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Title: Backcalculation of Thermal Conductivity of Tire Chips from Instrumented Test Section

Authors: Dana N. Humphrey, Andrew J. Fiske, and Robert A. Eaton

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Backcalculation of Thermal Conductivity of Tire Chips from Instrumented Test Section

Dana N. Humphrey, Professor of Civil Engineering, University of Maine, 5711 Boardman Hall, Orono, ME 04469-5711; Phone: 207-581-2170; Fax: 207-581-3888; E-mail: dana.humphrey@umit.maine.edu

Andrew Fiske, Geotechnical Engineer, Geotechnical Services, Inc., 258 East 90th Street, Davenport, IA 52806; Phone: 563-285-8541; Fax: 563-285-8545; E-mail: andrew.fiske@umit.maine.edu

Robert A. Eaton, Research Civil Engineer, U.S. Army Corps of Engineers Cold Regions Research & Engineering Laboratory, 72 Lyme Road, Hanover, NH 03755-1290; Phone: 603-646-4209; Fax: 603-646-4820; E-mail: beaton@crrel41.crrel.usace.army.mil

Abstract. A field trial was constructed in Richmond, Maine, in 1992 to investigate the use of tire chips as insulation to reduce the depth of frost penetration beneath roads. The tire chip layer was either 152 mm or 305 mm thick. Thermocouples were used to measure subsurface temperatures. Tire chips reduced frost penetration between 6 and 20 percent, with the higher percent reductions occurring in colder winters. For sections with a 305-mm tire chip layer, the freezing front penetrated to the bottom of the tire chip layer by mid-January and then there was negligible additional penetration into underlying subgrade soils during the remainder of the winter. In contrast, in the control section the freezing front continued to penetrate deeper into the subgrade soils during the entire freezing season. The subsurface temperature data was used determine the insitu thermal conductivity of the tire chips ($K_{tire\text{-}chip}$). Using a method based on steady state conditions, it was estimated that $K_{tire\text{-}chip}$ was between 0.29 and 0.42 W/m·°C. These values were then used in the modified Berggren equation to calculate the depth of frost penetration. This showed that the calculated penetration was 11% greater than actual with the lower thermal conductivity and 14% greater with the higher thermal conductivity. It was recommended that a $K_{tire\text{-}chip}$ of 0.29 W/m·°C be used in conjunction with a volumetric heat capacity of 198 Cal/m^3·°C and a latent heat of fusion of 1152 Cal/m^3 for the tire chips.

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Dana N. Humphrey, Professor of Civil Engineering, University of Maine, 5711 Boardman Hall, Orono, ME 04469-5711; Phone: 207-581-2170; Fax: 207-581-3888; E-mail: dana.humphrey@umit.maine.edu

Andrew Fiske, Geotechnical Engineer, Geotechnical Services, Inc., 258 East 90th Street, Davenport, IA 52806; Phone: 563-285-8541; Fax: 563-285-8545; E-mail: andrew.fiske@umit.maine.edu

Robert A. Eaton, Research Civil Engineer, U.S. Army Corps of Engineers Cold Regions Research & Engineering Laboratory, 72 Lyme Road, Hanover, NH 03755-1290; Phone: 603-646-4209; Fax: 603-646-4820; E-mail: beaton@crrel41.crrel.usace.army.mil

INTRODUCTION

Frost penetrating into subgrade soils can lead to two problems in road performance. The first is nonuniform frost heaving, which can cause an uneven driving surface and cracking of the pavement. The second is loss of supporting capacity during the spring melt. This occurs when ice lenses in frost susceptible subgrade soils melt and release excess water that weakens the road support structure. This weakening causes premature failure of paved surfaces, and if the road is unpaved, it can cause severe rutting. These two problems significantly increase road maintenance costs in northern climates. A possible solution to these problems is to use insulation to limit frost penetration into the subgrade soils. A promising insulating material for roadway applications are tire chips or tire shreds. These are made from scrap tires and, for this application, generally have a maximum size of 50 to 75 mm. In addition to their insulating properties, they have the added advantage of having a high permeability, which helps to drain water out of the road cross section.

In 1992 a field trial to investigate the insulating properties of tire chips was built on Dingley Road in Richmond, Maine. This project was a cooperative effort between the U.S. Army Engineer Cold Regions Research and Engineering Laboratory, Town of Richmond, Maine, and the University of Maine. The project was extensively instrumented with thermocouples to monitor the depth of frost penetration. In addition, the support characteristics of the road surface were measured on a regular basis. The project was monitored for seven winters from 1992 through 1999. Data from the first two winters was assessed in several papers and reports (*1*,*2*,*3*,*4*,*5*,*6*). These initial evaluations showed that tire chips have significant insulating properties. In addition, the thermal conductivity of tire chips was measured in the laboratory (*6*). The purpose of this paper is to use the data from the entire monitoring period for the Richmond Field Trial to determine the thermal conductivity of tire chips for use in design of future projects. The following sections describe the project, present the air and subsurface temperature data, and use the data to determine the insitu thermal conductivity of the tire chips used for this project. Further details may be found in Fiske and Humphrey (*7*). An ongoing study is examining the effect of reduced frost heave and improved drainage on pavement durability.

PROJECT DESCRIPTION

The Richmond field trial was constructed on a dead-end gravel road in the Town of Richmond, Maine. Richmond is located approximately 63 kilometers northeast of Portland, Maine. The road is mainly traveled by cars, light trucks, and school buses, but occasionally 10 to 40 fully loaded double and triple-axle dump trucks travel the road in a single day to haul sludge to farms at the end of the road. Prior to reconstruction, the road was surfaced with about 460 mm of sandy gravel and gravely sand. Even with this thickness of granular soil, the road would become so badly rutted during the spring melt that it was difficult for cars to travel the road. The subgrade soils ranged from gray silty clay to gray-brown silty gravely sand and were highly frost susceptible. The water table in summer and fall was 1 to 3 m below the ground surface (*6*). The test site was 290 m long and was broken into eight sections. Five of these sections contained tire chip layers with thicknesses of either 152 or 305 mm covered by either 305, 457, or 610 mm of granular soil as summarized in Table 1. The other three sections consisted of one control section that had an additional 305 mm of granular base added to the surface of the existing road, and two sections of the original roadbed that were instrumented. In some sections, approximately 356 mm of the existing gravel surface was left in place under the reconstructed road. One of the two existing road sections (designated Station -0+78 m; -2+56 ft) was paved in 1995. In 1996, the remaining sections of the field trial were paved with 75 mm of bituminous concrete. A longitudinal section of the field trial is shown in Figure 1. A typical cross section is shown in Figure 2.

The tire chips were uniformly graded with a maximum size of 50 mm and less than 10 percent by weight passing the No. 4 (4.75 mm) sieve. Tire pieces with a maximum size between 12 and 50 mm are termed tire chips as compared to tire shreds which have a maximum size between 50 mm and 305 mm (*8*). Thus, the tire material used in this field trial is appropriately termed tire chips. The tire chips were made from a mixture of glass and steel belted tires. The gravel base below a depth of 100 mm consisted of a well graded mixture of gravel and sand with less than 5 percent passing the No.200 (0.075 mm) U.S.-standard sieve and a maximum particle size of 152 mm. The upper 100 mm of the gravel base had a maximum particle size of 25 mm and about 7 percent passing the No. 200 sieve. The common borrow located beneath the granular base in Section E was a gravely sand with about 3 percent passing the No. 200 sieve. This material was salvaged from the surface course of the existing road and had essentially the same properties as the granular base. Construction procedures are described in Humphrey and Eaton (*1*).

INSTRUMENTATION

The monitoring instrumentation consisted of thermocouples, resistivity gauges, groundwater monitoring wells, and frost-free benchmarks to use as reference points for heave surveys. Two vertical strings of thermocouples were installed in each test section, the control section, and two sections of the undisturbed existing road. Each string consists of twelve 20-gauge copper constantan thermocouples, whose vertical spacing vary from 75 mm near the road surface to 305 mm at greater depths. The deepest thermocouple in a section is typically about 1.8 m. A typical cross-section is shown in Figure 3. To maintain the desired spacing, the thermocouples were mounted on a 25-mm diameter wooden dowel, which was installed in a 125-mm diameter hole drilled with a trailer mounted power auger. After placing the string in the borehole, the hole was backfilled with native soil that was tamped in place with a hand tamper. The resistivity gages consisted of 25-mm diameter copper rings spaced 50 mm apart on an epoxy filled core. They were intended to measure the depth of frost penetration by the difference in resistivity of thawed and frozen soil. However, they proved to be unsuitable for the subgrade soils at this site and produced no useful readings. Results of the heave survey are given in (*5*).

FREEZING INDEX

Hourly air temperature measurements were used to determine the air freezing index and duration of the freezing season for each winter from 1992-93 through 1998-99. The calculation procedure is given in Gilman (*9*). The freezing index and duration of the freezing season for each winter is summarized in Table 2. The average duration of the freezing season was 95 days and the average freezing index was 470 ºC-days. The reported mean freezing index for the area is 472 ºC-days (*9*,*10*). Thus, during the seven-winter monitoring period, winters were, on average, typical for the region. However, the winters of 1992-93 through 1995-96 varied from slightly warmer than average to significantly colder than average, while the winters from 1996-97 through 1998-99 were warmer than average. Plots of average daily temperature versus date for each winter are given in Fiske and Humphrey (*7*). It should be noted that, the freezing index may not accurately represent the coldness of a winter that has alternating thawing periods followed by very cold periods. Nonetheless, there is no convenient alternative to using the freezing index to represent the coldness of a winter.

MEASURED FROST PENETRATION

The subsurface temperature measurements where used to determine the depth of frost penetration throughout the course of each winter. The first step was to average the hourly temperature measurements to create a daily average for each sensor. This canceled out small fluctuations in readings that were due to electronic noise. Then, for each vertical string of sensors, the depth of the 0ºC isotherm for each day was found by linear interpolation between the pair of sensors where the temperature passed from below freezing to above freezing. The 0ºC isotherm was taken to be the depth of frost penetration.

The maximum depth of frost penetration for each winter is summarized in Figure 4. Data was not available for the winter of 1994-95, as well as for the existing road Station -0+78 m (-2+56 ft) before the winter of 1995-96. The tire chip insulation decreased the frost penetration by between 6 and 20 percent compared to the control section. Section C had more frost penetration than sections A and B. This indicates that the insulation is less effective when it is placed at a greater depth. Figures 5 and 6 display the frost penetration versus date for the winters of 1993-94, which was colder than average, and 1996-97, which was warmer than average. Similar plots for the remaining winters are given in Fiske and Humphrey (*7*). Comparing Figures 5 and 6, it is seen that there is a more pronounced difference between the control sections and the tire chip sections in the colder winter. For all winters, the control and existing road sections displayed rapid frost penetration over the first few weeks of the freezing season to a depth of about 760 mm, followed by slower frost penetration for the rest of the season. Sections D and E, which had a 305-mm tire chip layer, also displayed rapid frost penetration during the first few weeks of the freezing season, however, once the freezing front reached the bottom of the tire chip layer, there was little additional penetration. In Sections A, B, and C, which had 152-mm thick tire chip layers, the frost continued to penetrate at a slow rate once the freezing front reached the bottom of the tire chip layer but the rate of penetration was slower than in the control and existing road sections.

The variation of temperature with depth during the middle and latter portions of the freezing season clearly show the insulating effects of the tire chip layer. This was examined by selecting a day from each winter between late January and early March that was at the end of a period with consistently cold temperatures. The temperatures versus depth are shown in Figure 7 for February 16, 1994 (a colder than average winter) and Figure 8 for January 31, 1997 (a warmer than average winter). These show that the temperatures below the tire chip layer are warmer than the same depth in the control sections. It was also evident that the temperatures above the tire chip layer are colder than those at comparable depths in the control and existing road sections. This shows that the lower thermal conductivity of the tire chips reduced heat flow to the overlying layer.

BACKCALCULATION OF THERMAL CONDUCTIVITY

A two-part approach was employed in backcalculating the tire chip thermal conductivity using the subsurface temperature measurements. The first part was to assume that between the end of January and the end of February the heat flow in the sections with tire chips had reached steady state conditions, which means that the rate of heat being removed at the freezing front is approximately equal to the rate that heat is supplied from the unfrozen soil at greater depths. This assumption is justified by examination of the depth of frost penetration vs. date in Figures 5 and 6. It is seen that the depth of frost was essentially constant for the tire chip sections (Section A through E) after late January. Although, this is not the case for the control and existing road sections, data from these sections were not needed for the subsequent calculations.

For steady state conditions there would be a constant temperature gradient across each layer of uniform material as illustrated in Figure 9. In general, the temperature profiles in the tire chip sections (for example, Figures 7 and 8) resembled the theoretical temperature profile in Figure 9. The procedure is based on the equations for heat flow and continuity. From continuity, the heat flux (q) across each layer of soil is the same during steady state conditions. Therefore, for a three-layer system:

$$q_1 = q_2 = q_3 \tag{1}$$

The equation for steady state one-dimensional heat flow is:

$$q_n = K_n \cdot i_n \tag{2}$$

where: q_n is the heat flux, K_n is the thermal conductivity, and i_n is the temperature gradient across layer n. Using Equations 1 and 2, the following relationship can be found between the thermal conductivities of the second and third layers (K_2 and K_3):

$$K_2 = \frac{i_3}{i_2} \cdot K_3 \tag{3}$$

When the temperature gradient in two layers and the thermal conductivity of one layer are known, it is then possible to estimate the thermal conductivity of the unknown layer. For the Richmond field trial, the temperature gradients of the tire chip and subgrade soils were obtained directly from the temperature profiles (for example, Figures 7 and 8). By estimating the thermal conductivity of the subgrade soil it was possible to get an approximation of the thermal conductivity of the tire chips using Equation 3. In these calculations, layer 2 is the tire chips and layer 3 is the underlying subgrade soil.

These calculations were performed for each section and each winter of the trial period. Table 3 summarizes the results of these calculations. The values in parentheses represent unreliable data due to temperature profiles that deviated markedly from that shown in Figure 9. This situation occurred in some of the warmer than average winters. These values were not used in subsequent calculations. This analysis showed that the thermal conductivity of the tire chip layer is on average between 11% and 19% of that of the underlying soil. To determine the actual thermal conductivity of the tire chips, it is necessary to estimate the thermal conductivity of the underlying soil. Lawrence, et al. (*6*), reported that the soil beneath the tire chip layer in Sections A, B, and C was unsaturated frozen coarse-grained soil, and in Sections D and E it was saturated unfrozen fine-grained soil. Based on data reported in Kersten (*12*), a thermal conductivity of 2.6 W/ m·°C was selected for the subgrade soils (K_3) in Sections A, B and C, and 1.6 W/ m·°C was selected for the subgrade soils in Sections D and E. With these values it was possible to estimate the thermal conductivity of the tire chips in the field trial as summarized in Table 3. The values range between 0.29 and 0.42 W/m·°C.

The second part of the approach utilized the back-calculated thermal conductivity (K) in the modified Berggren method (*11*) to calculate the depth of maximum frost penetration. The calculated frost penetration values were then compared to the actual maximum frost penetration. Good agreement between the actual and theoretical frost penetration would indicate that the backcalculated thermal conductivity is reasonable. The material properties and layer thicknesses used as input for the modified Berggren equation are summarized in Tables 1, 2, and 4. The dry density and water content of the soils was based on field data measured during construction and experience with similar soils. The dry density of the tire chips was based on overburden pressure in conjunction with laboratory compression tests (*13*), and the water content was based on experience. The thermal conductivity of the soils was based on the dry densities and water content used as input to charts presented by Kersten (*12*). The modified Berggren equation was used for each section and each winter, using 0.29 and 0.42 W/m·°C for the tire chip thermal conductivity ($K_{tire\text{-}chip}$) . Results for the lower tire chip thermal conductivity are given in Table 5. Results for the higher thermal conductivity are given in Fiske and Humphrey (*7*).

The measured and calculated frost penetration are also compared in Table 5. The calculated frost depth is an average of 11% greater than the measured depth for the tire chip thermal conductivity of 0.29 W/m·°C. The difference was 14% when a tire chip thermal conductivity of 0.42 W/m·°C was used (*7*). In the control section, the difference between the calculated and the measured depths was -5% (the negative value indicates that the measured depth was greater than the calculated value). The close agreement for the control section indicates that the properties of the soils used in the analysis are reasonable. Based on these results, $K_{tire\text{-}chip}$ of 0.29 W/m·°C gave slightly conservative predictions of frost penetration (i.e., calculated depth of frost penetration slightly greater than measured). The results for $K_{tire\text{-}chip}$ of 0.42 W/m·°C were even more conservative. Therefore, a tire chip thermal conductivity of 0.29 W/m·°C is recommended for design of tire chip insulation layers in roadway applications. This value should be used in conjunction with a volumetric heat capacity of 198 Cal/m^3·°C and a latent heat of fusion of 1152 Cal/m^3 for the tire chips. For most circumstances, these values would lead to slightly conservative calculated depths of frost penetration. This value also compares favorably to thermal conductivities of tire chips measured in the laboratory and backcalculated from a second instrumented field trial in Orono, Maine (*6*,*7*).

SUMMARY AND CONCLUSIONS

Use of a 152 or 305-mm thick tire chip insulating layer on the Richmond Field Trial reduced the depth of frost penetration by between 6 and 20 percent compared to a control section. The higher percent reductions correspond to colder than average winters. For sections with a 305-mm thick tire chip layer, the freezing front penetrated to the bottom of the tire chip layer by mid-January and then there was negligible additional penetration into underlying subgrade soils during the remainder of the winter. In contrast, in the control section the freezing front continued to penetrate deeper into the subgrade soils during the entire freezing season. Two methods were used to determine the thermal conductivity of tire chips from the subsurface temperature measurements. The first used the observation that the thermal regime had reached nearly steady state conditions by late January to early March in sections with tire chips. This allowed the equations for steady state heat flow and continuity to determine a relationship between the thermal conductivity of the tire chips and the underlying soil. This lead to an estimated thermal conductivity of the tire chips between 0.29 and 0.42 W/m·°C. These values were then used in the modified Berggren equation to calculate the depth of frost penetration. This showed that the calculated penetration averaged 11% greater than actual with the lower thermal conductivity and 14% greater with the higher thermal conductivity. It is recommended that a thermal conductivity of 0.29 W/m·°C be used for designing tire chip insulation layers for roadway applications. In addition, it is recommended that a volumetric heat capacity of 198 Cal/m^3·°C and a latent heat of fusion of 1152 Cal/m^3 be used for the tire chips. Use of these values should result in a slightly conservative prediction of the depth of frost penetration for most highway applications.

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TABLE 1 LayerThickness

Section	Bituminous Concrete[1] (mm)	Granular Soil (mm)	Tire Chips (mm)	Underlying Existing Gravel (mm)
Control	76	305	0	460
A	76	305	152	356
B	76	305	152	356
C	76	457	152	356
D	76	457	305	0
E	75	610	305	0

[1] Road unpaved prior to August, 1995

TABLE 2 Duration of Freezing Season and Freezing Index

Winter	Duration of freezing season (days)	Freezing index (ºC-days)
1992-1993	107	607
1993-1994	83	742
1994-1995	111	395
1995-1996	99	573
1996-1997	69	286
1997-1998	99	298
1998-1999	95	392
Average	95	470

TABLE 3 Temperature Gradient in Tire Chip Section and Estimated Thermal Conductivity of Tire Chips

Section	Year	Gradient Relation	Average	Thermal Conductivity (W/m·ºC)
A	1992-1993	$0.09 \cdot K_3$	$0.11 \cdot K_3$	0.29[1]
	1993-1994	$0.07 \cdot K_3$		
	1994-1995	N.A.		
	1995-1996	$0.08 \cdot K_3$		
	1996-1997	$0.13 \cdot K_3$		
	1997-1998	$0.15 \cdot K_3$		
	1998-1999	$0.15 \cdot K_3$		
B	1992-1993	$0.13 \cdot K_3$	$0.16 \cdot K_3$	0.42[1]
	1993-1994	$0.16 \cdot K_3$		
	1994-1995	$0.09 \cdot K_3$		
	1995-1996	$0.08 \cdot K_3$		
	1996-1997	$0.15 \cdot K_3$		
	1997-1998	$(0.47 \cdot K_3)$		
	1998-1999	$0.32 \cdot K_3$		
C	1992-1993	$0.12 \cdot K_3$	$0.15 \cdot K_3$	0.40[1]
	1993-1994	$0.18 \cdot K_3$		
	1994-1995	$0.20 \cdot K_3$		
	1995-1996	$0.08 \cdot K_3$		
	1996-1997	$0.13 \cdot K_3$		
	1997-1998	$(0.33 \cdot K_3)$		
	1998-1999	$0.20 \cdot K_3$		
D	1992-1993	$0.15 \cdot K_3$	$0.19 \cdot K_3$	0.29[2]
	1993-1994	$0.16 \cdot K_3$		
	1994-1995	N.A.		
	1995-1996	$0.21 \cdot K_3$		
	1996-1997	$0.16 \cdot K_3$		
	1997-1998	$(0.57 \cdot K_3)$		
	1998-1999	$0.25 \cdot K_3$		
E	1992-1993	$0.14 \cdot K_3$	$0.19 \cdot K_3$	0.29[2]
	1993-1994	$0.17 \cdot K_3$		
	1994-1995	N.A.		
	1995-1996	$0.21 \cdot K_3$		
	1996-1997	$0.23 \cdot K_3$		
	1997-1998	$0.20 \cdot K_3$		
	1998-1999	$(0.40 \cdot K_3)$		
Average			$0.16 \cdot K_3$	0.34

() indicates unreliable data that was not used to calculate averages
N.A. represents years that data was not available
[1] Used $K_3 = 2.6$ W/m·ºC
[2] Used $K_3 = 1.6$ W/m·ºC

TABLE 4 Basic Material and Thermal Properties of Used in Modified Berggren Method

Layer	Dry Density (Mg/m^3)	Water Content (%)	Thermal Conductivity (W/m·ºC)	Volumetric Heat Capacity (Cal/m^3·ºC)	Latent Heat of Fusion (Cal/m^3)
Bituminous Concrete	2.32	0	1.4	447	0
Granular Soil	1.92	5	1.8	456	7860
Tire Chip	0.72	2	0.29 and 0.42*	198	1152
Existing Gravel	1.92	5	1.8	456	7680
Subgrade	1.76	16	1.7	563	22530

*For comparison, the calculations were performed with two thermal conductivities of the tire chips.

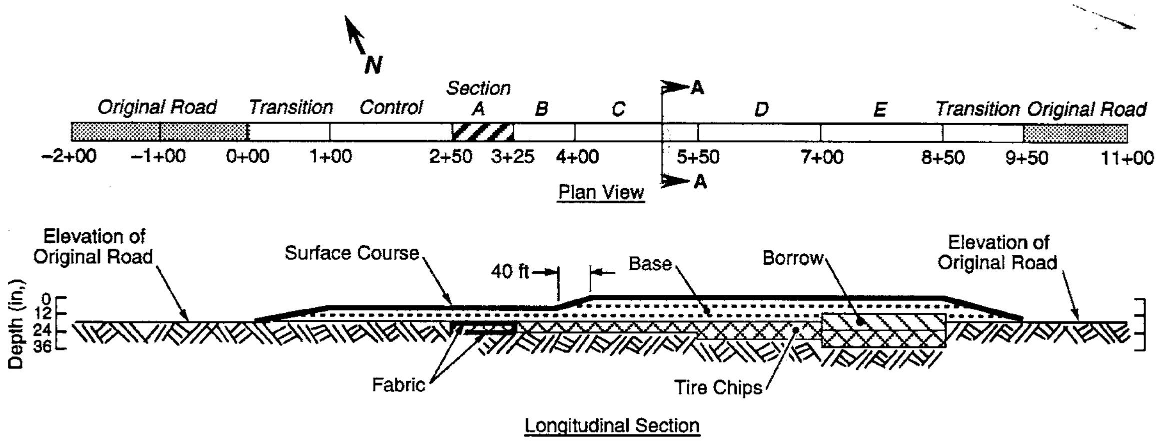
TABLE 5. Comparison of Calculated and Measured Maximum Frost Penetration Using $K_{\text{tire-chip}}$ = 0.29 W/m·°C

	Control			Section A		
Year	Calculated (mm)	Actual (mm)	% Difference*	Calculated (mm)	Actual (mm)	% Difference*
1992-1993	1140	1070	7	1010	970	5
1993-1994	1230	1230	0	1120	1010	10
1994-1995	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
1995-1996	1090	1070	2	1010	860	18
1996-1997	760	970	-21	860	660	31
1997-1998	760	890	-14	860	790	10
1998-1999	890	940	-5	910	810	13
Averages	990	1010	-5	970	860	14

	Section B			Section C		
Year	Calculated (mm)	Actual (mm)	% Difference*	Calculated (mm)	Actual (mm)	% Difference*
1992-1993	1010	840	21	1140	970	18
1993-1994	1120	910	22	1190	1070	7
1994-1995	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
1995-1996	1010	840	21	1120	890	26
1996-1997	860	810	6	990	910	8
1997-1998	860	760	13	990	610	63
1998-1999	910	790	16	1040	760	37
Averages	970	840	17	1090	860	27

	Section D			Section E		
Year	Calculated (mm)	Actual (mm)	% Difference*	Calculated (mm)	Actual (mm)	% Difference*
1992-1993	940	790	19	1090	970	13
1993-1994	1040	940	11	1140	970	18
1994-1995	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
1995-1996	940	890	6	1070	940	14
1996-1997	890	970	-8	1020	1020	0
1997-1998	890	860	3	1020	970	5
1998-1999	910	990	-8	1040	970	8
Averages	940	910	4	1070	970	10

*A positive percent difference indicates that the calculated depth of frost penetration is greater than the measured depth.



Note: 1 in. = 25.4 mm; stationing is in feet, 1 ft = 0.305 m

FIGURE 1 Plan view and longitudinal section of Richmond field trial (*5*).

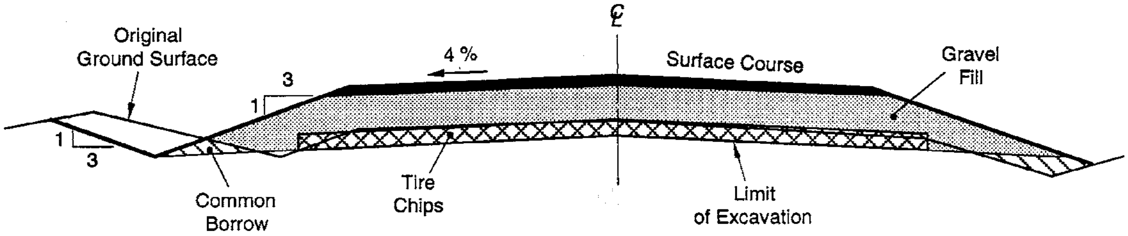
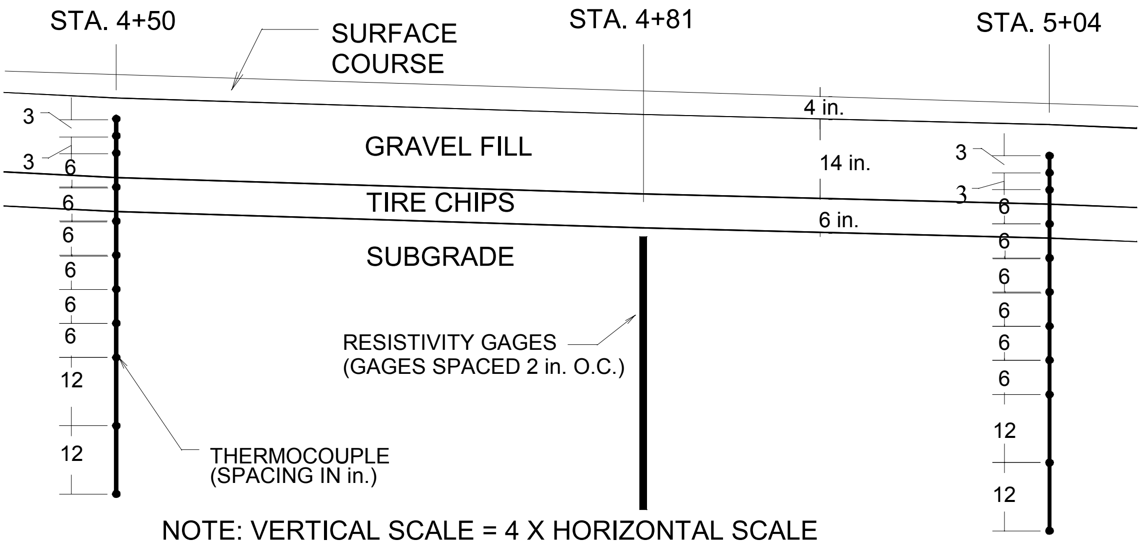


FIGURE 2 Typical cross section (5).



Note: 1 in. = 25.4 mm; stationing is in feet, 1 ft = 0.305 m

FIGURE 3 Location of instrumentation (*5*).

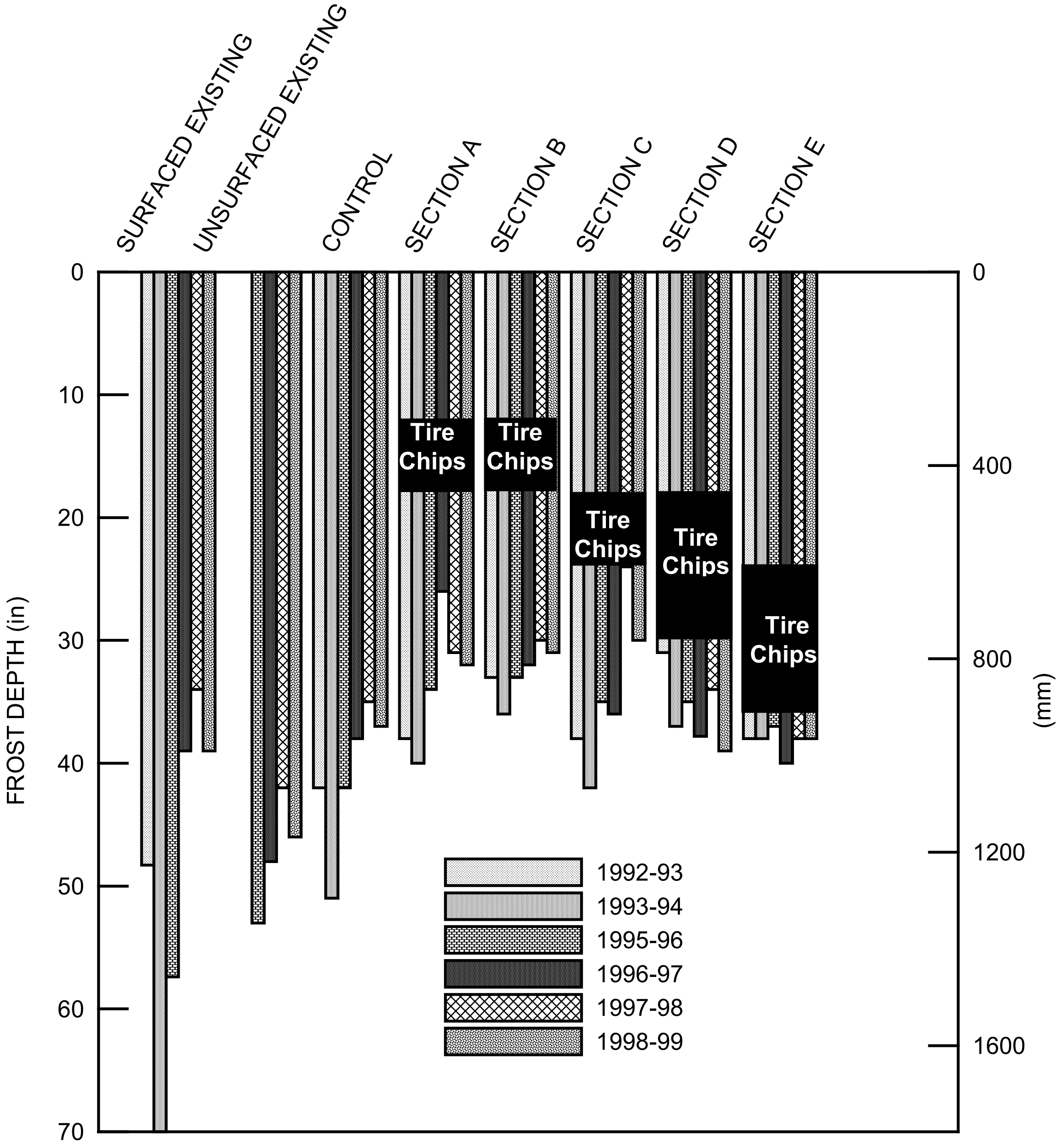


FIGURE 4 Maximum depth of frost penetration.

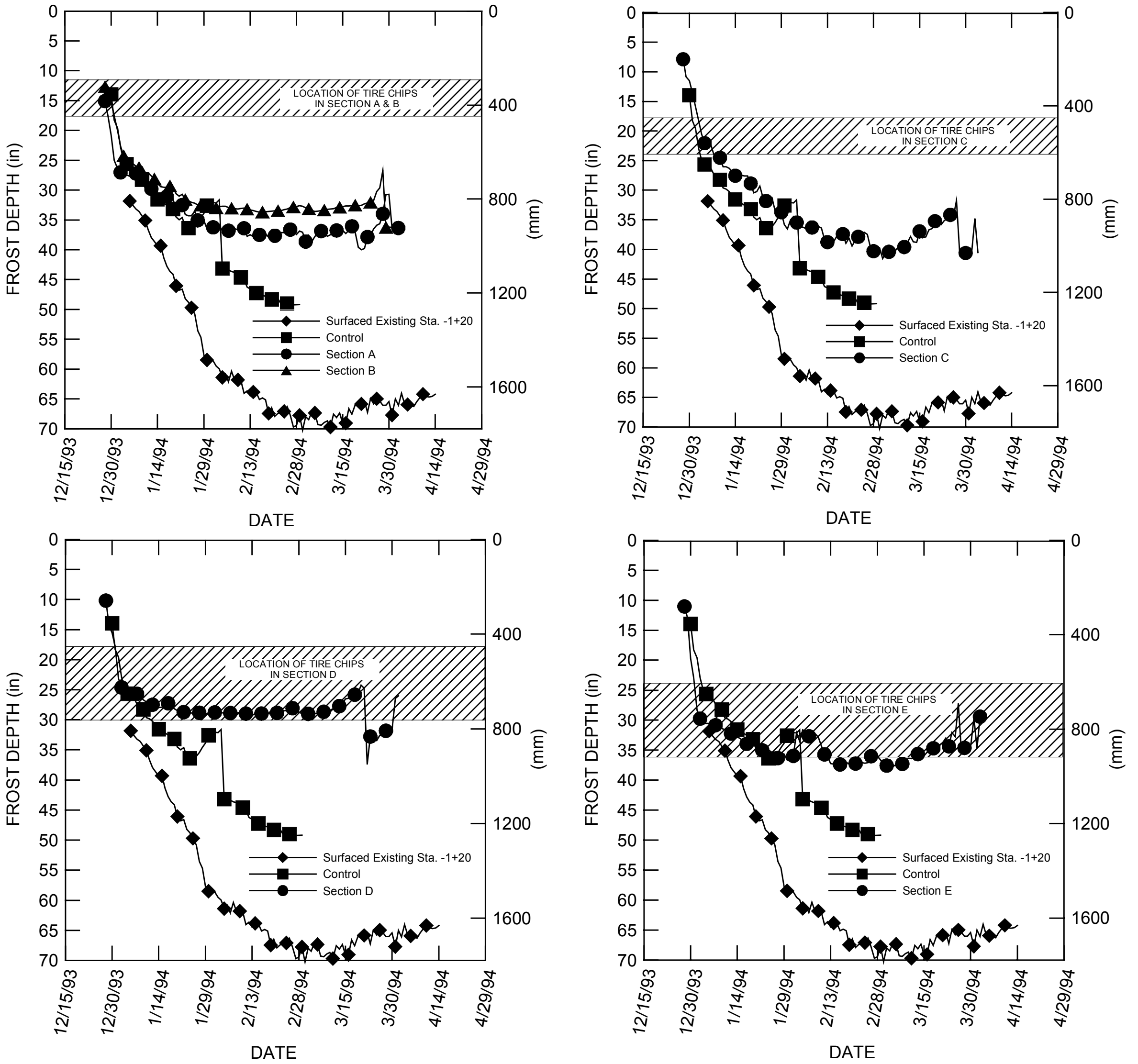


FIGURE 5 Depth of frost penetration for the winter of 1993-94.

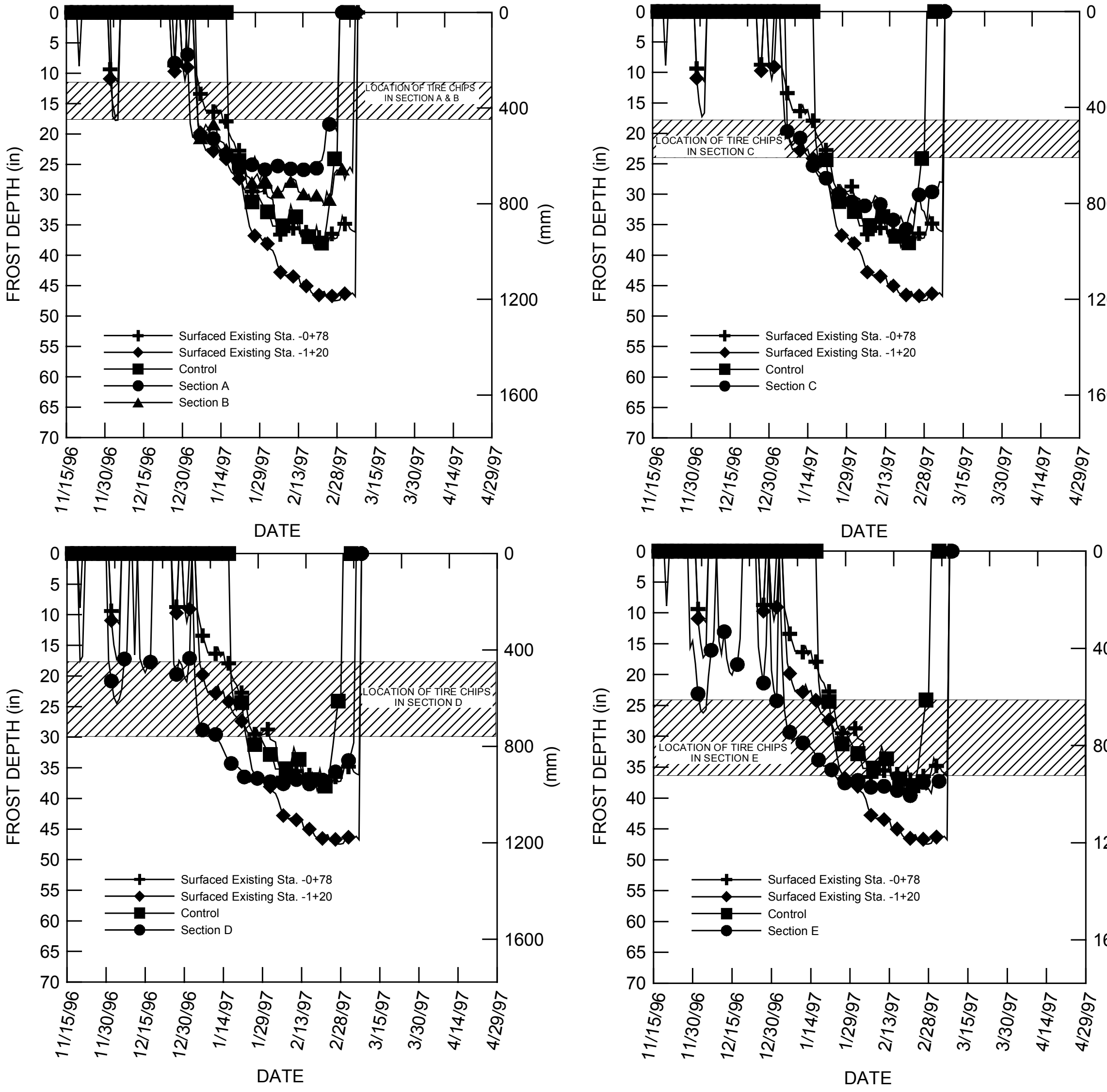


FIGURE 6 Depth of frost penetration for the winter of 1996-97.

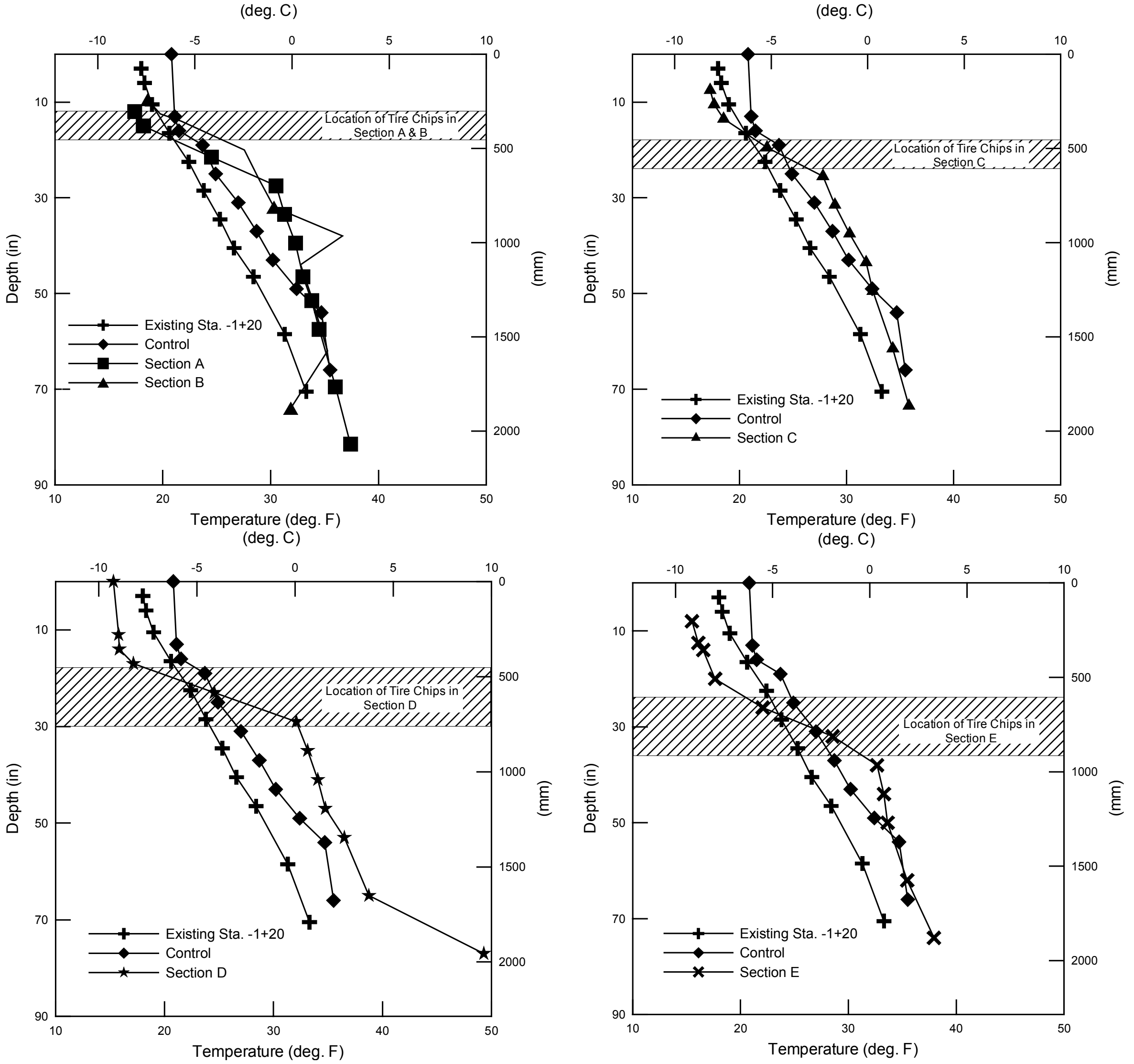


FIGURE 7 Temperature versus depth for 2/16/94.

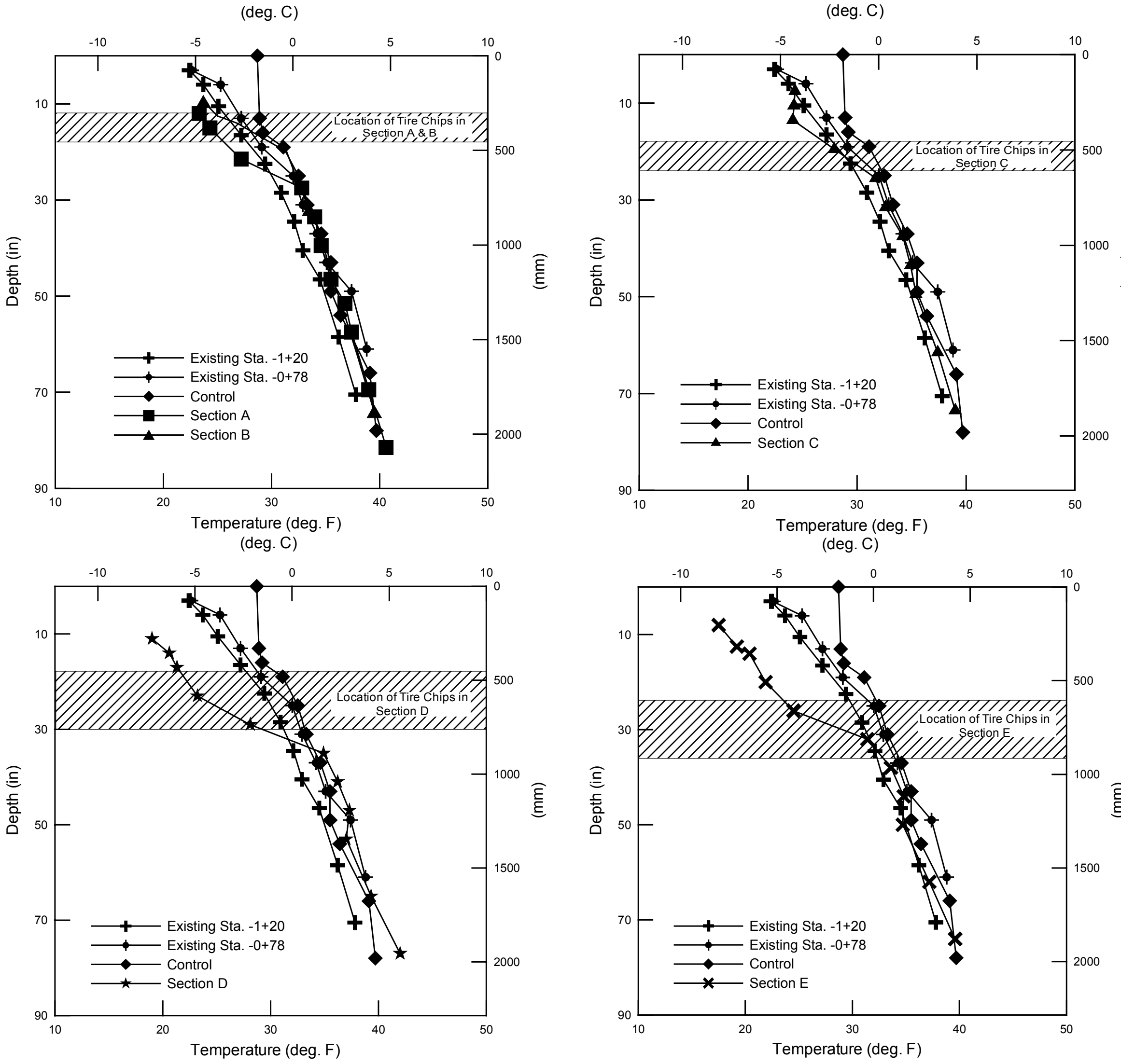


FIGURE 8 Temperature versus depth for 1/31/97.

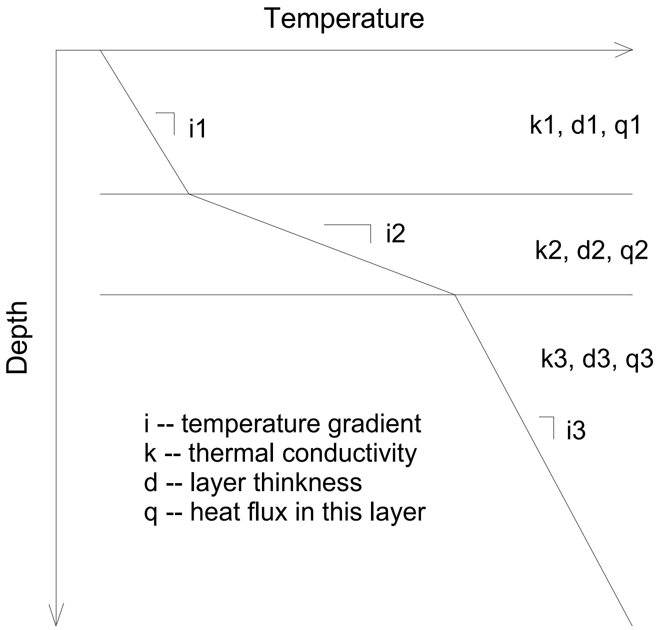


FIGURE 9 Temperature profile for steady state conditions in a three-layer system (*6*).