematic performance trends associated with mixtures using as much as 50 to 60% replacement of OPC. The testing presented makes the process of preliminary proportioning for minimum acceptable performance of such mixtures practical and manageable.

Mixture Evaluation using Thermal Profile Testing

About the method. Hydrating cementitious mixtures evolve heat in the first few hours in such a way that thermal records over time (thermal “profiles”) can be used to characterize certain mixture performance trends – especially those relating to setting and early strength development. The availability of inexpensive thermal sensors, data loggers, and data manipulation software has made this a practical tool for evaluation of concrete materials and mixtures. Sophisticated calorimetry methods are required to accurately measure the heat evolved by a hydrating mixture, but a thermal profile can provide a non-quantitative but repeatable and useful *indication* of this evolved heat. When used as a mix development or evaluation tool, thermal profiles for multiple hydrating mixtures similarly tested in the same environment are graphed on a common time scale for comparison. Early-age compressive testing of the same mixture samples can also provide useful supporting data.

Materials suppliers, concrete producers, and researchers have in recent years made increasing use of thermal profile testing, also known as *thermal measurement testing* or *semi-adiabatic calorimetry*, though the latter term is not a technically accurate description. Specific applications include evaluation of materials sources or within-source variability, optimization of admixture dosages, checking for potential materials incompatibility, troubleshooting field problems, and various other concrete mix development and quality control functions. Test mixtures may be lab or field concrete, mortar, or paste mixtures. Testing of laboratory paste is especially productive for materials screening and mixture development as discussed in this paper, and has been found to provide useful indications of parallel concrete performance (Cost and Gardiner 2009, Cost 2009, Sandberg and Liberman 2007). Specific use of thermal profile testing in this paper will be limited to the evaluation of setting trends, though insight into other areas of performance is also possible.

Equipment and methods. There are many variations of equipment, mixing methods, and data collection systems that can be productively used. Manufactured systems are becoming available, and setups assembled using adapted off-the-shelf hardware are equally useful. Example systems, test setups, and related hardware are shown in Figure 1. For mix development as discussed in this paper, it is desirable to be able to

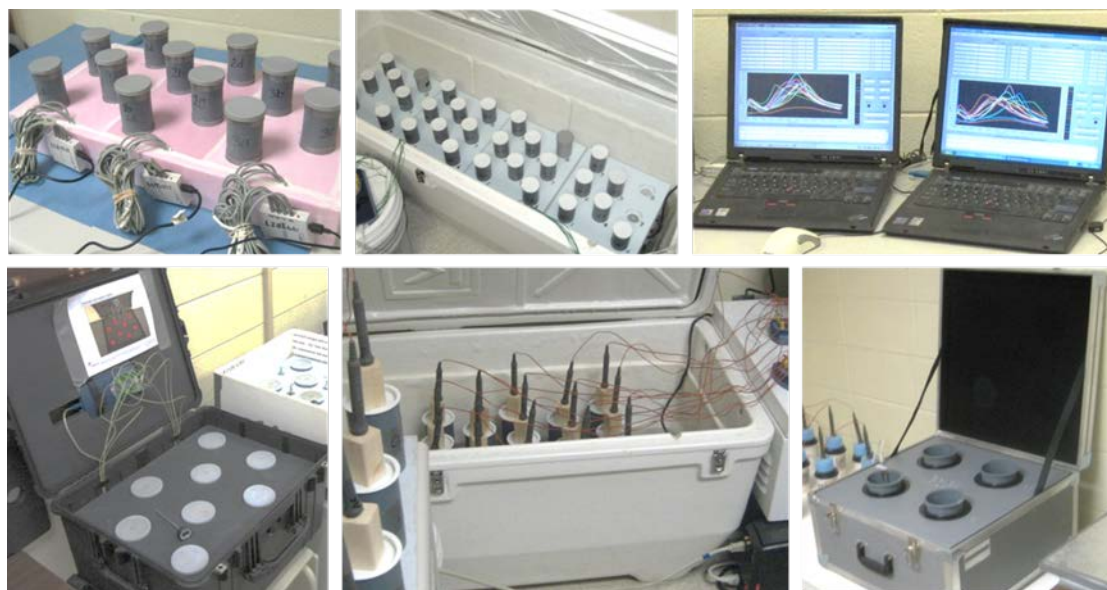


Figure 1. Thermal profile testing equipment and related hardware.

batch and test a significant number of mixtures in a short span of time, thus test setups with capabilities for multiple channels operating simultaneously are necessary. Devised equipment setups that were used in producing the data presented in this paper (some of these are shown in Figure 1) are capable of simultaneous data collection for up to 48 mixtures, supported by 3 laptop computers.

The data shown throughout this document are from laboratory paste mixtures that were proportioned according to the paste fractions of potential concrete mixtures. All data were collected using a system devised from thermocouple sensors isolated from ambient temperatures by foam insulation and held in contact with 5.1 x 10.2 cm (2 x 4 in.) plastic cylinder molds for hydrating paste samples (or inert sand and water for reference temperatures). Paste mixing was done for 75 seconds with a hand-held kitchen mixer. No insulation was used around the sample containers other than minimal insulation near thermocouple sensors. The curing environment throughout data collection was either lab ambient conditions or simulated cool weather field temperatures, using a temperature-controlled curing tank. Thermocouple data loggers connected to laptop computers were used with software that allows for live monitoring of thermal data during testing as well as post-test plotting of thermal records synchronized from the time of mixing for each sample. All data plots shown were generated using subtraction of the inert reference temperatures from corresponding hydrating sample temperatures for each data point ($T_{\text{sample}} - T_{\text{ref}}$), as an indication of temperature change caused only by hydration.

Interpretation of thermal profile and paste strength data. The features of a thermal profile for a normally-hydrating mixture generally include an initial exotherm associated with hydration of aluminate compounds, followed by a period of dormancy effected by the interaction of calcium sulfate with aluminates, then the “main peak” exotherm that results primarily from alite (tricalcium silicate) hydration. The timing of these features, the magnitude of peaks, and the shape of the resulting profile curve all provide performance information of interest, especially as thermal profiles for different mixtures with particular features are compared.

Thermal profile testing is an ideal tool for evaluating the potential for sulfate-balance incompatibility of materials, which clearly affects profile shape and timing (Cost 2006, Cost and Knight 2008, Cost 2011, Roberts and Taylor 2007). This issue is most commonly associated with mixtures containing significant proportions of ASTM C618 Class C fly ash, portland cement with less-than-optimum calcium sulfate content, and/or aggressive use of certain categories of chemical admixtures. No incompatibility of materials was identified in any of the mixtures included in this study; the interpretation of thermal profiles affected by incompatibility of materials is discussed in the cited references and other published papers.

For normally-hydrating mixtures not affected by incompatibility, main peak magnitudes and shapes can provide indications of hydration efficiency, though true strength effects can be most reliably gaged using actual strength tests. The strengths of paste or mortar fractions of concrete have often been used as a relative indication of actual concrete strengths (Cost and Gardiner 2009). For the protocol suggested in this paper, strengths of paste mixtures that model the paste fraction of envisioned concrete have been used, compared against paste strengths similarly modeled from reference concrete mixtures of known performance.

Thermal profiles are especially useful for indexing relative setting times, as evidenced by the timing of mixture main peaks. Corresponding concrete setting times as determined by ASTM C403 can often be estimated from this data (Cost and Gardiner 2009, Sandberg and Liberman 2007). Cost and Gardiner found that thermal profile-determined set indications of paste mixtures, while somewhat longer (by 41% to 51% in the data presented) than the ASTM C403 initial setting times of parallel concrete mixtures, tracked quite consistently with respect to the level of acceleration or retardation resulting from each changed mixture variable.

Example thermal profiles – effects of fly ash proportions and admixture type. Figure 2 shows thermal profiles for three laboratory paste mixtures that illustrate some typical effects of changes in fly ash replacement of OPC and water reducing admixture type. Corresponding 1-day paste compressive strengths are shown in the inset

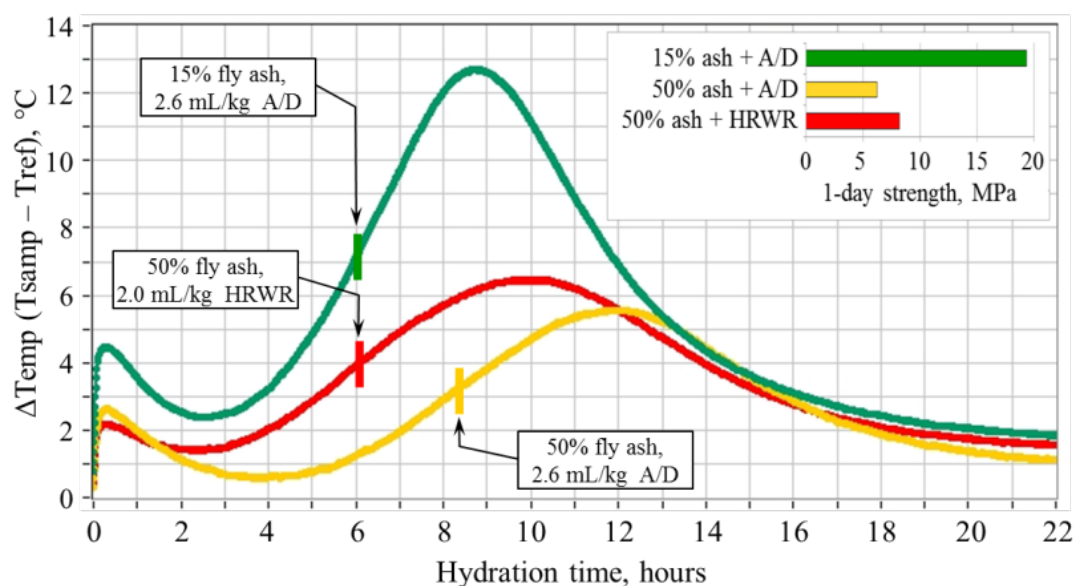


Figure 2. Example thermal profiles showing effects of fly ash content and admixture type. Note: 1MPa = 145 psi, 1 mL/kg = 1.54 fl oz/cwt.

bar chart. This example data is shown to illustrate how thermal profiles can be used to evaluate mixture performance, though the specific materials used are not common to those shown elsewhere in the paper. All mixtures were produced at a water-cementitious materials ratio (w/cm) of 0.40, using the same samples of ASTM C150 Type II OPC and ASTM C681 Class F fly ash. Initial mixture and curing environment temperatures were 23°C (74°F). Two different types of water reducing admixture were used – a lignosulfonate-based ASTM C494 Type A/D product and a polycarboxylate-based Type A/F high-range water reducer (HRWR). Dosage rates for each admixture were selected for essentially the same level of C494 Type A water reduction performance. Thermal profiles are shown with markers that index the “50% fraction” time of each mixture, or the elapsed time after mixing when 50% of the temperature rise from dormancy to main peak maximum occurs, as a simple index of relative setting time. This approach has been found useful in connecting the setting trends of laboratory paste with those of parallel concrete mixtures (Cost and Gardiner 2009, Sandberg and Liberman 2007).

Note that when fly ash replacement rate is increased from 15% to 50%, the 50% fraction thermal set indication shows over 2 hours of associated retardation, the main peak is severely attenuated, and the 1-day measured strength is about 68% lower. Changing the admixture type to a HRWR without other mix changes essentially restores the setting time (for this set of materials) and slightly improves the 1-day strength.

Mix Design Development and Optimization – Recommended Procedure

Preliminary considerations. An important preliminary step in achieving all of the mix design objectives (sustainability, constructability, and performance) is to identify and screen the materials available for the project. Selection of final materials and sources should consider their inherent performance attributes relative to setting time trends, early strength development, and incompatibility potential, in addition to their sustainability implications and envisioned proportion ranges. Water reducing admixtures for high SCM mixtures will usually need to be capable of a broad range of dosage rates and performance levels, and should not have significant retardation tendencies. Thermal profile testing is an ideal tool to assist the materials selection process, for all of these performance categories (Cost 2011), using groups of otherwise similar mixtures for comparison.

Target performance ranges for setting and early strength should be established based on the performance of traditional, accepted mix designs and contractor experiences relative to problematic performance thresholds. Paste mixtures that model the paste fractions of accepted paving mix designs can be used to help establish reference thermal setting ranges and early-age paste strengths.

Strategies for achieving referenced set and early strength performance in high SCM mixtures. Various proportioning strategies have been used to help offset the set retardation and slow strength gain performance of high SCM mixtures; selection of a specific approach may depend on available materials, costs, and project specification constraints. ASTM C150 Type III (high early strength) cement has been used (Bentz, et al. 1020, Bentz 2010) and some non-traditional materials such as calcium hydroxide, nano-sized limestone, external sources of calcium sulfate, and others have proved useful in laboratory experiments (Bentz, et al. 1020, Bentz 2010, Bentz 2011, Sato and Beaudoin 2007). A simple and reliable way of improving early strengths (as well as late-age, though this is not usually an objective) is to reduce w/cm with the use of

HRWR, which has been done in some successful high-volume fly ash projects (Mehta 2004, Naik et al. 1995, Singh 2007). This may be counterproductive for set time, however, as higher dosages of HRWR or other water reducing admixtures generally tend to retard setting.

Depending on the SCM type, chemical admixture(s), and construction temperatures, use of accelerating admixtures may be needed. These should be of the non-chloride formulations whenever steel reinforcement, and/or load-transfer dowels are part of pavement designs, or when otherwise required by the specifier. While some of these products may tend to slightly influence sulfate-balance incompatibility when used at higher dosages with other high sulfate-demand materials (Cost 2011), most cementitious combinations respond favorably with mild dosages. Mixture field performance should be monitored and the dosage rate adjusted as seasonal temperatures change.

Cementitious systems containing more finely ground limestone may also serve to improve both setting and strength gain performance. Cements with higher limestone content than allowed under traditional US specs for OPC may be currently available in the US under ASTM C1157 and will soon be available under ASTM C595 and AASHTO M 240 specifications for blended cements. Finely ground limestone is well documented to help mitigate set retardation in high SCM mixtures (Bentz et al. 2011, Gurney et al. 2012, Mounanga et al. 2011, Sato and Beaudoin 2007), with set acceleration generally proportional to the total available surface area of the calcium carbonate. Strength synergy of fine limestone content has also been documented, especially in combination with SCM's (Cost 2008, Cost and Bohme 2012, De Weerd et al. 2011, Gurney et al. 2012, Mounanga et al. 2011, Sato and Beaudoin 2007). Additional benefits may include improved paste density, lower permeability, and lower heat of hydration.

Testing and performance optimization. Thermal profile testing of paste mixtures can be used to answer most of the questions that must be resolved regarding influence trends of various materials and proportions, with minimal investment of time and resources. With careful planning, the data produced can guide the mix designer in selection of specific materials, strategies for performance enhancement, and approximate dosages of admixtures and other additives. Subsequent testing can also be done at different materials (and curing) temperatures to evaluate the effects of seasonal weather changes on performance of the concrete mixture and to guide related adjustments of proportions or selected admixtures.

Paste mixture testing should begin with preparation of a proportioning table that ideally includes enough replicate mixtures with sufficient increments of the variables of interest so as to assure that the desired performance results are likely achieved within the range. This testing must be done under the same conditions and using the same methods as mixtures used for identification of target performance ranges, and mixtures for both purposes can be done in the same series. Two or more testing events may be needed to refine and complete the mixture matrix, depending on how many simultaneous channels of data collection are available.

The process should continue with actual concrete batches to verify and refine performance, and ultimately to provide mix design submittal data. Field verification may also be required, and further minor proportion adjustments may be in order to refine placement and finishing properties in the field.

Example Testing for Optimization of a Sustainable Paving Mix

Materials used, proportioning options considered. The following example presents a series of paste mixtures and associated thermal profiles and early strength data as might be used in the development and optimization of a low clinker factor concrete mix design for a paving project. Cementitious materials used include a single sample of ASTM C150 Type II ordinary portland cement (OPC) and one sample each of two different SCM's – ASTM C618 Class F fly ash and ASTM C989 Grade 100 slag cement (ground granulated blast furnace slag, or GGBFS). Properties of these materials are summarized in Table 1. The objectives were to explore the feasibility of 50% OPC replacement using fly ash, and 50% and 60% OPC replacement using GGBFS, as well as the most useful performance optimization strategies in each case. A single polycarboxylate-based ASTM C494 Type A/F HRWR was used for all mixtures, with dosage adjusted according to the mixture w/cm and envisioned concrete slump requirements. W/cm was chosen based on experiences with the materials at higher levels of OPC replacement and the early strength needs, and was not otherwise changed as a test variable.

Other materials used included an ASTM C494 Type C non-chloride accelerating admixture (NCA) and two different fineness levels of ground limestone (LS) powder (approximately 96% calcium carbonate), used as separate additions. This approach provides performance trend comparisons of cements having significant LS content versus otherwise identical non-limestone cements. The finer ground LS powder approximates the LS fraction of a mill-ground portland-limestone cement (limestone is softer and more easily ground than clinker); the coarser was included for evaluation of LS surface area influences. The LS powders are referred to in graphs and tables according to their approximate median particle sizes (4 or 12 μm). They were proportioned to replace either 5% or 10% of the fly ash or GGBFS by mass, so that water to OPC ratio could be held constant regardless of LS content. Particle size distributions for each of the cementitious and LS materials were measured using a laser diffraction analyzer; a summary of this information is presented in Table 2.

Table 2. Particle size data for cementitious materials and limestone powder.

Particle Size Summary by % of Volume, μm					
	OPC	Fly Ash	GGBFS	4 μm LS	12 μm LS
<10%	2.1	2.6	1.3	1.1	1.5
<25%	7.5	7.8	3.3	1.9	4.2
<50% (median)	15.3	17.5	8.8	4.1	12.3
<75%	24.9	41.0	15.5	8.1	22.2
<90%	31.8	107.2	21.5	12.7	30.4

Thermal profile testing plan and procedures. A total of 36 paste mixtures were planned, including two “reference” mixtures modeling traditional low-SCM concrete (15% fly ash and 30% GGBFS), to help establish target thermal setting ranges and early-age paste strengths. Reference mixtures used a minimal 2.0 mL/kg (3 fl oz/cwt) dosage of HRWR, based on total cementitious content, that achieves about 5% to 7% water reduction in most concrete mixtures. A detailed proportioning plan was developed (not shown) with batch weights and dosages for each mixture. The plan included several incremental combinations of NCA and/or LS in each of three test mixture groups according to OPC replacement strategy and w/cm (50% OPC + fly ash @ 0.32, 50% OPC + GGBFS @ 0.32, and 40% OPC + GGBFS @ 0.29). Three mixtures were added to each group (using incremental NCA only) at lower temperatures (both mixture and curing environment) to evaluate cool weather performance trends and needed NCA dosage adjustments. Proportions for all mixtures appear in Table 3.

The 36 paste mixtures each contained 600g total content of powder materials, which were pre-weighed into plastic storage containers on the day prior to testing.

Table 1. Properties of cementitious materials used in testing.

OPC, ASTM C150		Fly Ash, ASTM C618		GGBFS, ASTM C989	
Property	Type II	Property	Class F	Property	Grade 100
SiO ₂ (%)	19.9	SiO ₂ (%)	53.9	S (%)	0.7
Al ₂ O ₃ (%)	4.9	Al ₂ O ₃ (%)	27.9	SO ₃ (%)	0.2
Fe ₂ O ₃ (%)	3.5	Fe ₂ O ₃ (%)	7.6	+ 45 μm (%)	1
CaO (%)	63.7	Sum of above, %	89.4	Blaine (m ² /kg)	560
MgO (%)	1.5	CaO (%)	1.3	Air Content (%)	3
SO ₃ (%)	3.9	MgO (%)	1.4	7-day SAI (%)	91
Na ₂ O (%)	0.2	SO ₃ (%)	0.2	28-day SAI (%)	115
K ₂ O (%)	0.4	Na ₂ O (%)	0.2	Density (S.G.)	2.89
C ₃ S (%)	58.9	K ₂ O (%)	0.9	Ref Cement Data:	
C ₂ S (%)	12.6	LOI (%)	2.4	Na ₂ O eq. (%)	0.69
C ₃ A (%)	7.0	7-day SAI (%)	77	C ₃ S (%)	61
C ₄ AF (%)	10.7	28-day SAI (%)	85	C ₂ S (%)	13
Na ₂ O eq. (%)	0.46	water req. (%)	98	C ₃ A (%)	7
Free CaO (%)	0.8	autoclave exp. (%)	-0.05	C ₄ AF (%)	8
LOI (%)	1.3	Density (S.G.)	2.26	Ref Cement Strength:	
Blaine (m ² /kg)	411	+ 45 μm (%)	27.3	7 days, MPa (psi)	26 (3760)
- 45 μm (%)	97			28 days, MPa (psi)	31 (4510)
Initial Vicat (min)	95			Blend Strength:	
Final Vicat (min)	190			7 days, MPa (psi)	23 (3400)
				28 days, MPa (psi)	36 (5170)

This batch size produced sufficient paste for filling two 5.1 x 10.2 cm (2 x 4 in.) plastic cylinder molds – one specimen was used for thermal profile testing and 1-day compressive strengths, and the other for 7-day strengths. All 36 mixtures were prepared and thermal measurements initiated (by the author and one colleague) in a single morning. Mix water was individually weighed for each batch, with all chemical admixtures dosed and dispersed into the mix water prior to introduction into the mixing bowl containing powder materials. The cycle of batching and mixing, filling sample containers, initiating thermal measurements, and preparing for the next mixture was typically accomplished in about 5 minutes; thermal data collection was begun within 2 minutes after initial wetting of cement for each mixture.

Data, discussion, and results. A 50% fraction thermal set indication time was determined from the thermal data for each mixture, for use in evaluation of the effects of different variables of interest on setting trends. The resulting hydration times at thermal set indication and the compressive paste strengths for each mixture are listed in Table 3. Thermal profiles and 1-day strengths for selected mixture groups are shown in Figures 3 through 7, beginning with the reference mixtures, in Figure 3. In each case the thermal set timing indication appears as a color-coded marker along the thermal profile. Proportioning variables of interest appear in callout boxes, with arrows pointing to the respective mixture thermal set markers. Bar charts above each group of thermal profiles present corresponding 1-day paste strengths; both 1- and 7-day strengths for each mixture are listed in Table 3.

Table 3. Proportions, thermal set indication, and strength results for all paste mixtures.

Note: 1 MPa = 145 psi, 1 mL/kg = 1.54 fl oz/cwt.

Mixture group	Initial mix temp.	Fly ash (%)	GGBFS (%)	NCA (mL/kg)	LS powder		Thermal set ind. (hours)	Paste strength	
					4 μ m (%)	12 μ m (%)		1 day (MPa)	7 days (MPa)
REF, w/cm = 0.40, 2.0 mL/kg HRWR	22°C	15	--	--	--	--	6.6	21.0	44.2
		--	30	--	--	--	5.6	18.1	41.9
50% OPC + Fly Ash, w/cm = 0.32, 9.1 mL/kg HRWR	22°C	50	--	--	--	--	9.9	10.1	27.1
		50	--	9.8	--	--	6.2	13.6	31.7
		50	--	13.0	--	--	5.7	14.2	31.7
		50	--	16.3	--	--	5.3	14.3	31.1
		45	--	--	5	--	8.1	13.2	35.2
		45	--	6.5	5	--	5.7	16.8	39.0
		40	--	--	--	10	7.8	12.4	35.6
		40	--	--	10	--	6.6	14.8	37.9
		40	--	6.5	10	--	5.2	17.2	39.8
	17°C	50	--	13.0	--	--	5.4	10.4	29.5
		50	--	16.3	--	--	3.8	10.4	29.5
		50	--	19.5	--	--	2.5	10.3	29.1
50% OPC + GGBFS, w/cm = 0.32, 9.1 mL/kg HRWR	22°C	--	50	--	--	--	7.2	14.9	46.0
		--	50	3.3	--	--	5.4	17.4	47.8
		--	50	6.5	--	--	5.2	17.9	48.4
		--	45	--	5	--	6.1	17.7	54.5
		--	45	1.6	5	--	5.5	19.6	57.9
		--	40	--	--	10	6.1	16.3	53.6
		--	40	--	10	--	5.4	18.8	59.2
		--	40	1.6	10	--	5.0	19.8	58.4
	17°C	--	50	3.3	--	--	5.8	16.0	45.2
		--	50	6.5	--	--	5.4	15.6	45.5
		--	50	9.8	--	--	4.8	14.2	47.6
40% OPC + GGBFS, w/cm = 0.29, 11.7 mL/kg HRWR	22°C	--	60	--	--	--	8.3	12.2	48.6
		--	60	3.3	--	--	6.3	13.8	47.7
		--	60	6.5	--	--	5.3	14.2	45.7
		--	55	--	5	--	7.4	13.4	53.3
		--	55	3.3	5	--	5.8	15.4	58.8
		--	50	--	--	10	6.6	12.6	53.3
		--	50	--	10	--	6.2	14.1	53.3
		--	50	3.3	10	--	5.3	15.0	55.2
	17°C	--	60	6.5	--	--	6.0	11.1	46.3
		--	60	9.8	--	--	4.9	11.0	47.6
		--	60	13.0	--	--	3.8	10.8	47.5

Reference mixtures and establishment of set and strength targets. Figure 3 shows thermal profiles and 1-day strengths for paste mixtures modeled from two routinely used concrete paving mix designs, both at w/cm = 0.40, with 2.0 mL/kg (3 fl oz/cwt) of HRWR. Based on the thermal set and strength performance of these mixtures and experiences with acceptable ranges of field concrete performance relative to these mix designs, target ranges for thermal set indication (5 to 7 hours) and 1-day strength (≥ 14 MPa or 2000 psi) were established as criteria for acceptable performance in low OPC

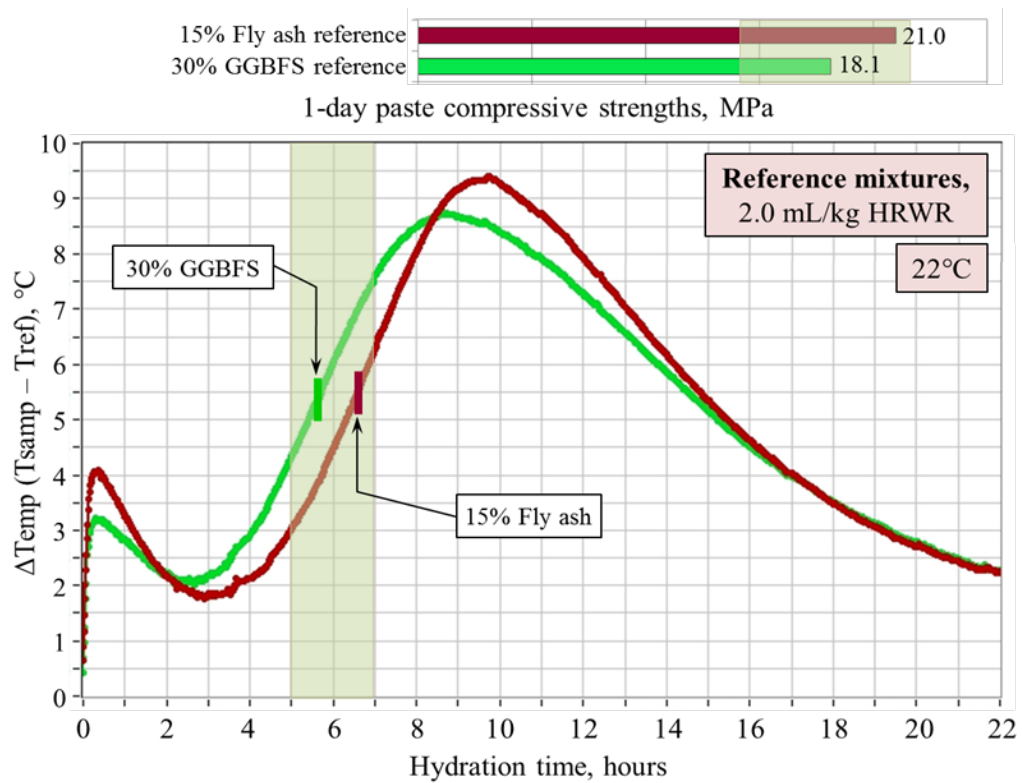


Figure 3. Thermal profiles and 1-day strengths for reference mixtures @ $w/cm = 0.40$. Note: 1 MPa = 145 psi, 1 mL/kg = 1.54 fl oz/cwt.

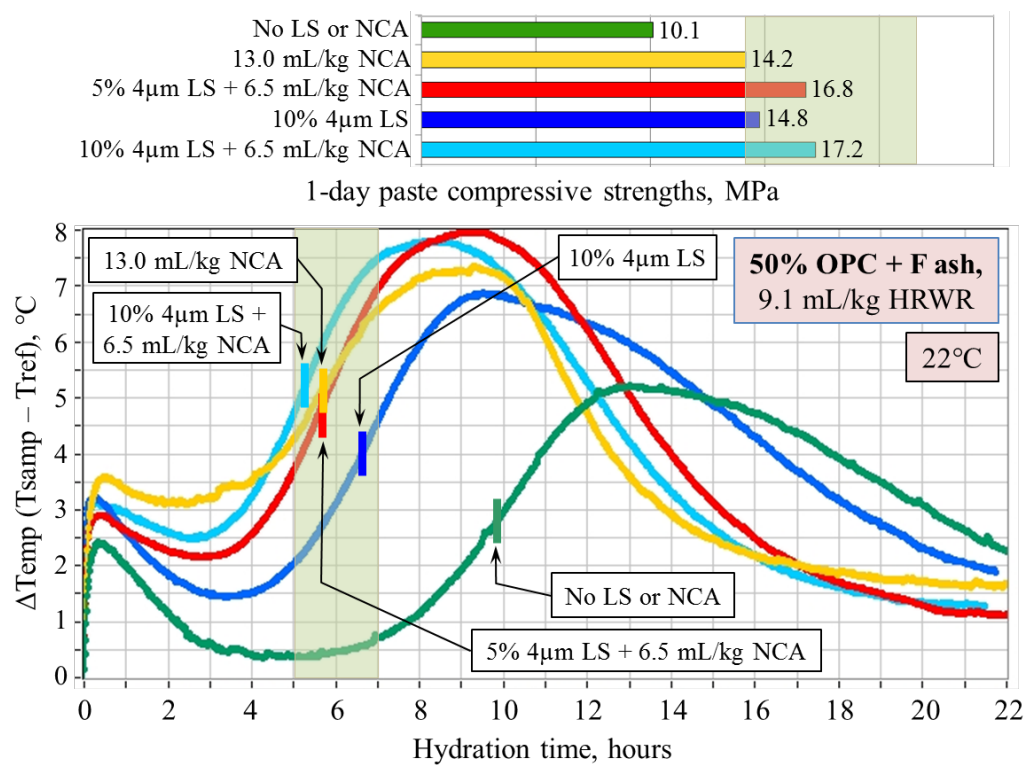


Figure 4. Thermal profiles and 1-day strengths for 50% OPC mixtures with Class F fly ash @ $w/cm = 0.32$. Note: 1 MPa = 145 psi, 1 mL/kg = 1.54 fl oz/cwt.

content mixes. These performance ranges appear as shaded bands on this and subsequent figures, for reference. These criteria will vary with experiences of the mix designer, and it is important to remember that these numbers are not associated with actual measured concrete set times or strengths, but the associated paste thermal profiles and strengths, for reference use only in this testing. By comparing these performance areas in groups of high-SCM mixtures with sequences of proportioning changes, it will be possible to assess which parallel concrete mixtures will likely produce acceptable performance, or what additional changes may be needed.

50% OPC mixtures with Class F fly ash. Figure 4 shows thermal profiles and 1-day strengths for selected 50% OPC mixtures with Class F fly ash. In order to boost the early strengths that would otherwise be quite insufficient, w/cm has been lowered to 0.32 with a higher 9.1 mL/kg (14 fl oz/cwt) dosage of HRWR. Even so, the baseline mixture with no other additions (appearing in green) develops about 4MPa (600 psi) less 1-day strength than the minimum target and thermal set is almost 3 hours longer than the maximum. As additions of NCA and/or 4 μ m LS are made, however, both properties can be brought into target ranges. Four other such mixtures using LS, NCA, or combinations are shown, though the mixture with NCA alone produces marginally acceptable strength.

50% OPC mixtures with GGBFS. Figure 5 presents profiles and 1-day strengths for selected 50% OPC mixtures with GGBFS. Again, a lower w/cm of 0.32 has been used with 9.1 mL/kg (14 fl oz/cwt) of HRWR. This combination comes closer to meeting targets than the baseline 50% Class F fly ash mixture, even without other additions, and lower dosages of NCA and even the coarser 12 μ m LS product are useful in boosting both performance properties well into acceptable ranges.

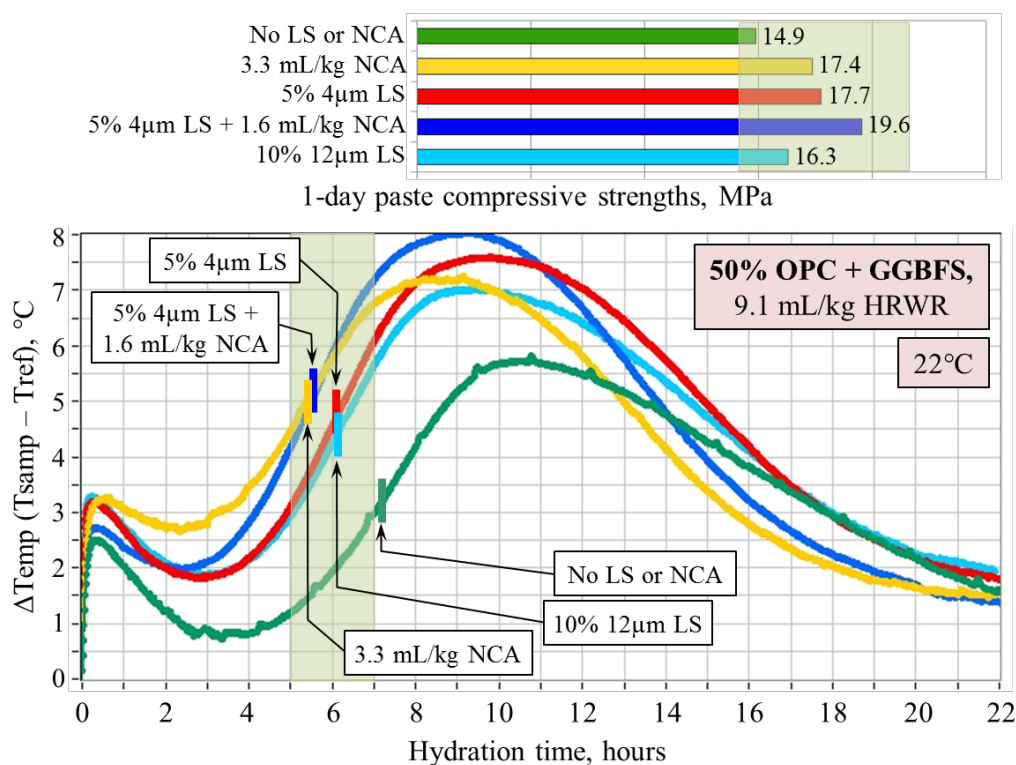


Figure 5. Thermal profiles and 1-day strengths for 50% OPC mixtures with GGBFS @ w/cm = 0.32. Note: 1 MPa = 145 psi, 1 mL/kg = 1.54 fl oz/cwt.

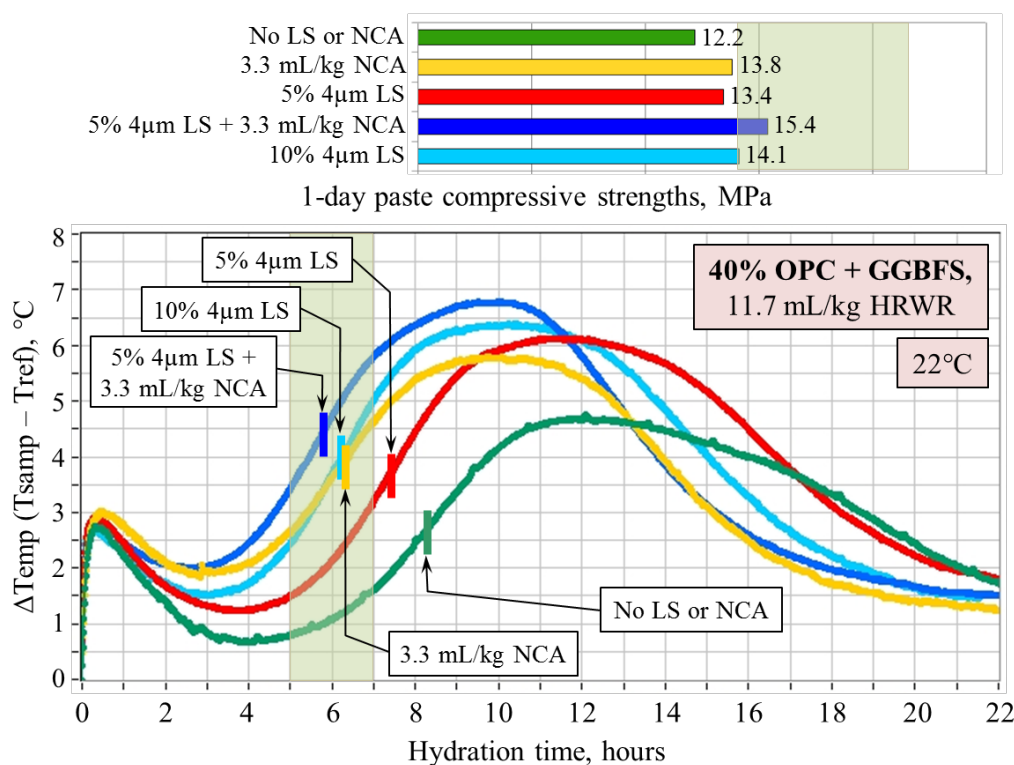


Figure 6. Thermal profiles and 1-day strengths for 40% OPC mixtures with GGBFS @ w/cm = 0.29. Note: 1 MPa = 145 psi, 1 mL/kg = 1.54 fl oz/cwt.

40% OPC mixtures with GGBFS. Figure 6 profiles and 1-day strengths were produced with only 40% OPC, at a still lower w/cm of 0.29, using a higher 11.7 mL/kg (18 fl oz/cwt) dosage of HRWR. The baseline mixture without other additives is now clearly deficient. Thermal set targets are still easily achieved with mild additions of NCA and/or 4 μ m LS, but only a couple of these mixtures meet minimum strengths.

Cool weather influences and adjustments. Sustainable mixtures with low OPC content tend to be more sensitive to seasonal changes than traditional mixtures. Figure 7 shows profiles and 1-day strengths for some selected mixtures from all three mixture groups, with varied and typically higher NCA dosages, produced and tested at a cooler 17°C (63°F). Mitigation of expected additional retardation is easily achieved with the NCA, but strength targets are more difficult to achieve – only the 50% GGBFS mixtures pass this test. Thus if any project paving may be expected to take place in lower temperature conditions, selection of mixtures with especially robust 1-day strengths at lab temperatures is recommended, along with performance checks at the lowest envisioned material and curing temps.

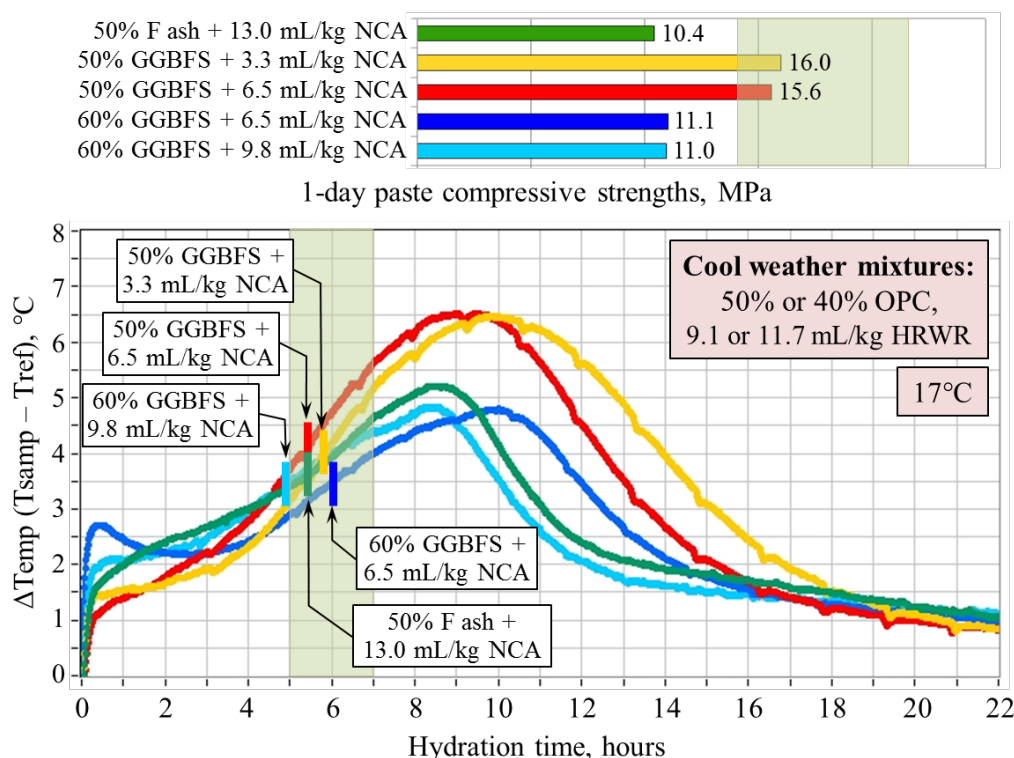


Figure 7. Thermal profiles and 1-day strengths for selected cooler weather mixtures from each mixture group. Note: 1 MPa = 145 psi, 1 mL/kg = 1.54 fl oz/cwt.

Summary and Conclusions

Thermal profile testing. Thermal profile testing is an extremely useful tool for screening of materials and initial proportioning for minimum basic performance requirements of low clinker factor concrete mixtures. It can also be used to guide proportion adjustments for different seasonal temperatures. Resulting mix designs should be verified in actual concrete, and some additional refinement for optimal fresh concrete properties and/or durability performance may be needed. But the use of thermal profile testing as a preliminary tool in the development and optimization of a complex, sustainable mix design can significantly reduce the personnel time and resources that would otherwise be required and can help to assure optimum results.

Strategies for managing setting and early strength performance. The inherently delayed setting and slowed strength gain tendencies of low clinker factor mixtures can be mitigated and restored to essentially traditional performance for the materials included in this testing, using combinations of lower w/cm with HRWR, accelerating admixtures, and cementitious systems with higher finely ground limestone content.

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