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Unique Thermosyphon Roadway Test Site Spanning 11 years

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ABSTRACT
Slope instability at the shoulders of roadways and settlement of embankments are common in permafrost areas. A test site incorporating three types of thermosyphons was installed at the Chena Hot Springs Road, northeast of Fairbanks, Alaska in 1998 with the objective to develop and improve the use of thermosyphons for roadways. Eleven years following the installation, the permafrost temperatures have decreased by up to 3 ºC. This study validates the use of thermosyphons for reducing or eliminating thaw settlement of roadways.

RÉSUMÉ
Instabilité des versants à l'accotements et tassement des remblais sont fréquents dans les zones de pergélisol. Un site de test comportant trois types de thermosiphons a été installé à la Route Chena Hot Springs, au nord de Fairbanks, en Alaska en 1998 avec l'objectif de développer et d'améliorer l'utilisation de thermosiphons pour les routes. Onze ans après l'installation, la température du pergélisol ont diminué de près de 3 ºC. Cette étude valide l'utilisation de thermosiphons pour réduire ou éliminer tassement dû au dégel des chaussées.

1 INTRODUCTION

Constructing roads over ice-rich discontinuous permafrost generally results in thaw settlement of the underlying ice-rich soils. Thermosyphons and air convection embankments are two methods that have been used to reduce embankment and foundation soil temperatures in order to reduce or eliminate thaw settlement (Forsstrom et al., 2002; Wen et al., 2005; Xu and Goering, 2008).

Thermosyphons are passive pressurized heat transfer devices that have been used for foundation stabilization in continuous and discontinuous permafrost areas since 1960. The best known installation of thermosyphons is on the Trans-Alaska Pipeline where over 124,300 units were installed (Heuer, 1979). Thermosyphons are sealed pipes charged with a working fluid. They operate by vaporization of the working fluid at the lower end, the evaporator, and condensation of the working fluid at the upper end, the condenser. Thermosyphons function, without external power and whenever the ground temperature is warmer than the ambient air temperature. Presently, carbon dioxide (CO_2) is the most commonly used working fluid; however the thermosyphons on the Trans Alaska Pipeline and the Qinghai-Xizang railway were charged with anhydrous ammonia.

An installation for demonstrating three new types of thermosyphons was completed in November 1998. The installation was done to demonstrate two previously developed thermosyphons that would operate with level as well as undulating evaporator sections and a totally buried system that would be unobtrusive to traffic and maintenance operations. Development and initial testing of these thermosyphons was funded by the Alaska Science and Technology Foundations (ASTF) and carried out as a joint project by staffs from Arctic Foundations Inc. (AFI), Cold Regions Research and Engineering (CRREL), and University of Alaska Fairbanks (UAF). The demonstration project was funded by the Experimental Features Program of the Federal Highways Administration (FHWA) in conjunction with the Alaska Department of Transportation and Public Facilities (AKDOT&PF). All thermosyphons tested and installed were manufactured by Arctic Foundations Inc. of Anchorage, Alaska. This paper examines the evolution of the ground thermal regime beneath a highway test section over an 11 year period in order to evaluate the effectiveness of different thermosyphon types reducing thaw penetration and settlement.

2 METHODS

2.1 Test Site

The test site is located in a valley with wetlands and underlying permafrost at mile 4.5, Chena Hot Springs Road, northeast of Fairbanks, Alaska (see Figure 1). The permafrost below the roadway embankment was thermally degrading prior to the installation of the demonstration project. Each type of thermosyphon was installed in a separate section with each section having a total length of 20 m (see layout in Figure 2).

Sixteen UAF/CRREL single-pipe thermosyphons were installed 2.4 m on center in the first section and have 2.4 m long finned condenser sections with fin areas of 6.5 m^2. The buried single-pipe evaporators with an outside diameter of 65 mm are 12.8 m in length on the south side of the road and 14.0 m in length on the north side of the road. Internal condensate collector and piping were used to ensure condensate return to the far end of the evaporator section. A "burper" section was also incorporated to eliminate vapor locking.

Figure 1. Map of Alaska.

Twelve Arctic Foundation Inc. (AFI) flat loop evaporator thermosyphons were installed in the second section. The evaporator piping for these units are 20 mm outside diameter forming horizontal grids 2.7 m wide by 12.2 m or 14.2 m long. Each of the vertical condenser sections has a nominal outside diameter of 80 mm, is 4.9 m in length with a finned area of 15.8 m^2.

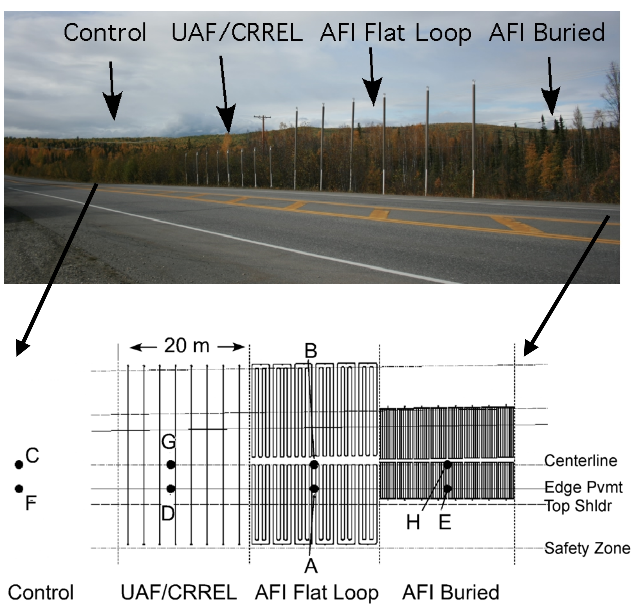

Figure 2. Layout of the installation including the control section, the UAF/CRREL section, the AFI Flat loop section, and the AFI Buried section. Four thermistor strings are located at the center of the roadway (C, G, B, H) and four strings at the edge of the pavement (F, D, A, and E).

Sixteen AFI thermosyphons were installed in the third section with totally buried evaporator and condenser sections. The 6.4 m long evaporators were installed vertically at the edge of the pavement and the condensers were installed horizontally just beneath the pavement and above the insulation. The 40 mm diameter condensers were placed in the non-frost-susceptible (NFS) fill, 0.3 m below the roadway surface and 0.6 m above the insulation. The condenser grids were 2.3 m wide by 5.5 m or 7.7 m in length. Rather than have a condenser section exposed to ambient air, these condenser sections are cooled by placement just below the bottom of the pavement. This results in warming of the pavement above the condensers and has the secondary benefit of sublimation of frost from the roadway surface.

2.2 Soil Properties

Soil samples at the site were taken from the eight thermistor string locations prior to the installation (see A, B, C, D, E, F, G, and H in Figure 2). In-situ soil properties from these locations are presented in Table 1.

Table 1. Characteristics of soils and construction materials. ρ_d= dry density in kg/m^3, and w=gravimetric water content in %.

Material	ρ_d (kg/m^3)	w (%)
Asphalt	2,210	0
Crushed aggregate	2,210	5
Type A (Sandy Gravel)	2,210	2, 5, or 11.3
Insulation (expanded polystyrene)	48	0
Silt (3 – 4.5 m depth)	1,300	35
Silt (4.5 – 6 m depth)	1,170	42.5
Silt (6 – 10.5 m depth)	1,010	55

A cross section of the installation is shown in Figure 3. Type A material (Sandy Gravel) was used as the bedding beneath and filling above the thermosyphons. The evaporators of the UAF/CRREL and the AFI flat units were installed horizontally on compacted and graded material at a depth of 1.4 m below the paved surface. A layer of 0.4 m type A material was placed above the thermosyphon evaporators followed by a 100 mm thick insulation and a 0.8 m thick layer of type A material. The roadway was finished with a 0.1 m thick crushed aggregate and a 38 mm layer of bituminous concrete pavement on top. The gravimetric moisture content of the gravel fill ranged from 5 to 11.3 % (see Figure 3 and Table 1). A Washington-Dens-O-Meter was used for field density tests and showed compactions ranging from 101% to 97% relative to the 95% compaction specification. Two layers of 50 mm thick expanded polystyrene (EPS) board stock was used as insulation at a depth of 0.9 m below the road surface. Thermal conductivity listed by the manufacturer was 0.029 – 0.031 W/m°C with compressive strength specified to be at least 276 kPa at 10 % deflection.

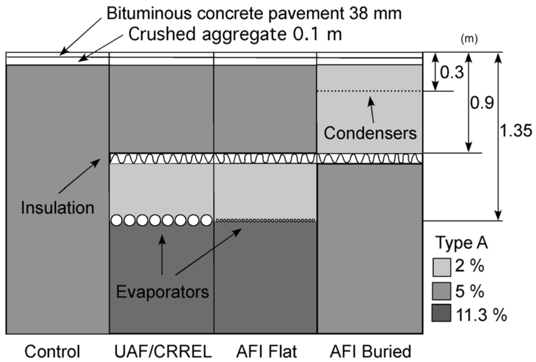

Figure 3. Cross section of the roadway installation. The gray scale illustrates water contents ranging from 2 % (light gray) 11.3 % (dark gray).

2.3 Monitoring

Eight thermistor strings (Alpha Thermistor part number 07A001-D3) were fabricated by UAF and installed vertically at the eight locations shown in Figure 2. Each thermistor string has six thermistors placed at 1.4 m, 2.0 m, 3.2 m, 4.7 m, 6.6 m, and 8.7 m below the pavement surface. The distance between the strings installed at the roadway centerline to the strings installed at the edge of pavement is 7.9 m. Measurements were recorded with a Campbell Scientific CR10X-1M-XR data logger from the start of the installation in November 1998 through January 2002. From September 2009 through the current date, data are recorded with a Campbell Scientific CR1000. In addition manual measurements were collected on June 1, 2006, September 10, 2009 and May 12, 2010.

3 RESULTS

Ground temperatures were measured continuously from the start of the installation in fall of 1998 for just over three years until measurements were discontinued in January 2002. The ground temperature measurements at the center of the roadway and edge of the pavement for the period of November 1998 – January 2002 are shown in Figures 4 and 5, respectively. Unfortunately the logger malfunctioned season of 2009 – 2010 resulting in that only manual measurements for June 1, 2006, September 10, 2009 and May 12, 2010 could be recovered. Whiplash curves for these dates and for 2000 are shown in Figures 6 and 7.

3.1 Control Section

At the center of the roadway the depth to the top of the permafrost remained relatively constant at a depth of 4.4 m for the first three years. In the winter, the -0.5 ºC isotherm also remained at a constant depth of 4.4 m during the first three years of operation. The permafrost temperature at this section of the roadway is warm (between 0 and -0.5 ºC).

At the edge of the pavement the maximum thaw ranged between 6.3 and 8.3 m for the first three years of operation. During the winter the -0.5 ºC isotherm is at about 4.5 m for the first three years of operation.

3.2 UAF/CRREL Units

The depth of maximum thaw decreased from 4.2 m to 2.6 m at the center of the roadway after one year of thermosyphon operation. After three years this depth was at 2.3 m. The depth of the -0.5 ºC isotherm increased by 3 m (from 4.6 to 7.4 m) in the winter. The permafrost temperature at deeper depths (below 4 m) has decreased at this location by about 0.5 ºC.

The maximum thaw depth decreased by more than 6 m at the edge of the pavement. The -0.5 ºC isotherm during winter decreased from 2.9 to 4.5 m.

3.3 AFI Flat Loop Units

The depth of maximum thaw decreased to about 2.5 m at the center of the roadway. The depth of the -0.5 ºC isotherm increased to about 4 m in the winter. The permafrost temperature at deeper depths (below 3.5 m) has decreased at this location by about 0.5 ºC.

At the edge of the pavement the maximum thaw decreased with 6.6 m after three years of operation. The depth of the -0.5 ºC decreased each year (from 4.3 to 6 m) during winter operation.

3.4 AFI Buried Units

Maximum thaw varied somewhat during the first three years of operation but did not change much from the original thaw depth. In the winter this was also true for the depth of the -0.5 ºC isotherm.

The edge of the pavement of this section of the roadway was not located in permafrost at the time of installation. During the first winter of operation the freeze depth was at 8.6 m and the two following winters the -0.5 ºC isotherm was located at a depth of 8.4 m. After one year of installation the maximum thaw depth was at 2.8 m. The temperatures below freezing in fall 1999 (compared to above freezing in fall 1998) implies that the permafrost degradation was reversed.

3.5 Whiplash Curves

The cooling effect of the thermosyphons from the start of operation and eleven years later are illustrated with whiplash curves in Figures 6 and 7. Data are not available for September after the first year of operation and therefore data from 2000 is shown in Figures 6 and 7 rather than 1999.

In general ground temperatures in September are lower at all sections compared to the control section (Figure 6). Ground temperatures below 4.7 m depth, in 2000, are slightly below freezing at all sections and similar to the temperatures at the control section. By September 2009, the ground temperature has decreased at all sections. The largest temperature difference compared to the control section is at the AFI flat loop section (-3 ºC) and the smallest is at the UAF/CRREL section (-1 ºC).

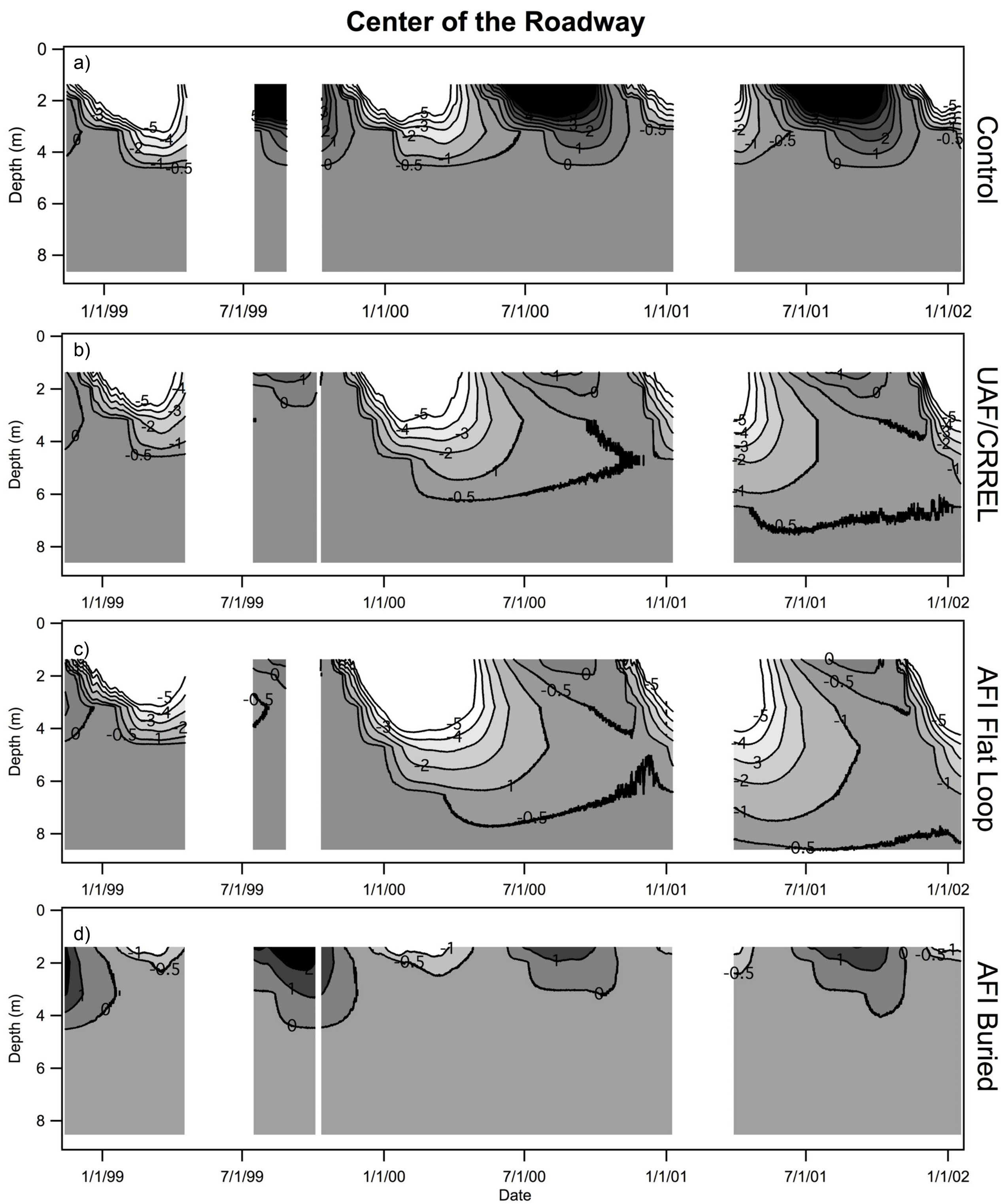

Figure 4. Center of the roadway ground temperature measurements from October 1998 to January 2002 at the a) control section, b) UAF/CRREL section, c) AFI flat loop section, and d) AFI buried section. The gray scale illustrates temperatures (ºC) ranging from warm (black) to cold (white). Temperature contours shown are: -5, -4, -3, -2, -1, -0.5, 0, 1, 2, 3, 4, and 5 ºC.

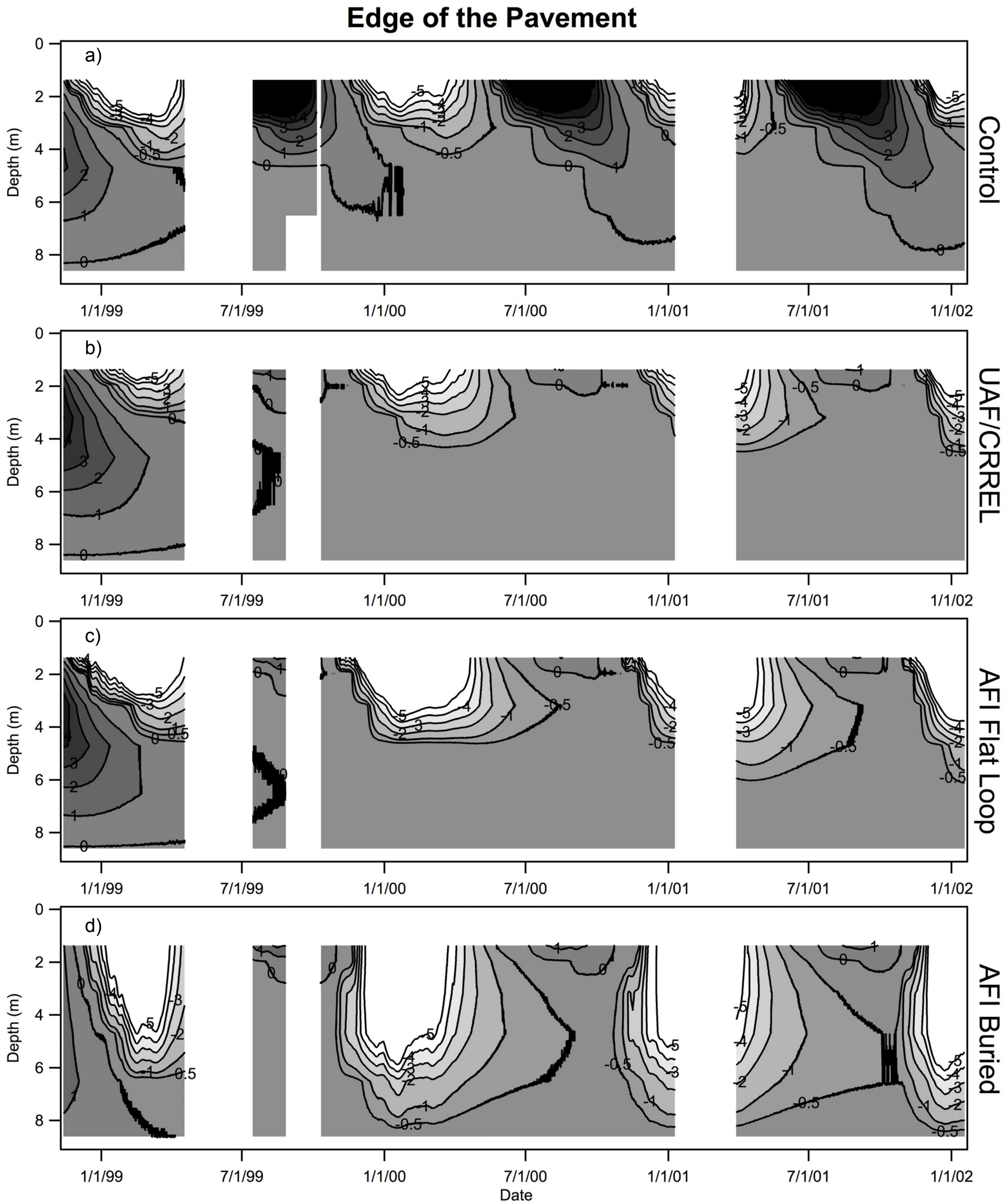

Figure 5. Edge of the pavement ground temperature measurements from October 1998 to January 2002 at the a) control section, b) UAF/CRREL section, c) AFI flat loop section, and d) AFI buried section. The gray scale illustrates temperatures (ºC) ranging from warm (black) to cold (white). Temperature contours shown are: -5, -4, -3, -2, -1, -0.5, 0, 1, 2, 3, 4, and 5 ºC.

At shallow depths there are only negligible temperature differences between September 2000 and 2009. When comparing these temperatures to the control section the temperature is about 7 to 9 ºC colder at all sections. This difference decreases to about 3 ºC at 3.2 m.

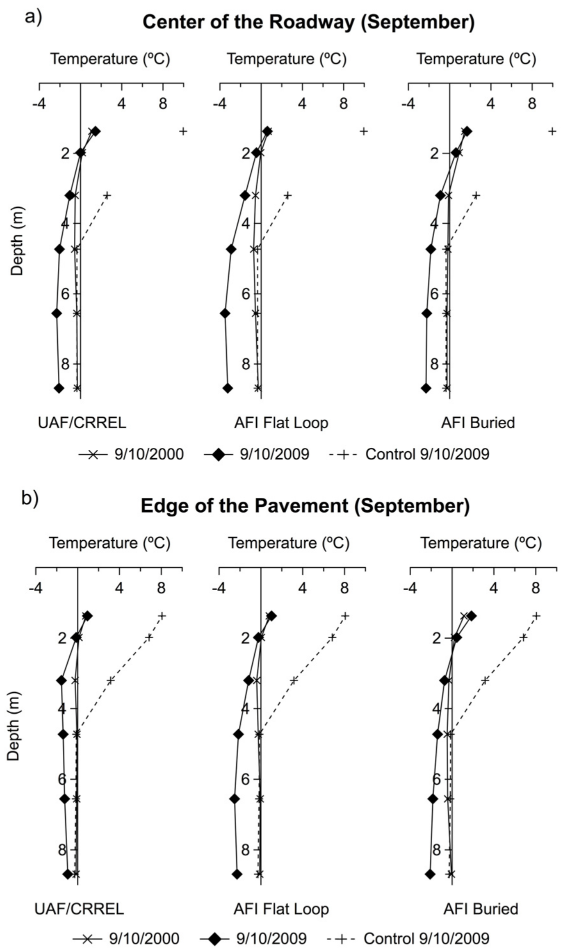

Figure 6. Whiplash curves on September 10 at a) the center of the roadway and at b) the edge of the pavement for years 2000 (solid cross) and 2009 (solid diamond). Dashed lines represent the temperature at the control section on September 10, 2009.

At the end of the winter all temperatures are colder than at the control section (Figure 7). At the center of the roadway the ground is frozen at shallow depths compared to unfrozen at the control section. In 2000, the temperature was 2 and 6 ºC colder at the AFI buried section and AFI Flat loop section respectively in 2000. This difference increased in 2009. The largest temperature difference was at the AFI flat loop section at a depth of 4.7 m where the temperature was 7 ºC colder than at the control section. At deeper depths the temperatures are similar as was measured in September.

The absolute accuracy of the temperature measurements may be plus or minus 0.2 °C. The author's experience with data from this site since before the test section was implemented leads us to believe that either some of the soils shown to be marginally frozen are right at 0 °C or there is something in this soil that is creating a depressed freezing point. Regardless, the temperature differentials between the control section and the test sections are great enough to validate the conclusions.

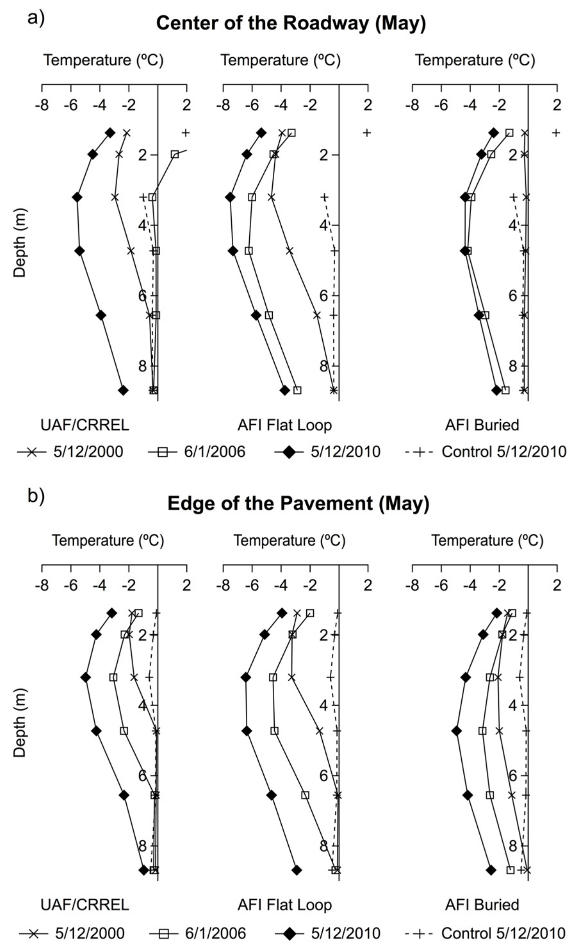

Figure 7. Whiplash curves on May 12 at a) the center of the roadway and at b) the edge of the pavement for years 2000 (solid cross), 2006 (open square) and 2009 (solid diamond). Dashed lines represent the temperature at the control section on May 12, 2010.

4 DISCUSSION

This study shows that the passive cooling systems investigated are operating effectively and can be used to prevent thaw settlement problems. It has also been shown that permafrost can be enhanced using thermosyphons in discontinuous permafrost locations.

At the three thermosyphon test sections the ground temperatures have decreased. Prior to the installation, the maximum thaw depth was at a depth of about 8.3 m. By 2009 this depth had decreased to about 2 m at all sections. The permafrost temperatures decreased by up to 3 ºC with greatest difference at the AFI flat loop unit. The larger fin area of the AFI flat units results in greater cooling capacity compared to the UAF/CRREL units. The AFI buried units were installed to cool the edge of embankment and therefore provide little cooling beneath the central portion of the roadway. Advantages of the buried thermosyphons are the non-visible condensers and the sublimation of frost from the pavement surface.

The average air freezing (FI) and thawing index (TI) for the duration of the operation have been approximately 2870 ºC-days and 2070 ºC-days respectively. This is similar to the last 30 years (see Figure 8) with FI and TI of 2830 and 2090 ºC-days respectively.

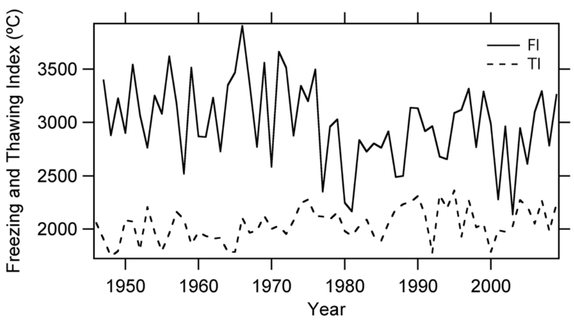

Figure 8. Average air freezing (solid) and thawing (dashed) index in Fairbanks.

Since the time of installation there has been some settlements and frost-jacking of the thermosyphons (see Figure 9a). The AFI Flat loop condenser on the south side is tilting with an angle of 3 to 4 º to the south and the units on the north side of the road is tilting with an angle of 1 to 2.5 º to the north (both with an outward angle from the road). These units are most likely settling. The UAF/CRREL units on the south side are tilting with an angle of 2.5 to 4.5 º to the north and the units on the north side are tilting with an angle of 0 to 2 º to the south (both with an inward angle to the road). These units are lighter and have most likely been frost-jacked. The condensers for the UAF/CRREL units and the AFI flat loop units were located out on the side slopes and near the toe of the roadway embankment to be clear of the safety zone required for the highway. In retrospect, the design of the test section should have included a more robust foundation for the condensers as permafrost degradation at the toe of the embankment is more certain than at the roadway centerline or shoulder. At a minimum, the embankment section including insulation should have been a few meters wider to help enhance the permafrost below the toe of embankment. There has also been a contraction crack formed in the pavement (Figure 9b) due to the effects of insulation. It is recommended that the insulation should be tapered to avoid this.

Prior to the thermosyphon installation regular maintenance of the roadway at the Chena Hot Springs Road was needed due to reoccurring thaw settlements. Since the installation, minor road maintenance of the test section has been needed (Potter, 2010). In comparison, a section at Chena Hot Springs Road (close to Bennett Rd) has required yearly maintenance to patch settlements. This section alone has an average yearly maintenance cost for AKDOT of approximately $20,000 – $30,000.

Figure 9 a) Evidence of settlement and frost jacking of thermosyphons and b) contraction crack in the pavement.

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