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Temperature variation in high slump drilled shaft concrete and its effect on slump loss

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Abstract

Drilled shaft refers to a deep foundation system where a single large diameter pier is used to replace a whole group of piles. High slump self-compacting concrete is used in drilled shafts due to its high fluidity and less proneness to segregation. The Florida Department of Transportation (FDOT) specifications require that such concrete should have a slump between 7 and 9 in. when placed and should maintain a slump of 4 in. or more throughout the concrete placement time. Furthermore, the mix for the slump loss test should be prepared at a temperature consistent with the highest ambient or initial concrete temperature (whichever is greater) expected during actual concrete placement. It is possible that the temperature of concrete inside the drilled shaft is lower than the ambient or initial concrete temperature due to the presence of ground water. If that is the case, slump loss would be less than the loss determined at the highest ambient or the initial concrete temperature, making the FDOT requirement unrealistic. However, it should be experimentally verified. This experimental study was conducted with the objective to establish profiles of concrete temperature in time from placement to hardening along depth as well as across width of the drilled shaft. Based on the gathered data, it was found that no significant temperature differential existed along the depth and across the width of the drilled shaft during the initial setting of concrete. The temperature of concrete inside the drilled shaft was same as initial concrete temperature before placement at all locations. This finding leads to the conclusion that concrete temperature inside drilled shaft is not affected by ambient temperature and/or the underground temperature conditions.

Keywords: Fresh concrete; Hydration; Temperature; Workability; Drilled shaft

1. Introduction

The terms *drilled shaft*, *caisson* and *drilled pier* are often used interchangeably in foundation engineering, all referring to a *cast-in-place* pile generally having a diameter of about 2.5 ft or more, with or without steel reinforcement and with or without an enlarged bottom. A drilled shaft may be more cost-effective than driven piles in bridge piers at river crossings, retrofit operations, high-mast lighting, earth-retaining structures, single column piers and similar applications [1].

Most drilled shafts are excavated using *open-helix augers* [1]. The auger is inserted and withdrawn repeatedly while rotating to drill a hole to the required depth. Then, the drilled hole is filled with concrete, usually with steel reinforcement so that the drilled shaft will be capable of resisting bending moments and uplift as well as compressive loads. The rebar cage is lowered into a drilled hole before the concrete is placed to form the drilled shaft. Concrete is placed in the drilled hole using a tremie pipe to prevent segregation of the concrete, erosion of the sides of the drilled hole and damage to the rebar that would occur if the concrete was allowed to free fall to the bottom of the shaft.

High slump self-compacting concrete is used in drilled shafts due to its high fluidity and less proneness to segregation. The placement of concrete in the drilled shaft must be completed within 30–45 min; otherwise, the concrete starts to lose its consistency and becomes stiffer, making pumping process harder. This loss of consistency in fresh concrete with elapsed time is called the *slump loss*. Slump loss occurs when the free water from a concrete mixture is removed by hydration reactions, by adsorption on the surfaces of hydration products and by evaporation. Under normal conditions, the volume of hydration products during the first half-hour after the addition of water to cement is small and the slump loss is negligible. Thereafter, concrete starts losing slump at a

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higher rate depending on the ambient temperature, cement composition and admixtures present [2].

The Florida Department of Transportation (FDOT) specification 346-3.2 requires that concrete used in drilled shaft (frequently called as drilled shaft concrete) should have a slump between 7 and 9 in. when placed and should maintain a slump of 4 in. or more throughout the concrete placement time as determined by the slump loss test [3]. Furthermore, it requires that the slump loss test for drilled shaft concrete should be conducted at a temperature consistent with the highest ambient or initial concrete temperature (whichever is greater) expected during actual concrete placement.

It is possible that temperature inside drilled shafts is lower than the ambient temperature or the initial concrete temperature due to the presence of ground water. In that case, the setting time would be longer and the magnitude of slump loss would be less than the loss determined at either ambient temperature or initial concrete temperature.

Based on the above premise, this research study was undertaken with the objective of determining temperature profiles of concrete in time from placement to hardening. For this purpose, three 4 ft diameter, 25 ft deep drilled shafts were constructed. Temperature probes connected with automatic data recorders were used to record the concrete temperature inside the drilled shafts. Based on the collected data, temperature profiles are plotted and analyzed.

2. Research significance

It is important to note that no published or unpublished research work on the topic of the temperature variation in drilled shaft concrete is found; hence, this research could be considered as groundwork and an initial effort in this area of research.

A clear answer as to whether the temperature in the drilled shaft is lower than the ambient or initial concrete temperature is provided by this investigation. It also provides a reliable set of temperature profiles data. These data can serve as a basis for any future investigation.

3. Methodology

A two-phase methodology, as described in the following sections, was developed by the investigators to carry out this research study.

3.1. Phase 1: exploratory testing to determine ground temperature variation along depth of drilled shaft placements

The purpose of this phase was to determine the ground temperature variation along depth to make a decision about what depth to be used in the test shafts of Phase 2. If there is no significant variation in temperature along depth, the test shafts do not have to be excessively deep.

3.2. Phase 2: field testing to determine temperature variation in freshly placed drilled shafts

Field testing involved the recording of temperature variation across the width (cross section) and along the depth of the drilled shafts. Three experimental drilled shafts, each 4 ft diameter and 25 ft in length (based on the Phase 1 results), were constructed. No casing was used. Steel cages with minimum reinforcement were used. Their basic purpose was to hold the temperature probes at the specified locations. The temperature in each probe was recorded through an automatic data recorder for 125 h until the concrete temperature started to stabilize.

4. Experimental details

Experimental details of both of these phases and the data collected are explained in this section. All testing were carried out in the southeast corner of Engineering Center, Florida International University, Miami, FL.

4.1. Phase 1: exploratory testing

In this phase, three 4 in. diameter holes were drilled up to 50+ ft depth and encased with plastic tubes. The temperature data were recorded on February 26, 2001 (afternoon) and then again on March 1, 2001 (morning). The following observations were recorded.

1. Temperature (of air or ground water) inside each hole at an interval of 2 ft up to a depth of 10 ft and then at an interval of 5 ft up to the full length of about 50 ft. Each reading was recorded when the temperature stabilized at that depth using a temperature probe attached with a string and connected to a digital thermometer. The temperature data were recorded in both downward and upward directions (by lowering the temperature probe from the surface to the full depth and then lifting it up to the surface) to reduce variations due to handling of the apparatus.
2. Ambient temperature at the test site.
3. Ambient temperature in the city using hourly weather data available from the Internet.

The purpose of recording the ambient temperature data was to compare them with the underground temperature data. The data helped to establish a temperature profile from the surface up to the full depth of the drilled shaft.

4.2. Phase 2: field testing

In this phase, three 4 ft diameter, 25 ft long circular shafts were drilled and then filled with concrete. The dimensions for the drilled shafts were selected to facilitate the installment of temperature probes so that enough data can be collected both across the width and along the depth of the drilled shafts. The depth of 25 ft was used as the Phase 1 results suggested that temperature remains practically constant underground and does not vary along depth. The construction and testing details are briefly explained in the following paragraphs and illustrated in Fig. 1.

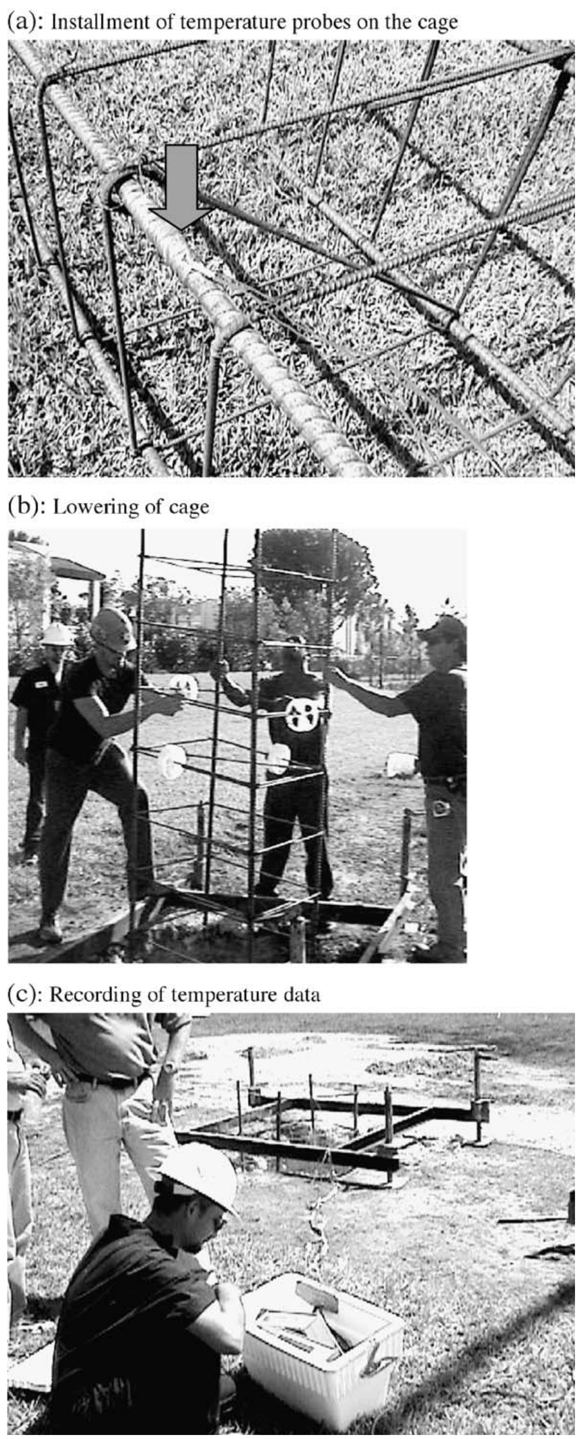

Fig. 1. Different stages of field testing (Phase 2).

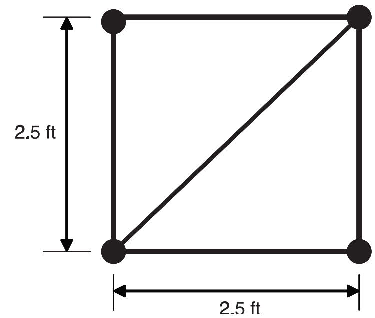

Fig. 2. Cross section of a steel cage.

4.2.1. Excavation/drilling

The water table was found to be at about 6–7 ft below the ground level during Phase 1; therefore, the so-called wet construction method was used for excavation using the auger cast drilling technique. The wet construction method is recommended for all sites where it is impractical to carry out a dry excavation for placement of the drilled shaft concrete [3]. The wet construction method consists of drilling the shaft excavation below the water table and keeping the shaft filled with fluid (mineral slurry, natural slurry or water depending on the soil condition) until the concrete is placed via tremie pipe that displaces the water or slurry. Excavation procedures as explained in FDOT specification 455-15.3 were followed [3]. For this project, use of slurry was not needed as the ground consisted of hard limestone. No casing was used in any of the shafts. The actual depth of the holes varied between 27 and 30 ft.

4.2.2. Steel reinforcement

The 25-ft-long square steel cages with cross-sectional dimension of 2.5 ft each way, as shown in Fig. 2, were placed in the drilled shaft holes. The cages were only used to attach the temperature probes. The steel cages consisted of four no. 4 main or longitudinal steel bars at each corner and no. 3 ties or loops at intervals of 1 ft along the length. In addition, every fifth tie (at 5-ft intervals) consisted of a diagonal no. 3 bar as shown in Fig. 3. This diagonal bar was used to attach the temperature probes across the width of the shafts.

4.2.3. Installation of temperature probes and recorders

The locations where the temperature probes were attached in each cage are shown in Fig. 3. Twelve temperature probes were installed in each cage as shown. The vertical distance between the probes was 5 ft. The temperature probes were connected to the automatic temperature recorder (Digi-Sense 12 Channel Scanning Thermometer with a range of -418 to -752 °F), with an accuracy of 0.8 °F. The recording interval was set at 3 min for the first 48 h and then at 8 min for the remainder of the data collection period. The total time of recording was ~ 125 h and data were recorded during this time

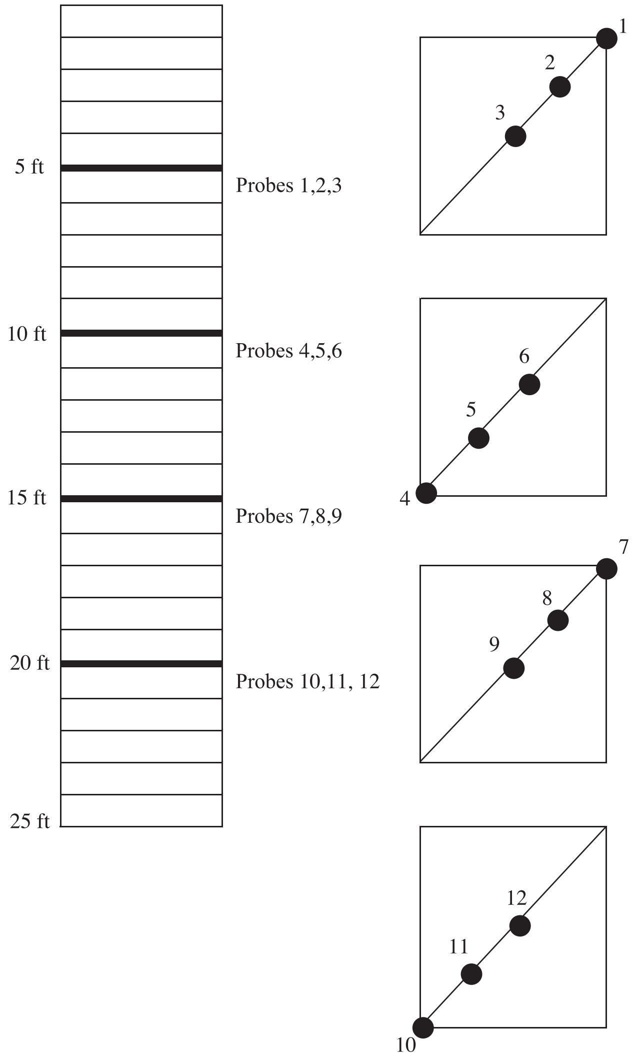

Fig. 3. Locations of temperature probes as attached to the reinforcement of each shaft.

continuously. The temperature recorder has a built-in real-time clock, nonvolatile memory and data ports to facilitate the transfer of data from the recorder to the computer at the end of the experiment.

4.2.4. Concrete mix design

FDOT standard mix design for drilled shafts (Class 4: no. 06-0281) was used for this investigation [3]. The targeted concrete strength was 4000 psi with a slump between 7 and 9 in. The mix proportions are shown in Table 1. Theoretically, a little over 9 cu yd concrete (1 truck load) was needed per shaft, but due to spillage and voids in the ground (and due to the fact that the shafts were about 1 or 2 ft deeper than 25 ft), ~ 12 cu yd of concrete (1.5 truck) per shaft was anticipated. In total, five concrete trucks were utilized. The slump and initial temperature data of the concrete in those trucks are shown in Table 2.

Table 1
Mix proportions for FDOT Class 4 concrete (per cubic yard)

Cement (Type I)	298 lb	Coarse aggregates	1667 lb	Superplasticizer	23.8 oz
Slag	447 lb	Fine aggregates	1053 lb	Total water content	308 lb
Slump	7–9 in.	Compressive strength	4000 psi	Air content	3.6%

Table 2
Slump and initial temperature data of the concrete

Truck	Slump at plant (in.)	Slump at the site (in.)	Initial concrete temperature (°F)	Ambient temperature at placement (°F)	Shafts placed
1	7.00	6.50	86	87	1
2	8.50	7.00	87	88	1 and 2
3	7.00	7.50	87	90	2
4	N.A.	8.00	86	91	2 and 3
5	N.A.	8.25	88	92	3

4.2.5. Placing of concrete

A 5 in. diameter pump was used to place concrete from the truck mixer to the drilled shafts using a tremie pipe. Concreting was carried out in accordance with FDOT specification 455 [3]. Pumping of the concrete was continuous over the three shafts (back to back). Approximately 30–40 min were spent to place concrete in each shaft.

An uplifting of the cages occurred during the placing of concrete due to the upward push of concrete on the cages. Manual pressure was applied to keep the cages at their designated depths. However, the cage of Shaft 3 (placed first) could not be pushed down to its original position and remained 2 ft above the ground level after concreting.

5. Test results and discussion

5.1. Phase 1: exploratory testing

The results of the Phase 1 exploratory testing are shown graphically in Fig. 4. The data clearly indicate that the ground temperature stabilizes at about 1–2 feet below the ground water table, which was found to be at around 6.5 ft under the ground surface. The average temperature stabilizing depth was found to be 10 ft below ground surface and the average temperature below ground water table was between 75 and 77 °F.

The test was performed on two different days at different timings (one in the morning and the other was around noon). Between the two days, the difference in ambient temperature was around 6–10 °F. However, consistent temperature (75–77 °F) was recorded in the

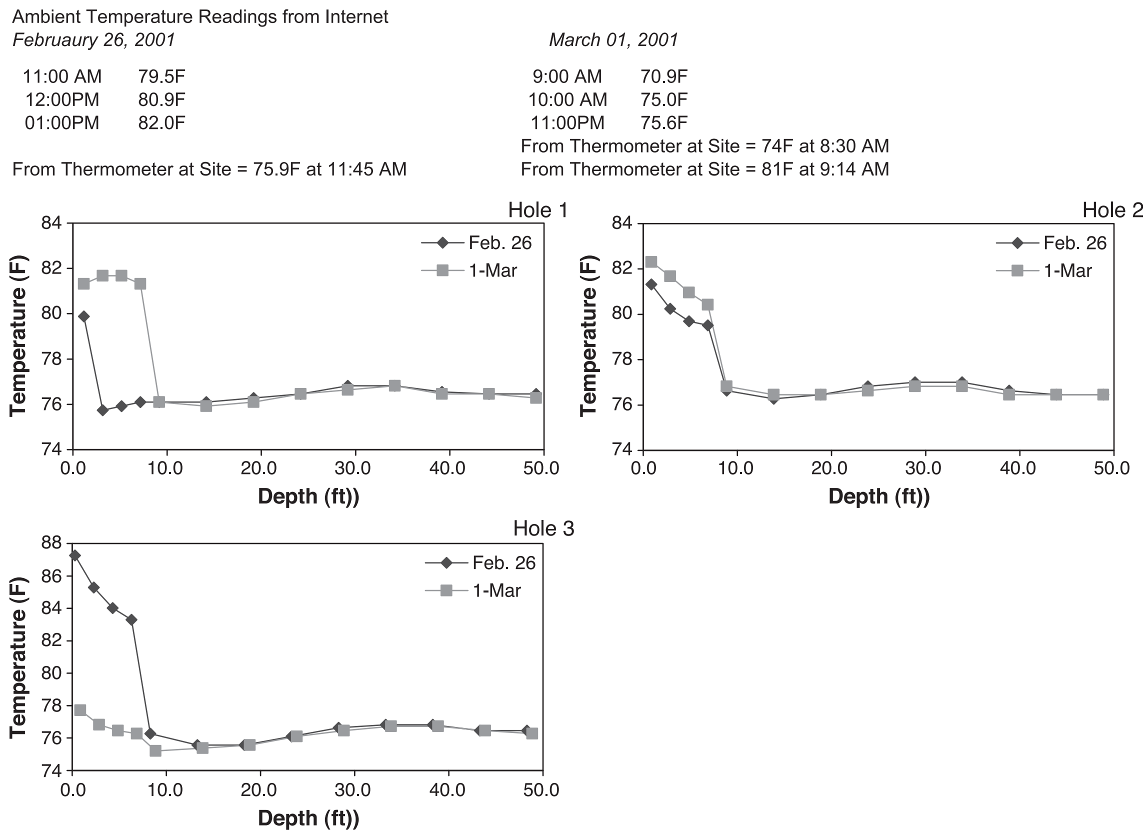

Fig. 4. Temperature variation along depth of drilled shaft placements (Phase 1).

test holes below the ground water table. This indicates that the temperature variations within the hole may not dependent on the atmospheric conditions.

These test results also implied that variations in slump loss in concrete would not be dependent on the depth of the drilled shaft. Hence, it was decided to reduce the depth of

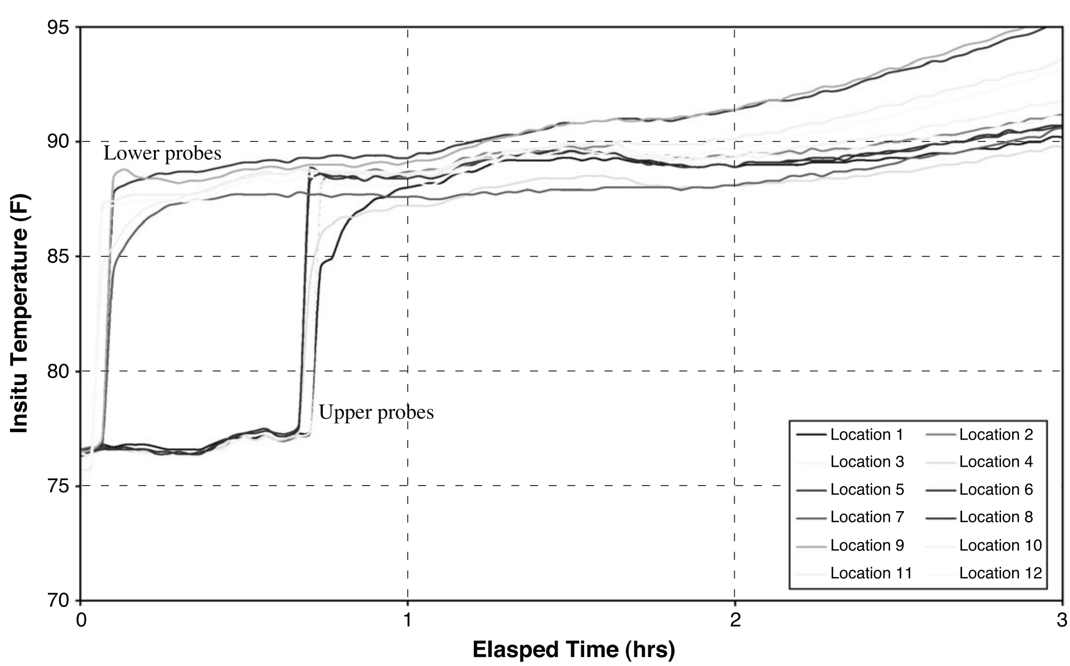

Fig. 5. Temperature variation with time in the shaft at different probe locations (during initial set).

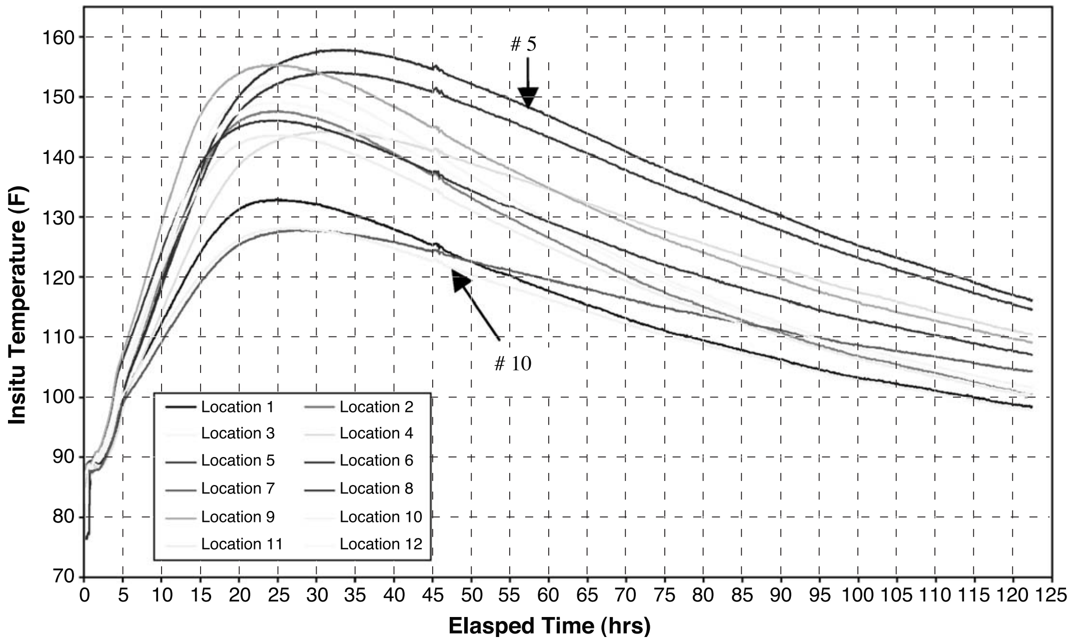

Fig. 6. Temperature variation with time in the shaft at different probe locations (until final set).

test shafts in Phase 2 to 25 ft. from the originally proposed depth of 50 ft.

5.2. Phase 2: field testing

In this phase, three 4 ft diameter, 25 ft long drilled shafts were filled with high slump concrete and temperature data were recorded across the width and along the depth of the shafts. Very consistent results were obtained from the three shafts. For the sake of simplicity, only Shaft 1 results are presented and discussed in this paper.

5.2.1. Initial and final setting of concrete in the drilled shaft

Temperature variations in concrete along the depth of the shaft during the first 3 h are shown in Fig. 5. Before concrete was placed, average temperature in the shaft was

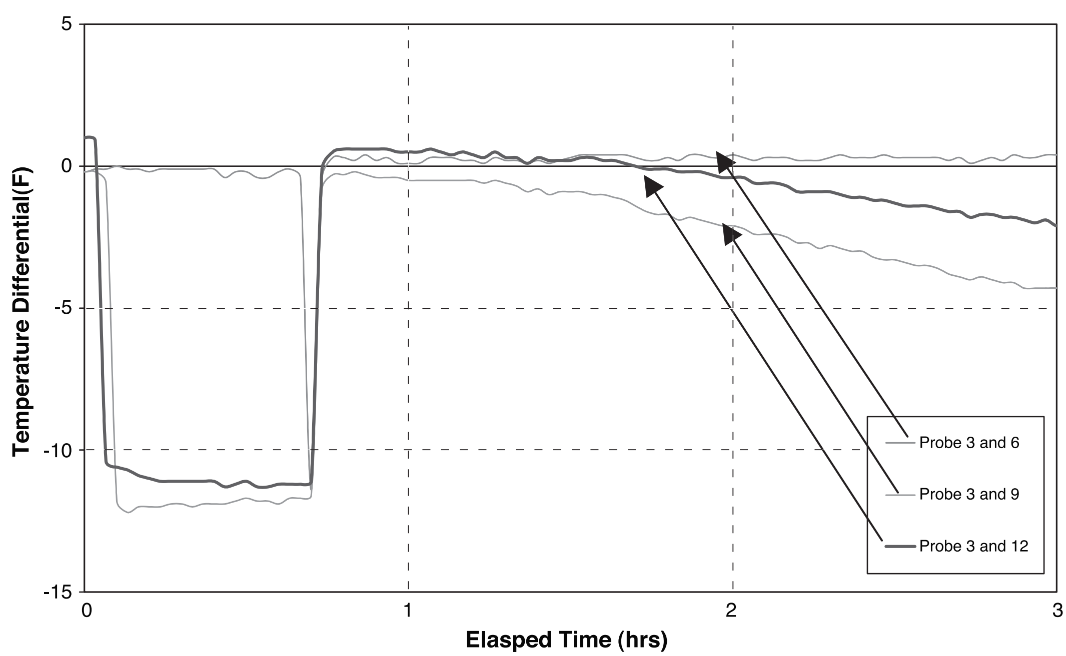

Fig. 7. Temperature differential with time in the shaft between probe locations at different depths (initial set).

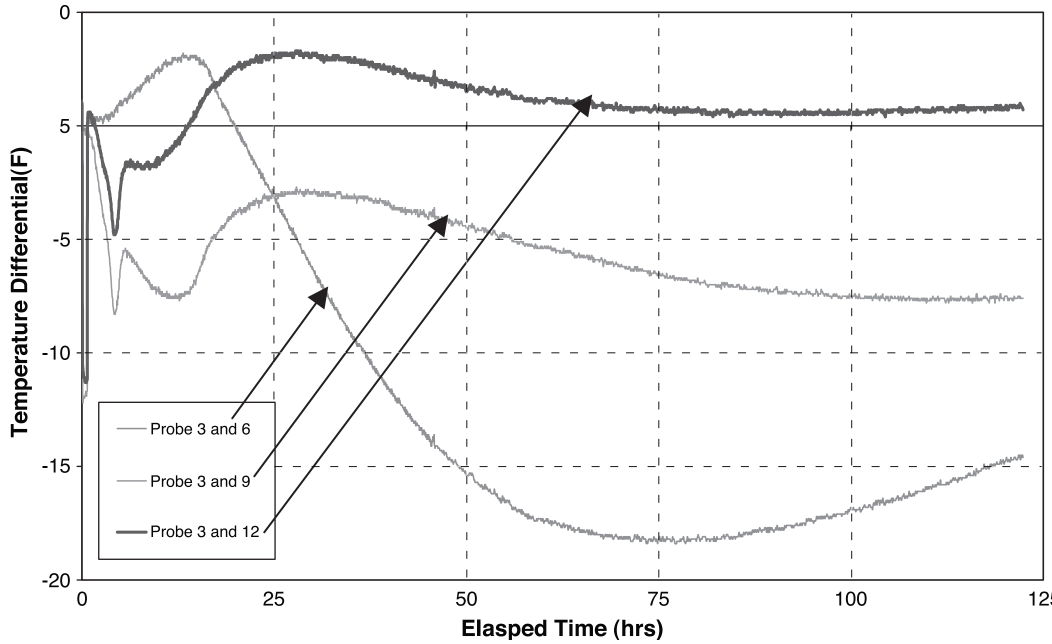

Fig. 8. Temperature differential with time in the shaft between probe locations at different depths (final set).

around 76 °F, which is about the same as found in Phase 1. However, after placing of concrete, temperature within the shaft suddenly rose, which is indicated by a nearly vertical line in the profiles (see Fig. 5) for each temperature probe. The magnitude of rise in temperature was by about 12 °F, which increased the average temperature in the drilled shaft to about 88 °F. Because two trucks were used to place Shaft 1 (~ 10 min were spent to move the first truck out and bring the second truck in position), the upper (probe nos. 3 and 6) (Fig. 5) and lower (probe nos. 9 and 12) (Fig. 5) temperature probes indicate different timings for temperature rise in the shaft.

After the initial temperature rise, there was very little increase in temperature (around 2–4 °F) during the first 2 h of concrete placement. Subsequently, the temperature began to rise at a higher rate, reaching its peak of about 155 °F in ~ 30 h and then beginning to decrease at a nearly constant rate (linear) as shown in Fig. 6.

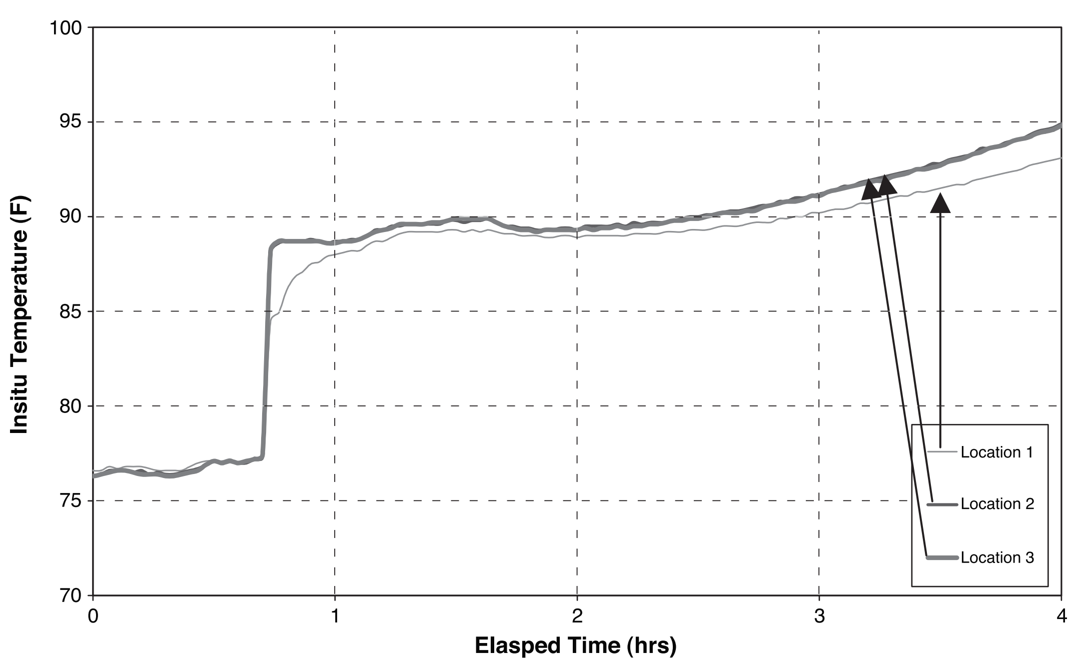

Fig. 9. Variation of temperature with time across width of the shaft at 5 ft depth.

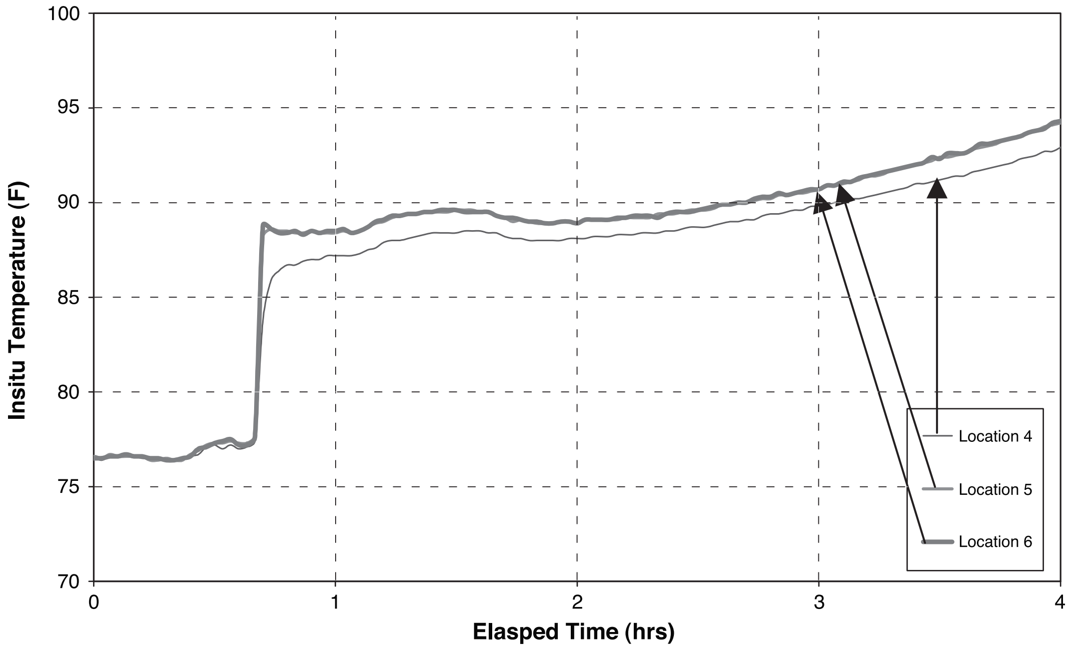

Fig. 10. Variation of temperature with time across width of the shaft at 10 ft depth.

These results indicate that the first increase in temperature was due to the placement of concrete in the drilled shaft. Initially, the temperature in the drilled shaft was lower than ambient temperature, as found in the first phase of the project. When the concrete was placed inside the shaft, the temperature increased and became equal to the internal concrete temperature. The setting of concrete began approximately after 2 h as indicated by the sharp rise in the slope of temperature curve (when the hydration in concrete began). This setting time is typical for the particular concrete mix [3]. This indicates that the internal drilled shaft conditions or temperature did not have much of an effect on the setting of concrete.

5.2.2. Variation of temperature along the depth of the drilled shaft

Temperature variations in concrete with time along the depth of the drilled shaft are already shown in Figs. 5 and 6.

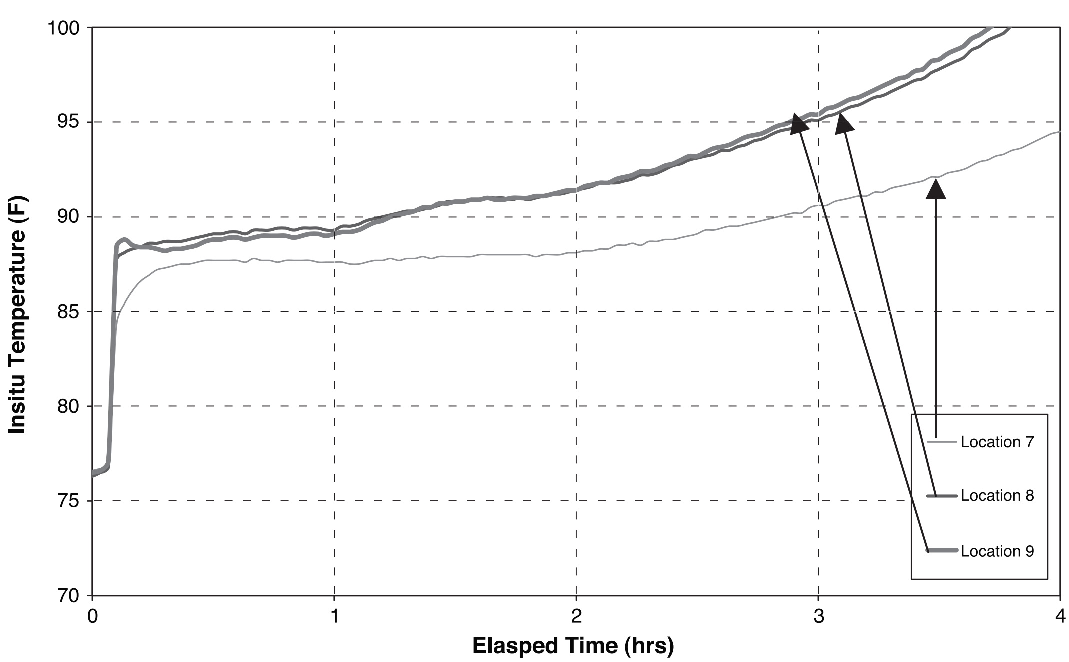

Fig. 11. Variation of temperature with time across width of the shaft at 15 ft depth.

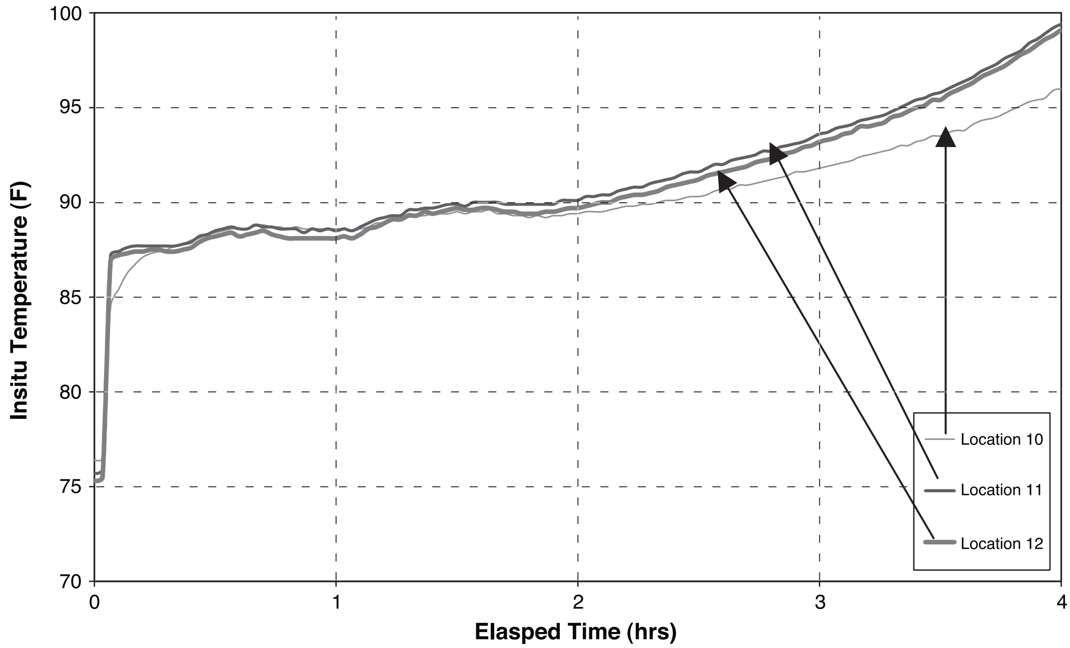

Fig. 12. Variation of temperature with time across width of the shaft at 20 ft depth.

Figs. 7 and 8 show the temperature differential along the depth of the shaft during initial setting and final setting of concrete, respectively.

It can be seen from Fig. 7 that during the time between the placement of concrete and the initial set, the maximum temperature differential exists between probe nos. 3 and 9, which were at 5 and 15 ft depths, respectively. The temperature of concrete at 15 ft depth is only 4 °F lower than the temperature at 5 ft depth. Although the temperature of concrete was not recorded at the surface with elapsed time, it can be reasonably assumed that it would be very close to the temperature at a depth of 5 ft (particularly because the water table was found at about a depth of 5.5 ft).

Thus, the temperature in concrete can be assumed to be constant within the drilled shaft, i.e., no significant temperature differential exists between the surface and the bottom of the shaft. However, temperature differential started to rise after about 2 h when the hydration began as indicated in Fig. 8.

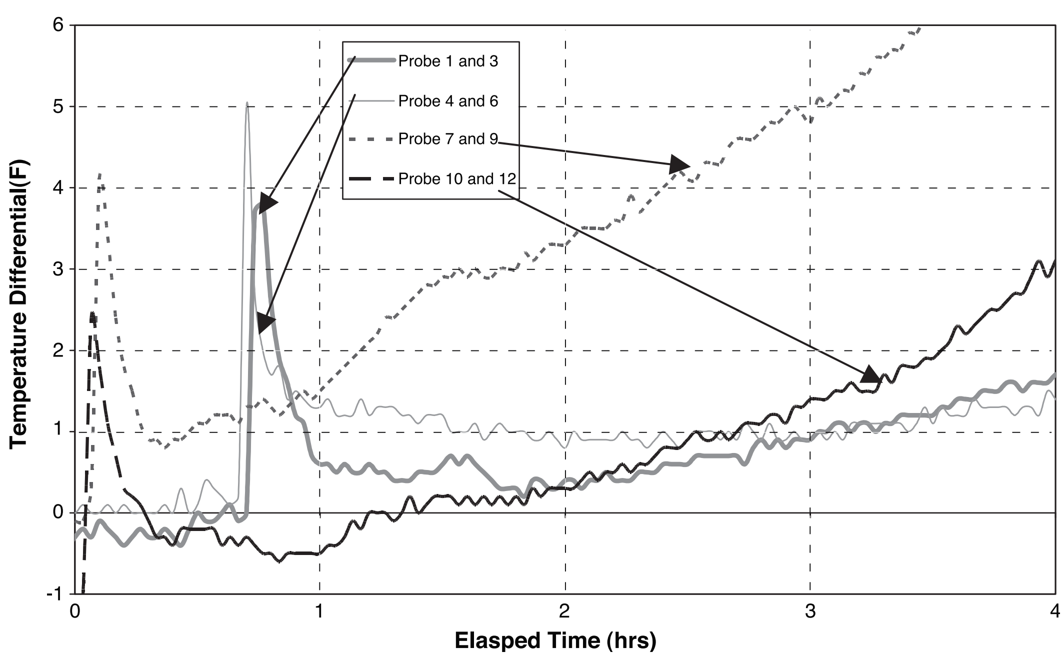

Fig. 13. Temperature differential with time between probe locations across width of the shaft (initial set).

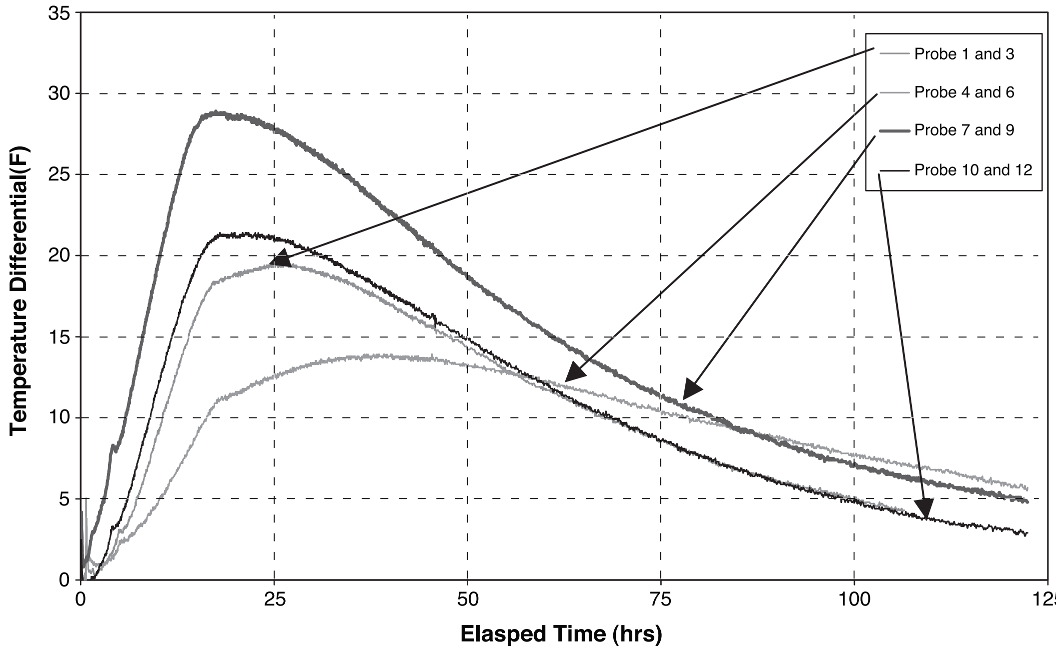

Fig. 14. Temperature differential with time between probe locations across width of the shaft (final set).

Based on the above observations, it can be concluded that the concrete temperature inside the drilled shaft right after placing concrete would be identical to the initial concrete temperature; hence, the slump loss test should be conducted at this temperature.

5.2.3. Variation of temperature across the width of the drilled shaft

In Figs. 9–12, variations in concrete temperature with time across the width of the drilled shaft at various depths are shown. These figures show that the concrete temperature is maximum at the center of the shaft and decreases gradually towards the sides of the shaft.

Figs. 13 and 14 illustrate the temperature differentials with time across the width of the drilled shaft. It is clear from the figures that during the first 2 h, the difference in temperature between center and side probes is only about 3–5 °F, an insignificant amount for all practical purposes. The maximum temperature differential of ~ 28 °F is found to exist after about 30 h when the temperature in concrete reached its peak.

Because the placing of concrete in each drilled shaft was completed within 30–45 min, no slump loss test was performed. As indicated earlier, the slump loss becomes significant after 45 min when the hydration of cement starts [2]. Because the placing of concrete was completed before that time limit, it can be reasonably assumed that the slump of concrete within the shaft was more than 4 in. at all times during placement as required by the FDOT specifications.

Based on the above results, it can be concluded that concrete temperature inside the drilled shaft right after placement would be identical to the initial concrete temperature (which in this case was very close to the ambient temperature, as it was a hot March day in Miami). Thus, it can also be concluded that the assertion that temperature inside the shaft could be lower due to presence of ground water was unsubstantiated and was not supported by the results of this study.

6. Conclusions

Based on the results of this study, the following conclusions can be drawn.

1. The ground temperature stabilizes 1–2 ft below the water table and is independent of the atmospheric conditions. In this study conducted in Miami, the average temperature below the water table was found to be 75–77 °F. Hence, it is concluded that the slump loss in concrete would be same at all depths below the water table.
2. The temperature within the drilled shaft is same as the initial concrete temperature at the time of concrete placement despite the fact that before concrete placement, the temperature within the drilled shaft was lower than the ambient temperature. There was no indication for concrete temperature within the drilled shaft being lower than the initial concrete temperature due to the presence of ground water.
3. There is no significant increase in concrete temperature within the first 2 h of placement. Hence, it may be concluded that the slump loss would be minimal if the placement of concrete is completed within 2 h from the start of operation.
4. No significant temperature differential exists along the depth and across the width of the drilled shaft during the

initial setting of concrete. Hence, the slump loss in drilled shaft concrete would be same at all locations.

5. Because the initial concrete temperature inside the drilled shaft was same as the initial concrete temperature before placement, the rate and amount of slump loss inside the shaft would be same as on the ground surface.

7. Recommendation

It is recommended that the concrete mix for the slump loss test shall be prepared at a temperature consistent with the highest initial concrete temperature expected rather than the highest ambient temperature during actual concrete placement.

This revision in the FDOT specifications will be beneficial during hot weather concreting (common in Florida during the most months of the year) when the ambient temperature is much higher than the actual initial concrete temperature. This will allow more time to place the concrete in the drilled shafts before the slump is dropped to a minimum level of 4 in.

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