EFFECT OF HEAT OF HYDRATION OF CEMENTITIOUS MATERIALS ON TEMPERATURE DEVELOPMENT OF DRILLED SHAFTS

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Abstract: *A three-dimensional finite element model was developed to simulate the heat generated and transferred with time in a drilled shaft. Thermal analysis was performed to assess the temperature development in a drilled shaft using several concrete mix designs. The obtained results show that the replacement percentage of supplementary cementitious materials significantly affect the heat of hydration and the temperatures in the drilled shaft. High volume fly ash blends should be considered in mass concrete structures as they give low temperatures and temperature differentials, thus low potential of early-age cracking. It was also concluded that all drilled shafts should be considered mass concrete structures regardless of the volume to surface area ratios.*

Keywords: *Mass concrete, isothermal calorimetry testing, drilled shaft, temperature differential, high volume fly ash.*

I. INTRODUCTION

Heat is generated during the hydration of cement causing a rise in internal temperature in concrete structures. The larger the concrete structure, the higher the internal temperature generated. Large concrete structures are characterized as mass concrete structures. Mass concrete is defined by the American Concrete Institute (ACI) as “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” [1].

During the curing of mass concrete structures, the temperature at the exterior surface is dissipated to the surrounding environment while the interior of the concrete remains hot—due to hydration reaction. The difference between the interior temperature and the exterior temperature is referred to as temperature differential.

In mass concrete applications, temperature differential plays an important role. Large temperature differentials can result in thermal cracking of the concrete which can substantially decrease the design life of a structure. The magnitude of the tensile stress is dependent on the thermal differential in the mass concrete, the coefficient of thermal expansion, modulus of elasticity, creep or relaxation of the concrete, and the degree of restraint in the concrete. Since the concrete is still in its early age, its full tensile strength is not developed, and if the tensile stresses are larger than the early-age tensile strength, cracking will occur. If cracking does occur, it will ultimately affect the ability of the concrete to withstand its design load, and allow the infiltration of deleterious materials which undermine durability.

To minimize the threat of thermal cracking in mass concrete, The Florida Department of Transportation (FDOT) developed standard specifications to control the temperature differential during design and construction of large concrete structures. Under the mentioned specifications, the maximum allowable temperature measured in a structure is 180°F (82°C) and the temperature differential between the concrete core—interior—and the exterior surface cannot exceed 35°F (20°C) [2-4].

In recent years, the FDOT has identified concrete structures which show susceptibility to thermal cracking commonly seen in mass concrete applications. These structures are characterized as segmental bridge pier segments, drilled shafts and all other bridge components. FDOT specifications [2] for drilled shafts are: “Drilled shafts: all drilled shafts with diameters greater than 6 feet shall be designated as mass concrete and a technical special provision shall be required.” The TSP in this particular instance generally takes the form of a mass concrete temperature control plan.

Drilled shafts are foundation elements that have been historically constructed without considering mass concrete effects and the possible long-term implications of the concrete integrity—due to water and matter infiltration into induced thermal cracks. For drilled shafts, however, any element with diameter greater than 6 feet (1.83 m) is considered a mass concrete element despite the relative high volume to area ratio. Figure 1 shows that drilled shafts greater than 4 feet (1.20 m) in diameter are candidates to be classified as mass concrete structures—based on the V/A ratio. As a result, understanding the parameters that affect the temperature rise—during the curing stage—in drilled shafts is of great interest to engineers.

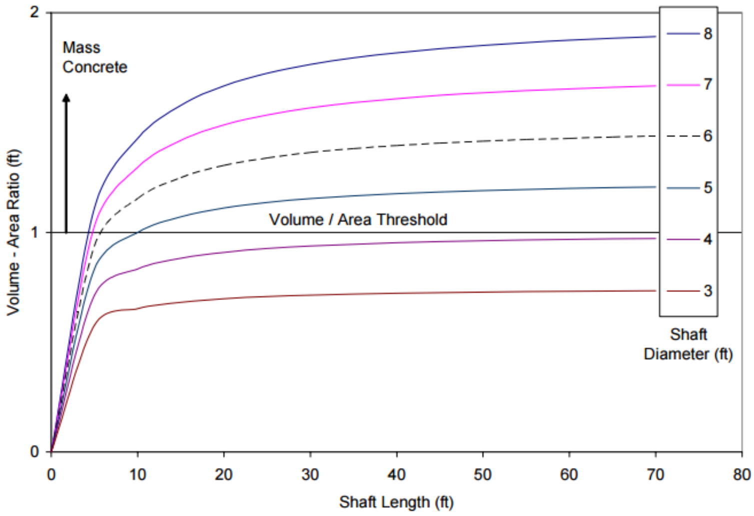


Figure 1. *Mass concrete determinations for shaft based on V/A ratio [4]*

This study uses finite element (FE) analysis and laboratory isothermal testing of cementitious materials of several concrete mixes to evaluate typical drilled shafts used in

Florida to determine whether some of them need to be treated as mass concrete structures.

II. ISOTHERMAL CALORIMETRY TESTING OF CEMENTITIOUS MATERIALS

In order to perform thermal analysis of the concrete segments, isothermal calorimetry testing [5, 6] was conducted on the several different FDOT typical concrete mix designs to obtain the heat of hydration and calculated adiabatic temperature rises to be used as input parameters for the analysis. Four FDOT approved concrete mix designs were used in the testing program as follows:

- Ternary Blend (TB) – FDOT Mix: 01-1149
- Slag Blend (SB) – FDOT Mix: 07-0852
- High-Volume Fly Ash (HVFA) – FDOT Mix: 05-1526
- Fly Ash Blend (FB) – FDOT Mix: 03-1870

The mixes selected represent actual FDOT mix designs used in concrete structure applications and they represent a suitable range of water-to-cement (w/c) ratios for analysis These mixes are comprised of pozzolanic materials mixed with Portland cement. Pozzolanic materials are known to lower the heat generated due to cement hydration when used as Portland cement replacements. The details of the concrete mixes (including the control mix) and paste fractions of cementitious materials that were tested are listed in tables 1 and 2.

The outputs from the isothermal calorimetry test consist of heat generation rate (heat flow) and consequent energy rise and cumulative energy (heat of hydration). The energy rise is then approximated to the energy rise of the hydrating concrete that is being represented by the mixture by multiplying by the percent cementitious content. The adiabatic temperature rise is calculated from the energy rise using the relationship described by the first law of thermodynamics and expressed in Equation 1 [7-9]:

$$\Delta T = \frac{\Delta Q}{mC_p} \tag{1}$$

Where: ΔQ = energy rise (J); m = mass of concrete (g); C_p = specific heat capacity (J/g-°C); ΔT = the change in temperature or temperature rise (°C).

The adiabatic temperature rises for concrete mixes were calculated and are shown in figure 2.

Table 1. *Constituents of Mixes Tested*

Mix Designation	Cement (kg/m³)	Supplementary Cementitious Material (kg/m³)			Fine Aggregate	Coarse Aggregate	W/c Ratio
		Fly ash	Slag	Metakaolin	(kg/m³)	(kg/m³)	
HVFA	217	217	-	-	638	1050	0.30
TB	235	156	-	55	667	985	0.34
SB	196	-	196	-	630	1056	0.40
FB	290	156	-	-	642	1010	0.36

Table 2. Paste Fractions of Cementitious Materials Tested

Mix	W/c Ratio	Cement	Fly Ash		Slag		Metakaolin	Water	Total
		(g)	(g)	(%)	(g)	(%)	(g)	(g)	(g)
HVFA	0.3	2.804	2.804	50%	-	-	-	1.683	7.291
TB	0.34	2.686	1.788	35%	-	-	0.633	1.737	6.844
SB	0.40	2.305	-	-	2.305	50%	-	1.863	6.473
FB	0.36	3.230	1.739	35%	-	-	-	1.789	6.759

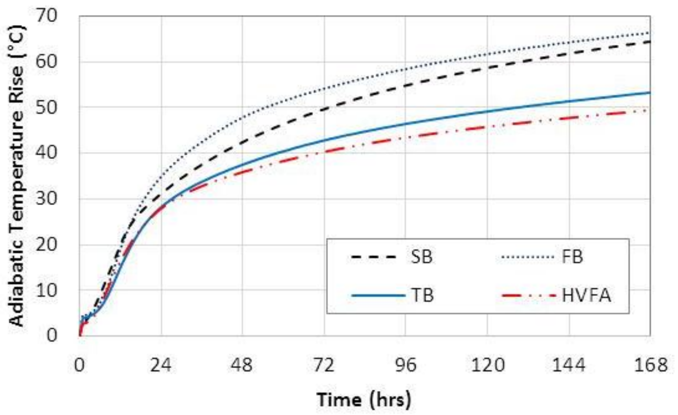


Figure 2. *Adiabatic temperature rises for the concrete mixes tested*

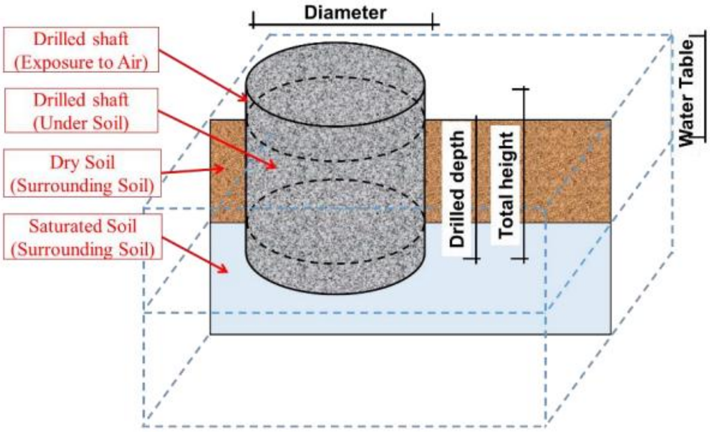
III. FINITE ELEMENT MODEL

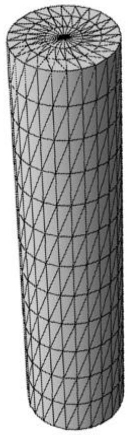
The finite element model in this study was developed using the TNO DIANA software. The general finite element model consists of a cylindrical mass concrete drilled shaft in a soil layer. The concrete is not insulated. The finite element model is composed of wedge/tetrahedron elements. The finite element mesh of one of the samples is illustrated in figure 3.

The modeled concrete drilled shaft has a segment length of 6 feet (1.83 m). Using this model, a diameter of 4 feet (1.20 m) would achieve a V/A ratio of 0.75 foot (0.23 m).

The boundary conditions imposed for thermal analysis consist of an initial temperature of the model and the external temperature. The initial temperature was set to 23°C (73.4°F) referring to the placement temperature of the concrete. The external and soil temperature was set to 23°C (73.4°F).

The fixed temperatures—external temperature— are applied to the bottom and sides of the drilled shaft. Fixed temperature is also applied to the top surface of the drilled shaft, the only difference being that the top surface is also affected by air convection—as it is exposed to the environment.





a) drilled shaft in soil layers *b) finite element mesh*

Figure 3. *Geometry and finite element mesh of drilled shaft in soil layers*

The material properties of soil [10,11] and concrete with varying mix designs used in the thermal analysis are listed in table 3.

Table 3. *Material Properties Used in Thermal Analysis*

Mix Designation	Thermal Conductivity (J/h-m-°C)	Specific Heat (J/kg-°C)	Density (kg/m^3)
HVFA	7920	1009	2236
TB	7920	1041	2228
SB	7920	1047	2236
FB	7920	1047	2259
Soil	972	800	1515

Effect of Heat of Hydration on Temperature Development of Drilled Shaft

The analysis discussed in this section was performed using concrete temperature rise data corresponding to typical FDOT concrete mix designs used for construction in Florida to investigate the effect of different heat of hydrations on temperature development of drilled shafts.

Figure 4 presents the temperature development results of the 4 concrete mix designs tested: TB, FB, SB and HVFA. As shown, the highest temperature is computed in the drilled shaft using the TB mixture. The lowest temperatures are calculated when using the HVFA mix. The HVFA mix is composed of 50 percent replacement of Portland cement with fly ash. This represents a high Portland cement replacement value, as a result the heat of hydration—and subsequent temperature rise—is lower. Additionally, the highest temperatures recorded occur during the first 30 hours after placement.

Figure 5 presents the temperature differential development results of the 4 concrete mix designs tested above. The trend follows that of the before mentioned results. The highest temperature differentials are calculated when using the TB mix whereas the lowest temperature differentials are calculated when using the HVFA mix—a result of the large percentage of

Portland cement replacement with fly ash. The results show that mix HVFA produced a maximum temperature differential value of 24°C while the TB blend produced a maximum temperature differential value of 26.8°C. All of these values exceed the allowable temperature differential limit set by FDOT (20°C). However, use of high volume fly ash as replacement for cement shows potential of reducing heat of hydration thus lowering the maximum temperature differential in drilled shafts.

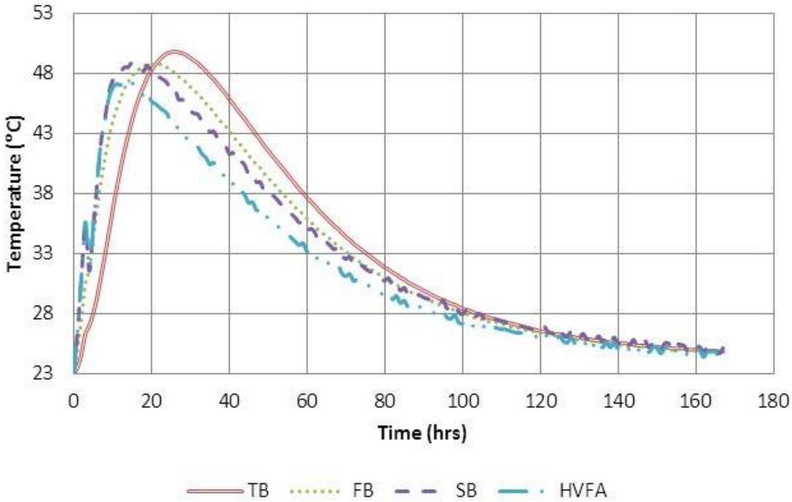


Figure 4. *Temperature development of drilled shafts with varying concrete mix designs*

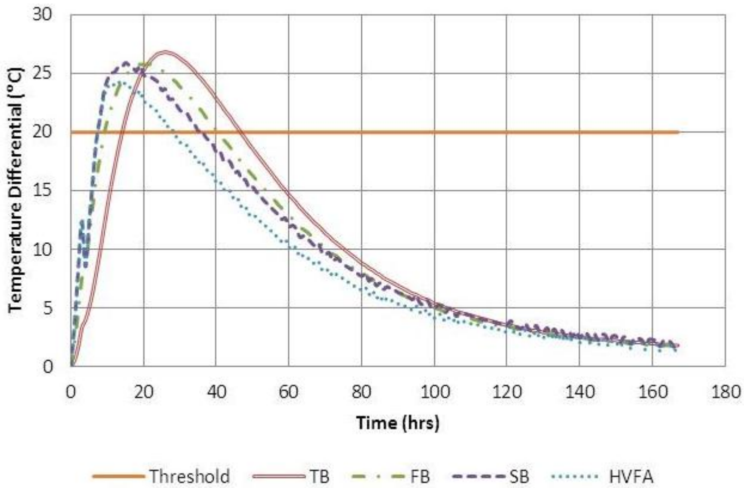


Figure 5. *Temperature differential development of drilled shafts with varying concrete mix designs*

IV. CONCLUSIONS

Maximum temperatures and maximum temperature differentials of drilled shafts are greatly influenced by heat generated due to hydration and concrete mix used. Use of pozzolanic material replacement—in particular HVFA—greatly reduces the maximum temperature and maximum temperature differential in drilled shafts thus minimizes thermal cracking potential in the concrete.

Trials with V/A ratios of drilled shafts less than 1.0 foot (0.3 m) produced maximum temperature differentials which failed limits set by FDOT. Therefore, in order to ensure the proper implementation of the developed method for thermal analysis, it is recommended that all drilled shafts be treated as mass concrete during design process.

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