3 Field Monitoring of Drilled Shaft Temperature, Velocity, Density, and Moisture

To understand the mechanism by which a drilled shaft cures under field conditions, two newly constructed drilled shafts (at a different site than the ones described in chapter 2) were monitored for up to seven days, immediately following concrete placement using the following four different geophysical logging methods: a) temperature logging to monitor the temperature gradient during concrete curing; b) crosshole sonic logging to monitor the effect of temperature on velocity variations; c) gamma-gamma density logging to monitor changes in density; and d) neutron-moisture logging to monitor changes in moisture.

3.1 Temperature Monitoring

Temperature monitoring was performed on two shafts using both temperature logging in the access tubes, and thermocouples embedded in the concrete. A third drilled shaft was also monitored at another site using only thermocouples embedded in the center and near the rebar cage during concrete pouring.

The tested drilled shafts were 0.9 m and 1 m in diameter, between 13-14.5 m in depth supporting a two-span bridge with two abutments and one pier with only two shafts per substructure unit. Each shaft contained four-50 mm diameter steel access tubes attached to the rebar cage. Continuous temperature logging was performed at abutment 1, shaft 1 and pier 2, shaft 2. Thermocouples were installed in abutment 2, shaft 2 to continuously monitor the temperature gradient of the concrete as the concrete cured. Class A (AE) concrete with a 28-day breaking strength of 27,600 kPa, placement slump of 25-100 mm, water/cement ratio of 0.44 (by weight), and air content of 5% was used to construct the drilled shaft.

3.1.1 Temperature Logging in Drilled Shaft 1 Abutment 1

The temperature monitoring results from abutment 1 shaft 1 (A1-S1) are shown in Figure 3.1. The plots show the temperature at 6 hours (black), 12 hours (blue), and 24 hours (red) after concrete placement. In this figure, the temperature logs from four access tubes in the shaft are displayed as a function of depth on the vertical axis. Also presented in the depth axis is the soil profile as reported during excavation. The soil profile consisted of a 0.2 m layer of gravel/boulders overlaying a 6.7 m sandy clay, 14 m clayey sand, and shale bedrock. The groundwater was encountered at a depth of 3.8 m. An initial rise in the shaft's temperature is observed in the first 24 hours after the concrete placement. Although not measured the soil temperature is estimated to be 10-15°C.

The complete thermal history of the shaft in the first 6 days after the concrete placement is presented in Figure 3.2. The temperature logs from the first 24 hours after concrete placement were combined with other temperature logs from two to six days. The data indicates a gradual decrease in temperature after the initial rise. Temperature values at five different depth points are plotted as a function of time in Figure 3.3. In this figure, the temperature values from the four access tubes are averaged at 3 m (in sand above the groundwater table displayed in black); at 6 m (in sand below the groundwater table in blue); at 9 m (clay in red); at 12 m (clay in green); and at 15 m (bed rock in magenta).

The following conclusions can be drawn from the temperature logging studies:

- At a given time period after the concrete placement, the shape of the temperature curve appears to be a function of the thermal conductivity of the

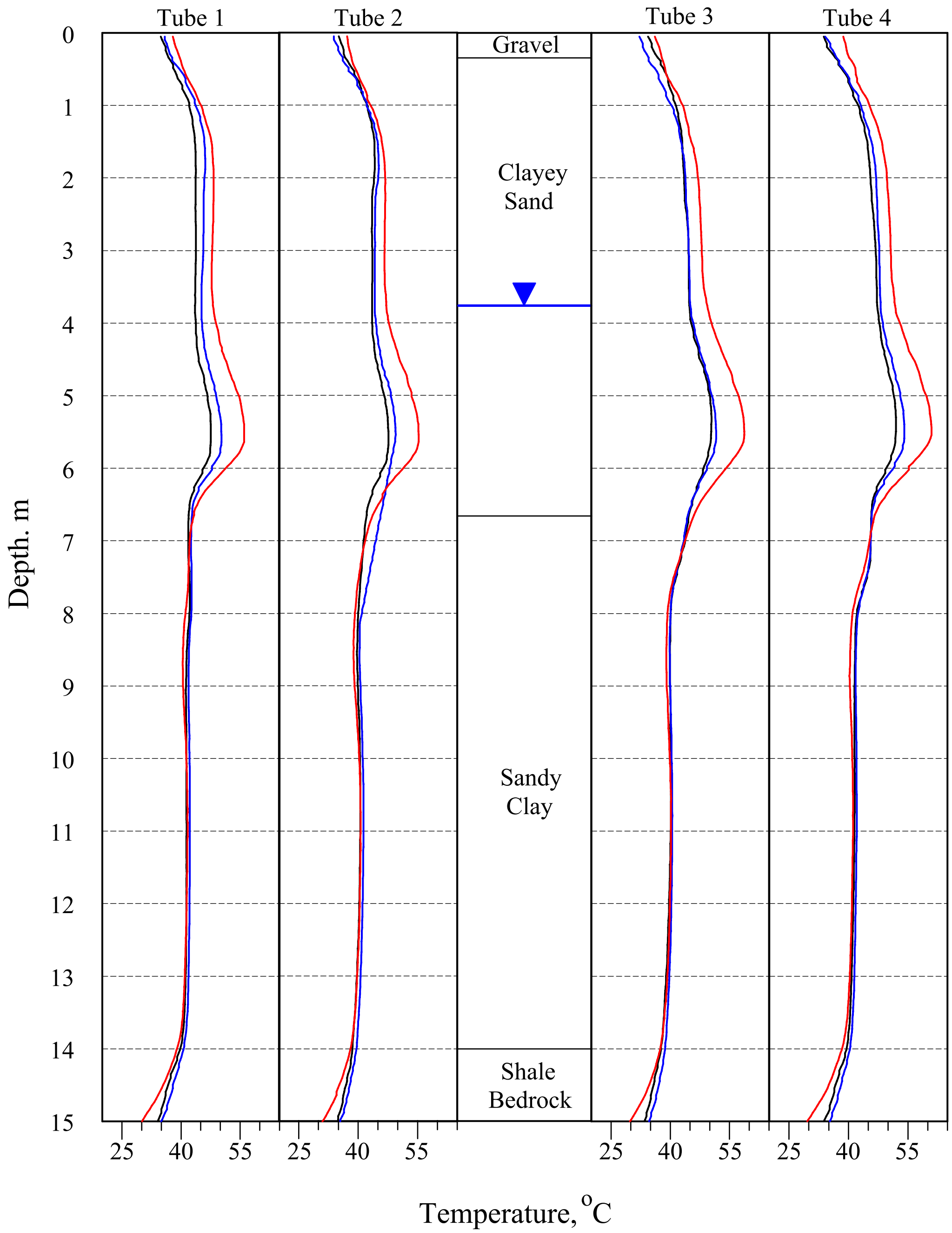

Figure 3.1 Temperature Monitoring of A1-S1 at 6 hrs. (Black), 12 hrs. (Blue) and 24 hrs. (Red) after Concrete Placement

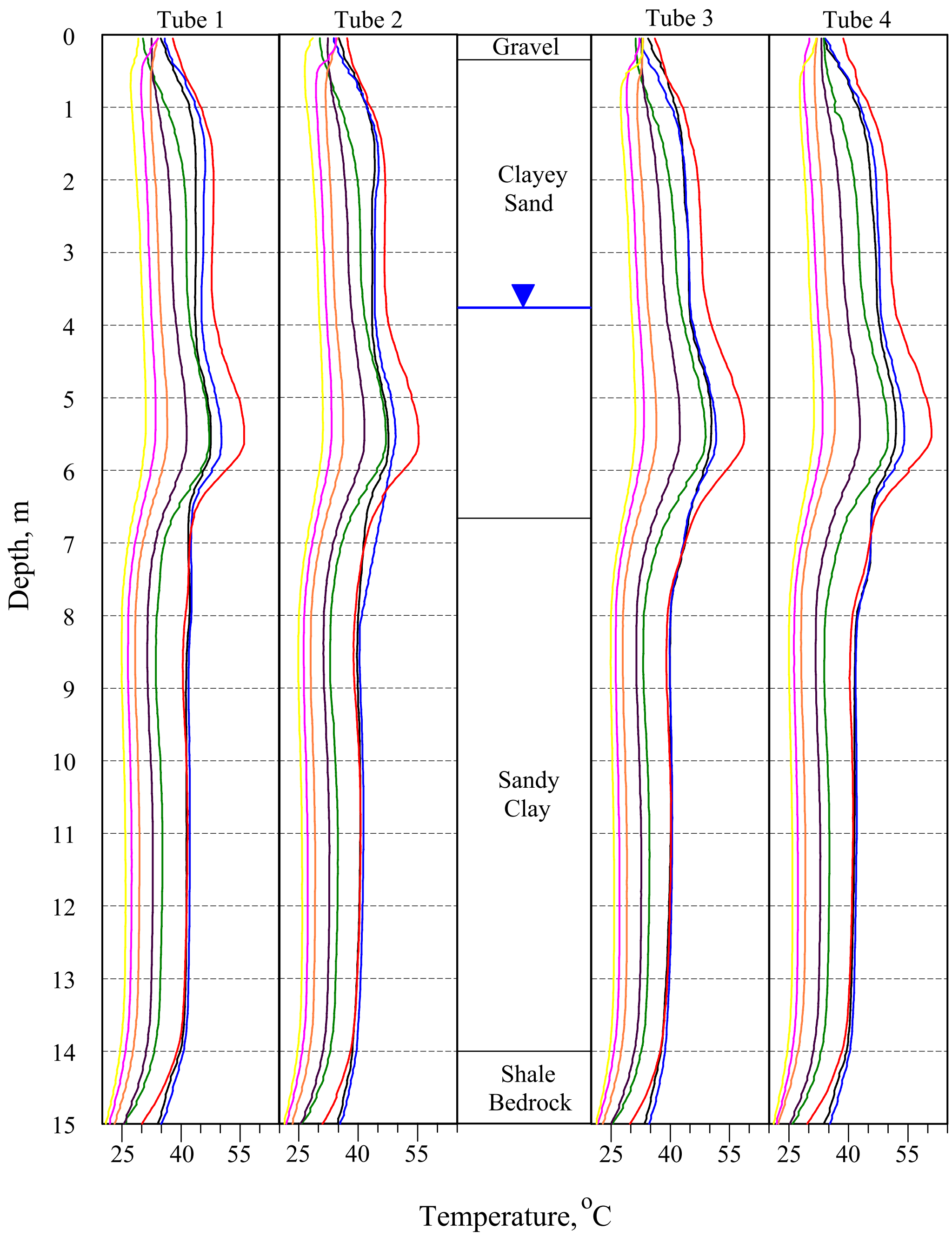

Figure 3.2 Temperature Monitoring of A1-S1 at 6 hrs. (Black), 12 hrs. (Blue), 24 hrs. (Red), 2 days (Green), 3 days (Purple), 4 days (Orange), 5 days (Teal), and 6 days (Yellow) after Concrete Placement

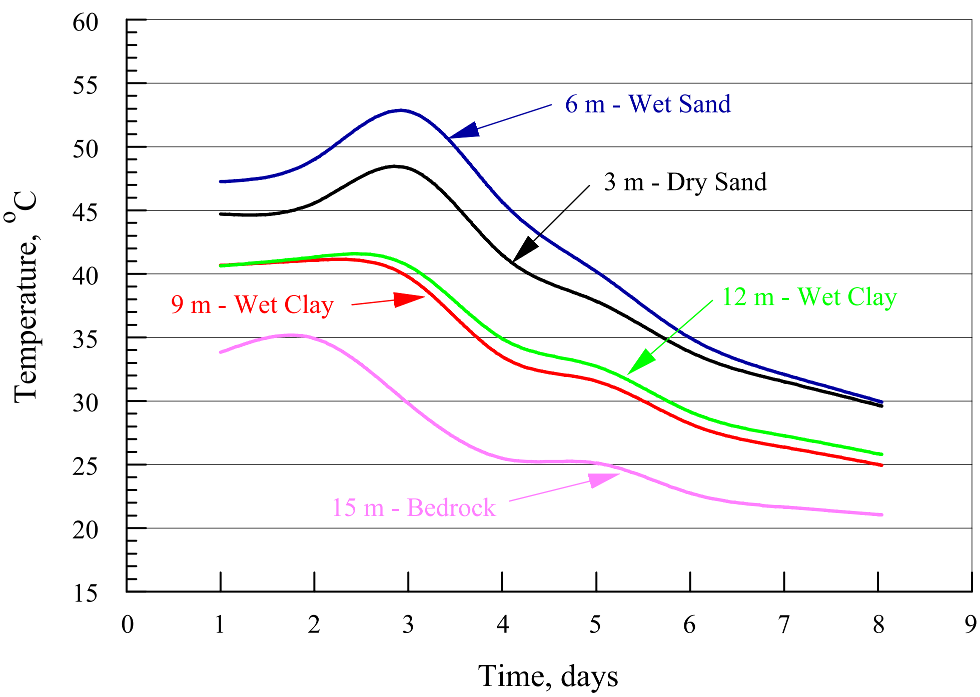

Figure 3.3 Temperature Monitoring of A1-S1 Averaged from the 4 Access Tubes at Depths of 3m (Black), 6 m (Blue), 9 m (Red), 12 m (Green), and 15 m (Magenta)

materials surrounding the drilled shaft. Therefore, in a typical drilled shaft, the shaft's temperature, and its curing rate or age, is non-uniform with depth. In this example, the shaft's temperature was highest (least cure) in the sand/gravel zones, cooler in the clayey zone, and coolest (most cure) at the bedrock level.

- In the sandy zone, shaft temperature rose more rapidly than at the clay and bedrock levels. From Figure 3.3, peak temperature was reached about 12 hours after concrete placement in the clay and bedrock levels, as compared to 24 hours in the sand level. Peak temperatures were reached after 12 hours at 9 m, 12 m, and 15 m depths and after 24 hours at 3 m and 6 m depths. The maximum temperature reached was at 52.7 ºC (at 6 m depth), and reduced to 30 ºC after 6 days. Maximum temperature differential in the shaft after 1 day of curing was about 23 ºC. This differential was reduced to 9 ºC after 6 days of curing, resulting in a more uniform temperature curve.

- A localized "hot spot" was observed in abutment 1 shaft 1 as shown in Figure 3.1 and Figure 3.2 between the depths of 3.7 and 7.7 m. According to the construction records, an additional 6-7.5 m^3 of concrete had to be used at these depths. Therefore, the higher temperature could be due to shaft belling at these depths. The groundwater table also had a minor effect on concrete temperature, but due to the shaft bulging at the water table elevation it is difficult to determine the exact effect.
- In the top 1 m near the surface, cooler temperatures were observed due to heat escaping to the air. For tubes 2 and 3, the shaft temperature decreased from 6 to 12 hours before rising to 24 hours (Figure 3.1). After 24 hours the temperature decreased, except for a temperature increase in the top 0.6 m after 3 days (Figure 3.2). High fluctuations in temperature were observed in top 0.6 m of the shaft.

3.1.2 Temperature Logging in Drilled Shaft 2-Pier 2

Temperature monitoring was also conducted in pier 2, shaft 2 (P2-S2). The results are shown in Figure 3.4 from 1 hour to 6 days after concrete placement. The soil profile consisted of 1.22 m of peat, with gravel overlaying 2.3 m of clay with organics, 11.28 m of clay, and shale bedrock. The groundwater was at the surface.

Temperatures at five depths are plotted as a function of time in Figure 3.5. In this figure, the temperature values from the four access tubes are averaged at 0.8 m (in

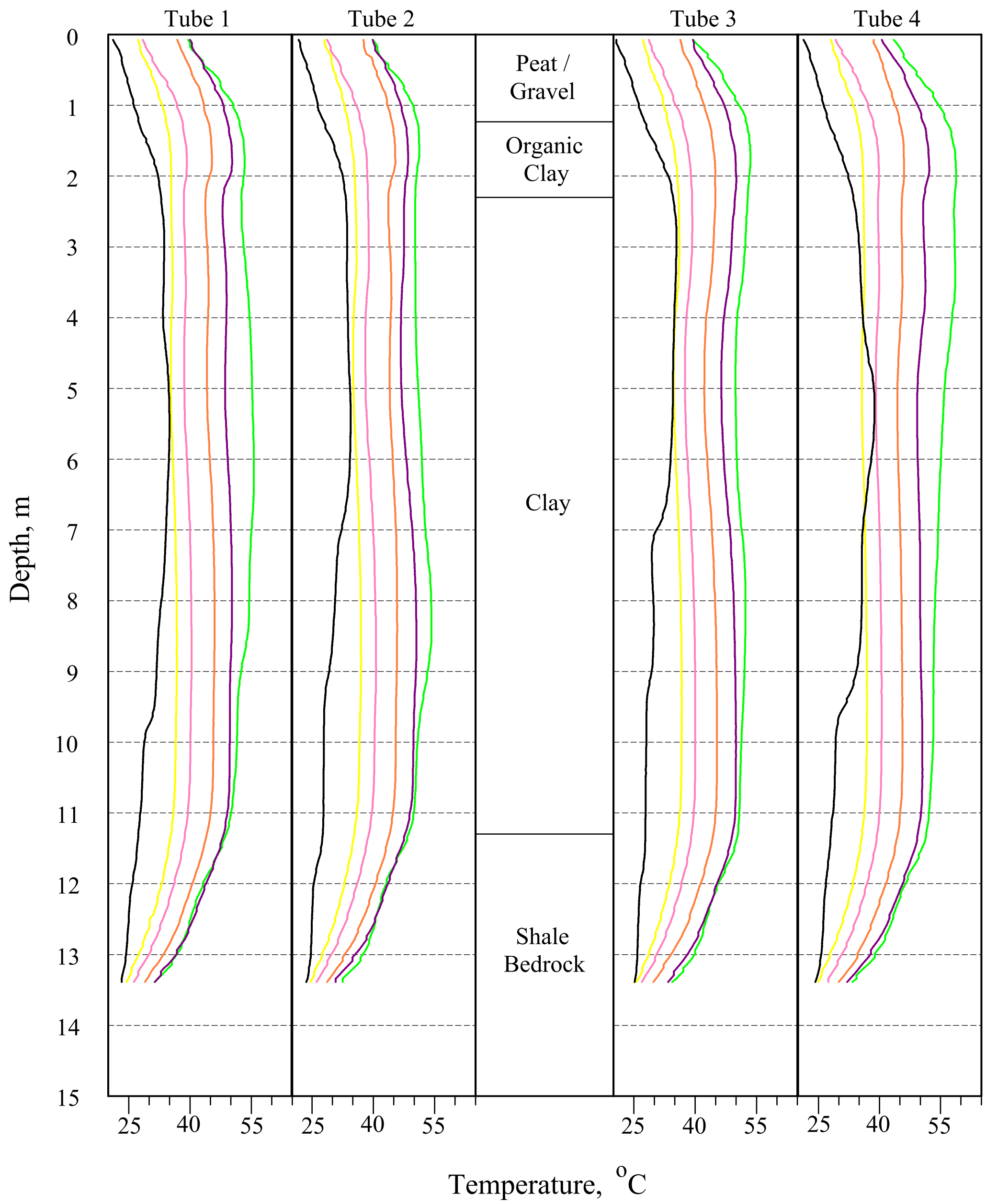

Figure 3.4 Temperature Monitoring of P2-S2. Temperatures at 1 hr. (Black), 24 hrs. (Red), 2 days (Green), 3 days (Purple), 4days (Orange), 5 days (Teal) and 6 days (Yellow) after Concrete Placement

gravel displayed in black); at 5 m (in clay in blue); at 10 m (clay in red); and at 12.5 m (shale bedrock in green). The following conclusions can be drawn from the temperature logging studies from this shaft:

- At a given time period after the concrete placement, the shape of the temperature curve appears to be a function of the thermal conductivity of the soil/rock interface in the hole. The shaft's temperature was highest (least cure) in the clay zone, cooler near the surface, and coolest (most cure) in the bedrock. No localized "hot spot" was observed in this dataset.
- As shown in Figure 3.5, peak temperatures were reached after 48 hours. The maximum temperature reached was at 53 ºC (at 5 m depth), and gradually reduced to 35 ºC after 5 days. The maximum temperature differential in the shaft was about 10 ºC after 6 hours of curing. This differential was reduced to 3.7 ºC after 5 days of curing, resulting in a more uniform temperature curve .
- Cooler temperatures were observed in the top 1 m due to heat escaping to the air.

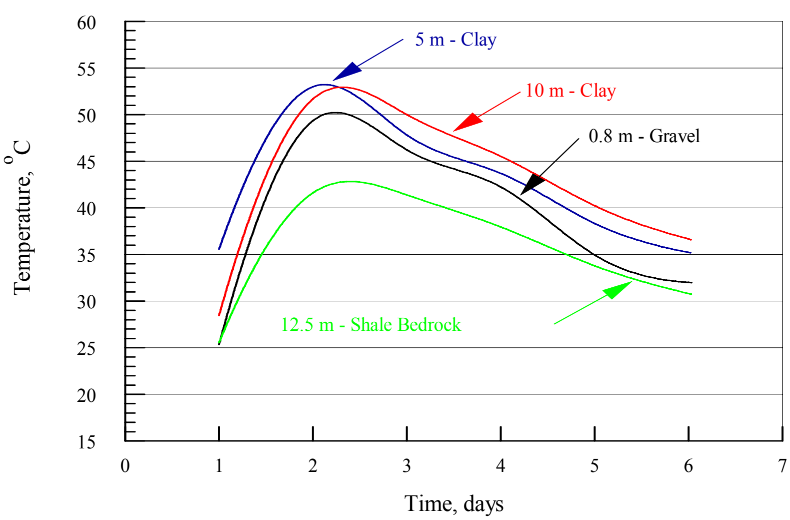

Figure 3.5 Temperature Monitoring of P2-S2. Temperatures are Averaged from the 4 Access Tubes at depths of 0.8 m (Black, Gravel), 5 m (Blue, Clay), 10 m (Red, Clay), and 12.5 m (Green, Shale Bedrock)

3.1.3 Temperature Monitoring With Thermocouples

Thermocouples were installed at two sites to monitor drilled shaft temperatures:
Site 1 - A third shaft (abutment 2, shaft 2) at the above site was monitored with two thermocouples, one installed at the center, and the other attached to the rebar cage (side) at 2.4 m depth. The center thermocouple was attached to a single rebar that was driven in the shaft immediately after concrete placement. This study was performed to investigate the temperature differential between the center of the shaft and the side of the shaft at the rebar cage.

Peak temperature was reached after 26 hours both at the center and at the rebar cage in the shaft (Figure 3.6). The maximum temperature reached was at 68.3 ºC at the center and 66.1º C at the cage. The maximum temperature differential between the center and the side was recorded as 5 ºC after 29 hours.

Site 2 - The temperature in a drilled shaft at another site was monitored for 18 days. The results are shown in Figure 3.7. Two thermocouple probes were installed outside the rebar cage in the north by northeast position at 3.66 m (shown in red) and 12.8 m (blue) depths. The groundwater table was at 8.23 m; therefore, the two probes were located at approximately 4.6 m above and below the groundwater table.
A Class A 19-cm concrete slump with 6.0% air was used to construct this drilled shaft. The concrete temperature at the placement was 11 ºC. Concrete temperature monitoring began about 1.5 hours following concrete placement. As shown in Figure 3.7, peak temperature was reached in 20 hours at 41.1 ºC.

The following conclusions can be drawn from this study:

- At both measurement depths, the temperature curves are similar in shape and decrease with time as the shaft loses heat.

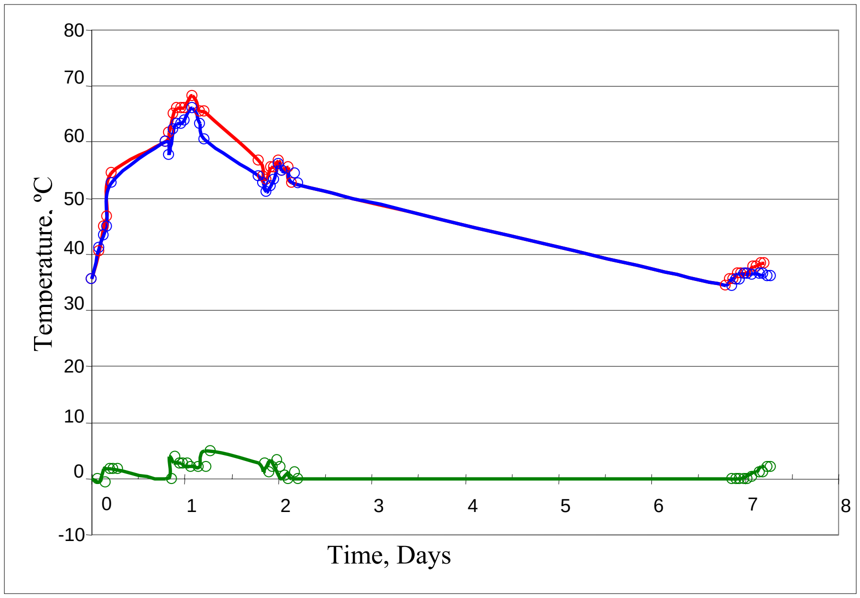

Figure 3.6 Temperatures from Embedded Thermocouples of A2-S2- Red at the Center of Shaft at 2.4 m, Blue Near Rebar Cage at Same Depth, and Green Temperature Differential Between Both Stations

- The shaft temperature measurements at the rebar cage are not uniform with depth. As expected, the groundwater table acted as a heat sink with the thermocouple placed at 4.57 m below the groundwater table measuring lower average temperatures than the one placed at 4.57 m above the groundwater table. Therefore, the shaft is generally hotter (less cured) above the groundwater table.
- Interestingly, at each measurement location, the temperature curve seems to recover and display distinct temperature jumps at about 4-day intervals. This is most likely due to the C_3A secondary hydration phase.
- The temperature differential between the two stations decreased with time as the shaft's temperature (or curing rate) stabilized. The temperature difference at the two stations is about 9 ºC for the first 1-5 days, decreasing to about 5ºC for the next 7 days, and converging to 3 ºC after 18 days of measurement.

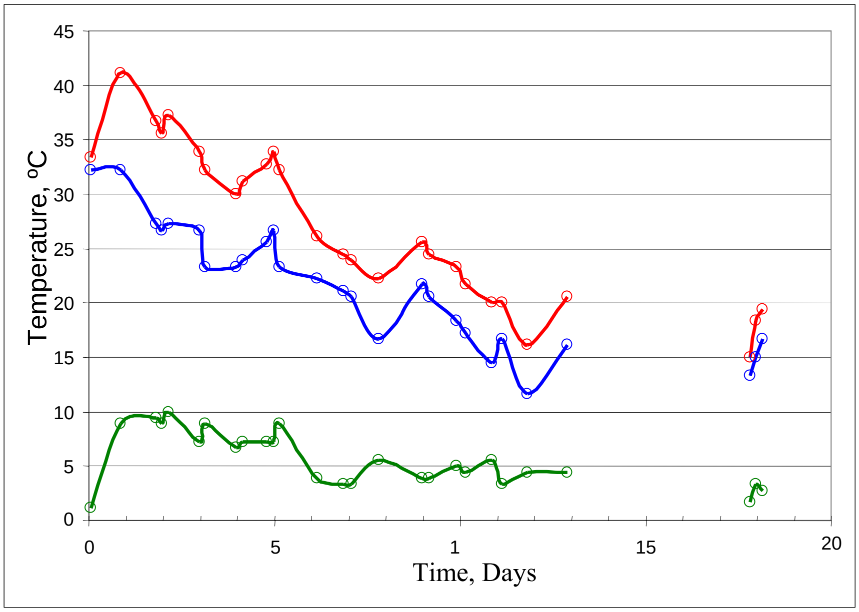

Figure 3.7 Temperatures from Embedded Thermocouples of Shaft P-3 at Site 2 Near Rebar Cage- Red at 3.66 m (Above Groundwater Table), Blue at 12.8 m (Below Groundwater Table), and Green is Temperature Differential Between Both Stations

3.1.4 Temperature Monitoring - Conclusion

From both the temperature logging and embedded thermocouples studies, the following can be concluded:

- For the small diameter shafts observed in this study (less than 1 m in diameter), peak temperatures of about 41-68 ºC were reached between 20-26 hours after concrete placement.
- Peak temperatures reduced to 23-35 ºC after 6 days and to 12 ºC after 12 days following concrete placement.
- The shaft curing rate is non-uniform as a function of depth in the first 6-7 days, depending on shaft diameter, materials properties surrounding the shaft, and depth of groundwater.

- After 6-7 days the temperature stabilizes, with a temperature differential of less than 5ºC throughout.
- CSL measurements collected before the first 7 days of concrete placement will have lower sonic velocities (as it relates to concrete strength) than the lab measurements, and will be non-uniform with depth, unless the concrete strengths are corrected by maturity calculations.
- Temperature logging can be used to measure shaft peak temperature and temperature differential between the center and the edge (with the insertion of a thermocouple in the center). This data can be used to mitigate thermal cracking and durability problems in the shaft. According to Gajda and Vangeem (2002), in mass concrete "temperature limits are specified to seemingly arbitrary values of 57ºC for the maximum allowable concrete temperature and 19ºC for the maximum allowable temperature difference between the center and the surface of the mass concrete section". A study is warranted to define these parameters in a drilled shaft environment.

3.2 Velocity Monitoring Results

The results of velocity measurements from abutment 1 shaft 1 obtained from 1 day to 6 days after concrete placement are depicted in Figure 3.8. Six crosshole sonic logs were acquired using 4 perimeter logs and 2 diagonal logs each. In the figure, static-corrected CSL results are plotted in 6 separate sub-plots from 6 different access-tube pair combinations as indicated on the top label. Depths were measured from the top of the shaft and are shown on the vertical axis. The soil profile surrounding the drilled shaft is presented in the depth axis. In Figure 3.9, the diagonal CSL paths 1-3 and 2-4 are plotted in an expanded scale. Figure 3.10 shows the average CSL values (averaged over the 6 days) from four access tubes at five different depth points, plotted as a function of time.

Large tube bending was observed in the top 7.5 m of the shaft (see path 3-4) making static correction more difficult to apply. Low velocity values were observed in the bottom 1 m of the shaft.

Limited CSL monitoring was obtained from pier 2 shaft 2 from 3 days and 4 days following concrete placement. As indicated in Figures 3.11 and 3.12, a small increase in CSL velocity is observed from 3 and 4 days following concrete placement

The following conclusions can be drawn from the velocity monitoring study:

- Velocities appear to have direct correlation with time of curing. This is apparent from pier 2 shaft 2 as shown in Figures 3.11 and 3.12. For abutment 1 shaft 1 in Figure 3.8, the CSL curves on the whole were increasing with time; but not continuously. For the long CSL paths 1-3 and 2-4 plotted in an expanded scale in Figure 3.9, the velocity increase was more apparent. However, when the CSL values from four access tubes are averaged at five different depth points in Figure 3.10, a clear increase in velocity is observed.
- At a given time period, the velocity values appear inversely correlated with shaft temperature. For pier 2 shaft 2, the velocity values in Figures 3.11and 3.12 correlated well with the shaft temperature shown in Figure 3.5, with clay indicating the lowest velocity (warmest), followed by gravel (cooler), and bedrock (coolest temperature). For abutment 1 shaft 1, average velocities should have increased from sand (warmest), followed by clay, and bedrock indicating highest velocity (coolest). This trend was generally observed; however, bedrock velocities were anomalously low (possibly due to a defect)

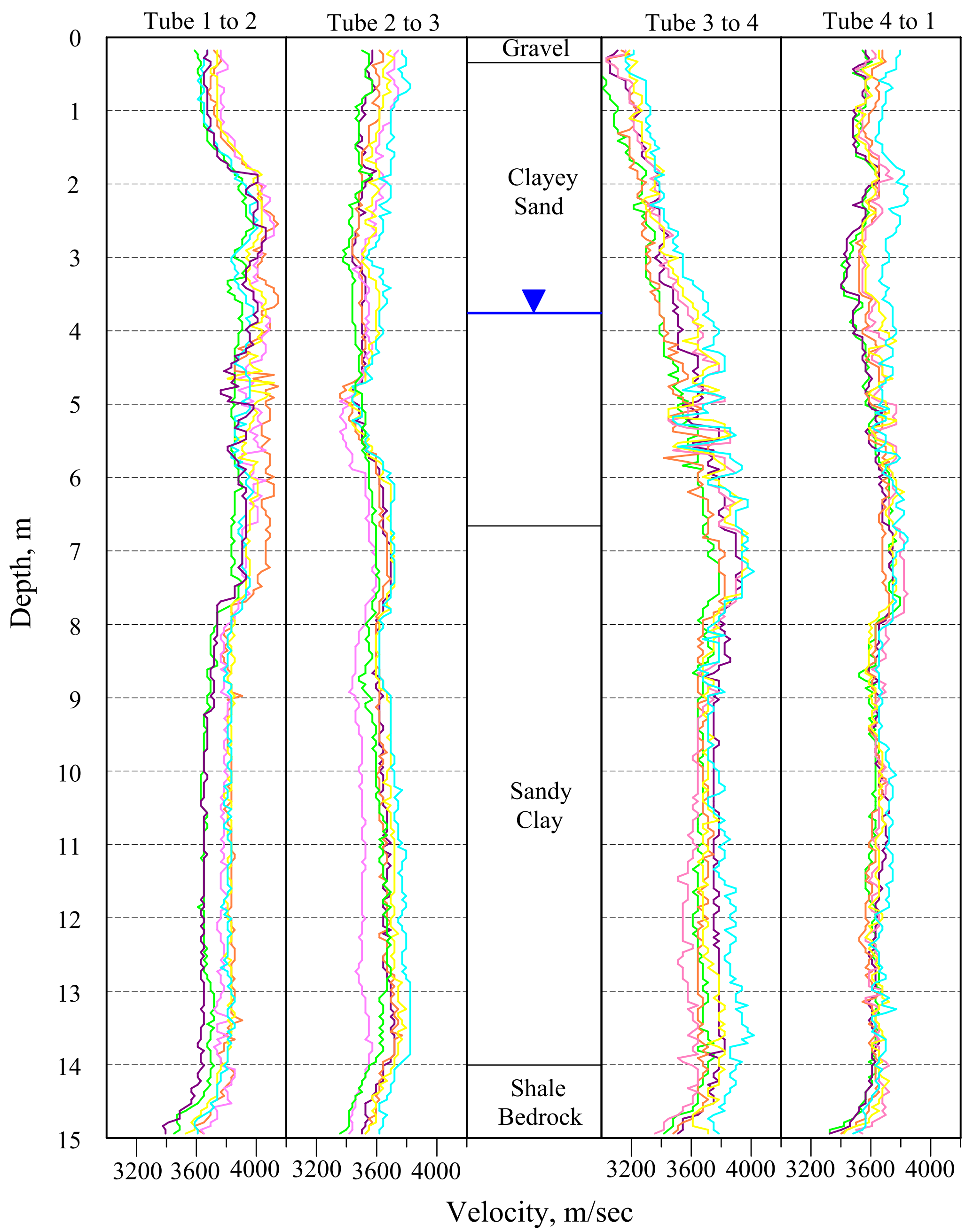

Figure 3.8 CSL Velocity Measurements of A1-S1- Velocities at 1 day (Red), 2 days (Green), 3 days (Purple), 4 days (Orange), 5 days (Teal), and 6days (Yellow) After Concrete Placement

and wet sand was anomalously high possibly due to being situated within the tube-bending zone.

- The velocity curves appears to taper off after about 4 days of curing.

3.3 Density Monitoring

Density monitoring results from abutment 1 shaft 1 obtained from 1 day to 6 days after concrete placement are presented in Figure 3.13. In this figure, the gamma-gamma density logs (GDL) are plotted in 4 separate sub-plots from the tested access tubes. Each individual sub-plot depicts the GDL results from 355 mm source-detector separation presented in a magnified density scale of 2,100-3,200 kg/m^3 (130-200 lbs/ft^3). Depths were measured from the top of the shaft and are shown on the vertical axis. The soil profile is also presented in the depth axis. The single-hole GDL results were more uniform than the CSL results, as they are not affected by tube bending. In Figure 3.14, GDL values from four access tubes are averaged at five different depth points and plotted as a function of time.

GDL monitoring was obtained from Pier 2 Shaft 2 from 1 day to 4 days after the concrete placement. As indicated in Figure 3.15, a steady increase in density values are observed in this dataset.

The following conclusions can be drawn from the density monitoring:

- Density values appear to slightly increase with time of curing. This is apparent from Pier 2 Shaft 2, as shown in Figure 3.15, for 1 to 4 days of curing. For abutment 1 shaft 1 in Figure 3.13, the density values also increased steadily from 1 to 4 days after the concrete placement. However, values then decreased after days 5 and 6. The reason is

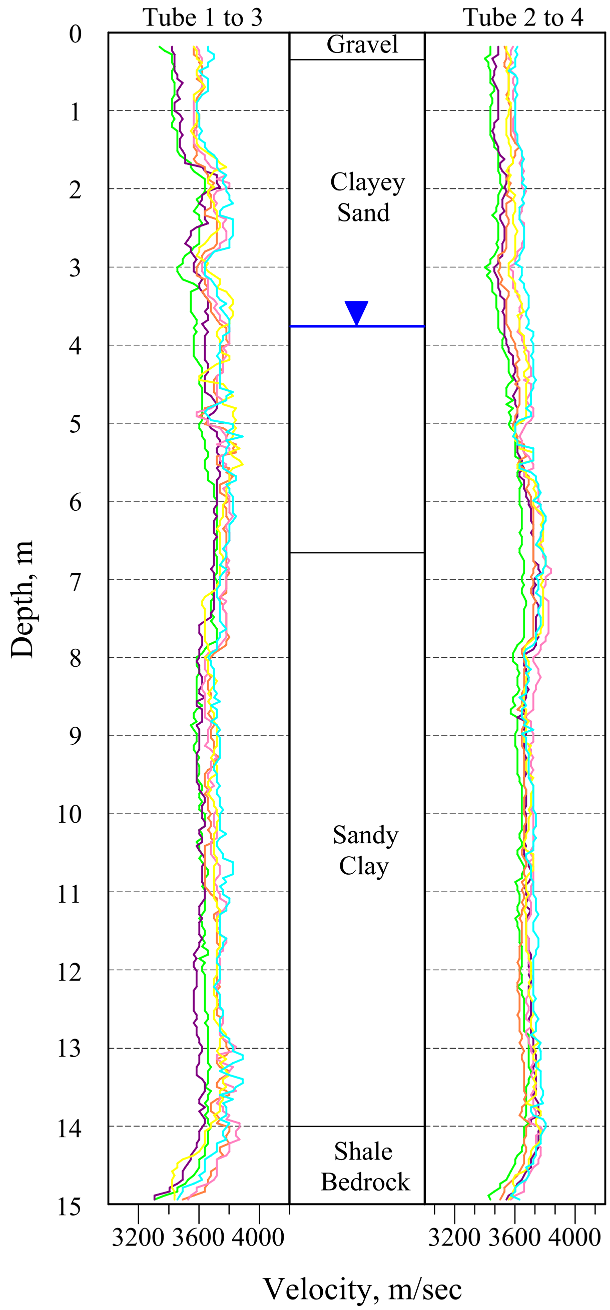

Figure 3.9 CSL Velocity Measurements of A1-S1 between Tubes 1-3 and 2-4 at 1 day (Red), 2days (Green), 3 days (Purple), 4 days (Orange), 5 days (Teal), and 6 days (Yellow) after Concrete Placement

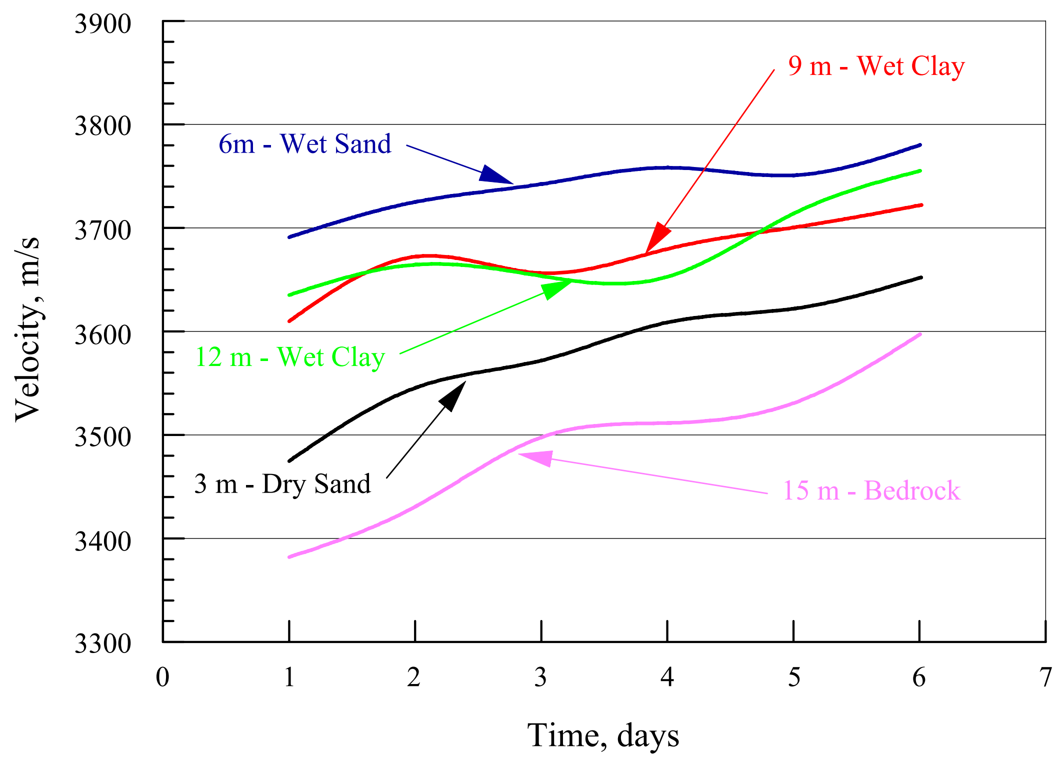

Figure 3.10 Average CSL Velocity Measurements of A1 S1. Static Corrected Velocity Values are Averaged from the 4 Access Tubes (and Six CSL Test Paths) at Depths of 3m (Black), 6 m (Blue), 9 m (Red), 12 m (Green), and 15 m (Magenta)

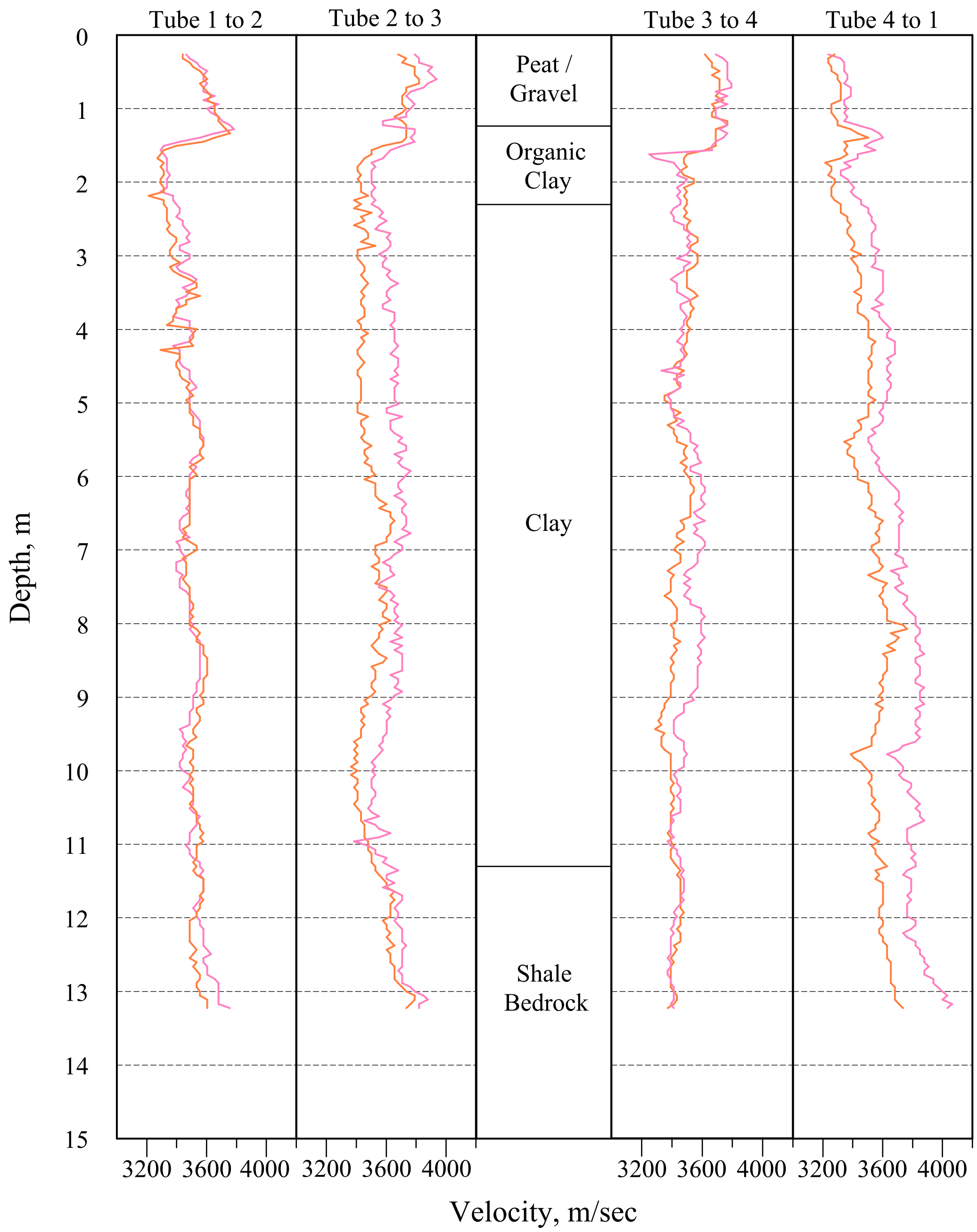

Figure 3.11 CSL Velocity Measurements of P2- S2- at 3 days (Purple) and 4 days (Orange) After Concrete Placement

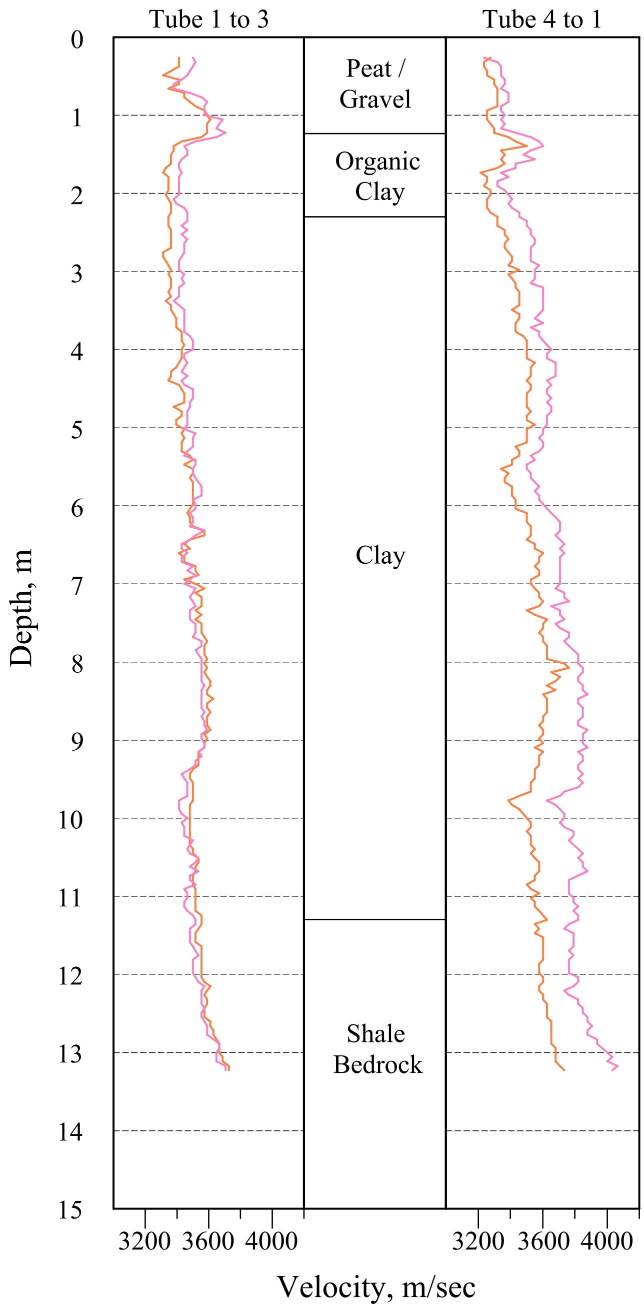

Figure 3.12 CSL Velocity Measurements of P2- S2- between Tubes 1-3 and 2-4 at 3 days (Purple) and 4 days (Orange) After Concrete Placement

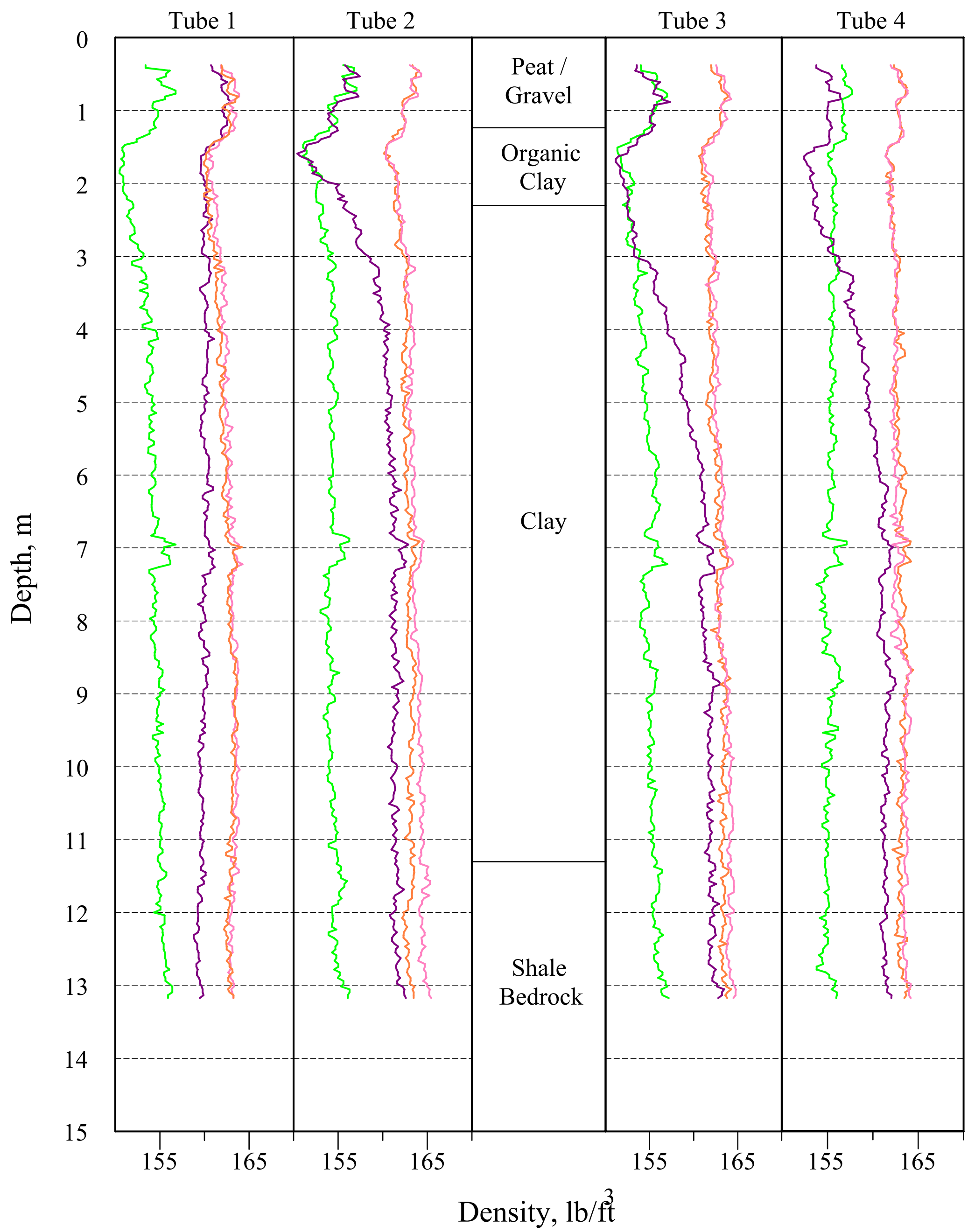

Figure 3.13 GDL Density Monitoring of A1-S1- with 1 day (Red), 2 days (Green), 3 days (Purple),and 4 days (Orange) After Concrete Placement

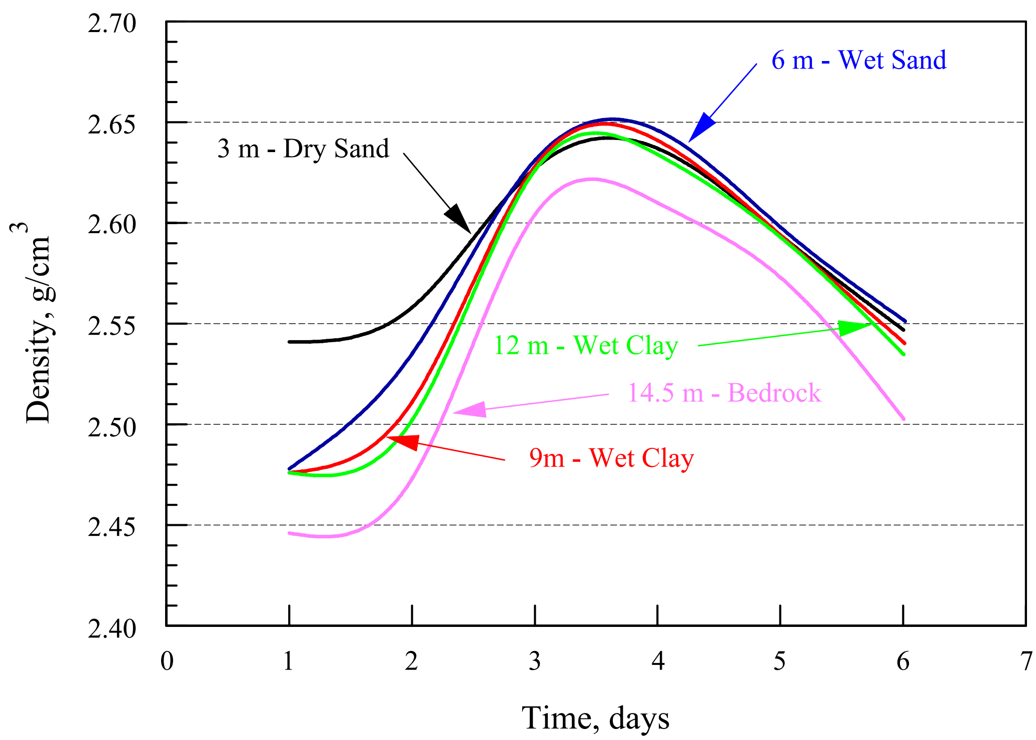

Figure 3.14 Average GDL Density Monitoring of A1-S1- Densities are Averaged from the 4 Access Tubes at Depths of 3 m (Black), 6 m (Blue), 9 m (Red), 12 m (Green), and 15 m (Magenta)

unclear—possibly due to the formation cracks in the concrete during curing.

- A decrease in density can be seen in Figure 3.14. In this figure, the averaged GDL values are plotted from 3 m (in sand above the groundwater table displayed in black); 6 m (in sand below the groundwater table in blue); 9 m (clay in red); 12 m (clay in green); and 15 m (bed rock in magenta) depth levels. The reason for this decrease in density appears to contradict all expectations. This could be attributed to the high variability in the GDL data quality, and should not be interpreted as exact values.
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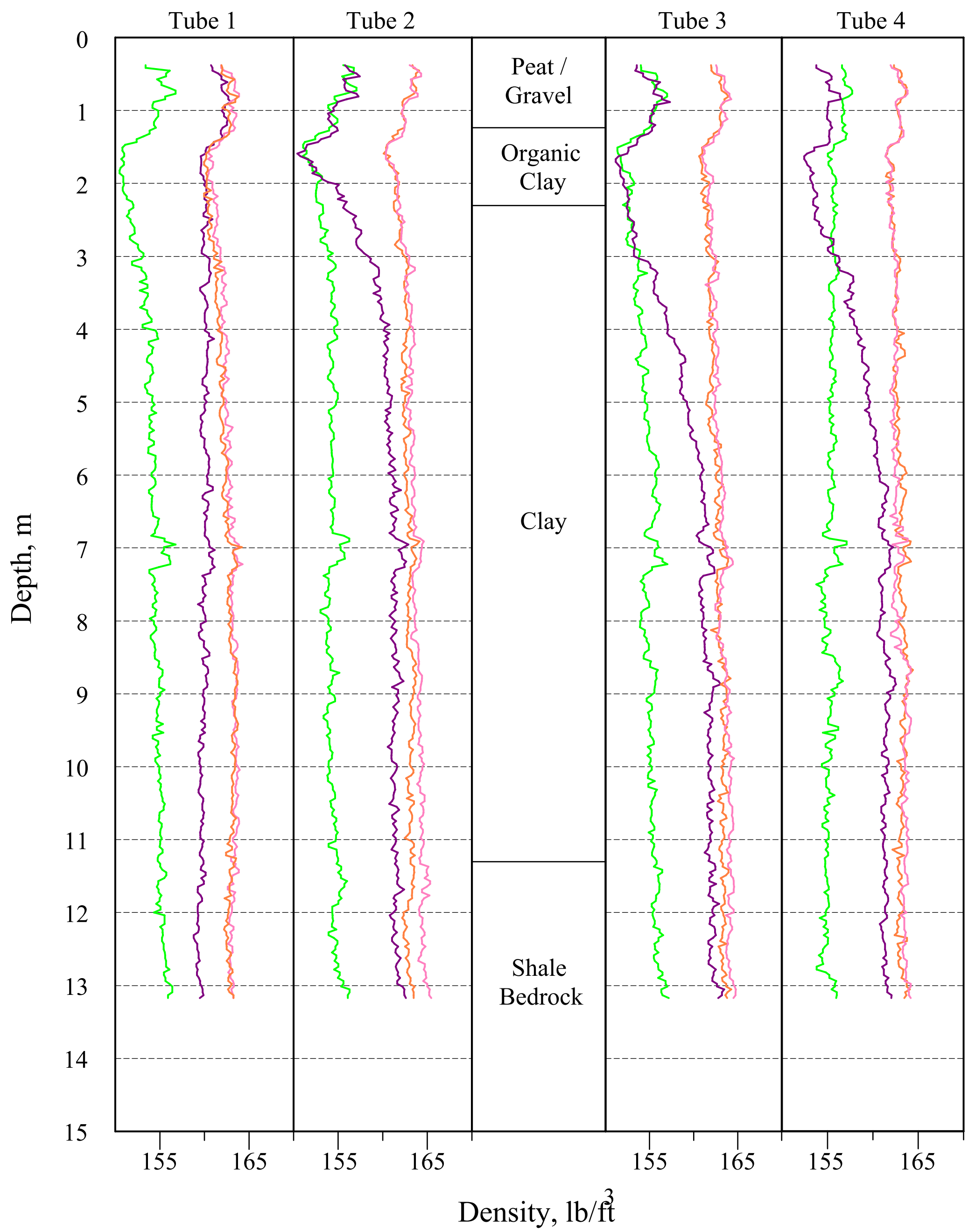

Figure 3.15 GDL Density Monitoring of P2-S2. Densities at 1 day (Red), 2 days (Green), 3 days (Purple), and 4 days (Orange) After Concrete Placement

- At a given time period, the shape of the density (GDL) curves appear to correlate with neutron monitoring logging (NML) moisture curves, as discussed in the next section. For pier 2 shaft 2, the density values in Figure 3.15 correlated well with the relative moisture levels shown in Figure 3.18, with gravel (lowest moisture, lowest density), followed by clay and bedrock (highest moisture, highest density). For abutment 1 shaft 1, however, an inverse correlation was observed—possibly due to anomalously low densities in the bedrock (due to a probable "defect") and anomalously high densities in the sand (possibly due to erroneous reading in the "hot spot" zone).

3.4 Moisture Monitoring

The neutron monitoring logging (NML) results from abutment 1 shaft 1 obtained from 1 day to 6 days after concrete placement is depicted in Figure 3.16. In this figure, the NML results are plotted in 4 separate sub-plots from the tested access tubes. Each individual sub-plot is presented in a magnified scale of 90-170 counts per second (cps). Lower counts denote higher moisture content; therefore, in each sub-plot, moisture content increases from left to right. Depths were measured from the top of the shaft and are shown on the vertical axis. The soil profile as reported by the boring logs is also presented in the depth axis. In Figure 3.17, NML values from four access tubes are averaged at five different depth points and plotted as a function of time. A more limited NML monitoring was obtained from pier 2 shaft 2 from 2 days to 4 days after the concrete placement, and is displayed in Figure 3.18.

The following conclusions can be drawn from the neutron monitoring logging:

- Relatively speaking, the moisture level in abutment 1 shaft 1 in Figure 3.16 was lowest at the bedrock followed by clay and sand (highest), due to

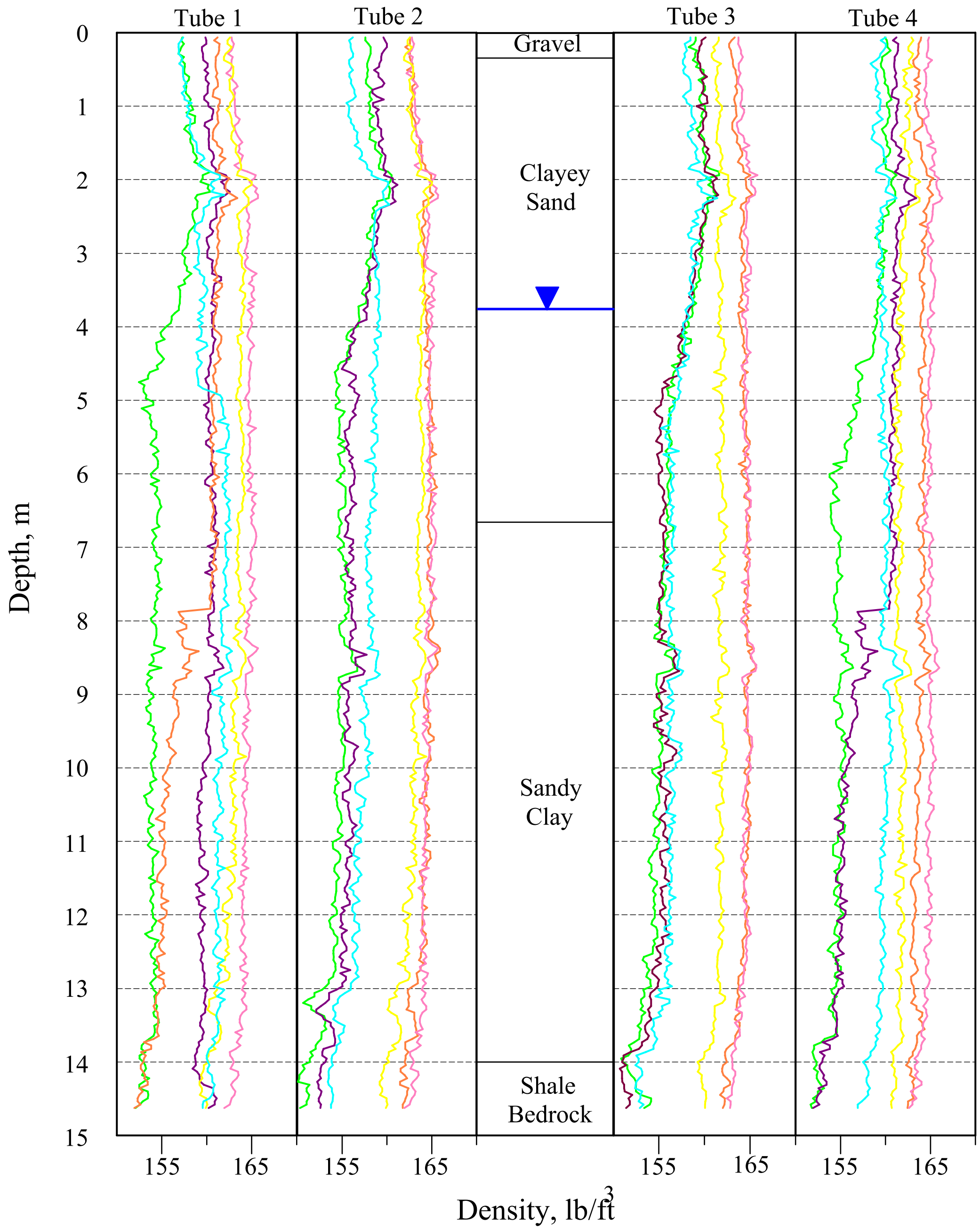

Figure 3.16 NML Moisture Monitoring of A1-S1- at 1 day (Red), 2 days (Green), 3 days (Purple), 4 days (Orange), 5 days (Teal), and 6 days (Yellow) After Concrete Placement

different hydration rates at these levels. This trend is also demonstrated in Figure 3.17 where the averaged NML values are plotted from 3 m (in sand above the groundwater table in black); 6 m (in sand below the groundwater table in blue); 9 m (clay in red); 12 m (clay in green); and 15 m (bedrock in magenta). Similar results were observed in the NML data from pier 2 shaft 2 (Figure 3.18).

- After 24 hours, moisture values appear to change negligibly with time of curing.

3.5 Summary of NDE Monitoring

It appears that the curing strength of the concrete in a drilled shaft is not only a function of time, but also a function of the physical properties of the surrounding soil/rock and the depth of the groundwater table. Specifically, two parameters from the soil profile can be observed to account for the variations in physical properties: thermal conductivity and permeability. Thermal conductivity affects relative changes in temperature. Permeability below the groundwater table affects thermal conductivity. The temperature in turn controls the curing rate and concrete strength—as it relates to incremental changes in velocity and density.

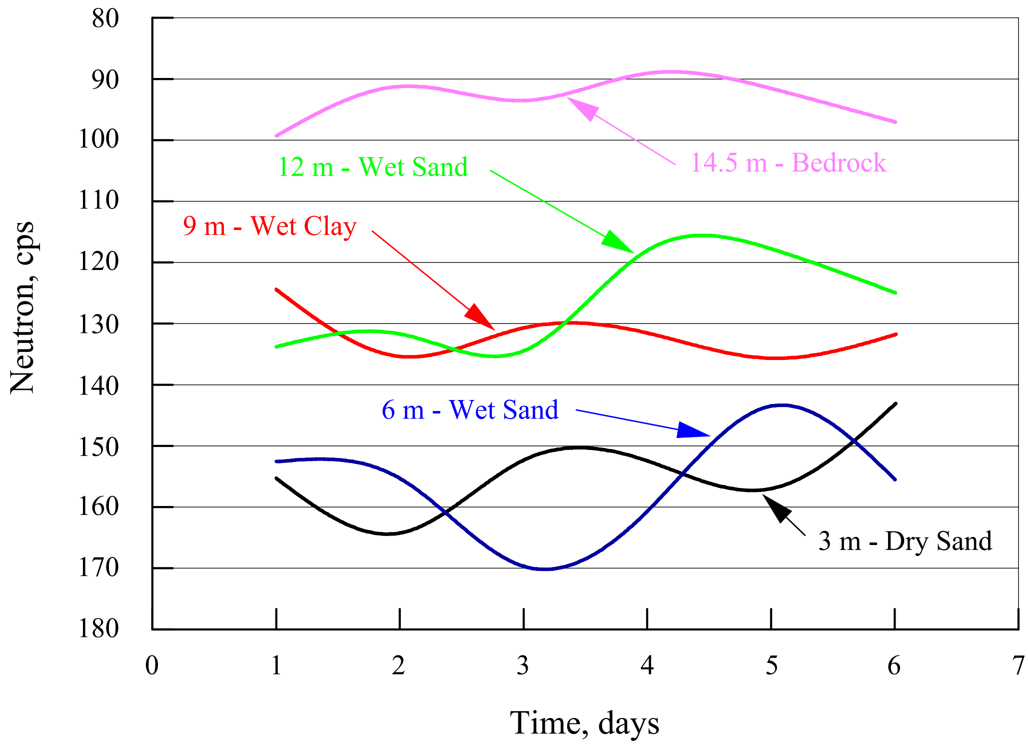

Figure 3.17 NML Moisture Monitoring of A1-S1. Moisture Values are Averaged from the 4 Access Tubes at Depths of 3 m (Black), 6 m (Blue), 9 m (Red), 12 m (Green), and 15 m (Magenta)

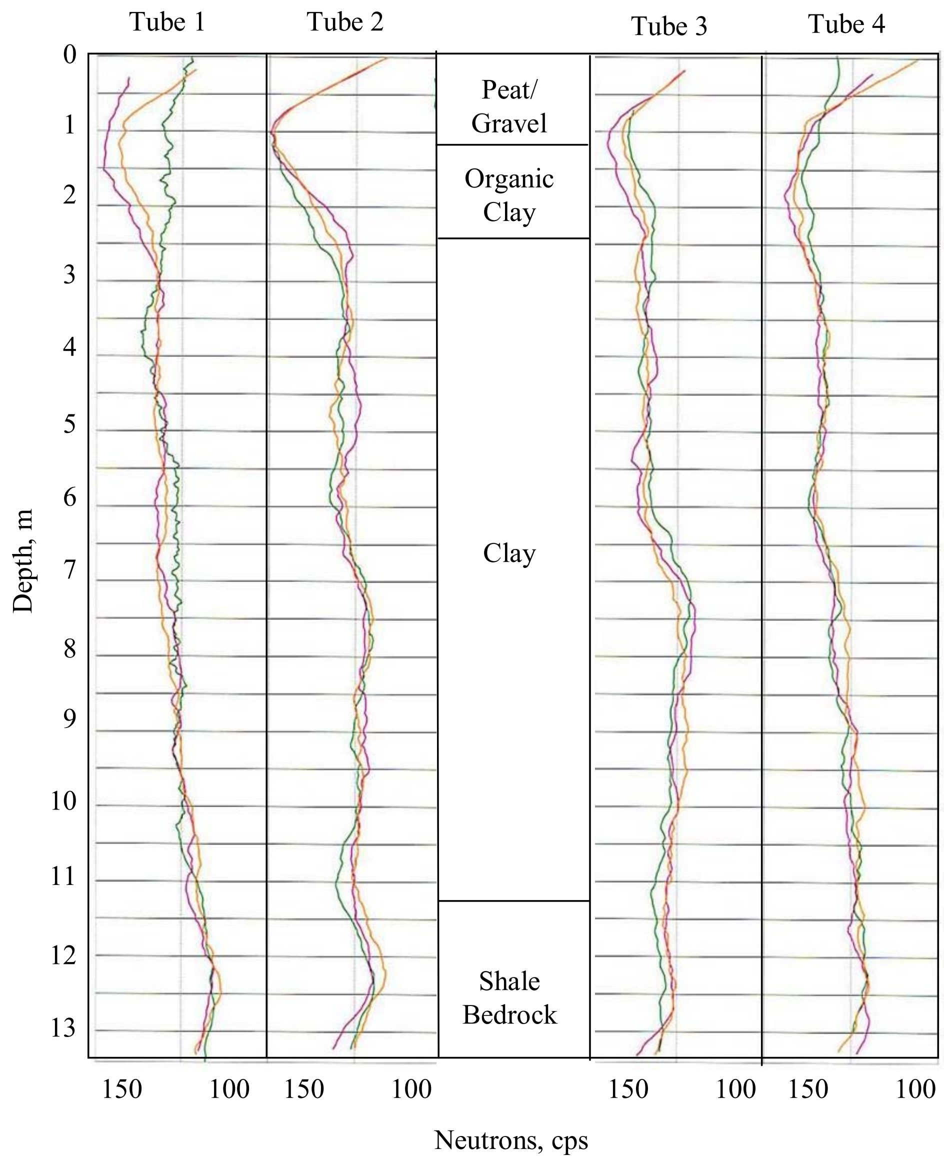

Figure 3.18 NML Moisture Monitoring of P2-S2- at 2 days (Green), 3 days (Purple), and 4 days (Orange) After Concrete Placement