Highway Structure Stabilizing Through Convection Pipe Cooling (CPC)

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ABSTRACT
An experimental research site has been constructed in the Northwest Territories to examine the efficacy of long, narrow, hollow pipes inserted into the ground as a cooling mechanism to stabilize permafrost. The pipes were installed in four different ways in order to achieve a broader picture of the mechanisms at work. The resulting ground temperatures over the winter months are presented. Promising results have been obtained.

RÉSUMÉ
Un site de recherche expérimental a été construit dans les Territoires du Nord-Ouest afin d'étudier l'efficacité de tuyaux creux, longs et étroits insérés dans le sol comme mécanisme de refroidissement pour stabiliser le pergélisol. Les tuyaux ont été installés de quatre façons différentes afin de déterminer leur mécanisme de fonctionnement. Les résultats du suivi des températures du sol au cours des mois d'hiver sont présentés dans cet article. Des résultats prometteurs ont été obtenus.

1 INTRODUCTION

Permafrost underlies about half of Canada's landmass and is a critical component of Canada. Although the permafrost regions are not densely populated, their economic importance has increased considerably in recent decades because of the abundant natural resources in the north circumpolar region and improved methods of extraction and transportation to population centers. Economic development has brought expansion of the human infrastructure (Hunter, 2003).

Roads and other transportation infrastructure are of vital economic, social, and political importance in Canadian permafrost regions. The stability of road foundation systems, or embankments, in many Canadian northern communities relies on the strength of the underlying permafrost. Road embankment stability, thermal stability, and hydraulic drainage design within permafrost terrain are all inter-related design, construction, operation, and maintenance issues which require coordinated, dynamic, innovative engineering solutions. Most northern construction projects are subject to continuous or extensive discontinuous permafrost conditions. The degradation of permafrost resulting from ground disturbance and/or climate change has been negatively affecting both embankment and subgrade stability in northern Canada, increasing maintenance costs of the roads and decreasing their useful life span. This poses a significant challenge since feasible highway systems are required for sustainable economic growth.

There currently exist numerous methods to stabilize permafrost. Passive systems are effective methods for permafrost stabilization. Most passive systems rely on convection as the predominant cooling mechanism. Thermosiphons and air convection ducts have proven to be effective passive permafrost cooling systems. These systems are, however, time consuming and costly to install; the use of these systems along any sizeable length of highway would likely prohibitively increase the cost of construction. Therefore, significant research and development efforts continue to be devoted to finding alternative techniques for mitigating permafrost degradation, and to properly and cost-effectively design roads in the warming Canadian North.

The *Department of Transportation* in the Northwest Territories has teamed up with the *University of Ottawa*, *GeoStabilization International*, and *Terratech Consulting* to develop a new method of permafrost stabilization henceforth referred to as convection pipe cooling (CPC). An experimental CPC test site was constructed in Yellowknife. The objectives of this paper are to present:

- The developed CPC method
- The constructed test site
- The preliminary monitoring results of the temperature evolution at the test site

2 SITE DESCRIPTION

The experimental test site is located in the city of Yellowknife. Figure 1 shows the geographical location of the site. Yellowknife is characterized by a continental climate with short, dry, cool summers. According to the meteorological data, the temperature can typically vary from -29°C to 21°C over the course of a year. The cold season goes from November to March with an average daily high temperature below -13°C. Figure 2 illustrates the daily average low and high temperature in Yellowknife.

Figure 1. Location of the test site in Yellowknife

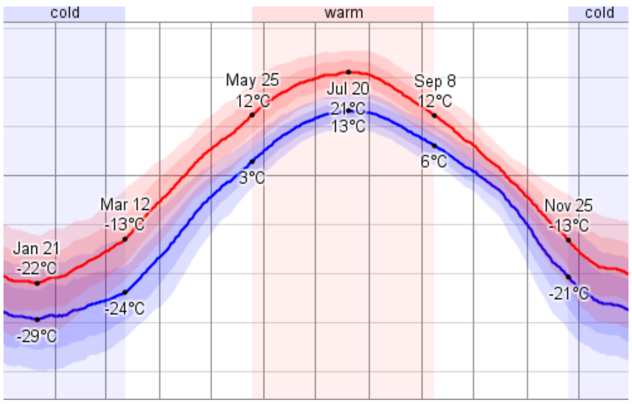

Figure 2. The daily average low (blue) and high (red) temperature with percentile bands in Yellowknife (source: WeatherSpark, 2015)

The ground of the test site is comprised mostly of a silty-clay soil.

3 CONVECTION COOLING PIPE DESCRIPTION

The convection cooling pipe (CPC) method involves installing long, narrow, steel pipes vertically or sub-vertically into the ground. The pipes facilitate passive convection as the cooling mechanism. The top end of the pipes is covered with clean blast rock. The rock forms an air convection embankment (ACE). The ACE is an effective method used to lower embankment temperatures. The CPC method takes advantage of airflow within the ACE to drive the cooling effect below the road structure, deep into the subgrade. Frozen conditions deep below the structure will eliminate the risk of consolidation and differential settlement.

Convection through the pipes will shorten the travel distance for heat to escape from the ground, in a similar manner to how wick drains expedite embankment dewatering. Refer to Figure 15 for a diagram detailing the cooling mechanism of the CPC method.

A key aspect of the CPC method is the practicality of it; it is logistically and economically feasible. The system takes advantage of standard practices in highway design and construction. The pipes are installed using proprietary technology; a compressed air launcher, seen in Figure 3, can install hundreds of these pipes in a day. The rapid installation speed reduces construction time to a fraction of normal rates. These time savings are directly translated to cost savings. In addition, there is no above ground infrastructure to pose safety and aesthetic risks.

Figure 3. A compressed air launcher (GSI, 2015) greatly increases the installation speed of the CPC pipes over conventional drill and install methods.

4 FIELD INVESTIGATIONS

An outdoor experimental test site has been completed in Yellowknife. The experiment is providing quantitative insight into the following aspects of the CPC method: 1] the ability of open-ended, narrow pipes to facilitate convection cooling below the ground surface; 2] the effect of a secondary air passage channel by the insertion of a smaller diameter tube within the convection pipe; 3] the effect of installing the convection pipes at various angles to the vertical; and 4] the thermal gradient effect of the convection pipes. Comprehensive temperature monitoring and soil sampling programs have been conducted. The constructed test site, ongoing monitoring, and soil sampling programs are briefly described below.

4.1 Constructed Test Site

The following photos (Figures 4 to 14) were taken throughout the construction of the test site:

Figure 4. PEX pipes to contain the thermistor strings are attached to the 6 m long steel pipes.

Figure 5. The attached steel and PEX pipes are placed into the predrilled hole.

Figure 6. All convection pipes and thermistor string holders have been placed to a depth of 6 m below the original ground surface. ACE construction begins.

Figure 7. ACE construction continues.

Figure 8. Holes are drilled in the bottom of the tremie tube (described in section 4.2) to facilitate the second airway.

Figure 9. The tremie tube has been inserted in the steel pipe. The PEX pipe to contain the thermistor string is seen alongside. A larger PVC pipe protects the system.

Figure 10. Each of the thermistor strings are prepared for insertion by protecting the exposed wiring, and locking the PVC cap into the correct position.

Figure 11. The thermistor string is fed into the PEX pipe, alongside the steel convection pipe.

Figure 12. The white PVC manifold contains and protects the thermistor strings.

Figure 13. A plywood roof is constructed over the system to protect against precipitation entering the convection pipes during testing.

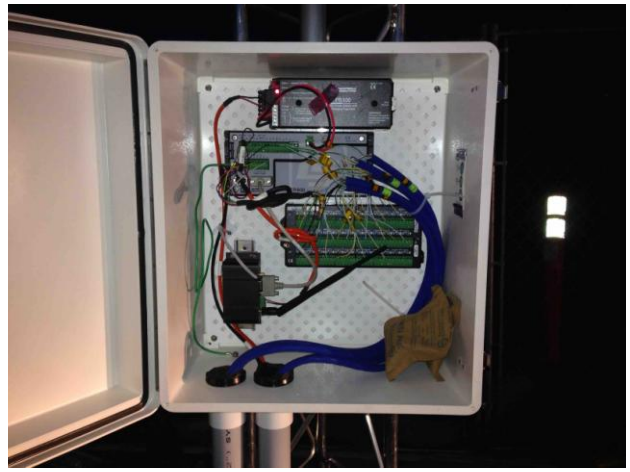

Figure 14. All thermistor strings feed into the datalogger contained in a fiberglass enclosure on site.

Figure 15 shows a cross section of the test site at point T4 in Figure 16. The cold air enters the CPC through the air convection embankment (ACE). The cold air in the pipe warms as it absorbs heat from the ground, and then exits the system through convection. As it exits, more cold air is brought in to replace it, and the cycle continues. The cross section is not to scale.

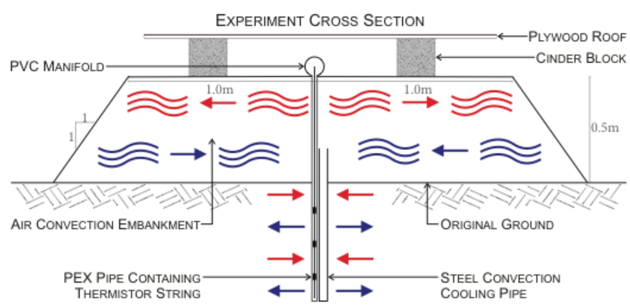

Figure 15. Experiment cross section at point T4.

4.2 Field Monitoring Program

The field monitoring program uses five (5) thermistor strings to record ground temperatures (Figure 16). Each thermistor string contains six (6) temperature probes spaced 1 m apart. The temperature probe reads ground temperatures with an accuracy of ±0.10 ºC. Each temperature probe delivers a reading every minute. The data logger takes the readings and outputs the maximum, minimum, and average temperatures every hour. Four (4) steel pipes were installed at the test site. All steel pipes had an outside diameter of 40 mm and a length of 6 m. The pipes were sealed on the bottom end to prevent water infiltration (Figure 4).

At point T4 on Figure 16 a steel pipe was installed vertically. A thermistor string was installed along the pipe. The first probe is located at 0.1 m below the ground surface, and the last of six (6) probes is located at 5.1 m below the ground surface.

At point T3 a steel pipe was installed vertically, with a 12.5 mm diameter PEX tremie tube placed within it. The tremie tube is perforated in increments along the bottom

0.6 m. The tremie tube is used to allow for a secondary air passage channel. The thermistor string is installed along the steel pipe in the same manner as at point T4.

At point T2 a steel pipe is installed at 15º off the vertical. This was done to examine the effects of a moderate incline on the pipe. The thermistor string is installed along the steel pipe in the same manner as at point T4.

At point T1 a steel pipe is installed at 40º off the vertical. This was done to examine the effects of a steep incline on the pipe. The temperature string is installed along the steel pipe in the same manner as at point T4.

Points T4, T3, T2, and T1 are all spaced 1.5 m apart.

Points P2 and P3 contain a placeholder PEX pipe for a thermistor string. They do not contain steel convection pipes. P2 and P3 were installed to examine the gradient cooling effect of the convection pipes.

At point T5 a thermistor string is installed vertically to record ground temperatures away from the CPC system in order to establish baseline readings.

All thermistor strings are installed inside a 25 mm diameter PEX tube. The tube was then filled with silicone fluid. The silicone fluid [1] allows the temperature probes to provide more accurate readings, [2] prevents water infiltration and freezing, [3] allows the temperature strings to be removed and replaced if necessary.

All thermistor strings feed back to a data logger that records the readings every minute. An ambient temperature probe with a solar radiation shield was also installed at the test site to record air temperatures every minute.

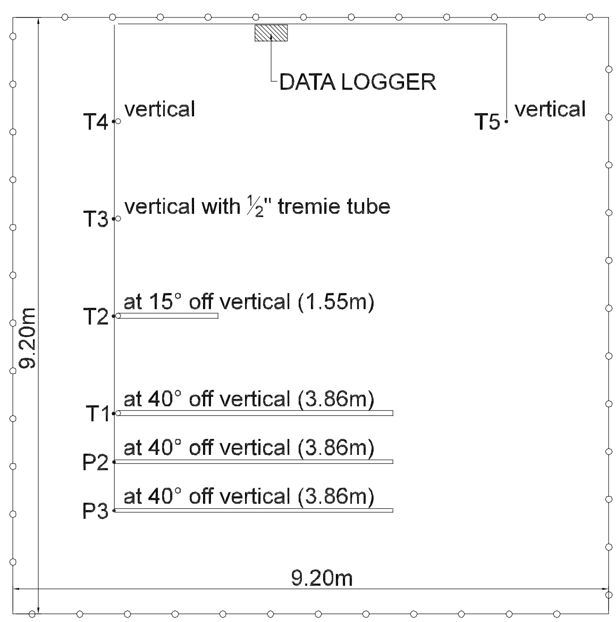

Figure 16. Plan view of the field monitoring program site.

4.3 Soil Sampling

During the drilling program to install the steel and PEX piping, soil samples were taken. These samples are being used to determine relevant soil properties, such as thermal conductivity, thermal diffusivity, soil density, soil water content, soil permeability, chemical composition of the pore water, grain size distribution, and plasticity. These properties will be used during numerical modeling and to analyze of the performance of CPC method with respect the thermal stability of the embankment and subgrade.

5 RESULTS AND DISCUSSION

These readings were plotted on time versus temperature graphs. Temperature versus depth graphs were also developed to compare the initial temperature readings to the latest readings, at depth. The results are shown below.

5.1 Vertical CPC Time versus Temperature Plots

Figures 17 and 18 show the ground temperature changes at various depths without CPC and with CPC, respectively. Figure 19 depicts a comparison of the aforementioned temperature changes. On February 5th the temperature recorded at a depth of 0.1 m was approximately -15.4 C with CPC, whereas a value of -8.1 C was measured without CPC. This suggests that the CPC is effectively contributing to decrease the temperature in the ground. At the start of April the ground temperatures for the first two probes (0.1 m and 1.1 m depths) with and without CPC begin to converge. This stands to reason as the probes are relatively close to the ground surface and will be subject to atmospheric temperature changes.

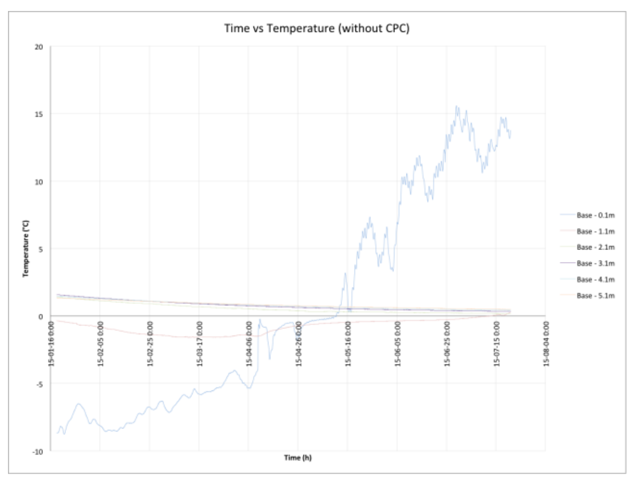

Figure 17. Time vs Temperature plot without CPC.

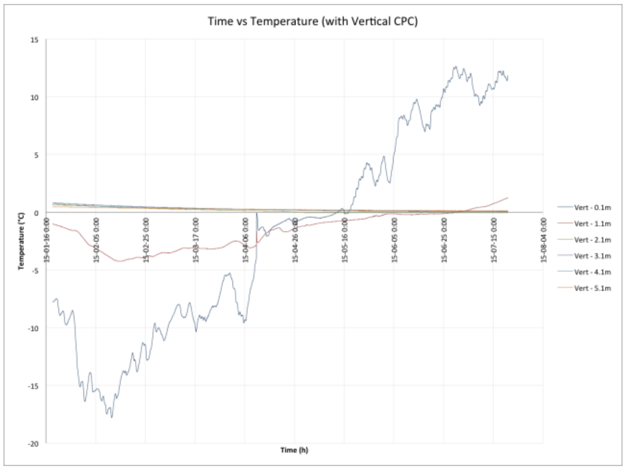

Figure 18. Time vs Temperature plot with Vertical CPC.

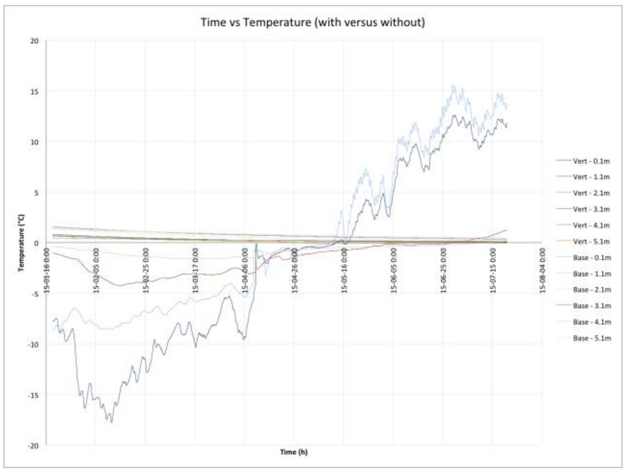

Figure 19. Time vs Temperature plot comparison.

5.2 Vertical-Tremie Tube CPC Time versus Temperature Plots

Figures 20 and 21 show the ground temperature changes at various depths without CPC and with CPC, respectively. Figure 22 depicts a comparison of the aforementioned temperature changes. On February 15th the temperature recorded at a depth of 1.1 m was approximately -4.9 C with CPC, whereas a value of -1.2 C was measured without CPC. This suggests that the CPC is effectively contributing to decrease the temperature in the ground. At the start of April the ground temperatures for the first two probes (0.1 m and 1.1 m depths) with and without CPC begin to converge. This stands to reason as the probes are relatively close to the ground surface and will be subject to atmospheric temperature changes.

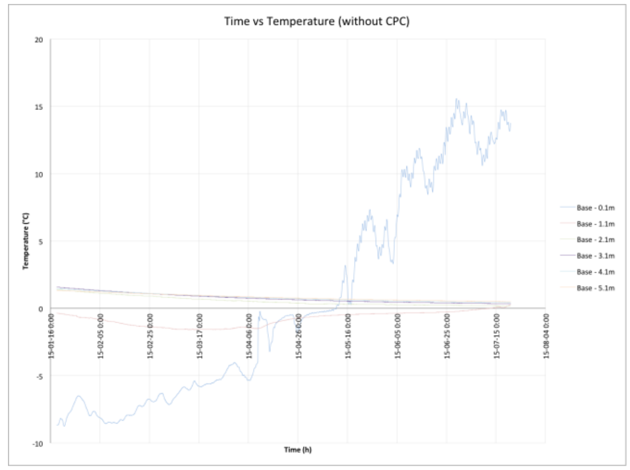

Figure 20. Time vs Temperature plot without CPC.

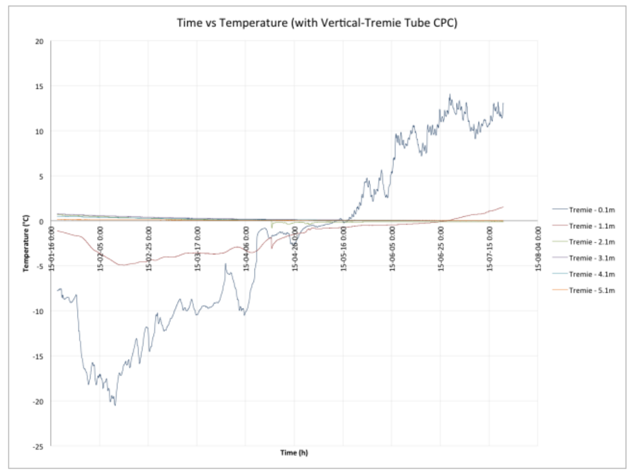

Figure 21. Time vs Temperature plot with Vertical-Tremie Tube CPC

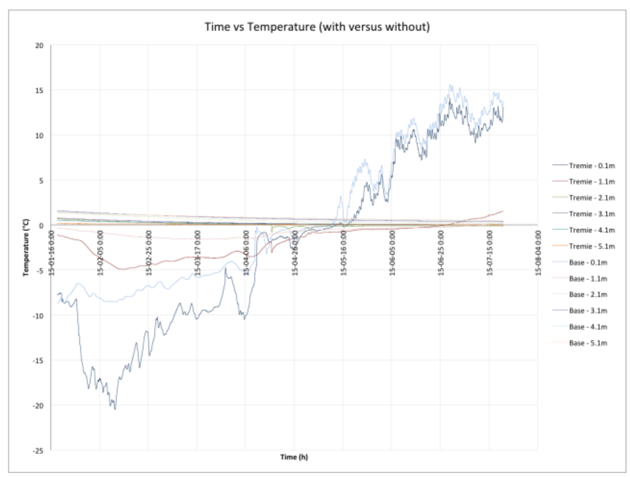

Figure 22. Time vs Temperature plot comparison.

5.3 15º CPC Time versus Temperature Plots

Figures 23 and 24 illustrate the ground temperature changes at various depths without CPC and with CPC, respectively. A comparison of the aforementioned temperature changes is shown in Figure 25. It can be again noted that the ground temperatures with CPC are lower than those without. At the start of April the ground temperatures for the first two probes (0.1 m and 1.1 m depths) with and without CPC begin to converge. This stands to reason as the probes are relatively close to the ground surface and will be subject to atmospheric temperature changes.

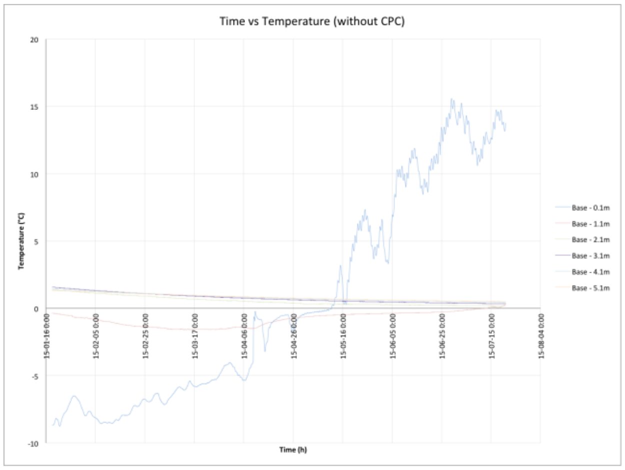

Figure 23. Time vs Temperature plot without CPC.

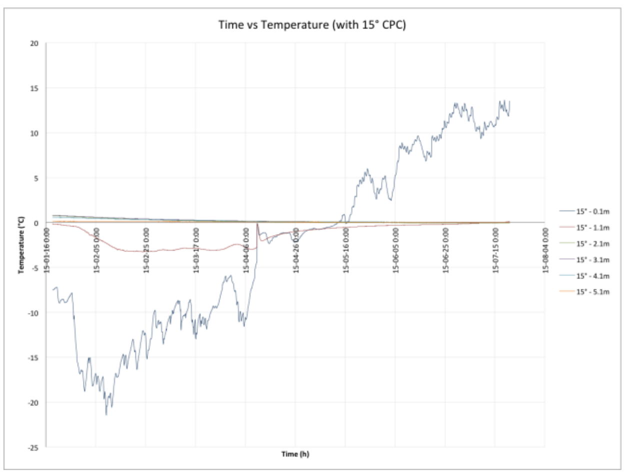

Figure 24. Time vs Temperature plot with 15º CPC.

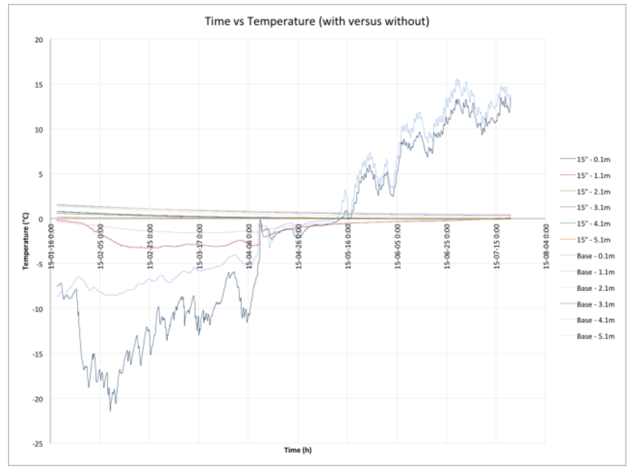

Figure 25. Time vs Temperature plot comparison.

5.4 40º CPC Time versus Temperature Plots

Figures 26 and 27 depict the ground temperature changes at various depths without CPC and with CPC, respectively. Figure 28 show a comparison of the aforementioned temperature changes. The results presented in these figures indicate that the CPC contributed to ground cooling in the colder months. At the start of April the ground temperatures for the first two probes (0.1 m and 1.1 m depths) with and without CPC begin to converge. In May the first two temperature probes below the ground surface monitoring the CPC system began to show higher temperatures than their baseline counterparts. This may be due to the geometry; since the CPC system is at a 40º angle to the vertical, the probes are 23% higher to the ground, which has a significant effect on atmospheric temperature penetration.

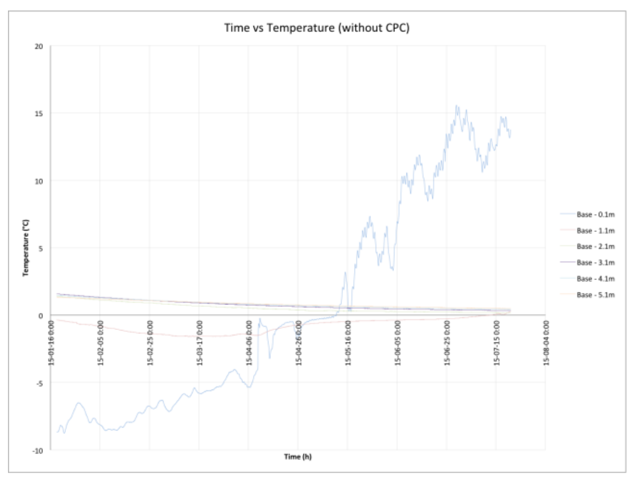

Figure 26. Time vs Temperature plot without CPC.

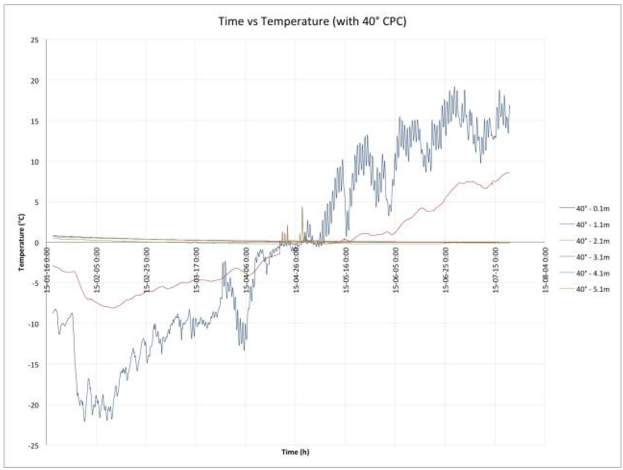

Figure 27. Time vs Temperature plot with 40º CPC.

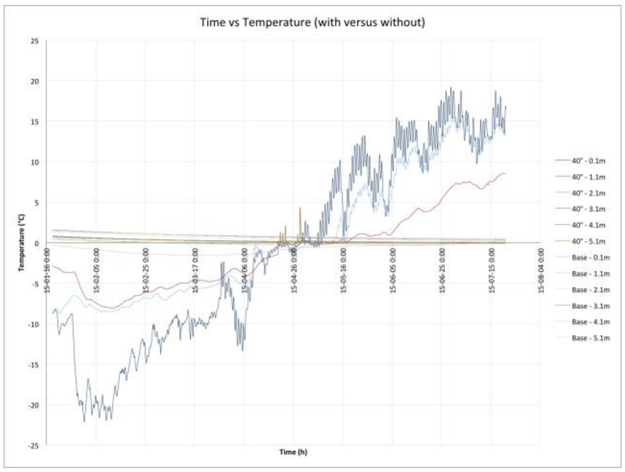

Figure 28. Time vs Temperature plot comparison.

5.5 Temperature versus Depth Plots

Figures 29-31 show a universal decrease in soil temperature around the convection cooling pipes, as compared to the baseline data.

More drastic temperature fluctuations are noticeable in the first two temperature probes below ground level. This indicates that conduction contributes to the change in ground temperatures up to 1-2 m below the ground surface. The depth of ground cover over these probes will also play a role in the significant temperature flux. Upon further geotechnical investigation, these differences will be quantified.

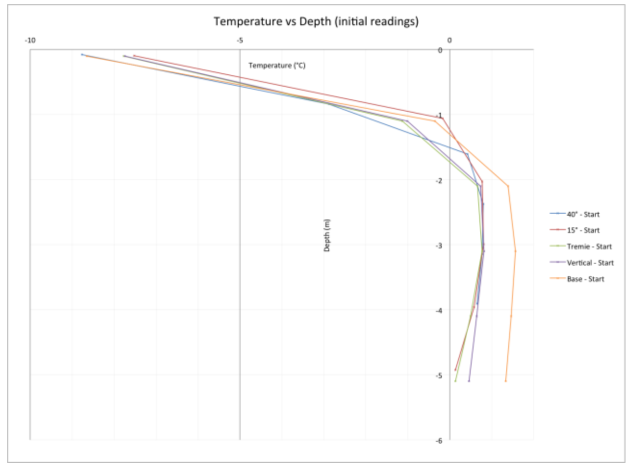

Figure 29. Temperature vs Depth plot of the initial readings.

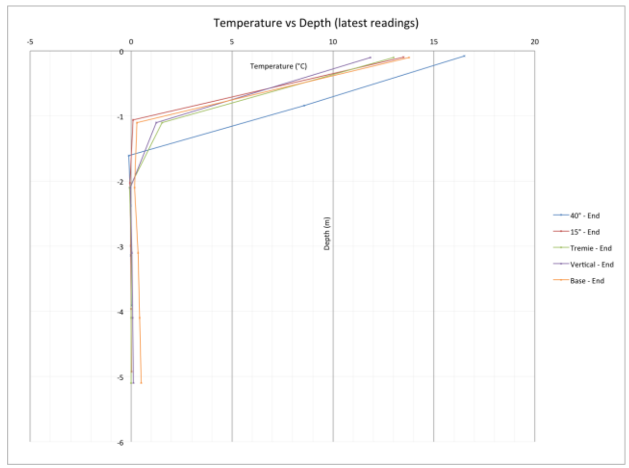

Figure 30. Temperature vs Depth plot of the latest readings.

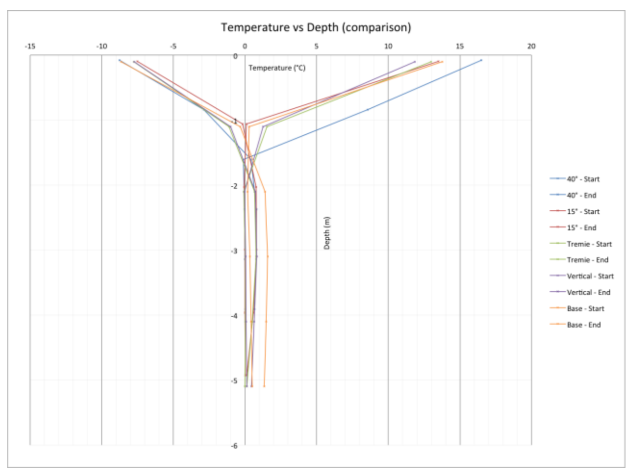

Figure 31. Temperature vs Depth plot comparing the initial and latest readings.

6 CONCLUSIONS

This paper has presented the preliminary results of the field performance of a novel technique consisting of an effective combination of two heat extraction systems to lower ground temperature and ensure road embankment stability. A heat extraction system using air convection in a low road embankment made of clean coarse aggregate is combined with a heat extraction system using vertical and sub-vertical convection cooling pipes that are inserted in the underlying ground. This approach is in contrast with conventional methods used in the North such as the air convection high embankment approach and thermosyphons. The obtained preliminary results of the convection pipe cooling (CPC) method are promising. Further data collection is still required to obtain a more complete view of the mechanisms at work. The system will be reconfigured in the fall to examine the gradient cooling effect. The experimental results will be used to validate the numerical model for the assessment of the thermal stability of road embankment equipped with CPC systems. Once the model has been calibrated, it can be used as the design tool for future implementation.

7 ACKNOWLEDGEMENTS

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