Evaluation of soil insulation effect on thermal behavior of drilled shafts as mass concrete
Sangyoung Han1*, Sanghyun Chun1, Kukjoo Kim2, Adrian M. Lawrence1 and Mang Tia1

Abstract: This study focused on investigating the early-age thermal behavior of drilled shafts under different surrounding soil’s thermal properties. Four 1.8 m (6 ft) diameter drilled shafts were constructed using two different concrete mixes and two different soil conditions. A finite element (FE) model was developed to estimate the temperature development of drilled shafts at early-age and validated using temperatures measured from full-scale drilled shafts constructed in the field. The validated analytical model was then used to perform a parametric analysis to evaluate the effects of the surrounding soils at different moisture conditions on change in thermal behavior of drilled shafts at early-age. Results indicated that the FE model developed was capable of accurately predicting temperature development of drilled shafts at early-age. A drier surrounding soil (i.e., gravimetric moisture content of 0% through 6%) was able to serve as a better insulating material that leads to reduced temperature difference in the drilled shafts. Also, it was identified the use of high-volume fly ash concrete mix in conjunction with relatively low heat of hydration can reduce the temperature difference in the drilled shaft.

Subjects: Heat Transfer; Concrete & Cement; Foundations and Piling
Keywords: mass concrete; drilled shaft; soil’s thermal properties; moisture content; maximum temperature difference

1. Introduction

1.1. Background
Thermal cracking in mass concrete usually occurs due to high heat of hydration in the massive structure. It has been well recognized that the significant amount of generated heat and a rapid heat dissipation near the surface leads to nonuniform volume change (i.e., internal temperature differential) and this phenomenon produces an internal restraint which induces tensile stress on the

ABOUT THE AUTHOR
Sangyoung Han is a Ph.D. student of Civil Engineering in University of Florida. His research area focuses on the concrete mechanical behavior and how to make the optimized design of concrete structures. The team for this project was made up of experts in topic of mass concrete. The research program funded by Florida Department of Transportation. The research program conducted by this team investigates the effects of various parameters on the possibility of thermal cracking in mass concrete structure.

PUBLIC INTEREST STATEMENT
Current society constructs the massive structures for its aesthetic and accommodation needs. In general, the mass concrete is exposure to harsh environmental condition contacted with soil and water directly. Thereby, the special treatment should be considered to mitigate mass concrete issues such as thermal cracking and reducing strength. This study could contribute the achieving integrity of concrete structure, which significantly affects on human safety.
surface that causes thermal cracking (ACI 207, 2005; ACI 207, 2007; Mehta and Monteiro, 2014; Tia et al., 2010). To mitigate thermal cracking in mass concrete, it is required to reduce the maximum temperature and the maximum temperature difference. During the last few decades, several criteria or guidelines regarding thermal behavior of mass concrete were established. The American Concrete Institute (ACI) recommends the limit for the peak concrete temperature of 70.0°C (158.0°F) at the center of structure (i.e., maximum temperature) and the maximum internal concrete temperature difference of 19.4°C (35.0°F) for the temperature differential between the location of the innermost structure and the nearest exterior surface from the center (i.e., maximum temperature difference) in mass concrete (ACI 301, 2016). The Florida Department of Transportation (FDOT) requires the maximum concrete temperature of 82.2°C (180.0°F) with the maximum concrete temperature difference less than 19.4°C (35.0°F) (FDOT, 2016a).

Previous research (Tia, Lawrence, Ferraro, Do, & Chen, 2013) primarily evaluated whether the absence of an insulating layer between mass concrete foundations and saturated soil can cause problems associated with an abnormal high peak temperature difference in the mass concrete at early-age. It was indicated that foundation footings constructed in saturated sand without considering adequate protective insulation between the soil and its outside surfaces exhibited the highest potential to induce thermal cracking, even though typical soil properties suggested that dry soil (i.e., moisture content is close to zero) may be an appropriate insulating material in mass concrete for footing applications. This issue on foundation footings raise a concern in drilled shafts regarding the expected high peak temperature difference particularly in Florida, since for most cases, all surfaces are usually surrounded by saturated soil.

However, only a few researches were conducted to evaluate the effect of soil insulation properties on change in temperature development of a drilled shaft for mass concrete applications. Therefore, there is a need to investigate the insulation properties of soil under various moisture conditions using actual measured properties from in situ soil that provides more comprehensive understanding and analysis of thermal response characteristics for mass concrete placed in the field. In this study, a full-scale field test was performed to measure the actual temperature development and distributions in four concrete drilled shafts surrounded by soils with different moisture conditions. Also, finite element (FE) analysis was conducted to evaluate the effects of soils as an insulator on mass concrete using different insulating properties of soil under various moisture conditions.

1.2. Objectives and scope
This study focused on the evaluation of the effects of the soils with different moisture contents by mass as an insulator on change in thermal behavior of a drilled shaft using a full-scale field test and FE analysis. The main objectives of this study are as follows:

- Evaluate the temperature development of a drilled shaft under saturated and drained soil conditions.
- Develop an FE model to evaluate the effects of soils as an insulator on mass concrete using different insulating properties of soil under various moisture conditions.
- Identify the effects of soils with different degree of moisture contents on change in thermal cracking potential for drilled shafts based on maximum temperature and temperature differential approaches.

Four full-scale drilled shafts were constructed to monitor the maximum temperature and the maximum temperature difference for two concrete mixtures (i.e., one with high heat of hydration and one with low heat of hydration) and under two different soil conditions (i.e., saturated—sandy soil with approximately 16% moisture content by mass and drained soil conditions—sandy soil with approximately 6% moisture content). The temperature data were recorded to analyze the effects of
the soils with different degrees of moisture content on change in thermal behavior of a drilled shaft as mass concrete, and further validated based on the FE analysis conducted using the computer program DIANA 9.4.4 (DIANA, 2011).

2. Thermal behavior of mass concrete
Thermal cracking is a primary concern in areas of mass concrete and there are several relevant requirements in current specifications for mass concrete applications. Mass concrete is defined by the ACI 116 (ACI 116, 2005) that any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change to minimize cracking. Also, the FDOT defines mass concrete in drilled shafts and stated that all drilled shafts with diameters greater than 6 ft shall be designated as mass concrete (FDOT, 2016b). Any drilled shafts with a diameter greater than 1.8 m (6.0 ft) would, therefore, require the submission of a Technical Special Provision (TSP). The TSP in this particular case generally takes into account the form of a mass concrete temperature control plan since the size of the diameter (i.e., typically an elongated shape due to a relatively long height compared to the diameter) directly produces a high volume-to-surface area (V/A) ratio, which leads to a much higher potential for thermal cracking (Do, 2014; Tiao et al., 2013; Ulm & Coussy, 2001).

Previous studies (Alrtimi, Rouainia, & Haigh, 2016; Hanson, Edil, & Yesiller, 2000; Zhang & Wang, 2017) have reported the effects of moisture contents on change in thermal properties of soils as an insulator. Thermal conductivity is defined as the quantity of heat transferred through a unit area of the conducting body in unit time under a unit temperature gradient. The thermal conductivity of soils is dependent primarily upon both the density of materials and the moisture contents of the soil. In general, the increased moisture content of soil results in increased thermal conductivity of soil due to the adhesion between soil particles and water. This process expands the area which replaced air with water and efficiently enhances the heat flow.

3. Full-scale field tests

3.1. Construction of drilled shafts
Four drilled shafts were constructed based on ACI’s construction guidelines (ACI 336, 2001). These drilled shafts were designed with a diameter of 1.8 m (6 ft) and a length of 2.1 m (7 ft) and those were constructed with a 1.8 m (6 ft) depth of natural soil (i.e., a soil type American Association of State Highway and Transportation Officials (AASHTO) classification of A-3 (fine sand). Two drilled shafts (Shafts 1 and 2) were intended to be placed under the natural water table condition (i.e., the saturated soil condition); however, the other two (Shafts 3 and 4) were intended to be placed under the drained soil condition with the five well points installed for dewatering.

3.2. Concrete mixture design
In this study, two concrete mixtures were selected for evaluation, termed as (1) Mix 1: 30% Type I/II Portland cement plus 70% blast furnace slag (expected low heat of hydration) and (2) Mix 2: pure Type I/II Portland cement (expected high heat of hydration). Table 1 presents the properties of fresh concrete for two mixtures designed and placed in each drilled shaft. Among the two drilled shafts placed in the saturated soil condition, one (Shaft 1) used a slag-cement concrete mixture (Mix 1) with a relatively low heat of hydration, and the other (Shaft 2) used a pure Portland cement concrete mixture (Mix 2) with a high heat of hydration. Similarly, among the two drilled shafts placed in the drained soil condition, one (Shaft 3) used a slag-cement concrete mixture (Mix 1) with a relatively low heat of hydration, and the other (Shaft 4) used a pure Portland cement concrete mixture (Mix 2) with a high heat of hydration.

3.3. Draining water for drilled shafts 3 and 4
One of the main purposes of this full-scale field evaluation was to investigate the effect of moisture condition of soil on change in thermal behavior in a shaft. The natural water table was located at around 1.2 m (4 ft) below the surface during the construction of drilled shafts. Shafts 1 and 2 only required to
remove water from the inside of temporary casing during the construction that allows to install temperature sensors and to pour the concrete by a tremie pipe. The natural water table was maintained at a constant level of 1.2 m (4 ft) from the surface for 7 days as shown in Figure 1(a). On the other hands, the soil around Shafts 3 and 4 was dewatered during the tests. The 4.3 m (14 ft) long well points were

| Table 1. Mix designs of concrete used in drilled shafts |
|--------------------------------------------------------|
| Properties                                              | Mix 1 | Mix 2 |
|---------------------------------------------------------|-------|-------|
| Cement [kg/m³ (lb/yd³)]                                 | 165.5 (279) | 558.9 (942) |
| Slag [kg/m³ (lb/yd³)]                                   | 388.0 (654) | –     |
| Fly ash [kg/m³ (lb/yd³)]                               | –     | –     |
| #89 Stone [kg/m³ (lb/yd³)]                             | 723.8 (1,220) | 722.0 (1,217) |
| Silica sand [kg/m³ (lb/yd³)]                           | 668.5 (1,127) | 770.7 (1,299) |
| Water [kg/m³ (lb/yd³)]                                 | 162.0 (273) | 162.6 (274) |
| Air entraining admixture [g/m³ (oz/yd³)]              | –     | 11.8 (0.32) |
| Water reducing admixture [kg/m³ (oz/yd³)]             | 4.2 (113.3) | 4.2 (112.6) |
| Actual slump [cm (in.)]                               | 24.9 (9.8) | 24.1 (9.5) |
| Temperature [°C (°F)]                                  | 24.4 (76.0) | 24.4 (76.0) |
| Actual air [%]                                         | 3.5   | 4.0   |
| Unit weight [kg/m³ (lb/ft³)]                           | 2146 (134) | 2178 (136) |
| Water-to-cement ratio                                  | 0.29  | 0.29  |

Figure 1. Full-scale drilled shafts constructed. (a) Drilled Shaft 1 and 2 in saturated soil condition. (b) Drilled Shaft 3 and 4 in drained soil condition.
installed at five points around Shafts 3 and 4. The locations of five well points were well distributed by using the two at the outside of Shaft 3, the two at the outside of Shaft 4, and the one located at between Shaft 3 and 4 as shown in Figure 1(b). The pumping was operated continuously for seven days and the capacity of the initial draw used was 132 liters per minute.

3.4. Data acquisition system

The all-in-one types of temperature loggers (e.g., internal sensor, battery, and self-memory) were installed at various locations in the concrete drilled shafts to monitor the temperature development and distribution during the early age period of the concrete. Temperatures at the various sensor locations were monitored for at least 7 days after the placement of concrete. A total of 15 temperature data sensors were embedded in each drilled shaft to monitor the thermal behavior. Figure 2 illustrates the positions of temperature sensors in each concrete shaft. As shown in Figure 2, sensors 1 through 5 were placed along the vertical centerline and sensors 6 through 10 were placed in the middle between the center and the surface. Sensors 11 through 15 were installed 0.1 m (4 in.) from the surface.

3.5. Discussions on temperature profiles measured

Figure 3 shows the actual maximum temperatures and the maximum temperature difference observed for the four drilled shafts. It is noted that the maximum temperature was obtained from sensor C3 which was located at the center of the shaft as shown in Figure 2. According to ACI 301 (ACI 301, 2016), the maximum temperature difference should be monitored along the lines parallel to the element side (i.e., radially in this case). Therefore, the maximum temperature difference for each shaft was calculated using temperature differential between point C3 and C13 in Figure 2.
It was indicated that the use of a slag-cement concrete mix (Mix 1) significantly reduced the maximum temperature difference in the drilled shafts. However, the maximum temperature differences of all four shafts evaluated exceeded the maximum limit of 19.4°C (35.0°F) required by FDOT specifications for mass concrete. For Shafts 1 and 3 consisted of a slag-cement concrete mix placed in saturated and drained soils conditions, the maximum temperature differences measured were 24.5°C (44.1°F) and 22.0°C (39.6°F), respectively. For Shafts 2 and 4 including a pure Portland cement concrete mix placed in saturated and drained soil conditions, the maximum temperature differentials were 30.7°C (55.3°F) and 27.6°C (49.7°F), respectively. For these cases, the measured maximum temperatures also exceeded the FDOT's maximum temperature requirement for mass concrete (i.e., 82.2°C [180.0°F]).

4. Finite element modeling

4.1. Model dimension, meshing, and boundary conditions

A FE model was developed to simulate the temperature development of four drilled shafts for analytical evaluation in terms of its thermal behavior at early-age. The simplified FE model was designed using two-dimensional (2-D) axisymmetric geometry with an axial symmetric coordination of a 0.9 m (3 ft) in radius and a 2.1 m (7 ft) in length. The soil was modeled using two layers in consideration of natural water table level. The top of soil layer included a 1.2 m (4 ft) depth and the areas below for bottom of soil layer. The conditions and properties of surrounding soil were input as parametric values to evaluate their effects on change in thermal behavior of drilled shafts. The thermal properties of soil and concrete, the heat produced during the hydration of the concrete, and environmental boundary conditions were required as inputs for FE model to analyze thermal behavior of drilled shaft.

The FE model developed consisted of a drilled shaft with surrounding soil modeled using the extended elements of 3.6 m (12 ft) radially outward from the outer surface of the shafts to simulate the fully dissipated heat from the drilled shaft. The shaft structure was modeled as a total length of 2.1 m (7 ft) including 1.8 m (6 ft) drilled into the soil and the uppermost 0.3 m (1 ft) exposed above the ground surface. The boundary load conditions used for thermal analysis consisted of an initial temperature of concrete, a fixed environmental temperature of side and bottom soil, and an external ambient temperature. An initial concrete temperature of 27.0°C (80.6°F) was used for FE model. The initial and constant soil temperature of 23.0°C (73.4°F) was used by assuming that the soil temperature around the drilled shaft remains in a stable condition. The external temperature was applied to all exposed surfaces in the model to take into account the fact that these surfaces were exposed to the atmospheric environment. In this study, the constant ambient temperature of 20.0°C (68.0°F) was used that indicates the
average temperature during the temperature monitoring period in the field. The FE model developed and each temperature condition applied are summarized in Figure 4.

4.2. Material characterization

Thermal conductivity is usually obtained from the reciprocal R-value, which characterizes the capacity of insulating materials to resist heat flow. Laboratory tests were conducted to obtain R-value of soil using the soil samples collected from the site for field tests. The method designated by the American Society for Testing and Materials (ASTM) D5334 (ASTM D5334, 2014) was used to determine R-value of soil with respect to varied moisture contents. The results obtained from four soil samples were found to be almost identical. Figure 5 shows R-values determined for different gravimetric moisture contents. It was identified that R-value dramatically decreased with the increase in moisture content until moisture content reached approximately 6.0% by mass, indicating that the insulation level reached the lowest value and remained with no further change with the increase in moisture content. These results were used as inputs for the FE thermal model to simulate the change in insulation properties of soil.

For FE thermal analysis, the same mix design properties (i.e., the one selected for use in field tests) of concrete mixture were used for pre-processing method to input the temperature increase. Also, one additional mix design (high-volume fly ash, HVFA) was used for comparison purpose since Mixes 1 and 2 failed to meet FDOT’s requirement in the field test for a mass concrete. The mix design of HVFA approved by FDOT was expected to produce less hydration heat. For FE model inputs, the adiabatic temperature increase of concrete was obtained by conversion method using the concrete hydration heat produced and measured during the isothermal calorimetry testing in accordance with ASTM C1702 (ASTM C1702, 2015) as shown in Figure 6. Figure 7 shows the temperature increase with respect to the equivalent age

Figure 4. Geometry and boundary conditions for thermal FE model developed.
obtained from the isothermal calorimetry test for each mixture. Table 2 represents the composition of the paste fractions for concrete mixtures evaluated.

4.3. Validation of FE model
In particular, it is imperative to obtain accurate thermal properties and initial temperature of concrete for use in FE model to accurately predict thermal behavior of drilled shafts under various soil conditions. Table 3 tabulates thermal properties and initial temperature of four drilled shaft concretes evaluated. It is noted that the specific of heat for each concrete material was obtained from previous study (Markandeya, 2014). The heat capacity was then calculated by multiplying the density of material (g/m$^3$) and specific heat of each material (J/g°C). The thermal conductivity of concrete was adjusted by matching the computed temperatures from the FE model with those measured from a field test. The measured temperature at each sensor location was compared
with the predicted temperature to validate the parameters for FE model developed. Figure 8 shows the comparison between predicted and measured temperature development for four drilled shafts evaluated. It was found that the predicted temperatures matched within the 10% difference as compared to the measured temperatures. This indicated that the FE thermal model developed was able to accurately predict the temperature development in concrete drilled shafts in an early age.

Table 2. Paste fractions for concrete mixtures evaluated

|       | Cement (g) | Slag (g) | Fly Ash (g) | Water (g) | W/C Ratio | Total (g) |
|-------|------------|----------|-------------|-----------|-----------|-----------|
| Mix 1 | 1.5375     | 3.5874   | –           | 1.4862    | 0.29      | 6.6251    |
| Mix 2 | 5.1249     | –        | –           | 1.4862    | 0.29      | 6.6251    |
| HVFA  | 2.8040     | –        | 2.8040      | 1.6830    | 0.30      | 7.2910    |

Table 3. Thermal properties and initial temperature of four drilled shaft concretes evaluated

|       | Specific heat (J/g·°C) | Heat capacity (J/m³·°C) | Thermal conductivity (J/s·m·°C) | Initial temperature (°C) |
|-------|------------------------|-------------------------|-------------------------------|--------------------------|
| Shaft 1 | 1.052                   | 2,257,122               | 2.10                          | 26.5                     |
| Shaft 2 | 1.049                   | 2,299,388               | 2.20                          | 25.5                     |
| Shaft 3 | 1.062                   | 2,244,790               | 2.00                          | 23.0                     |
| Shaft 4 | 1.010                   | 2,248,215               | 2.20                          | 29.0                     |

Figure 8. Comparison between measured temperature development and analytical results. (a) Drilled shaft 1. (b) Drilled shaft 2. (c) Drilled shaft 3. (d) Drilled shaft 4.
5. Parametric study to evaluate the effect of gravimetric moisture content

Parametric study was conducted to investigate the effect of moisture contents of surrounding soils on thermal behavior of drilled shafts using different thermal properties of soil at different moisture conditions. Table 4 exhibits the input properties used for parametric study.

Figure 9 shows the maximum temperature differential as a function of moisture contents of soil. In general, the proportional relationships were identified between the predicted temperature developments and the moisture contents of soil until the maximum temperature difference reached approximately a moisture content of 6%. Beyond this point, the temperature difference remained unchanged regardless of the increase in moisture content from 6% to 16%, and the same trend was observed for all mixture designs evaluated. It appeared that this observation was attributed to thermal conductivity of soil associated with its moisture contents. Previous research indicated that thermal conductivity of soil increased as the moisture contents increased until the moisture contents reached to 6% (i.e., moisture contents of drained soil condition varied from 6% to 16%) (Tia et al., 2016). However, when moisture contents exceeded 6%, the thermal conductivity of soil remained nearly constant. This clearly indicated that change in moisture contents of soil within a range from 0% to 6% were highly associated with the change in maximum temperature difference. Also, the thermal results show that increasing the length of the drilled shafts from 2.1 to 5.8 m (7 and 19 ft) did not change the temperature development in the drilled shafts with all mixtures.

### Table 4. R-values and converted thermal conductivity of composite soil samples

| Moisture content (%) | R-value (m²·°C/W) | Thermal conductivity (J/s·m·°C) |
|----------------------|-------------------|---------------------------------|
| 0.0                  | 3.762             | 0.2658                          |
| 2.0                  | 2.469             | 0.4051                          |
| 4.0                  | 1.158             | 0.8634                          |
| 6.0                  | 0.660             | 1.5150                          |
| 8.0                  | 0.703             | 1.4235                          |
| 10.0                 | 0.552             | 1.8136                          |
| 12.0                 | 0.522             | 1.9164                          |
| 14.0                 | 0.465             | 2.1523                          |
| 16.0                 | 0.513             | 1.9512                          |

Figure 9. Predicted maximum temperature differences vs. moisture contents of soil.
In addition, all FE results exhibited that the maximum temperature differences predicted for all mixtures evaluated exceeded the maximum temperature difference required by ACI 301 (ACI 301, 2016) except the Mix 1 and HVFA at a soil moisture content near 0%. This observation seems to relate the fact that the temperature of concrete at the core of shaft increased relative to its adiabatic condition. However, since the surface of shafts was not insulated, heat dissipation from near-surface concrete occurred with a faster rate due to the increased thermal conductivity of soil as shown in Figure 10. Therefore, even though the maximum concrete temperature calculated in the mixtures were Mix 1 (66.6°C [151.9°F]) and HVFA (57.7°C [135.9° F]), specials measures for the mitigation of concrete temperatures would need to be undertaken to ensure that the maximum concrete temperature difference does not exceed 19.4°C (35.0°F).

6. Conclusion

This study focused on the investigation of the early-age thermal behavior of drilled shafts under different surrounding soil conditions using full-scale field tests and FE analysis. The measured temperatures from the drilled shafts were used to validate the FE model developed. The validated FE model was then used to perform a parametric analysis for evaluating the effects of surrounding soils with different moisture conditions on change in thermal behavior of drilled shafts at early-age. Also, different concrete mixes with different heat of hydration were used for parametric study. The main findings are summarized as follows:

- The FE model developed to analyze thermal behavior of drilled shafts at early-age was able to accurately simulate temperature development in drilled shafts. The measured temperatures in the four full-scale drilled shafts compared well with those predicted by the FE model.
- The use of concrete with lower heat of hydration was found to significantly reduce the temperature difference in the drilled shafts at an early-age based on the results of both full-scale field tests and FE analysis.
- The results of parametric thermal analysis clearly showed that the use of drier surrounding soil resulted in significantly reduced temperature difference in the drilled shafts.
- All the drilled shafts with a diameter greater than 1.8 m (6 ft) exhibited a temperature difference greater than 19.4°C (35.0°F) at early age required by ACI and FDOT.
- No crack was observed in all drilled shafts. Nevertheless, abnormally high temperature also raises the issues of reduced strength as well as delayed ettringite formation. Therefore, it is still very important to mitigate the high temperature in mass concrete to maintain the integrity of mass concrete structure.

![Figure 10. Temperature distribution in soil for 7 days after concrete placement. (a) Dry sand. (b) Saturated sand.](https://doi.org/10.1080/23311916.2018.1468202)
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Author details

Sangyoung Han1
E-mail: syhan@ufl.edu
ORCID ID: http://orcid.org/0000-0002-1616-9703
Sanghyun Chun1
E-mail: shchun@ufl.edu
Kukjoo Kim1
E-mail: klukkim@ufl.edu
Adrian M. Lawrence2
E-mail: alawrence@ce.ufl.edu
Mang Tia1
E-mail: tia@ce.ufl.edu

1 Engineering School of Sustainable Infrastructure and Environment, Department of Civil and Coastal Engineering, University of Florida, Gainesville, FL, USA.
2 Department of Military Strategy, Joint Forces Military University, Daejeon, South Korea.

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