Hydration Modulation Measures to Mitigate the Negative Effects of Paving Concrete in Hot Weather

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Abstract

Concrete Placement above a temperature of 35°C (95°F) is typically prohibited in many specifications for construction due to concerns over early-aged cracking, early stiffening, increasing setting temperature, and reduction of ultimate concrete strength etc. A common way to control or modulate the concrete placement temperature has been to cool the concrete constituents (e.g., aggregates and water) or the concrete mixture by using ice or injecting liquid nitrogen. However, these temperature modulation measures often increase the cost of the concrete. In the present study, an attempt has been made through laboratory testing to investigate the effect of hydration modulation measures such as modifying mixture proportions in terms of fly ash proportions in order to combat the negative effect of high temperature placement. Use of fly ash contents greater than 25-30% is an affective way to control the high heat generation and excessive drying shrinkage that is characteristic of high placement temperature and can mitigate the negative effect of high set temperature gradients that can result from placing artificially-cooled concrete under hot weather conditions.

Introduction

Concrete placement above a temperature of 35°C (95°F) is typically prohibited in many specifications for construction due to concerns over rapid setting and increased setting temperatures (Schindler and McCullough 2002). In order to enable a satisfactory concrete workability, cooling measures such as the use of ice or liquid nitrogen at batch plant for concrete placed under elevated temperatures are often applied. Offsetting high temperature effects with the addition of water has adverse effects since an increased water to cementitious ratio (w/cm) in concrete mixes tend to lead to a higher capillary porosity of the hardened concrete and increasing the risk of shrinkage crack formation.

The placement of concrete in hot weather is prone to increase early-aged cracking and reduce ultimate concrete strength due to several factors but one factor would be increased amounts of evaporation. Early stiffening may also be another factor due to high temperature placement making finishing more difficult to

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complete. High temperature placements tend to accelerate the curing process, reduce the finished strength of the concrete, increase the rate of slump loss, reduce the available handling time before concrete becomes too stiff to finish, and contribute to development of cold joints and cracks. Without special measures, placement at concrete temperature above 32°C to 38°C may leads to these types of difficulties. For the above reasons, some transportation agencies have adopted a concrete temperature limit of 35°C for the placement of concrete in hot weather.

Combinations of high air temperature, low relative humidity and high wind speeds typically comprise the most difficult weather conditions for paving. These conditions, when aided by inadequate curing, create a very high potential for reduced performance life. ACI Recommended Practices 305 addresses the special problems of hot-weather concreting. There are of course several options available to address the effects of high temperature placement some of which relate to cooling the concrete during the mixing process. Keeping concrete temperature low during the mixing and transportation stages helps to reduce evaporation, minimize heat development, and slow the hydration rate prior to placement of the mix. As previously noted, a common way to control or modulate the concrete placement temperature has been to cool the aggregates, which may be done as simply as sprinkling them with water and allowing the evaporation process to cool them (Mindess and Young 1981). Other temperature modulation methods include using ice or injecting liquid nitrogen (LIN) into the mixer during the batching process. However, both of these methods increase the cost of the concrete.

With the limiting aspects associated with the temperature modulation measures surrounding the temperature limit of 35°C, economic considerations warrant a closer look with respect to mitigation techniques to ensure the quality of concrete placed under hot weather conditions. Even though the concrete placement temperature may approach or exceed 35°C, it may be possible to control damaging factors by employing hydration modulation measures such as modifying mixture proportions with fly ash along with improved curing or placement practices. Therefore, an attempt has been made in the reported study to investigate the effect of modifying the mixture proportion in terms of fly ash proportions in order to combat the negative effect of high temperature placement. Therefore, the purpose of this investigation was to ascertain the viability through laboratory testing of hydration modulation measures to place concrete in hot weather without the aid of liquid nitrogen or similar costly temperature cooling measures. The effect of temperature modulation measures on the set temperature gradient was also investigated relative to the effect of placing artificially-cooled concrete under hot weather condition.

Laboratory Testing Program

A laboratory test program was conducted investigating hot weather concrete placement relative to three factors: placement temperature, fly ash (FA) content and cement content. To this end, a factorial design for these factors was prepared as listed in Table 1. The placement temperature was considered at three levels (i.e., 24, 35 and 41℃) whereas FA content and cement content are both two levels factors.

Table 1 Test Variables for the Laboratory Program.

Placement Temperature (^{0}C)	FA Content (%)	Cement Factor
24	25	5
35	40	6
41		

Table 1 consists of 12 test runs where seven of the tests (out of these 12 runs) selected for testing are listed in Table 2. A total of four mixtures (Table 3) were used to make up these 7 test runs. Mixture I was investigated at 24, 35 and 41^{0}C whereas mixture II was investigated at 35 and 41°C. The mixtures III and IV were investigated at only 41°C. Test run 1 (mixture I with 24^{0}C) served as a control mix whereas test runs 6 and 7 served as possible mixtures for hot weather paving. The required materials, i.e., coarse aggregate, fine aggregate, class F ash, cement (ASTM Type-I), water reducing admixture etc., to conduct the above 7 test runs were supplied by Lone Star Infrastructure of Pflugerville, Tx.

Table 2 Physical Layout of the Seven Test Runs.

Test Run	Placement Temperature (^{0}C)	Fly Ash (FA) Content (%)	Cement Factor (CF)
1	24	25	5
2	35	25	5
3	35	25	6
4	41	25	5
5	41	25	6
6	41	40	5
7	41	40	6

Note: CAF = 0.72, w/cm = 0.45, 6% air and 8% medium range water reducer

Table 3 Four Mixtures Associated with 7 Runs in Table 2.

Mixture No.	Mixture Proportion
Mixture 1	CF 5, 25% FA
Mixture II	CF 6, 25% FA
Mixture III	CF 5, FA 40%
Mixture IV	CF 6, FA 40%

Test Methods

The following discussion addresses the tests that were selected to investigate the early age concrete behavior as a function of placement temperature, fly ash and cement content. The concrete components, i.e., coarse aggregate, fine aggregate, cement, water etc. were kept inside an environment chamber with pre-set temperature overnight for each test run prior to mixing. Concrete mixing and specimen casting for each test run was carried out inside the chamber with for a given placement temperature. Therefore, it can be assumed that the placement temperature of a particular test run was close to the corresponding room temperature.

Compressive strength: Relative to the effects of placement temperature on concrete, strength gain over time is a major concern. Accordingly, the compressive strength testing was carried out. Cylindrical specimens of 20.32 x 10.16 cm (8 x 4 inch) were cast and tested for compressive strength at 1, 3, 7, and 28 days according to ASTM C39. The specimens were cast and cured inside the environmental chamber at a given temperature for 24 hours; thereafter all specimens were moist cured at a constant temperature of 21°C.

Heat of hydration: Possible placement temperature affects on concrete hydration were characterized in terms of adiabatic heat signature (AHS) and adiabatic temperature rise (ATR). AHS is defined as the heat of hydration and the rate of heat released as a function of curing age of a cementitious mixture during hardening. ATR is defined as the adiabatic temperature rise and its rate as a function of curing age of a cementitious mixture during hardening. ATR is the maximum possible temperature increase of a concrete mixture when it is perfectly insulated. AHS and ATR were determined for all the seven test runs by using Quadrel Q-Drum device manufactured by Digital Site Systems, Inc.

Concrete setting: Setting is a key property that needs to be considered when examining the effects of high temperature on concrete. Setting in many respects is related to the rate of strength gain as well as the rate of hydration in concrete, which can be an issue under high temperature conditions. Penetration testing (ASTM C403) was conducted to determine (a) the time of initial and final set of the concrete – which is obtained by measuring the penetration resistance at different needle diameters and time, and (b) the concrete temperature over the setting period.

Drying shrinkage: Two concrete bar specimens per concrete mixture were cast according to ASTM C157. A vibrating wire gage (VWG) was placed in one specimen and a chilled mirror (relative humidity sensor) was placed in the other bar to monitor both shrinkage strain and relative humidity as a function of time. The dew point temperature was monitored by the use of chilled mirror sensors which was used subsequently to calculate the relative humidity (RH) inside the concrete. The calculated relative humidity data was determined at one hour intervals whereas VWG data were recorded automatically every 15 minutes by a data logger. The relationship between free shrinkage and RH can be established by this method. Setting, heat of hydration and shrinkage data are useful to reveal any detrimental affects of placement temperature on the rate of concrete strength gain.

Cracking frame test: Two cracking frame tests (test runs 4 and 5) were conducted for a concrete placement at 41°C to measure the time of crack formation at the pre-fabricated notch and to validate analysis of stress, strength and creep strain for the given mixture (Vepakomma et al. 2002).

Results and discussion

The different concrete properties previously described were determined for each test run listed in the factorial design (Table 2). The test results are subsequently described.

Effect of fly ash replacement on compressive strength: Earlier research (Mindess and Young 1981) shows that ultimate strength of the concrete cast in low temperature ranges is higher than concrete cast in high temperature ranges. From concrete microstructural investigations, many researchers (Verbeck and Helmuth 1968) have concluded that low temperature curing promotes a relatively more uniform microstructure of the hydrated cement paste, especially the pore size distribution since it contributes to higher ultimate strength. It is also well known that 28 day compressive strength of concrete without any supplementary cementitious materials (e.g., fly ash) placed and cured at temperatures over 20°C is always lower than the corresponding strength of concrete placed and cured at the temperature below 20°C. Compressive strength up to 28 days for all the 7 test runs was presented in Figure 1. Figure 1 shows that up to 28 days of age, the higher the temperature (up to 41°C) the more rapid the cement hydration and the strength development. For mixtures with 25% or more fly ash, the higher the placement temperature the greater the strength development (up to 28 days of age). Therefore, the increase of placement temperature is of benefit for early age (up to 28 days) strength development in case of concrete with reasonable amount of fly ash (≥ 25%). Research (Wainwright et al. 1992) has indicated that hot dry placement conditions (45°C and 30% RH) can be detrimental to the durability related properties of the ordinary Portland cement (OPC) mix but favorable to the improvement of properties of the OPC/fly ash mix. An increase of curing temperature seems to have no detrimental effect on the long-term compressive strength of the fly ash mixture (Maltais and Marchand 1997). In test run 6 (i.e., mixture III placed at 41°C), the data trends show greater early strength development (at 5-7 days of age) than the strength achieved by combination 1 (i.e., mixture I placed at 24°C). However, at later ages (beyond 7 days) the rate of strength gain of mixture III was slower but showed slightly higher strength than mixture I. Therefore, concrete mixtures with high fly ash replacement (e.g., 40%) at high placement temperatures (e.g., 41°C) can often meet 7 day strength requirements. The strength of concrete containing 25% fly ash placed at a high placement temperature (HPT) tends to have a higher rate of strength gain at early ages and a lower rate of strength gain at later ages than those placed at low temperatures. Mixture IV (40% FA, CF 6) placed at 41°C (test run 7) showed a better strength development at early ages in comparison with test runs 1 and 6. It seems that a higher cement factor (e.g., CF 6) in conjunction with high FA content (e.g., 40%) at HPT enhances the pozzolanic reaction and hence its contribution to strength. Similarly, mixture IV shows lower heat generation (discussed subsequently) as well. Therefore, at a HPT of 41°C, high fly ash replacement (e.g., 40%) along with relatively high cement factors (e.g., 6) could be a good choice to maintain low heat development and at the same time satisfying high strength requirements. However, if 40% fly ash mixtures with lower cement contents can meet the strength requirements, then this combination may also be a good choice.

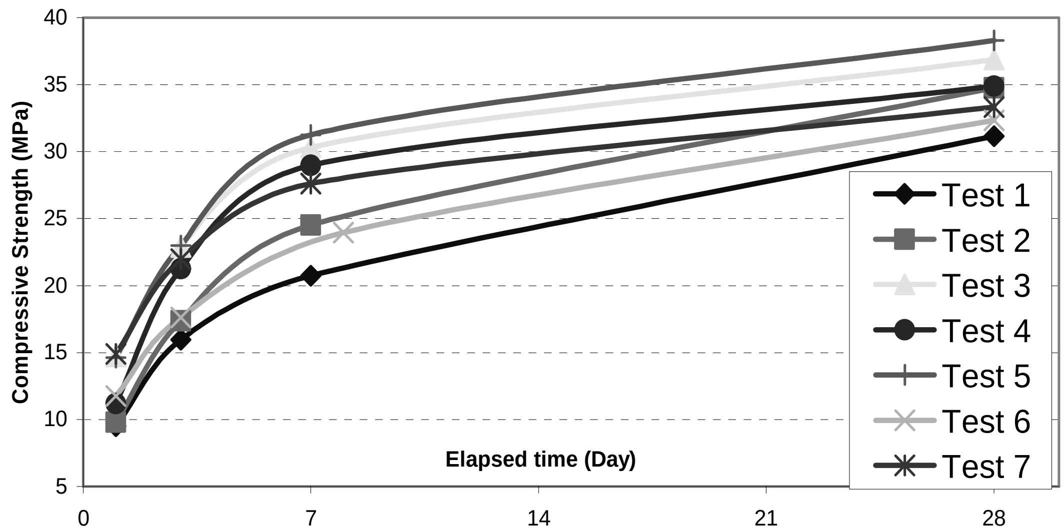


Figure 1 Compressive Strength as a Function of Time for the Seven Runs.

The data in Figure 2 show strength – maturity (temperature – time) relations for the seven test runs at three different placement temperatures of 24°C, 35°C and 41^{0}C. The data shows that strength-maturity of a given concrete mixture is affected by the placement temperature.

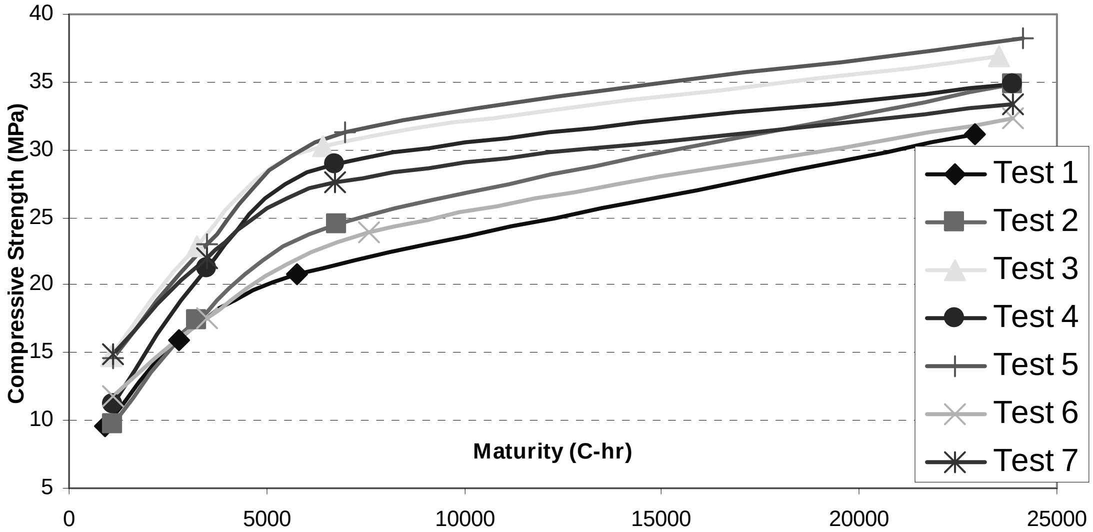


Figure 2. Compressive strength vs. maturity for the seven runs.

***Heat of hydration*:** The results of adiabatic heat signature (AHS, J/gm) and adiabatic temperature rise (ATR, °C) testing are presented in Figures 3 and 4. As indicated, the higher the placement temperature the greater the adiabatic heat signature (AHS, J/gm) and adiabatic temperature rise (°C) (Figures 3 and 4). The heat of hydration determined by Q-drum test at 24°C, 35°C and 41°C placement temperatures are 287, 317 and 346 J/gm, respectively for mixture I (Table 4). The high heat development within 3-4 days for concrete placed at 41^0C can be reduced by increasing the fly ash content. AHS of both run 6 (CF 5, 40% FA placed at 41°C) and 7 (CF 6, 40% FA placed at 41°C) is lower than test run 4 (CF 5, 25% FA placed at 41°C). In this manner, it can be concluded that fly ash contents greater than 25-30% could be an affective way to control heat generation at early ages (up to 4 days). However, minimum strength requirements should also be satisfied at the same time in order to meet practical considerations in the field. As previously noted, at higher cement factors (e.g., 6), the minimum strength requirements can be met using 40% fly ash. However, mixture with a cement factor of 5 can also be used if the 7 day strength requirement is not a stringent issue.

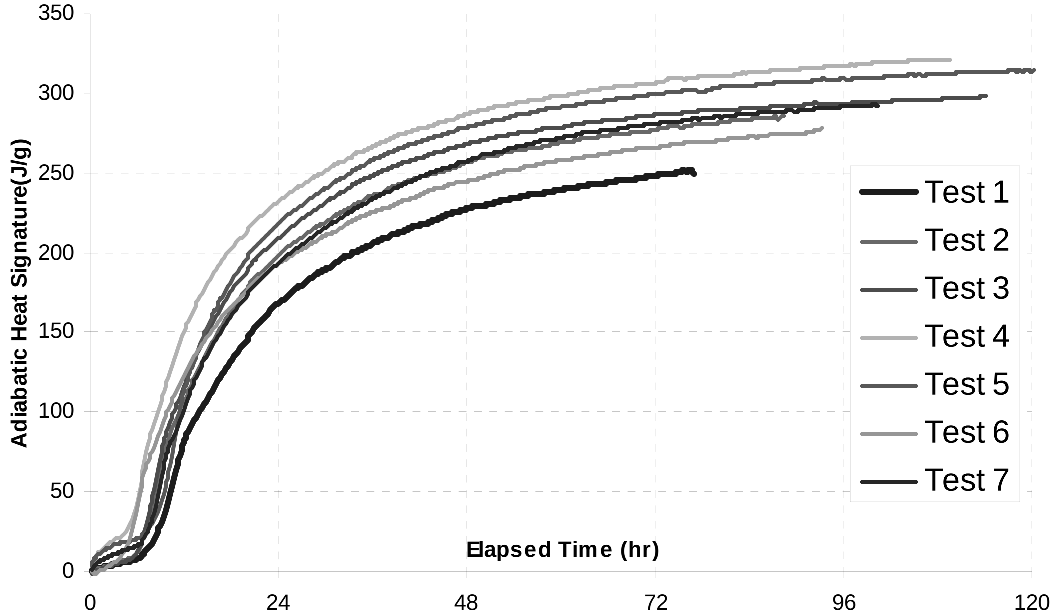


Figure 4 Adiabatic Heat Signature (AHS) as a Function of Time for the Seven Runs.

Table 4 Adiabatic Heat Signature (AHS) in J/Gm for the 7 Runs.

Test run	AHS (J/gm)					
	1 Day	**2 Days**	**3 Days**	**4 Days**	**28 Days**	**90 Days**
1	176.50	239.50	259.00	-	285.74	287.44
2	198.41	256.56	277.49	291.12	312.15	317.50
3	209.11	267.96	286.80	293.77	315.22	324.01
4	213.00	269.00	288.00	298.50	330.50	346.00
5	218.64	278.65	299.59	309.36	340.00	370.00
6	193.06	245.16	266.33	279.12	296.00	305.00
7	193.29	257.49	281.45	291.68	310.98	317.03

Initial and final setting: The times of initial and final setting were determined for all the 7 runs by using the penetrometer test method (ASTM C 403). The results are presented in Table 5. The temperature at 25.4 mm (1 in) below the surface of the specimen for all the 7 test runs was monitored periodically during setting time measurement. Set temperature, i.e., the temperature at final setting, was determined from these temperature measurements and presented in Table 5 along with the predicted time-temperature maturities. A perusal of Table 5 shows that increasing placement temperature causes reduction in both the initial and final setting time. It is also observed that both initial and final setting time slightly increases as the Class F fly ash content changes from 25% to 40%. The final setting time for mixture with 40% fly ash replacement tends to be delayed by about 30 minutes. The concrete maturities at final set for all the 7 test runs are more or less in the similar range (Table 5). The concrete attains higher maturity in a shorter period of time at HPT than that at LPT. The set temperatures were well above the ambient temperature at low temperature placement whereas it was either similar or slightly above the ambient temperature at high temperature placement. Obviously, the set temperatures determined in this manner are not the same as set temperatures in the pavement.

Table 5 Maturity and Set Temperature at Final Set for the Seven Runs.

Test runs	Initial set time (hours)	Final set time (hours)	Final set maturity (^{0}C-hr)	Final set temperature (^{0}C)
1	7.60	9.78	372.62	28.9
2	6.34	8.03	334.80	34.8
3	6.66	8.20	349.29	35.4
4	5.08	6.51	324.88	39.5
5	5.36	6.55	327.00	42.6
6	5.4	6.82	336.00	42.9
7	5.75	6.93	335.57	42.3

Drying shrinkage: Free drying shrinkage strain for all the 7 mixtures was measured by the vibrating wire gauge (VWG) and is presented in Figure 5. The rate of drying shrinkage in HPT concrete tends to increase considerably within the first 24 hours compared to the LPT concrete irrespective of fly ash replacement. The rates of shrinkage strain after 24 hours were comparable among all the mixes irrespective of placement temperature and fly ash replacement (Figure 5). Following are the key observations from the shrinkage testing:

a) Over the monitoring period of 4-5 days, the higher the placement temperature the higher the shrinkage strain irrespective of mixture.
b) The higher the cement factor the higher the shrinkage irrespective of placement temperature or fly ash content. However, at 25% fly ash, a 5 sack mixture showed higher shrinkage than a 6-sack mixture at a placement temperature of 41°C up to 15 hours. Apparently, the concrete achieves greater stiffness at a CF of 6 than that at a CF of 5. Possibly the greater early age stiffness reduced the shrinkage strain. However, the same mixture showed higher strain than a 5-sack mix after 34 hours.
c) 40% fly ash concrete placed at a high temperature (e.g., 41°C) reduces the shrinkage strain below that for a 25% fly ash mixture. Therefore, a higher fly ash content (e.g., 40%) tends to counteract drying shrinkage under HPT.

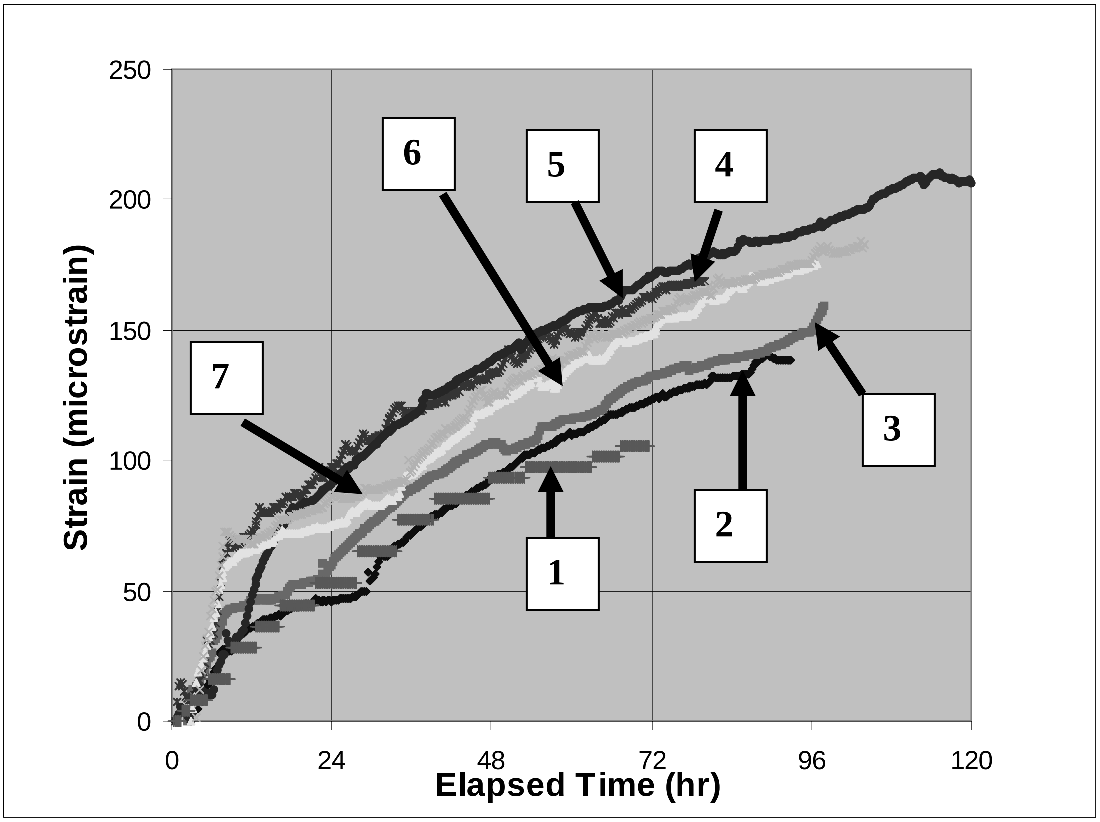


Figure 5 Drying Shrinkage with Time for the Seven Runs.

Cracking frame test: Cracking frame tests (Figure 6) were conducted for runs 4 and 5, i.e., mixtures with different cement factors (5 and 6) but with the same fly ash content (i.e., 25%) and placement temperature (i.e., 41°C). The purpose of this test was to monitor the time of crack formation in the concrete as a function of strength gain and creep development. The concrete specimen cross section at the center portion is 5.2 x 14.6 cm and at the ends of the dovetails 5.2 x 32.89 cm. The length of the concrete specimen is 1 meter. The concrete in the cracking frame was notched at mid span to induce cracking at that location. The crack formed at 82 hours after placement for the 6-sack mix whereas the crack formed at 92 hours for the 5-sack mix. It is interesting to note that crack formation was delayed by about 10 hours in the 5-sack mix.

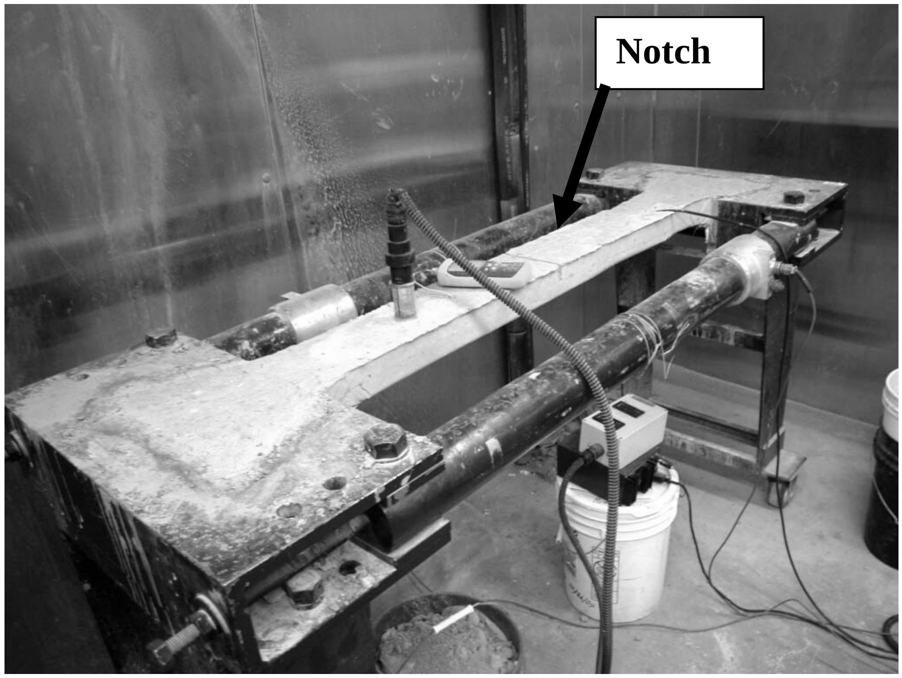


Figure 6. Cracking Frame Test for Test Run 5.

Set temperature under field conditions: To examine concrete behavior under field conditions, set temperature profile and set temperature at mid depth of a 33 cm (13 in) CRC pavement were predicted using the Temperature and Moisture Analysis for Curing Concrete ($TMAC^2$) program (Jeong et al. 2001) where inputs (e.g., set maturity, heat of hydration) were developed from the laboratory test results. The following are the required inputs for the $TMAC^2$ program.

a) Temperature, relative humidity, wind speed, solar radiation as a function of time
b) Set maturity and heat of hydration (J/gm) for each mixture

A typical 24 hour Texas summer (June-July, Figure 7) weather cycle was used for the $TMAC^2$ calculation. Set temperature calculations were performed for both morning and afternoon placements which consisted of set temperature near mid depth of the slab as well as the variation of set temperature with depth.

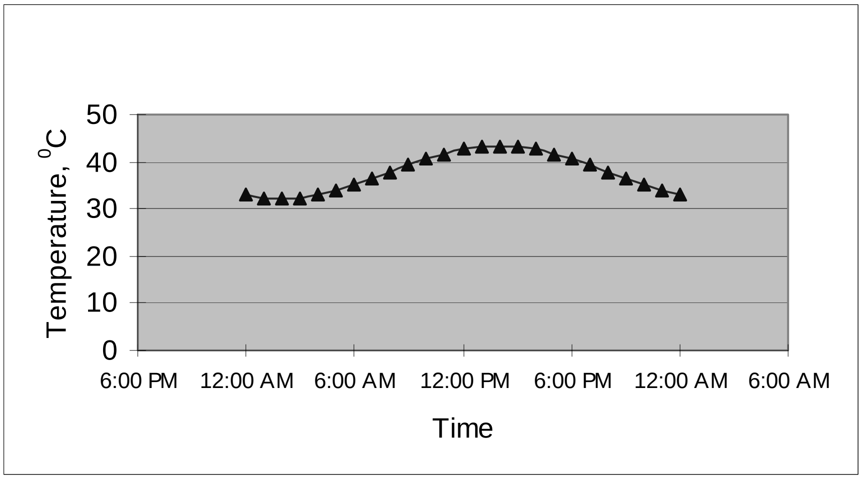
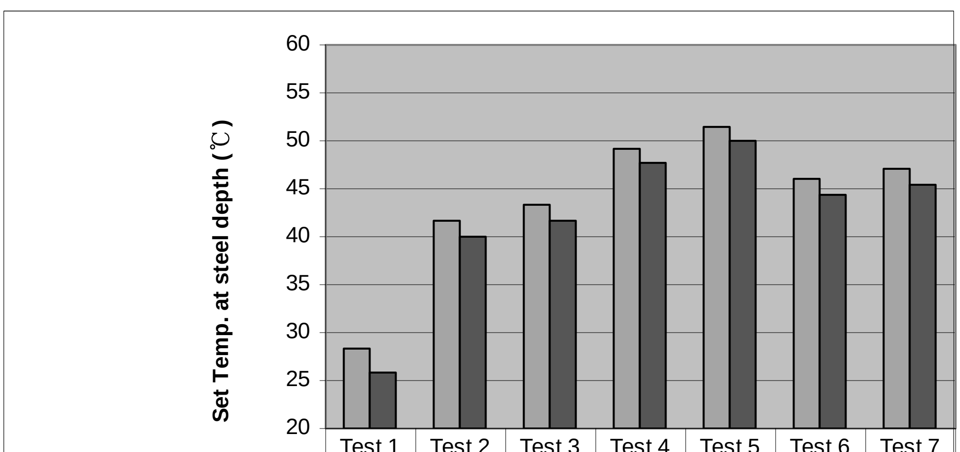


Figure 7 Typical Texas Summer 24 hour Temperature Cycle.

Calculated set temperatures (Figure 8) near mid depth (14 cm below the surface) for all seven runs show the following trends

a) As expected, the set temperature is higher than the placement temperature.
b) Set temperature is higher under morning placements than in afternoon placements
c) An increase in fly ash replacement from 25 to 40% is well correlated with reduction in set temperature in both morning and afternoon placement.

Mixture II (CF 6 with 25% FA) placed at 41^0C (test run 5) shows the



	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
Placed in the morning	28.3111	41.5944	43.2778	49.0722	51.4778	46.05	47.0778
Placed in the afternoon	25.9333	40.0444	41.6222	47.6111	50.0111	44.4	45.3944

Figure 8 Set Temperature Near Mid Depth.

maximum set temperature of 52°C under a morning placement whereas the same mix shows 50°C set temperature under an afternoon placement. The result also shows that using 40% fly ash replacement drops the set temperature near mid depth of the pavement by 7%.

The set temperature gradient, i.e., the temperature difference between bottom and top of slab at final setting determines the thermal stress development in concrete pavement. Set temperature gradient (Figure 9) for the mixture I (Table 3) were calculated using TMAC^2 program based on the assumption that the mixture is placed under both hot weather (Figure 7) and cool weather but with different placement temperatures, i.e., 24, 35 and 41°C. It is also assumed that temperature modulation techniques (e.g., ice or liquid nitrogen application) are employed to make the placement temperature 24 and 35°C in a hot weather with a temperature fluctuation form 32 to 43°C. It is interesting to note that mixture I (25% FA and CF 5) shows highest temperature gradient at lowest placement temperature (24°C). Therefore, in a hot weather, the greater the difference between placement temperature and ambient temperature the greater will be the set temperature gradient even with fly ash added to the concrete. This is an indication that placing artificially-cooled concrete under hot weather can cause high set temperature gradient in pavement. Therefore, application of temperature modulation techniques to reduce the placement temperature in a hot weather will impose a high temperature gradient which leads to more thermal stress development and a higher probability of random cracking. A perusal of Figure 9

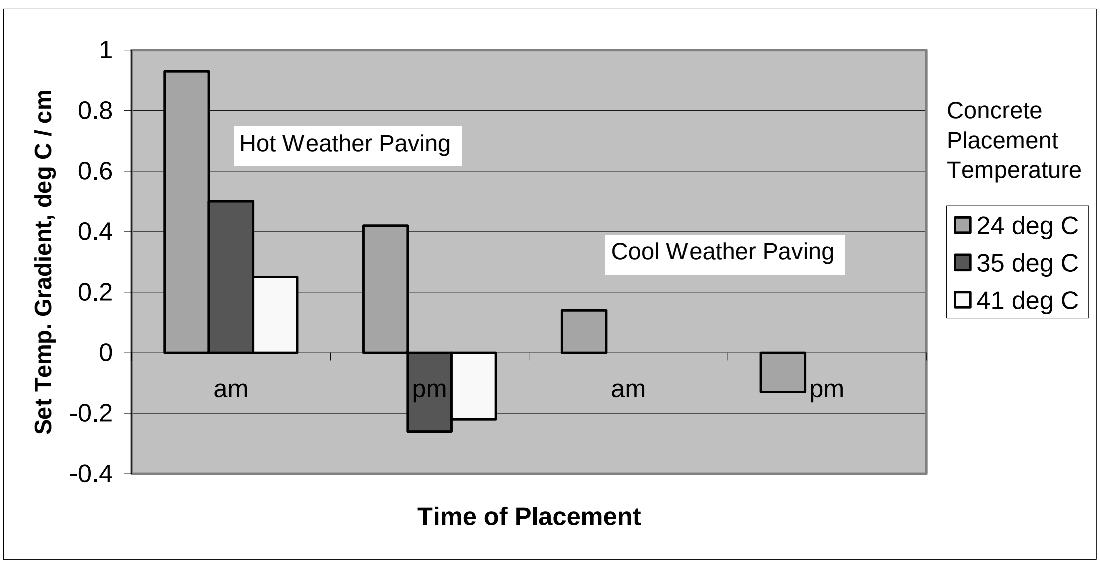


Figure 9 Set Temperature Gradient as a Function of Placement Temperature for Mixture I.

shows that a slab placed in the morning shows a tendency to develop a higher set temperature gradient than a slab placed in the afternoon. However, the pavement with 40% fly ash replacement has a lower set temperature gradient compared to a 25% fly ash replacement at the same placement temperature of 41°C.

The set temperature gradient is critical in the mechanism of curling related crack formation. As the temperature in the slab changes from the set conditions due to ambient temperature effects, slab curvature is induced because the difference from the set condition varies with depth, even if no set temperature gradient existed in the slab. Because of the effect of time and temperature of placement, it is anticipated that concrete placed in the morning will experience a greater amount of liftoff at the corners and tensile stress in the slab than concrete placed in the afternoon. Tensile stress is induced at top of the slab under upward curling and at the bottom of the slab under downward curling due to the restraint caused by the self-weight of the slab and to some extent friction between slab bottom and sub-base. The consequence of this will be the slabs placed in the morning will experience a higher rate of cracking than the slabs placed at other times of the day.

These considerations are critical to the execution of saw-cutting operations for crack control purposes. It is clear that the timing of the saw cutting is a greater issue during morning placements. Another consideration is the distance between joints or more relevant to the width of the paving lane. Figure 10 is a chart taken from ACI Committee 325 recommendations for maximum joint spacing in concrete pavement construction which suggests that slab thickness and sub-layer support have an effect on the maximum possible spacing. With these factors in mind, the maximum width of paving should not be over 4.57 (15 ft) to 4.88 (16 ft) meter without placement of a longitudinal saw cut at mid-span. It may be possible to place at wider paving widths if the set temperature gradients are minimized or limited to certain levels by placing under cool weather or afternoon conditions as is suggested by the data shown in Figure 10. These considerations are particularly relevant to 5.49 meter (18 ft) paving widths where a 3.66 meter (12 ft) lane and 1.83 meter (6 ft) shoulder are placed in one pass and the saw cut at the shoulder line. Stress levels in this instance are typically too low to induce a crack at the saw cut location verses a random crack occurring at the mid-span area (Figure 11). Figure 11 depicted the calculated tensile stresses at the shoulder line saw cut and mid-span area in a 5.49 meter (18 ft) wide pavement for all the seven test runs. A perusal of Figure 11 shows that (i) tensile stress at the saw cut notch is always lower than that at the mid-span area – chances of random crack formation at the mid-span area will be more than that at saw cut, (ii) in general tensile stress both at saw cut notch and mid-span area increases with increasing placement temperature, (iii) increase of cement content causes tensile stress to increase slightly both at the saw cut notch and mid-span area, (iv) using 15% more fly ash than conventional 25% replacement drops the tensile stress at the saw cut notch by 16-20% and at the mid-span area by 16-22% in a hot weather (41^0C).

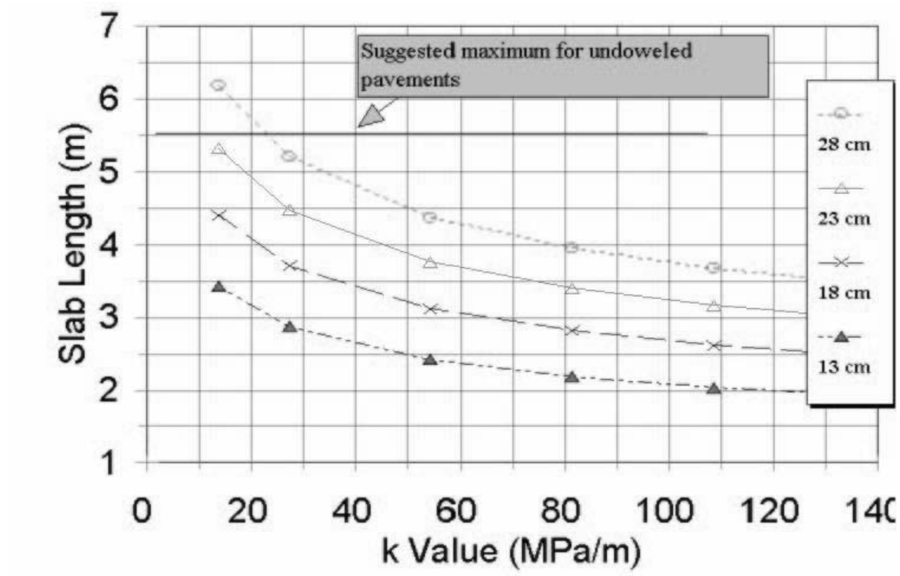
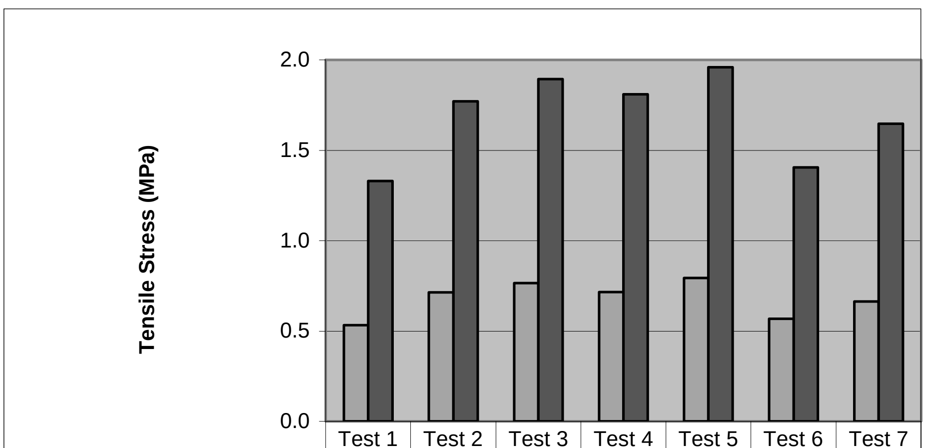


Figure 10 Maximum Joint Spacing for Concrete Paving (ACI 325. 12R-02).



	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
Stress at sawcut notch	0.53213	0.71393	0.76512	0.71529	0.79281	0.56729	0.66278
Stress at mid-slab	1.33039	1.7708	1.89488	1.81021	1.96027	1.40518	1.64724

Figure 11 Tensile Stress (18 Hours after Placement) at the Saw Cut and Mid-Span Area.

Summary and Conclusion

An attempt has been made in the present study to investigate the effect of modifying concrete mixture proportion in terms of varying fly ash replacement in order to combat the negative effect of high temperature placement. The main purpose was to verify whether concrete can be placed under hot weather without the use of placement temperature modulation methods and at the same time to examine detrimental effects associated with the 35°C limit. The following conclusions are based on the findings of this investigation

a) The increase of placement temperature is of benefit for the strength development (up to 28 days) in concrete containing greater than 25% fly ash. It is well known that 28 day compressive strength of concrete without any supplementary cementitious materials (e.g., fly ash) placed and cured at temperature over 20°C is always lower than the corresponding strength of concrete placed and cured at the temperature below 20°C. It seems that concrete with fly ash as supplementary cementitious material does not suffer from this type of later age strength reduction at high placement temperature.
b) Use of fly ash contents greater than 25-30% is an affective way to control the high heat generation at the early ages (up to 4 days). However, strength requirements particularly at 7 days may need to be modified to allow for slow rates of strength gain. In accordance with compressive strength test results, at a slightly higher cement factor (e.g., 6) and 40% fly ash replacement, minimum strength requirements can be met. However, a mixture with 40% fly ash content provides a higher long-term compressive strength than a mixture with 25% fly ash replacement warranting consideration of this alternative as long as the slower rate of strength gain at the early ages can be tolerated.
c) Increasing placement temperature causes reduction in both initial and final setting time.
d) Higher the placement temperature the higher the shrinkage within the time span of 4-5 days for a particular mixture. Higher fly ash replacement (e.g., 40%) can counteract the high drying shrinkage characteristics of high placement temperature (e.g., 41°C).
e) The increase in fly ash replacement from 25 to 40% is well correlated with reduction in set temperature and set temperature gradient in both morning and afternoon placement. It causes concrete placed at 41°C to appear set temperature gradient wise, to appear as if it were placed at 35°C. it improves the possibly of controlling cracking in 18 foot paving widths.
f) Use of high fly ash replacement in the order of 40% can mitigate the negative effect of high set gradients that can result from placing cool concrete under hot weather condition.
g) Conventional curing practice or material modification cannot overcome poor saw-cut location. Eliminating the potential of random cracking would also reduce the ability to induce a crack at the notch.

Therefore, it is expected that the usage of judicious amounts of fly ash will mitigate negative effects of hot weather placement conditions such as early-aged cracking due to rapid drying and other associated effects. Based on the above, it can be concluded that damaging factors associated with hot weather concreting can be controlled by proper combination of fly ash and cement content and that placement of paving concrete over 35°C(up 41°C) can be accommodated with out significant affect on performance.

Acknowledgments

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