PERFORMANCE OF MONTANA HIGHWAY PAVEMENTS DURING SPRING THAW

by

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Highway pavements in seasonal frost areas undergo annual freeze–thaw cycles. Pavements constructed for the design load capacity can become weak during spring thaw. In 1995, the Montana Department of Transportation (MDT) initiated a study on developing road restrictions during the spring thaw. Selected sites throughout Montana were instrumented. Field measurements of deflection, moisture, and temperature were made during the winter/spring of 1996–1997 and 1997–1998. The analysis determined thaw-weakening characteristics of the sites and developed subgrade modulus values for use in future design of pavement structures in Montana. Based on the moisture data, the base course layers at Dickey Lake, Wolf Point, Scobey/Redstone, and East Glacier are prone to thaw weakening. Deflection data indicate that the bases at Bull Mountain, Swan Lake, and Scobey Redstone may be prone to thaw weakening. The subgrade at Dickey Lake, East Glacier, Bull Mountain, Swan Lake, and Scobey/Redstone may also be prone to thaw weakening. The length of thaw weakening varied from 4 days (Scobey/Redstone) to 3 weeks (East Glacier). This report provides a general description of the test sites, the measurements and analysis of the data, results of the analysis, and recommendations based on the results. In addition, the report quantifies the effects of thaw weakening on typical roads in Montana based on deflection, surface and subsurface moisture, temperature, and other atmospheric measurements taken by MDT.</td></tr>
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Table of Contents

FIGURES

Tables

ABSTRACT

Highway pavements in seasonal frost areas undergo annual freeze–thaw cycles. Pavements constructed for the design load capacity can become weak during spring thaw. In 1995, the Montana Department of Transportation (MDT) initiated a study on developing road restrictions during the spring thaw. Selected sites throughout Montana were instrumented. Field measurements of deflection, moisture, and temperature were made during the winter/spring of 1996–1997 and 1997–1998. The analysis determined thaw-weakening characteristics of the sites and developed subgrade modulus values for use in future design of pavement structures in Montana. Based on the moisture data, the base course layers at Dickey Lake, Wolf Point, Scobey/Redstone, and East Glacier are prone to thaw weakening. Deflection data indicate that the bases at Bull Mountain, Swan Lake, and Scobey Redstone may be prone to thaw weakening. The subgrade at Dickey Lake, East Glacier, Bull Mountain, Swan Lake, and Scobey/Redstone may also be prone to thaw weakening. The length of the thaw-weakening period varied from 4 days (Scobey/Redstone) to 3 weeks (East Glacier). This report provides a general description of the test sites, the measurements and analysis of the data, results of the analysis, and recommendations based on the results. In addition, the report quantifies the effects of thaw weakening on typical roads in Montana based on deflection, surface and subsurface moisture, temperature, and other atmospheric measurements taken by MDT.

Keywords: Pavements, Thaw weakening, Moisture, Temperature, Moduli, Base, Subgrade.

INTRODUCTION

Highway pavements in seasonal frost areas undergo annual freeze–thaw cycles. Pavements constructed for the design load capacity can become weak during spring thaw. During the winter, water is drawn up to the freezing front from shallow water tables by capillary action and converted to ice lenses. This formation of ice lenses is manifested on the surface as frost heave. During the spring, the ice lenses are converted back to liquid water and, depending on the hydraulic conductivity of the subsurface layers, these layers can become saturated. In addition, more moisture can be introduced into the subsurface layers from infiltration of melting snow and rain from the surface. As a result, the bearing capacity of the base, subbase, or subgrade, or all three, can be reduced and damage may be observed on the surface as potholes, alligator cracking, or rutting. The amount of damage can vary. However, it has been reported that 90% of the damage to pavements can occur during the thaw-weakening periods. To reduce this damage, load restrictions need to be applied during these periods. However, the timing and length of the load restriction period can be a financial burden to the trucking industry and need to be determined with care.

In 1995, the Montana Department of Transportation (MDT) initiated a study on developing road restrictions during the spring thaw. The project began with field studies to identify the extent of the effects of thaw weakening on highway pavements. Selected sites throughout Montana were instrumented. Attempts were made to obtain field measurements of deflection, moisture, and temperature during the winter/spring seasons of 1996–1997 and 1997–1998. Measurements were made to cover the four periods in a freeze–thaw cycle: period of deep frost, period of rapid strength loss, period of rapid strength recovery, and period of slow strength recovery (Shepherd and Vosen 1997).

The U.S. Army Engineer Research and Development Center's Cold Regions Research and Engineering Laboratory (CRREL) was contracted by MDT to assist in the analysis of the test data from 10 sites. The analysis was to determine the thaw-weakening characteristics of the sites and to develop subgrade modulus values for use in the future design of pavement structures in Montana. This report provides a general description of the test sites, the measurements and analysis of the data, results of the analysis, and recommendations based on the results. In addition, the report quantifies the effects of thaw weakening on typical roads in Montana, based on deflection, surface and subsurface moisture, temperature, and other atmospheric measurements taken by MDT.

SITE DESCRIPTION

Ten sites were chosen throughout the state of Montana for this project based on their subgrade soil classification, geologic region, and their closeness to weather monitoring stations (Shepherd and Vosen 1997) (Figure 1). Montana can be divided into two geologic regions (Shepherd and Vosen 1997). These are the Rocky Mountain and the Plains regions. Sites representing the Rocky Mountain region include East Glacier, Sweetgrass, Swan Lake, Dickey Lake, and Livingston. Loma, Scobey/Redstone, Alzada, Roundup/Bull Mountain, and Wolf Point represent the Plains region.

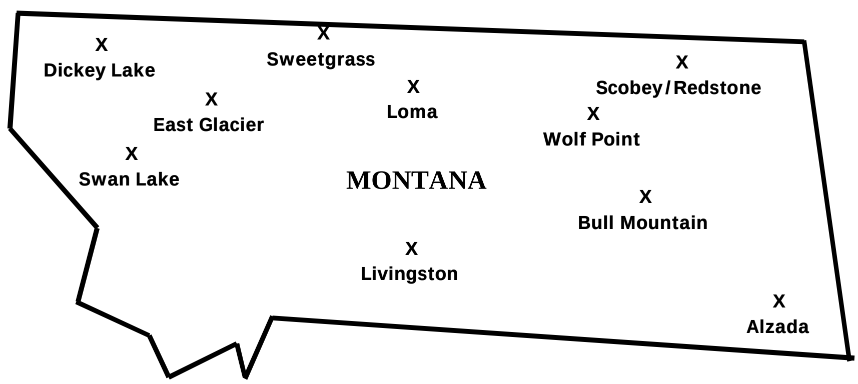

Figure 1. Location of test sites in Montana.

All the pavement structures in this study were flexible pavements, which represent 97% of Montana roads (Shepherd and Vosen, 1997). With the exception of Swan Lake, the pavement structure at the sites consisted of an asphalt concrete layer over an unstabilized base, over the natural subgrade. At Swan Lake, in addition to the base course, there was a subbase layer over the natural subgrade. The asphalt concrete layers at the test sites ranged from 76 to 330 mm (3 to 13 in.), and base thickness ranged from 138 to 686 mm (5.5 to 27 in.). The subgrade soil classifications are based on the American Association of State Highway Transportation Officials (AASHTO, 2002) system. The subgrade soils, based on the top 0.6 m (2 ft), were classified as A-2, A-4, or A-6. Site names, AASHTO soil classifications of the base and subgrade, and road layer thickness are given in Table 1. Other soil tests conducted by MDT were for moisture content and R-values. Available gradation and Atterberg limit test results for some of the sites are presented in Appendix C.

Table 1. Layer material type and thickness.

Site name	Subgrade	Layer thicknesses		
		Asphalt mm (in.)	Base mm (in.)	Subbase mm (in.)
Loma	A-1	152 (6)	686 (27)	No subbase
East Glacier	A-4	76 (3)	584 (23)	No subbase
Sweetgrass	A-6	330 (13)	483 (19)	No subbase
Swan Lake	A-1	122 (4 ¾)	122 (4 ¾) *	127 (5)
Dickey Lake	A-2-4	127 (5)	427 (17)	No subbase
Scobey/Redstone	A-6	229 (9)	140 (5 ½)	No subbase
Alzada	A-6	235 (9 ¼)	603 (24)	No subbase
Livingston	A-1	152 (6)	518 (20 ½)	No subbase
Roundup/Bull Mtn	A-4	254 (10)	432 (17)	No subbase
Wolf Point	A-6	178 (7)	152 (6)	No subbase

*Pulverized plant mix surfacing (PMS).

Of the 10 sites, only two have any amount of shading that would increase frost penetration and delay thaw weakening. They are Dickey Lake, which is located on the north side of a hill, and Swan Lake, which is located among trees.

FIELD INSTRUMENTATION AND TESTING PROGRAM

Each test site was instrumented with VITEL Hydra Soil Probes. Subsurface soil temperature, soil dielectric constant, and soil conductivity were measured hourly with these probes and recorded with VX1004 data loggers, manufactured by VITEL, Inc., Chantilly, Virginia.

A brief summary of the probe is given here. Basically, it is a moisture probe. It determines the soil moisture and salinity from a 50-MHz high-frequency complex dielectric constant measurement. The dielectric constant can be separated into its real and imaginary components. The real component has been shown to be sensitive to the moisture content of the soil. The imaginary (conductive) component can be related to the salinity of the soil. Subsurface temperatures were directly measured using thermistors located in the probe head. The volumetric moisture content is determined from calibration equations provided by VITEL for sands, silts, and clays. These calibrations are part of the data acquisition system provided by VITEL. Sensor locations provided by the MDT are shown in Table 2.

In October 1997, the VITEL probes at seven sites were checked by CRREL and 64% of the sensors were found to be fully operational. With respect to temperature, we found that 94 % of the sensors were functioning properly.

In addition to the subsurface instrumentation, the sites were located in areas where Road Weather Information Systems (RWIS) were available. Plans were made initially to supplement the VITEL data with data from the SSI system. However, when the data were reviewed, we found that data from the SSI sensors were recorded at irregular intervals, based on how often the closest weather station dialed into the site. Because of this irregularity and also because only 36% of the data were available for the analysis period (1996–1997), measurements from the SSI system were not used. Also, no data were found for Bull Mountain and only a few readings were found for Livingston, East Glacier, and Alzada.

Pavement deflection measurements for the 1996–1997 period were obtained nondestructively with the MDT Road Rater, manufactured by Foundation Mechanics, Inc. (Foundation Mechanics, no date specified), El Segundo, California. Surface deflections were measured from steady-state dynamic loads (9 to 22 kN, or 2000 to 5000 lb). The loads were applied through a 305-mm-diameter steel plate at a frequency of 25 Hz. Deflections were measured at distances of 0, 203 (8), 305 (12), 610 (24), 914 (36), and 1219 mm (48 in.) from the center of the plate.

For the 1997–1998 period, deflection measurements were made with the JILS-20T falling weight deflectometer (FWD). The deflections were measured at distances of 0, 203 (8), 305 (12), 458 (18), 610 (24), 914 (36), and 1219 mm (48 in.) from the center of the plate. The falling weight loads ranged from 27 to 71 kN (6000 to 16,000 lb). Based on test data notes, the JILS-20T FWD system replaced the Road Rater about at the end of September 1997. Comparison measurements were made at Dickey Lake, Sweetgrass, and Loma using both the Road Rater and the FWD.

Table 2. Location of VITEL sensors for measuring moisture, temperature, and salinity.

Site name	VITEL sensor depths (mm from pavement surface)								
	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8	Sensor 9
Dickey Lake	292 (11 ½ in.)	584 (23 in.)	813 (32 in.)	MD*	1168 (46 in.)	1468 (57 ¾ in.)	—-†	—-	—
Wolf Point	229 (9 in.)	381 (15 in.)	762 (30 in.)	914 (36 in.)	1118 (44 in.)	1422 (56 in.)	1803 (71 in.)	—	—
Sweetgrass	2289 (90 in.)	1887 (74 ¼ in.)	1586 (62 ½ in.)	1387 (54/ ½ in.)	1237 (48 ¾ in.)	1087 (42 ¾ in.)	864 (34 in.)	572 (22 ½ in.)	—
Scobey/Redstone	305 (12 in.)	445 (17 ½ in.)	673 (26 ½ in.)	813 (32 in.)	965 (38 in.)	1168 (46 in.)	1473 (58 in.)	1867 (73 ½ in.)	—
East Glacier	457 (18 in.)	737 (29 in.)	1110 (43 ¾ in.)	1260 (49 ½ in.)	1461 (57 ½ in.)	1760 (69 ¼ in.)	2161 (85 in.)	—	—
Alzada	279 (11 in.)	808 (31 ¾ in.)	960 (37 ¾ in.)	1138 (44 ¾ in.)	1288 (50 ¾ in.)	1438 (56 ½ in.)	1638 (64 ½ in.)	1938 (76 ¼ in.)	2339 (92 in.)
Bull Mountain	432 (17 in.)	665 (26 ¼ in.)	902 (35 ½ in.)	1207 (47 ½ in.)	1422 (56 in.)	1702 (67 in.)	2108 (83 in.)	—	—
Livingston	229 (9 in.)	411 (16 ¼ in.)	747 (29 ½ in.)	970 (38 ¼ in.)	1270 (50 in.)	1473 (58 in.)	1778 (70 in.)	2159 (85 in.)	—
Loma	541 (21 ¼ in.)	960 (37 ¾ in.)	1184 (46 ½ in.)	1483 (58 ¼ in.)	1684 (66 ¼ in.)	1984 (78 in.)	2385 (94 in.)	—	—
Swan Lake	668 (26 ¼ in.)	818 (32 ¼ in.)	968 (38 in.)	1168 (46 in.)	1468 (57 ¾ in.)	1869 (73 ½ in.)	—	—	—

* MD = Missing Data (sensor installed at unknown depth).

† Indicates that sensor string has no sensors with that number.

For the 1996–1997 period, deflection measurements were taken monthly throughout the year, with the exception of spring, when they were taken biweekly. The test program consisted of one drop at each test point between 9 and 22 kN. The test section size of 30.5 m was selected in such a way that half the section was either to the right or left of the location where the VITEL probes were installed. The test points were 1.5 m. apart. A total of 21 non-destructive testing (NDT) tests were conducted for each site using the “Road Rater” for most of the year.

During our analysis, we found that, during the spring thaw period, deflection tests were conducted at four or five test points. In addition to NDT testing, air temperature and, in some instances, pavement temperatures were recorded during the tests. Pavement temperatures included surface temperatures and temperature in the middle of the asphalt concrete (AC) layer (defined by MDT as the “material” temperatures).

In the 1997–1998 season, when the JILS 20-T (annotated JILS 201 in the data remarks) was used, each location had 20 tests per date. Some sites were tested at least once per month, and during February, March, and April, there were multiple tests, up to four in one instance. The system was normally programmed to apply four loads, but occasionally three or five loads were programmed. In other instances, the system was programmed to apply one load four times, and then the sequence was repeated with three or four other loads. The normal loads used were 26.7, 35.6, 40.0, and 44.5 kN (6000, 8000, 9000, and 10,000 lb), with 26.7, 40.0, 53.4, and 62.3 or 66.7 kN (6000, 9000, 12,000, and 14,000 or 15,000 lb) occasionally used.

ENVIRONMENTAL DATA ANALYSIS

Approximate coordinates for the test sites were obtained through discussions with Montana DOT personnel. Air temperature data for the sites were obtained from the National Weather Service. The weather stations were chosen based on proximity to the test site. The coordinates of the test sites and the nearest weather station are shown in Table 3 below. Some data gaps are present, but they are not critical. However, deflection data were available and were analyzed.

Table 3. Location of weather station sites relative to test sites.

Test site	Latitude	Longitude	NWS station	Latitude	Longitude
Dickey Lake	48° 42'N	114° 48'W	Fortine 1 N	48° 47'N	114° 54'W
Wolf Point	48° 39'N	105° 26'W	Scobey 4NW	48° 50'N	105° 29'W
Sweetgrass	48° 59'N	111° 57'W	Sweetgrass	49° 00'N	111° 58'W
Redstone	48° 49'N	105° 01'W	Bredette	48° 33'N	105° 16'W
East Glacier	48° 27'N	113° 13'W	East Glacier	48° 27'N	113° 13'W
Alzada	45° 01'N	104° 25'W	Albion 1 N	45° 13'N	104° 16'W
Bull Mtn.	46° 14'N	108° 27'W	Roundup	46° 27'N	108° 33'W
Livingston	45° 39'N	110° 32'W	Livingston Mission Field	45° 42'N	110° 26'W
Loma	47° 56'N	110° 30'W	Loma 1 WNW	47° 57'N	110° 32'W
Swan Lake	47° 30'N	113° 41'W	Lindbergh Lake	47° 25'N	113° 43'W

Several of the VITEL probes failed 5 to 6 months after installation. For example, five out of the six probes at Swan Lake stopped functioning within 5 months from installation and five out of eight probes at Livingston stopped functioning within 6 months from installation. A power surge, possibly from lightning, was thought to be the most likely cause according to MDT. In addition, we found that data were missing during the winter and thaw periods in Alzada. Results from these sites were not used in the analysis. Additional probes, and probes at additional sites, failed during the following year (1997–1998).

The subsurface moisture, in conjunction with deflection data, was used to determine if the pavement structure was susceptible to thaw weakening. When deflection data are unavailable, the moisture contents can provide a good indication of the thaw-weakening susceptibility of the base and subgrade. A good illustration of this is the moisture data in the base course from Dickey Lake (Figure 2). As seen in Figure 2, the moisture content in the base increased sevenfold from its non-frost value during the spring thaw. This increase translates to a period of weakening.

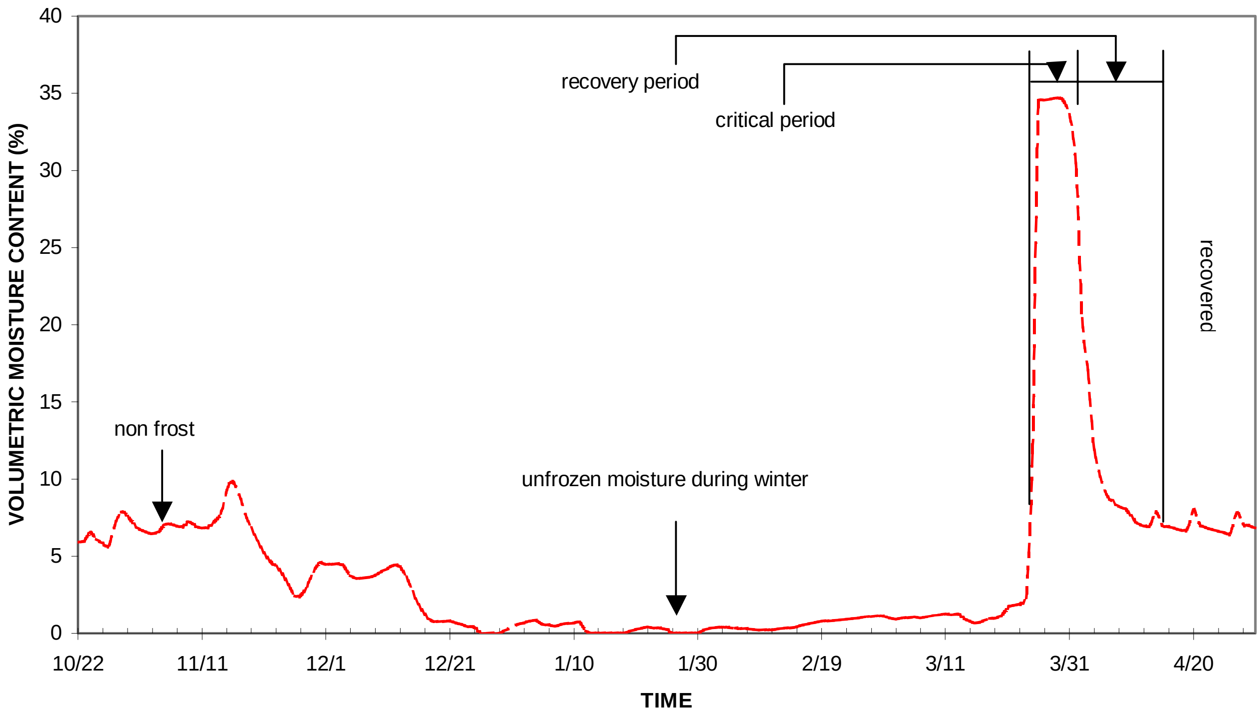

Figure 2. Definitions of critical and recovery periods used in the analysis.

For our analysis (see Figure 2), the non-frost moisture content was taken as the average mean moisture content for October, when the mean ground temperature was still positive. The unfrozen moisture content during the winter is the average moisture content where the ground temperature is stable at its lowest temperature. The critical period, determined using the moisture data, is the time when the moisture content exceeds the non-frost value during the spring thaw to its maximum value. Recovery is at the end of the maximum value to the time when it levels out to either the non-frost level or just close to it.

Moisture and temperature data were recorded hourly. The hourly moisture contents and temperatures were converted to daily mean values and are presented in Appendix A. The subsurface temperature data provided information on the length of the freezing season and was used to estimate the maximum frost penetration. In addition, when available, daily mean air temperatures at or near the site is presented in Appendix A. The frost depth presented in Table 4 is defined as the maximum depth where the temperature reached 0°C. (For the 1997–1998 winter, the frost depth was interpolated from the Vitel probe temperature data. This was done using the deepest probe that indicated below freezing temperatures, and the temperature indicated by the next deeper probe.) The time that the ground is frozen is defined as the period (to the nearest month) when the ground temperature remains below 0°C.

Table 4. Estimated frost depth and period of freezing from measured temperatures and moisture content.

Location	Frost depths (m)		Period of freezing	
	1996–1997	1997–1998	1996–1997	1997–1998
Loma	2.39	—*	December–April	—
East Glacier	2.16	—	September–April	—
Sweetgrass	2.29	1.60	September–April	November–March
Swan Lake	—	—	—	—
Dickey Lake	>1.60†	1.32	November–April	November–March
Scobey/Redstone	>1.88†	1.85	September–April	November–April
Alzada	>1.93†	—	—	—
Livingston	>1.27†	—	—	—
Bull Mountain	1.70	—	—	—
Wolf Point	>1.80†	1.66	September–April	November–April

* Insufficient to note the trend or missing temperature data.
† Frost penetration exceeded the deepest measurement sensor.

Thaw weakening is caused by excess moisture and the rate of dissipation in the pavement structure. On the basis of the moisture distribution in the pavement structure, we can surmise the potential for thaw weakening. Detailed descriptions of the seasonal moisture variation in the base and subgrade at five sites are given below: Dickey Lake, Wolf Point, Sweetgrass, Scobey/Redstone, and East Glacier. At these sites there were complete or near complete temperature and moisture data in the base and subgrade. (However, East Glacier moisture and temperature data were not collected for the 1997–1998 season.) Unfortunately, the selected sites were in the northern half of the state.

Dickey Lake

The base and subgrade gradation, as obtained during the instrumentation stage, are shown in Figures 3 and 4. Details of the gradation and Atterberg limits are presented in Table C-1. Under the

AASHTO soil classification system (AASHTO, 2002), the base was an A-1-a soil. Bedrock was found at a depth of 1.5 m (58 in.) from the surface. The subgrade was found to vary with depth. The top 900 mm (36 in.) ranged between an A-2-4 and A-4 soil (Table C-1). The bottom part of the subgrade turned out to be more granular and was classified as an A-1-b subgrade. The percentage of material finer than the 0.075-mm (#200) sieve size in the base ranged between 10 and 13%, and in the subgrade, between 18 and 37%. On the basis of the plasticity index, the fines were classified as non-plastic. Initial gravimetric moisture contents taken at the time of instrumentation installation (mid-November 1995) ranged between 8 and 10% in the base and between 13 and 18% in the subgrade. The moisture measurements in the subgrade were taken at depths between 686 and 1270 mm (27 and 50 in.). The depth of the water table was not reported.

The moisture and temperature response during the fall-winter-spring seasons of 1996–1997 and 1997–1998 in the base and subgrade are shown in Figure A-1. Based on the temperature measurements, frost penetration reached at least to a depth of 1.6 m (60 in.) in 1996–1997, and about 1.35 m (about 54 in.) in 1997–1998. The minimum average air temperature during the 1996–1997 winter was –22°C. The air freezing index[*] for the winter-spring of 1996–1997 was greater than 792°C degree-days (1425°F degree-days) (see Figure 5). (As the air temperature data for November are missing, there is no indication of how much greater the freezing index would have been. However, it is safe to assume that the November data would have increased the freezing index.) Based on the air freezing index, the freezing season started when the air freezing index was at its maximum (November 14th, 1996 and November 8th, 1997).

[*] Air freezing Index is the measure of the departure of the mean daily temperature below a given standard, 0°C (32°F); these departures, called freezing degree days, are summed over a season to give the air freezing index. For example, a day with an average temperature of –5°C (23°F) represents 9 freezing degree-days by the Fahrenheit scale (5 freezing degree-days by the Celsius scale).

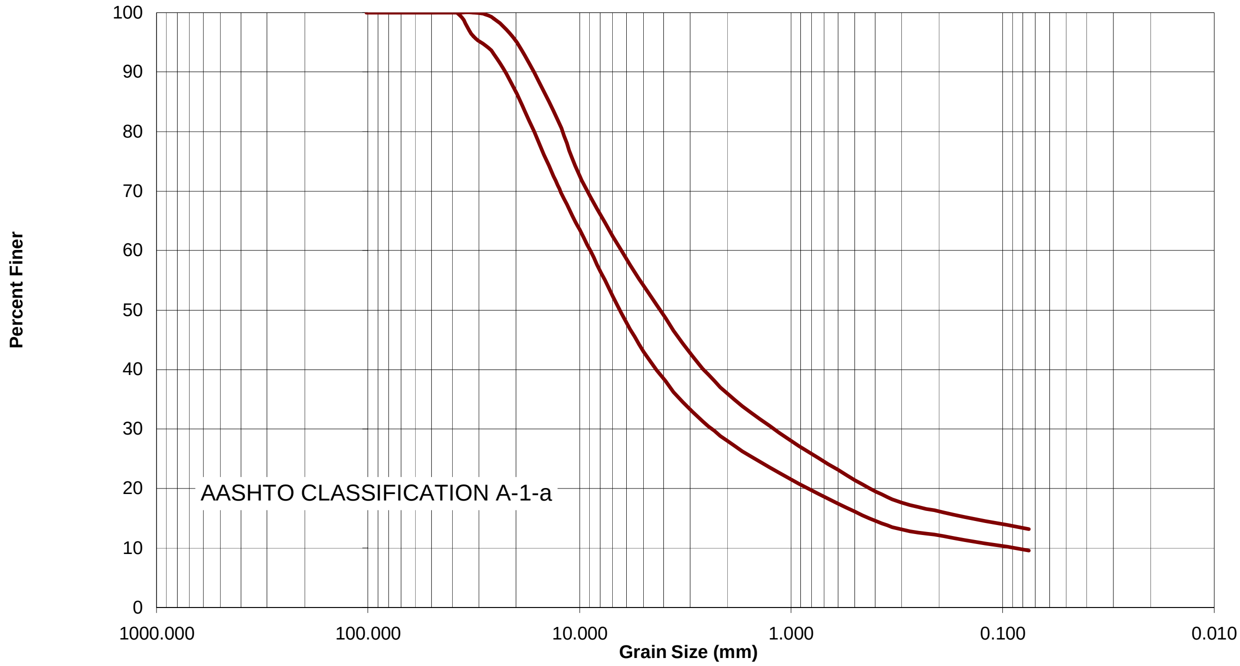

Figure 3. Base course grain size distribution at Dickey Lake.

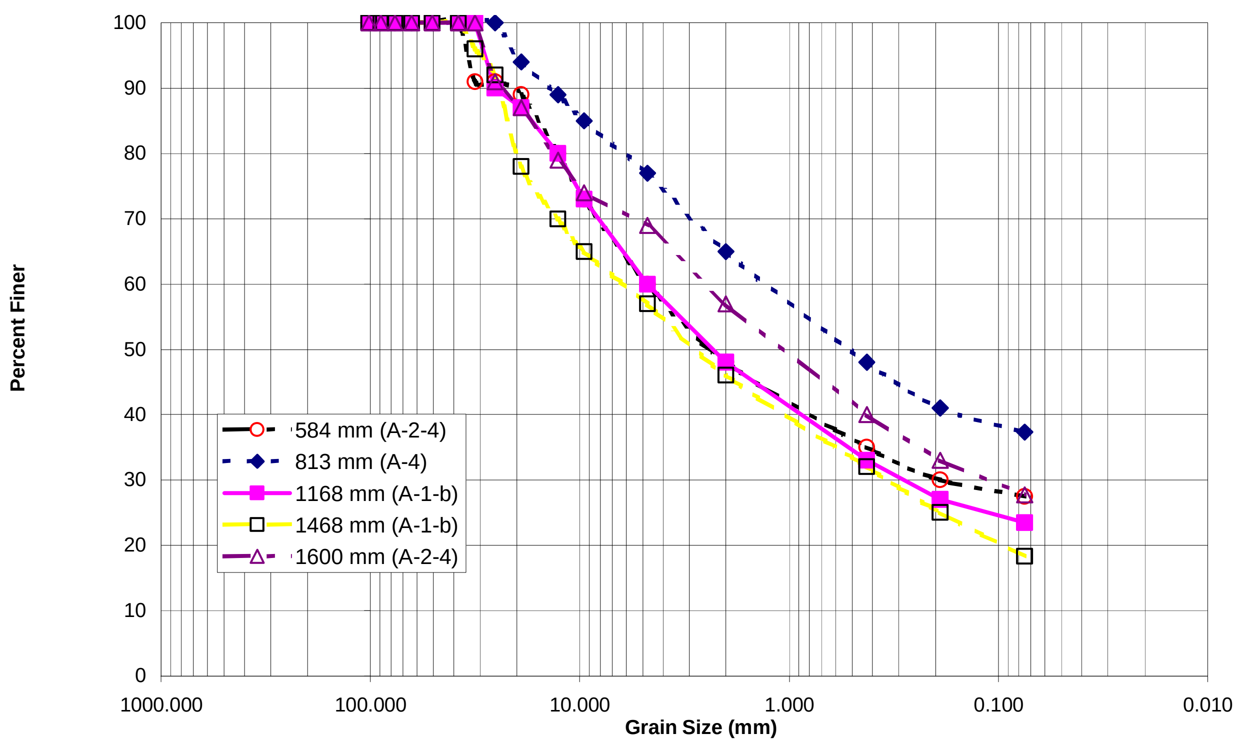

Figure 4. Subgrade grain size distribution at Dickey Lake.

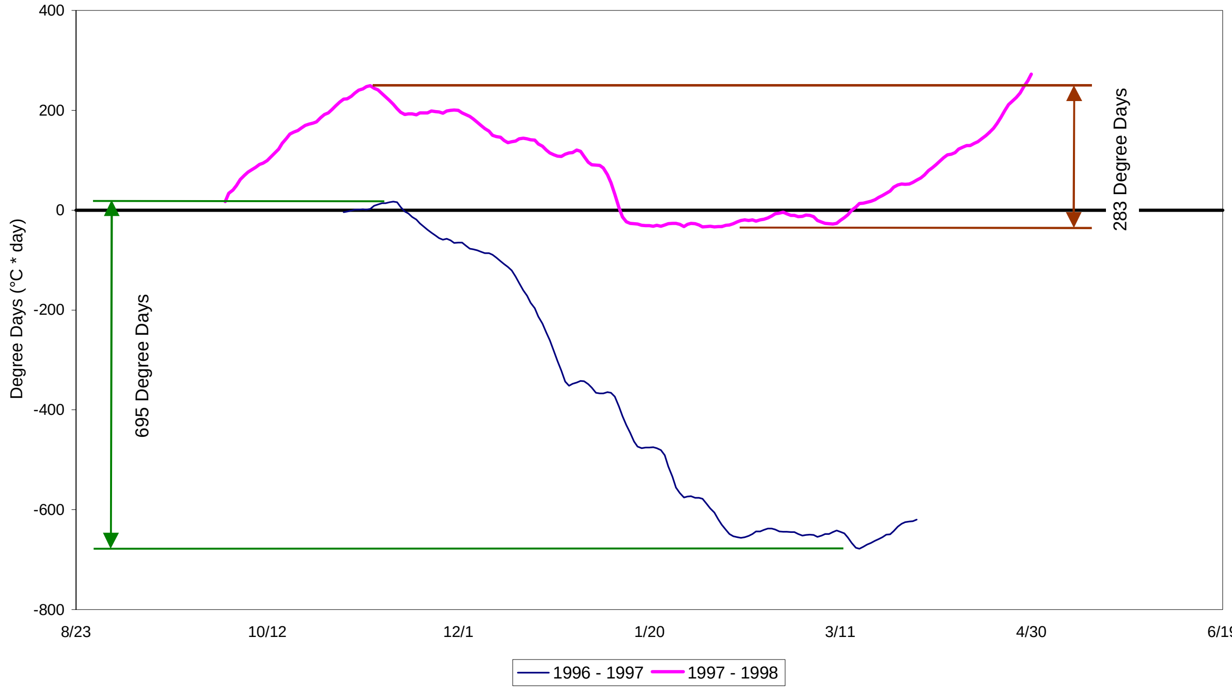

Figure 5. Air-freezing index at Dickey Lake for winter/spring 1996–1997 and 1997–1998.

The measurements in the base were made at a depth of 292 mm (11 in.) from the AC surface, which is about the mid-point of the base layer. Prior to freezing, the mean daily volumetric moisture content in the base was approximately 5.5% (COV = 8.8%) at the start of the 1996–1997 winter, and 6.7% (COV = 5.4%) at the start of the 1997–1998 winter. This is based on the average of the moisture measurements for October. This suggests that the base is a fairly dry material. Although the base was classified as an A-1-a soil, there was a substantial increase in moisture content during the 1997 thaw (~4× the non-frost value). Based on the moisture data, thawing started around March 20th 1997, when the moisture content was greater than 5.5%. The temperature in the base at this time was –2.2°C. The next day (March 21st), the moisture content in the base was approximately 21% and on March 22nd, it peaked around 22% during the 1997 thaw. The temperature in the base at maximum moisture content was –1.7°C.

This increase in moisture content happened at a rate of approximately 9%/1°C. This rapid increase occurred when the temperature in the base was between –4 and –2°C. It is possible that the increase in moisture content was attributable to infiltration of melting snow into the base course from the surface or from melting ice lenses in the base course. Recovery of the base started on

March 23rd and continued to about April 13th, where the moisture content leveled to approximately 7%. The 10 to 13% fines in the base could explain this recovery time. Janoo et al. (Janoo et al, 1997) found that, when base course layers under airport pavements contained more than 3% fines, it affected the rate of moisture dissipation during the thaw period. Based on the assumption that the moisture content in the layer controls the strength of that layer, the critical period for the base lasted approximately 3 days (March 20th–March 22nd) and it required another 20 days to recover to near its original moisture content.

The base freezing index was 553°C degree-days (995°F degree-days) (Figure 6). According to Figure 6, freezing of the base started around November 16th 1996, and thawing started on March 30th 1997. This is 8 days after the base had reached its critical moisture content of 22%.

In 1998, based on the moisture data, thawing began on the 17th of February, when the moisture content first rose above 6.7%, and it peaked at about 29% on the 22nd of February 1998. There was a second peak at about 20% on March 2nd, and a third peak at about 16% on the March 12th. At the start of thaw in 1998, the temperature in the base was –2.0°C. The temperature in the base at maximum moisture content was also –2.0°C.

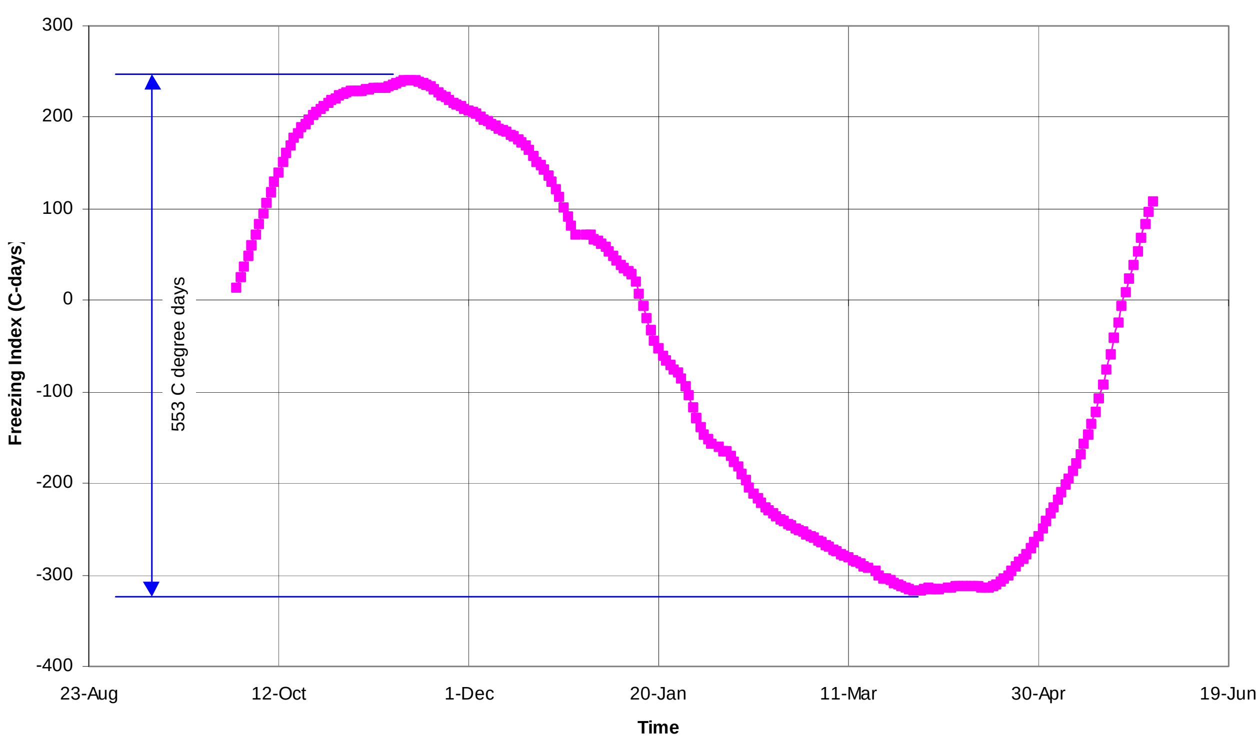

Figure 6. Base freezing index for winter/spring 1996–1997 at Dickey Lake.

On March 30th 1997, the base moisture content was approximately 9%, which was close to its recovered moisture content. It may be coincidental that the time of critical moisture content was the same time as the air freezing index indicated thawing.

The top parts of the subgrade at Dickey Lake were characterized as A-2-4 and A-4 soils using the AASHTO soil classification system (AASHTO, 2002). The first set of measurements in the subgrade that is shown in Figure A-1 was taken at a depth of 30 mm (1.2 in.) below the bottom of the base in the A-2-4 soil. The results from these measurements can be used to infer the response at the top of the subgrade. The response at the top of the subgrade is very important in pavement engineering, as vertical elastic strain on top of the subgrade is currently used in one of the definitions of failure.

The subgrade moisture response (Figure A-1) is similar to that of the base. The mean non-frost moisture content is about 6.2% (COV = 10%) at the start of the 1996–1997 winter, and 6.2% (COV = 9.0%) at the start of the 1997–1998 winter. As with the base, the moisture content dropped rapidly as the subgrade froze. The minimum temperature reached was –11°C during the 1996–1997 winter. During the 1997–1998 winter, a data gap caused the loss of the minimum temperature. When the subgrade was frozen, the moisture content was approximately 0%. Thaw began when there was a rapid increase in moisture content. This rapid increase started around March 24th and became critical on March 25th during the 1996–1997 winter. The temperature in the subgrade on March 24th was –2.3°C. The moisture content peaked at about 35% on March 27th and remained at the peak value for 4 days. Recovery started around April 1st and ended around April 17th. The average moisture content at the end of recovery is approximately 7%. Based on the moisture data, the thaw-weakening period began around March 25th and ended around April 17th—23 days. Again, the significant period of thaw weakening could be attributed to the high fines content in the layer (27% finer than 0.075 mm).

In the 1997–1998 winter, the rapid moisture content increase started about March 13th and became critical on March 14th. The temperature in the subgrade on March 13th was –2.2°C. The moisture content peaked at about at 19% on March 14th. Recovery started around March 14th and ended around April 13th. The average moisture content at the end of recovery is approximately 7%. Based on the moisture data, the thaw-weakening period began around March 13th and ended around April 12th, a period of 30 days. Again the significant period of thaw weakening could be attributed to the high fines content in the layer (27% finer than 0.075 mm).

The ground freezing index at the top of the subgrade is shown in Figure 7. The ground freezing index for the top of the subgrade was 506ºC degree-days (911ºF degree-days). According to the freezing index, freezing started on November 17th and ended on April 17th for the 1996–1997 winter. This means that if we had based the beginning of thaw on temperature, we would have missed the thaw period by 23 days and the subgrade by this time had recovered to its non-frost moisture content.

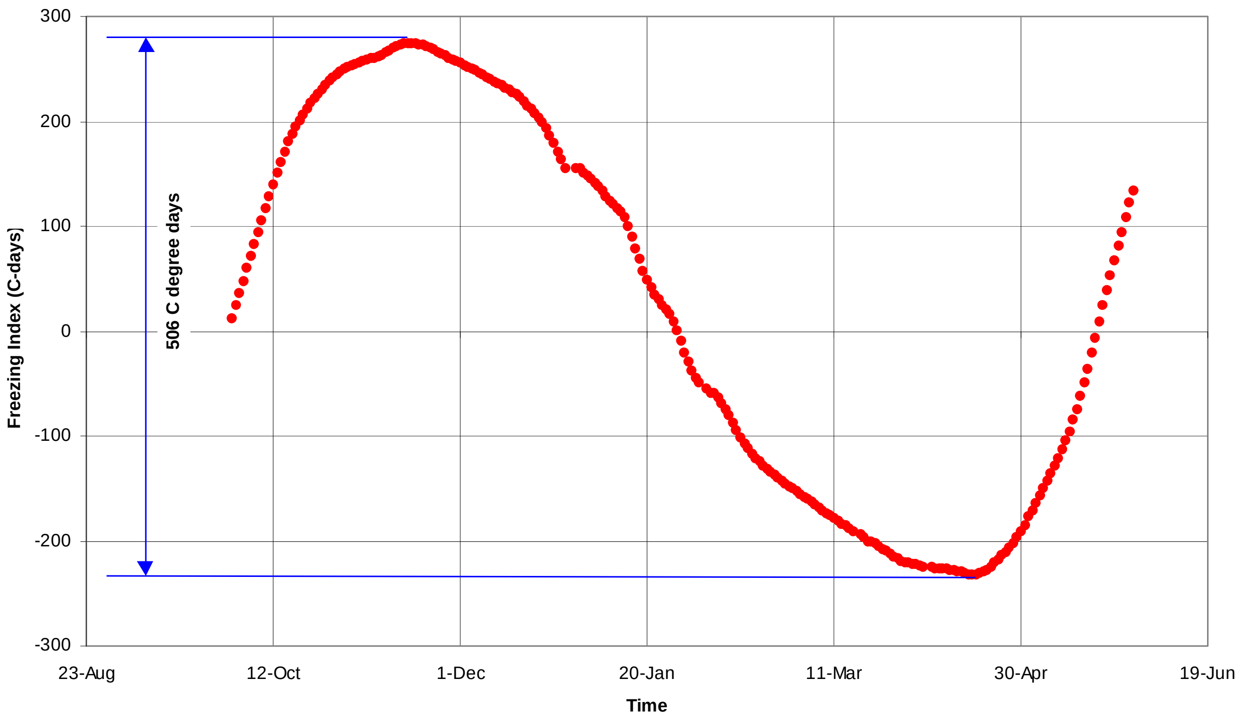

Figure 7. Ground freezing index for top of subgrade for winter/spring 1996–1997 at Dickey Lake.

At location 813 (Figure A-1), 259 mm (10 in.) from the bottom of the base, the non-frost moisture content is approximately 21% (COV = 3%) for the 1996–1997 winter/spring season, and the non-frost moisture content is approximately 20% (COV = 1%) for the 1997–1998 winter/spring season. The minimum temperature at this depth was –6°C in 1996–1997. During the 1997–1998 winter, a data gap caused the loss of the minimum temperature. The mean unfrozen moisture content was approximately 14.5%. During the spring of 1997, thaw occurred (with respect to moisture) when there was a rapid increase in moisture content around April 3rd. The temperature at this depth at this time of rapid moisture increase was –0.6°C. The critical moisture content was 34% and it occurred around April 4th. Recovery began the day after and ended around April 19th. The recovered moisture content was 21%. The ground freezing index at this depth was 188°C degree-days (338°F degree-days). Freezing at this depth started on December 18th and ended on April 16th. Again, as before in the top of the subgrade, if temperatures had been used to determine the thaw period, it would have been missed.

During the spring of 1998, thaw occurred (with respect to moisture) when there was a rapid increase in moisture content around March 15th. The temperature at 259 mm (10 in.) from the bottom of the base at this time of rapid moisture increase was –0.3°C, and did not rise above 0°C until March 16th. The critical moisture content was about 26% and it occurred around March 27th. Recovery began the day after and ended around April 16th. The recovered moisture content was about 20%. At this depth, the start of the freezing period was within the data gap mentioned above.

At the depth of 1168 mm from the surface and below, it is difficult to say if the layer has any significant moisture change during the1997 thaw period (Figure A-1). The soil was classified as an A-1-b soil and has a significant amount of fines (18–24%). The mean non-frost moisture content was around 8%. At this depth, the minimum temperature reached was –4.5 °C. The mean unfrozen moisture content during the winter was close to 0.5%. However, as before, the moisture content began to increase when the subgrade temperature was around –2°C. At the end of thaw, the moisture content rapidly increased to its non-frost value of 8%.

In the fall of 1997, the mean non-frost moisture content was around 6%. However, the moisture content began to increase rapidly when the subgrade temperature was around –1°C on March 15th 1998. The critical moisture content peaked at 17% on March 28th. Recovery began the day after and ended around April 21st. At the end of recovery period, the moisture content had returned to its non-frost value of 6%.

At 1468 mm, during the winter/spring season of 1996–1997, the soil started to freeze around January 19th and started to thaw around March 3rd (Figure A-1). The temperature hovered around the 0°C mark until April 13th. The average non-frost moisture content during the non-frost period is around 15%. The moisture content increased at a rapid rate around March 27th, when the ground temperature was again around –2°C. Again, it is difficult to conclude whether or not there was a period of increased moisture content. It is possible that there may have been an increase of approximately 1.5 to 2× the non-frost moisture content during the spring thaw.

During the 1997–1998 winter/spring seasons, although there is the above-mentioned data gap, the temperatures appear not to have gone below 0°C at this depth (1468 mm). The temperature hovered around the 1°C mark until March 18th. The average non-frost moisture content during the non-frost period is around 12%. The moisture content increased at a rapid rate around March 15th, when the ground temperature was around 1°C. The critical moisture content peaked at around 20% on March 27th. Recovery began the day after and ended around April 21st. There was an increase of approximately 1.5× the non-frost moisture content during the spring thaw at this depth.

In summary, at Dickey Lake, the base course and the upper subgrade layer show significant increase in moisture content during the spring thaw. This suggests that the pavement structure is prone to thaw weakening. Table 5 summarizes the periods of thaw weakening and recovery. The critical periods in Table 5 are based on the time when a rapid increase in moisture content surpasses its non-frost value. At Dickey Lake, the thaw weakening is controlled by the base course. It lasted approximately 25 days in 1997 and 30 days in 1998.

Table 5. Summary of freezing, thaw-weakening periods, and moisture contents at Dickey Lake.

a. 1996–1997 winter.

Layer	Depth (mm)	AASHTO	% finer than 0.075 mm	Start of freezing	End of freezing	Start of critical period	Start of recovery	End of recovery	Thaw-weakening period
Base	292	A-1-a	8-10	18-Nov	26-Mar	20-Mar	22-Mar	13-Apr	20-Mar to April 13
Subgrade	584	A-2-4	28	19-Nov	13-Apr	25-Mar	31-Mar	15-Apr	25-Mar to April 15
	813	A-4	37	20-Dec	13-Apr	3-Apr	5-Apr	16-Apr	3-Apr to April 16
	1168	A-1-b	24	21-Dec	17-Apr	—*	—	—	—
	1468	A-1-b	18	19-Jan	3-Mar	—	—	—	—

* Dashes indicate that there was no weakening at these depths, therefore, no critical period.

Layer	Depth (mm)	Length of (days)				Average volumetric moisture content (%)			
		Freezing	Critical	Recovery	Thaw weakening	Non-frost	Freezing	Critical period	Recovered
Base	292	128	2	22	24	5.5	0	22	7
Subgrade	584	145	6	15	21	6	0	35	7
	813	114	2	11	13	20	4	34	22
	1168	117	—*	—	—	8	0	—	8
	1468	43	—	—	—	15	0	—	15

* Dashes indicate that there was no weakening at these depths, therefore, no critical period.

b. 1997–1998 winter.

Layer	Depth (mm)	AASHTO	%finer than 0.075 mm	Start of freezing	End of freezing	Start of critical period	Start of recovery	End of recovery	Thaw-weakening period
Base	292	A-1-a	8 - 10	12-Nov	18-Mar	7-Feb	22-Feb	15-Mar	7-Feb to 15-Mar
Subgrade	584	A-2-4	28	16-Nov	19-Mar	15-Feb	16-Mar	12-Apr	15-Feb to 19-Mar
	813	A-4	37	ND*	16-Mar	15-Mar	27-Mar	15-Apr	15-Mar to 15-Apr
	1168	A-1-b	24	ND	21-Mar	14-Mar	28-Mar	16-Apr	14-Mar to 16-Apr
	1468	A-1-b	18	ND	†—	14-Mar	28-Mar	18-Apr	—

*ND—Missing temperature data.
† Dashes indicate that there was no weakening at these depths, therefore, no critical period.

Layer	Depth (mm)	Length of Period (days)				Average volumetric moisture content (%)			
		Freezing	Critical	Recovery	Thaw weakening	Non-frost	Freezing	Critical period	Recovered
Base	292	126	15	21	36	7.5	ND	29	7.5
Subgrade	584	123	29	27	56	7	ND	19	7
	813	ND*	12	19	31	20	ND	26	20
	1168	ND	14	19	33	7	1	17	6.5
	1468	ND	14	21	35	12.5	7	19.5	12.5

*ND—Missing temperature data.

Wolf Point

The gradations of the base and subgrade at Wolf Point are shown in Figures 8 and 9. Additional details of the gradation and Atterberg limits can be found in Appendix C. Based on results from sieve analyses, the base was classified as an A-1-b soil. The subgrade varied between an A-6 and an A-7-6 soil (Table C-2). The percentage finer then the 0.075-mm (#200) sieve size in the base ranged between 12 and 15% and in the subgrade, between 50 and 56%. The plasticity index of the subgrade ranged between 19 and 27%. Initial moisture contents taken at the time of instrumentation installation (mid-September, 1996) ranged between 18 and 21% in the subgrade. These readings in the subgrade appear to correlate with the volumetric moisture contents.

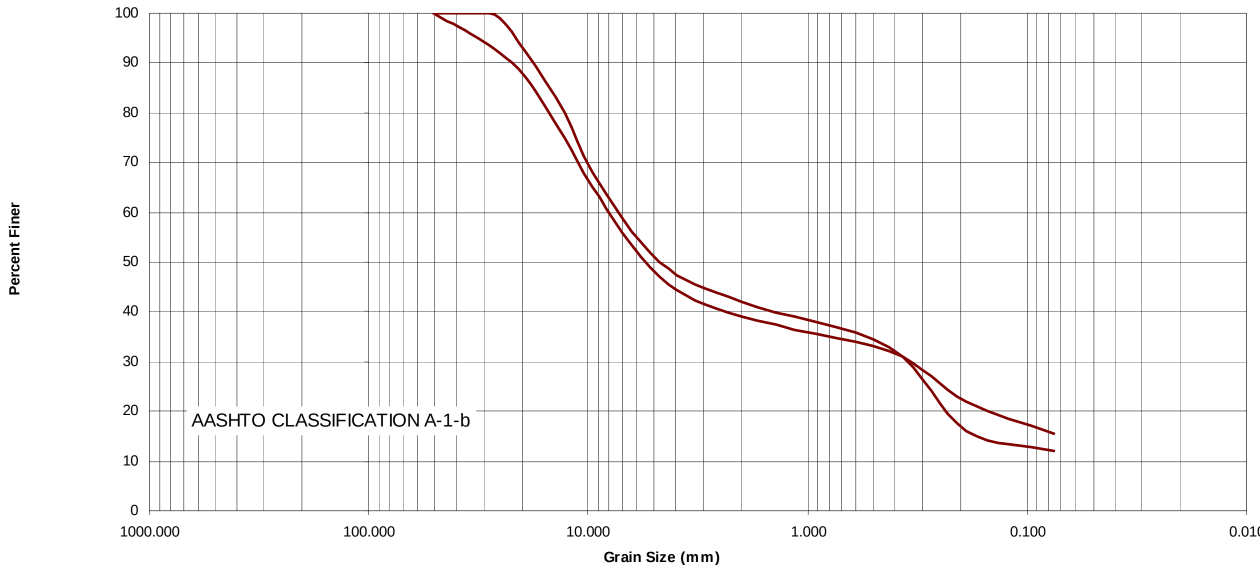

Figure 8. Base course grain size distribution at Wolf Point.

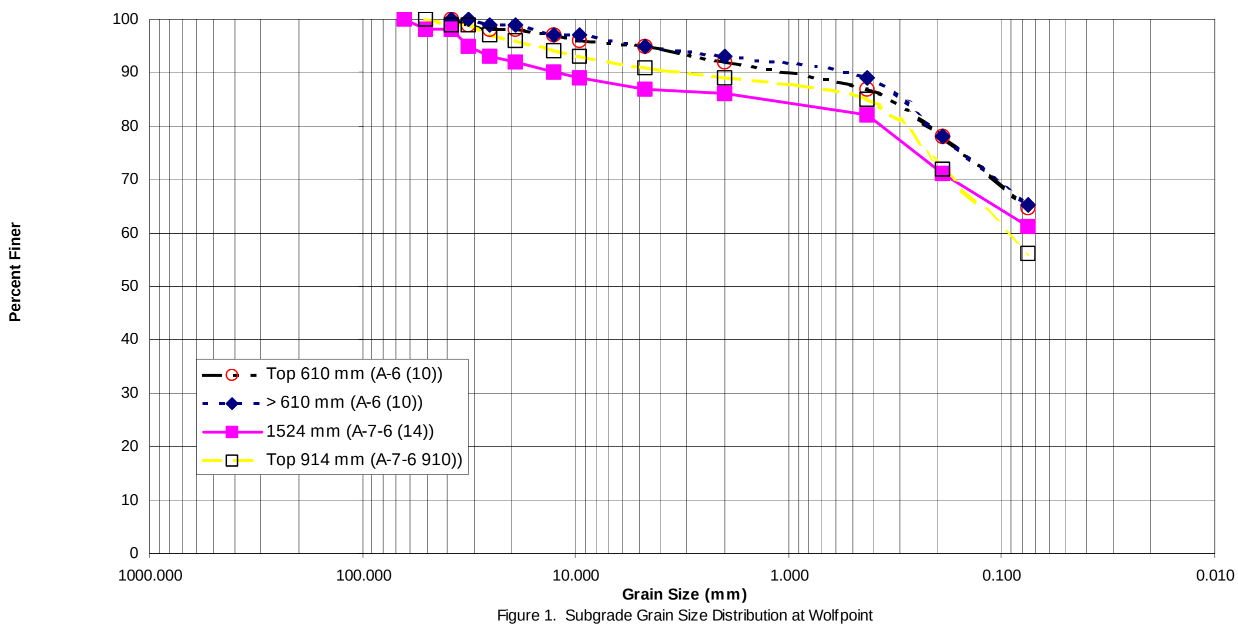

Figure 9. Subgrade grain size distribution at Wolf Point.

The air freezing index at Wolf Point was 1595ºC degree-days (2873ºF degree-days) during the 1996–1997 winter. Freezing started around the end of October and ended around mid-March. Based on the temperature data, frost penetrated to at least 1.8 m (71 in.). The moisture content and temperature data in the base and subgrade are shown in Figures A-2, A-3, A-11, and A-12. Volumetric moisture and temperature data in the pavement structure were missing during part of the winter.

1996–1997 Data Analysis

The non-frost volumetric (month of October) moisture content of 46% (Figures A-2 and A-3) appears to be high. Assuming a specific gravity of 2.65, we can translate this moisture content to a gravimetric moisture content of approximately 17%. Measurements from a nuclear density moisture meter during the installation of the gages in mid-September indicated a gravimetric moisture content around 8%. Either water entered the pavement from the surface or measurements of moisture content in the base course are suspect. However, assuming the trend in moisture content as a function of time is correct, it suggests that there may be a thaw-weakening period.

The minimum temperature reached in the base was –24°C. At around this temperature, the unfrozen moisture content was approximately 10%. The critical moisture content was around 57%, and the critical period was between April 21 and May 3. This thaw-weakening period started later in the spring (approximately 9 days after the end of freezing). The weakening may be attributable to an influx of melting snow into the base course.

The subgrade at Wolf Point was classified as an A-6 to an A-7-6 soil. These soils in general tend to be frost-susceptible. However, based on the moisture contents (Figures A-2 and A-3), the subgrade appears to recover rapidly to its non-frost value during thaw at all depths, with the exception of 914 mm. At this depth, the data suggest some thaw weakening lasting for approximately 4 days. The critical period is for approximately 2 days. Recovery to its non-frost moisture content occurs within the next 2 days. The moisture content during the critical period increased by about 16%, compared to its non-frost value.

A summary of the results for Wolf Point is given in Table 6. The base layer may be prone to thaw weakening. If so, the period of thaw weakening is approximately 2 weeks, staring in mid-April. However, this increase in moisture content is possibly attributable to an influx of melting snow from the surface. The subgrade appears to recover to its non-frost moisture content at the end of thaw. Although freezing temperatures and frost-susceptible soils were found at Wolf Point, there was practically no thaw weakening of the subgrade. This leads to the conclusion that there was no nearby source of water for the freezing front (a deep or nonexistent water table).

Table 6. Summary of freezing and thaw-weakening periods, and moisture contents at Wolf Point.

a. 1996–1997 winter.

Layer	Depth (mm)	AASHTO	% finer 0.075 mm	Start of freezing	End of freezing	Start of critical period	Start of recovery	End of recovery	Thaw-weakening Period
Base	229	A-1-b	12-15	8-Nov	12-Apr	21-Apr	3-May	9-May	21-Apr to 3-May
Subgrade	381	A-6	65	13-Nov	26-Mar	—†	—	—	—
	762	A-6	65	23-Nov	18-Apr	—	—	—	—
	914	A-7-6	56	29-Nov	22-Apr	21-Apr	23-Apr	25-Apr	21-Apr to 25-Apr
	1118	A-7-6	57	30-Nov	8-May	—	—	—	—
	1422	A-7-6	60	ND*	13-May	—	—	—	—
	1803	A-7-6	62	22-Jan	19-May	—	—	—	—

*ND – Missing temperature data.
† Dashes mean that data do not show event to have occurred.

Layer	Depth (mm)	Length of (days)				Average volumetric moisture content (%)			
		Freezing	Critical	Recovery	Thaw weakening	Non-frost	Freezing	Critical period	Recovered
Base	229	155	12	6	18	46	8	57	37
Subgrade	381	133	—†	—	—	39	19	—	39
	762	146	—	—	—	40	22	—	40
	914	144	2	2	4	37	19	41	37
	1118	159	—	—	—	40	21	—	36
	1422	ND*	—	—	—	42	34	—	41
	1803	117	—	—	—	39	36	—	39

*ND – Missing temperature data.
† Dashes mean that data do not show event to have occurred.

b. 1997–1998 winter.

Layer	Depth (mm)	AASHTO	%finer than 0.075 mm	Start of freezing	End of freezing	Start of critical period	Start of recovery	End of recovery	Thaw-weakening period
Base	229	A-1-b	12 - 15	10-Nov	22-Mar	14-Feb	18-Feb	22-Mar	14- Feb to 22-Mar
Subgrade	381	A-6	65	14-Nov	25-Mar	21-Feb	24-Feb	27-Mar	21-Feb to 27-Mar
	762	A-6	65	11-Dec	2-Apr	—*	—	—	—
	914	A-7-6	56	7-Jan	9-Apr	—	—	—	—
	1118	A-7-6	57	27-Dec	16-Apr	—	—	—	—
	1422	A-7-6	60	17-Jan	15-Apr	—	—	—	—
	1803	A-7-6	62	—	—	—	—	—	—

* Dashes mean that data do not show event to have occurred.

Layer	Depth (mm)	Length of Period (days)				Average volumetric moisture content (%)			
		Freezing	Critical	Recovery	Thaw weakening	Non frost	Freezing	Critical period	Recovered
Base	229	132	4	32	36	33	18.5	43	32
Subgrade	381	131	3	31	34	38	30	38	38.5
	762	112	0	0	0	37.5	30	—*	38
	914	92	0	0	0	35	25.5	—	34
	1118	110	0	0	0	34	28	—	34
	1422	88	0	0	0	—	—	—	—
	1803	0	0	0	0	—	—	—	—

* Dashes mean that data do not show event to have occurred.

1997–1998 Data Analysis

The non-frost volumetric (month of October) base moisture content was 35%. The minimum temperature reached in the base was –20°C. The critical moisture content was around 43%, and the critical period was between 14 and 18 February. Based on the moisture contents (Figures A-2 and A-3), the subgrade appears to recover rapidly to its non-frost value during thaw at all depths.

A summary of the results for Wolf Point is given in Table 6. There appears to have been no thaw weakening in the spring of 1998. As mentioned earlier, although freezing temperatures and frost-susceptible soils were found at Wolf Point, there was practically no thaw weakening of the subgrade. This again supports the conclusion that there was no nearby source of water for the freezing front (i.e., the water table is either deep or nonexistent).

Sweetgrass

The response of the moisture during the thaw period is similar to that of Wolf Point. With the possible exception of the base, there is no indication of thaw weakening based on the response of the moisture content in the base and subgrade.

The base was mostly classified as an A-1-a soil (Figure 10). The subgrade was classified between an A-4 and an A-6 soil (Figure 11). The percent finer than 0.075 mm (#200) sieve ranged between 7.5 and 13% in the base and between 47 and 68% in the subgrade. Details of the gradation can in found in Table C-3.

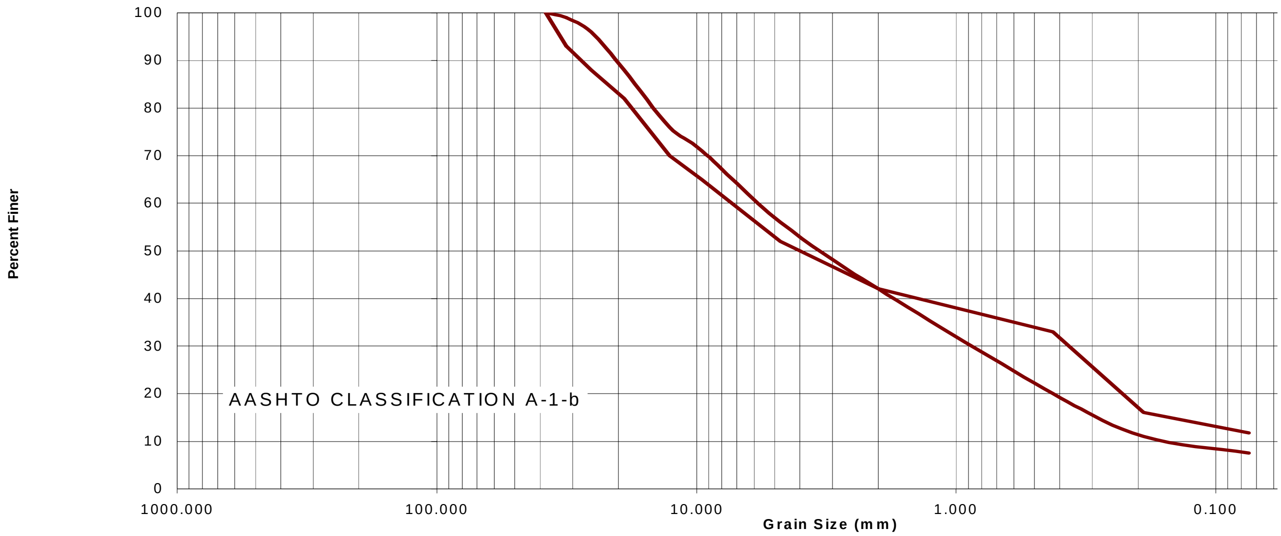

Figure 10. Base course grain size distribution at Sweetgrass.

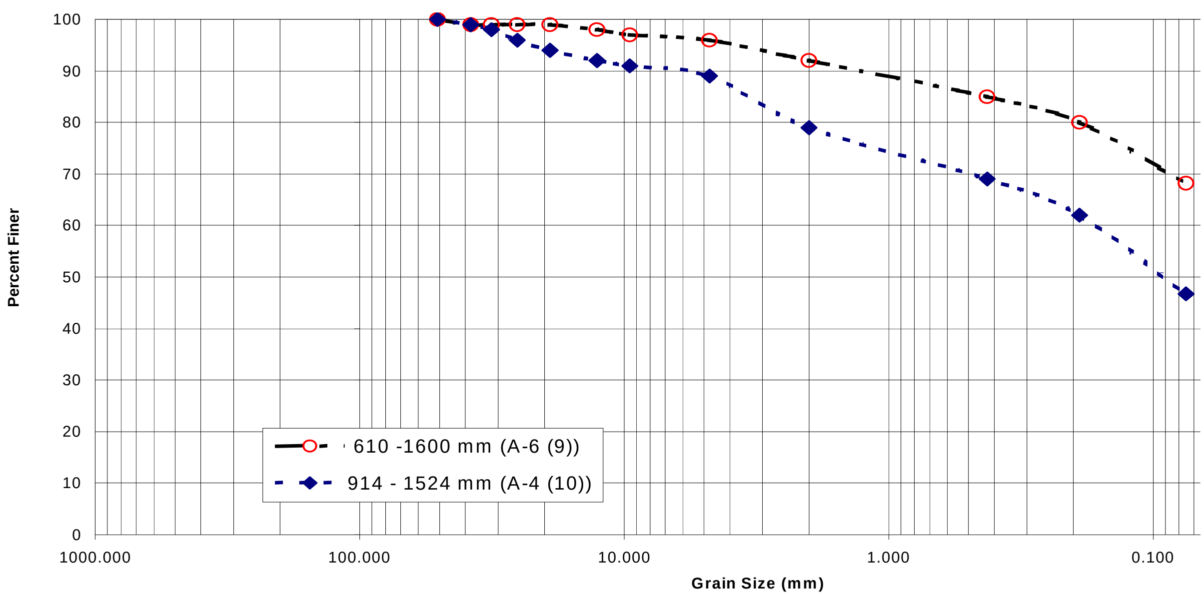

Figure 11. Subgrade grain size distribution at Sweetgrass.

1996–1997 Data Analysis

Detailed moisture and temperature data for the winter and spring 1996–1997 period can be found in Figures A-4, A-5, A-13, and A-14. The air freezing index at this site was 841ºC degree-days (1346ºF degree-days). The base (Figure A-13) started to freeze around mid-November and was thawed by late March. The measured minimum temperature in the base was –16°C. The non-frost moisture content was around 4%. When frozen, the moisture content dropped to zero and at the end of thaw recovered to 4%.

The subgrade started to freeze around the same time and it was completely thawed by the middle to third week of April. There was no increase in moisture content during the spring thaw. At the end of winter, the moisture content rapidly increased to its non-frost value, as shown in Figure A-4. We can conclude that the pavement structures at Sweetgrass do not undergo any thaw weakening. The results are summarized in Table 7. Again, as seen at Dickey Lake, the rapid increase in moisture content during spring thaw occurs around –2.5°C. This rapid increase in moisture content occurred about 2 weeks prior to when the ground temperature was above 0°C.

1997–1998 Data Analysis

Detail temperature and moisture data for the winter spring 1997–1998 period can also be found in Figures A-4, A-5, A-13, and A-14. Because of a gap in the data (mid-November to mid-February), it is not possible to tell when the base or subbase started to freeze. However, the base was thawed by mid-March. The measured minimum temperature in the base was -3.5°C; however, the data gap is large enough that lower temperatures may have occurred. The non-frost moisture content was around 4%. At the end of thaw, the moisture content recovered to 4%.

The subgrade was completely thawed by the second or third week of April. The moisture content plot shows that there was no increase in it above the non-frost value during the spring thaw. At the end of winter, the moisture content rapidly increased to its non-frost value, as shown in Figures A-4 and A-5. We can conclude that the pavement structures at Sweetgrass did not undergo any thaw weakening this season. The results are summarized in Table 7. Like Dickey Lake, the rapid increase in moisture content during spring thaw occurs around –2.5°C. (Where the data gap doesn't hide the response of the subgrade. Below 1087 mm, the data gap hides the response of the subgrade to freezing and thawing.) This season, the rapid increase in moisture content occurred about 4 weeks prior to when the ground temperature was above 0°C.

Table 7. Summary of freezing, thaw-weakening periods and moisture contents at Sweetgrass.

a. 1996–1997 winter.

Layer (mm)	Depth	AASHTO	% finer than 200	Start of freezing	End of freezing	Start of critical period	Start of recovery	End of recovery	Thaw weakening period
Base	572	A-1-a & A-1-b	8-13	15-Nov	25-Mar	—*	—	—	—
Subgrade	864	A-6	68	19-Nov	15-Apr	—	—	—	—
	1087	A-6	47-68	24-Nov	17-Apr	—	—	—	—
	1237	A-6 & A-4	47-68	28-Nov	17-Apr	—	—	—	—
	1387	A-6 & A-4	47-68	11-Dec	19-Apr	—	—	—	—
	1586	A-6 & A-4	68	13-Jan	26-Mar	—	—	—	—
	1887	A-6	—	4-Jan	22-Apr	—	—	—	—
	2289	—	—	26-Jan	21-Apr	—	—	—	—

* Dashes indicates that there was no weakening at these depths, therefore, no critical period.

Layer	Depth (mm)	Length of (days)				Average volumetric moisture content (%)			
		Freezing	Critical	Recovery	Thaw weakening	Non-frost	Freezing	Critical period	Recovered
Base	572	130	—*	—	—	3	0	—	4
Subgrade	864	147	—	—	—	28	8	—	30
	1087	144	—	—	—	34	16	—	35
	1237	140	—	—	—	37	21	—	37
	1387	129	—	—	—	31	25	—	34
	1586	72	—	—	—	37	30	—	38
	1887	108	—	—	—	31	27	—	32
	2289	85	—	—	—	35	—	—	35

* Dashes indicates that there was no weakening at these depths, therefore, no critical period.

b. 1997–1998 winter.

Layer	Depth (mm)	AASHTO	%finer than 0.075 mm	Start of freezing	End of freezing	Start of critical period	Start of recovery	End of recovery	Thaw-weakening period
Base	572	A-1-a & A-1-b	8-13	13-Nov	20-Mar	—*	—	—	—
Subgrade	864	A-6	68	—	24-Mar	—	—	—	—
	1087	A-6	47-68	—	25-Mar	—	—	—	—
	1237	A-6 & A-4	47-68	—	25-Mar	—	—	—	—
	1387	A-6 & A-4	47-68	—	25-Mar	—	—	—	—
	1586	A-6 & A-4	68	—	—	—	—	—	—
	1887	A-6	—	—	—	—	—	—	—
	2289	—	—	—	—	—	—	—	—

* Dashes indicates that there was no weakening at these depths, therefore, no critical period.

Layer	Depth (mm)	Length of Period (days)				Average volumetric moisture content (%)			
		Freezing	Critical	Recovery	Thaw weakening	Non-frost	Freezing	Critical period	Recovered
Base	572	127	—*	—	—	3.5	—	—	3.5
Subgrade	864	—	—	—	—	29	—	—	30
	1087	—	—	—	—	34.5	—	—	34
	1237	—	—	—	—	36	—	—	36
	1387	—	—	—	—	40.5	—	—	40
	1586	—	—	—	—	38	—	—	37
	1887	—	—	—	—	33.5	—	—	31.5
	2289	85	—	—	—	35	—	—	35

* Dashes indicates that there was no weakening at these depths, therefore, no critical period.

Scobey/Redstone

The base was clsssified as an A-1-b. The subgrade was classified as an A-6 (Figures 12 and 13). Additional details of the gradation and Atterberg limits can be found in Table C-4. The percentage finer than the 0.075 mm (#200) sieve was about 15% in the base and approximately 65% in the subgrade.

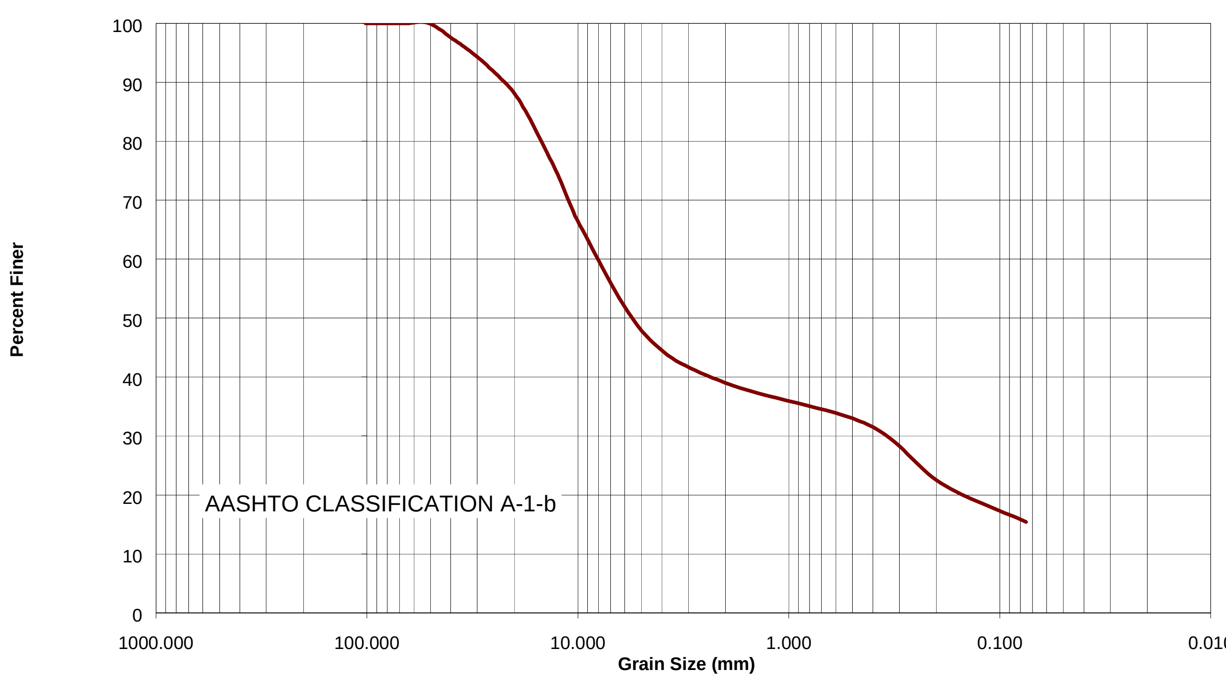

Figure 12. Base course grain size distribution at Scobey/Redstone.

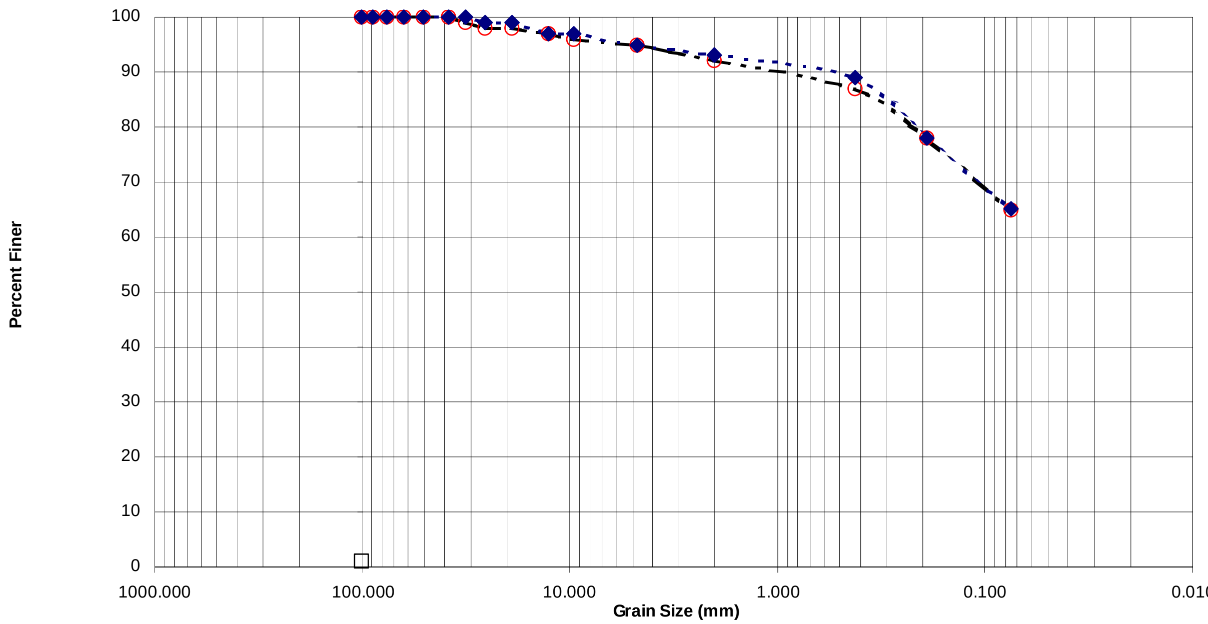

Figure 13. Subgrade grain size distribution at Scobey/Redstone.

The response at Scobey/Redstone is similar to that of Sweetgrass. The base is prone to thaw weakening and the subgrade in general is not. The moisture and daily mean temperature measurements are presented in Figures A-6, A-7, A-15, and A-16. Subsurface moisture and temperature data were missing during both winter periods (1996–1997 and 1997–1998). The air freezing index for this site was 1346ºC degree-days (2442ºF degree-days).

1996–1997 Data Analysis

The non-frost moisture content in the base course was 21% (Figure A-6). During the winter, the mean air temperature reached a minimum of –32°C. The minimum average daily temperature during the winter in the base layer was at least –17°C. At this temperature, the unfrozen moisture content was around 5%. There was a rapid increase in the moisture content on March 20th, when the base temperature was –1.5°C. The critical moisture content of 25% was reached 2 days later. Recovery of the base course started on March 22nd and was completed by March 29th. The base had a thaw-weakening period of approximately 9 days.

The subgrade at all depths, with the exception of 965 mm, recovered to its non-frost moisture content at the end of freezing (Figures A-6 and A-7). At 965 mm, there was some thaw weakening of the layer. The critical period was for about a day. Full recovery took place by 5 days. The thaw-weakening period lasted about 6 days. A summary of the freezing, thawing and moisture content at various depths are presented in Table 8.

Table 8. Summary of freezing, thaw-weakening periods and moisture contents at Scobey/Redstone.

a. 1996–1997 winter.

Layer (mm)	Depth	AASHTO	% finer than 200	Start of freezing	End of freezing	Start of critical period	Start of recovery	End of recovery	Thaw-weakening period
Base	305	A-1-b	15	12-Nov	22-Mar	20-Mar	22-Mar	24-Mar	20-Mar to 24-Mar
Subgrade	445	A-6	65	12-Nov	26-Mar	—	—	—	—
	673	A-6	65	20-Nov	15-Apr	—	—	—	—
	813	A-6	65	—*	18-Apr	—	—	—	—
	965	A-6	65	—	21-Apr	19-Apr	20-Apr	25-Apr	19-Apr to 25-Apr
	1168	A-6	65	10-Dec	28-Apr	—	—	—	—
	1473	A-6	65	26-Dec	5-May	—	—	—	—
	1867	A-6	65	—	14-May	—	—	—	—

* Dashes indicates that there was no weakening at these depths, therefore, no critical period.

Layer	Depth (mm)	Length of (days)				Average volumetric moisture content (%)			
		Freezing	Critical	Recovery	Thaw weakening	Non-frost	Freezing	Critical period	Recovered
Base	305	130	2	2	4	21	6	25	21
Subgrade	445	134	—*	—	—	33	10	—	34
	673	146	—	—	—	33	14	—	33
	813	—	—	—		33	17	—	33
	965	—	1	5	6	32	20	39	32
	1168	139	—	—	—	33	18	—	32
	1473	100	—	—	—	29	18	—	28
	1867	—	—	—	—	27	23	—	27

* Dashes indicates that there was no weakening at these depths, therefore, no critical period.

b. 1997–1998 winter.

Layer	Depth (mm)	AASHTO	%finer than 0.075 mm	Start of freezing	End of freezing	Start of critical period	Start of recovery	End of recovery	Thaw-weakening period
Base	305	A-1-b	15	14-Nov	—*	—	—	—	—
Subgrade	445	A-6	65	15-Nov	26-Mar	—	—	—	—
	673	A-6	65	13-Dec	1-Apr	—	—	—	—
	813	A-6	65	—	3-Apr	—	—	—	—
	965	A-6	65	7-Jan	6-Apr	—	—	—	—
	1168	A-6	65	12-Jan	10-Apr	—	—	—	—
	1473	A-6	65	19-Jan	10-Apr	—	—	—	—
	1867	A-6	65	—	—	—	—	—	—

* Dashes indicates that there was no weakening at these depths, therefore, no critical period.

Layer	Depth (mm)	Length of Period (days)				Average volumetric moisture content (%)			
		Freezing	Critical	Recovery	Thaw weakening	Non-frost	Freezing	Critical period	Recovered
Base	305	—	—*	—	—	18	12	—	20
Subgrade	445	131	—	—	—	33	4	—	33
	673	109	—	—	—	31	9.5	—	31
	813	—	—	—	—	31	8.5	—	30
	965	89	—	—	—	31	25.5	—	31
	1168	88	—	—	—	34	27.5	—	32
	1473	81	—	—	—	27	30	—	27.5
	1867	—	—	—	—	—	—	—	—

* Dashes indicates that there was no weakening at these depths, therefore, no critical period.

1997–1998 Data Analysis

The non-frost moisture content in the base course was 20% (Figure A-6). During the winter, the mean air temperature reached a minimum of –32°C. There was a rapid increase in the moisture content on February 20th, when the base temperature was –0.6°C. A data gap hides whether there was a critical moisture content or not.

The subgrade at all depths recovered to its non-frost moisture content at the end of freezing (Figures A-6 and A-7). A data gap prevents any conclusions about whether there was or was not a thaw-weakening period for this spring season.

A summary of freezing, thawing, and moisture content at various depths is presented in Table 8. There was some thaw weakening of the base and subgrade at Scobey/Resdstone, under some conditions of temperatures, but others did not produce thaw weakening. The thaw-weakening period, when it occurs, is for about a week. At this site, we found that the rapid increase in moisture content started when the ground warmed up to around –1.5 to –1°C.

East Glacier

Figure 14 indicates that the base course is an A-4 soil. The amount of fine material is about 84%. The subgrade (Figure 15) classifies as an A-6 material, with the percentage of fines in the area of 65%. Additional detail on the gradation and Atterberg limits can be found in Table C-5.

The mean daily moisture contents and temperatures as a function of depth are presented in Figures A-7, A-8, A-16, and A-17. The critical period for 1996–1997, based on moisture content, started on April 2nd and remained critical until April 22nd. Recovery started on April 23rd and was fully completed after April 26th. The thaw-weakening period for the base layer was approximately 3 weeks. The moisture content during the critical period was 10% more than its non-frost value of 28%. The rapid increase in moisture content occurs when the base temperature was around –1.0°C. No air temperature was available for this site for determining the air freezing index.

There are no data for the fall, winter, and spring of 1997–1998.

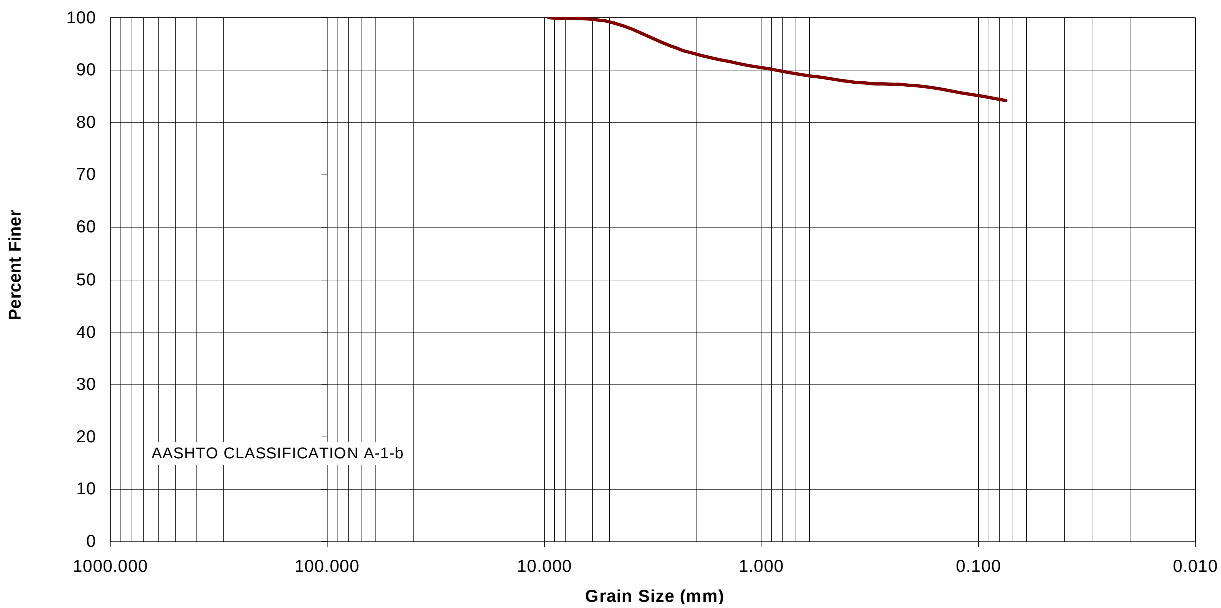

Figure 14. Base course grain size distribution at East Glacier.

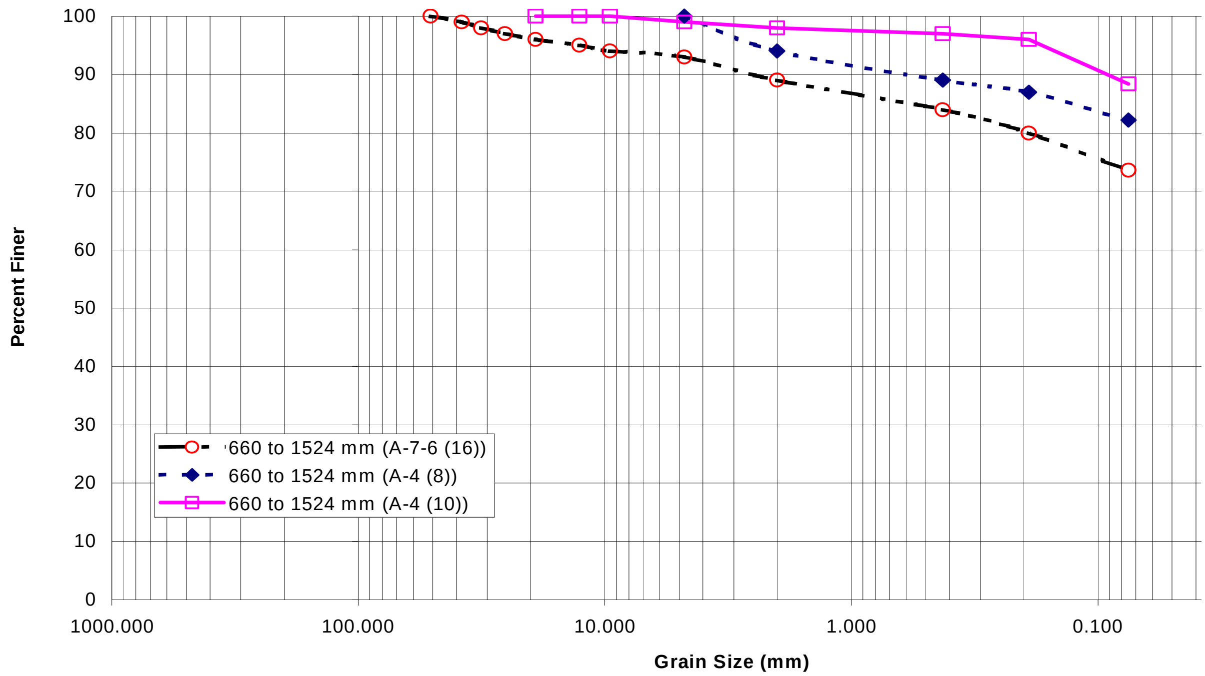

Figure 15. Subgrade grain size distribution at East Glacier.

Based on the moisture measurements, the critical period for the top part of the subgrade (z ≤1260 mm) started between April 16th and 18th. However, the moisture content did not recover to its non-frost value at the end of May. The non-frost moisture content varied between 34 and 37%. The critical moisture content varied between 41 and 47%. The unfrozen moisture content during the winter varied between 14 and 22%. Starting at 1461 mm and below, there was no increase in moisture content during thaw and this area recovered rapidly to its non-frost value. Table 9 gives these results.

In summary, moisture and temperature data from five sites were used to evaluate the potential for thaw weakening. These sites were limited to the northern half of Montana, as data were unavailable from the southern sites either owing to malfunction of instrumentation or because they were not collected during the period of analysis.

Table 9. Summary of freezing, thaw-weakening periods and moisture contents at East Glacier, 1996–1997 winter.

Layer (mm)	Depth	AASHTO	% finer 200	Start of freezing	End of freezing	Start of critical period	Start of recovery	End of recovery	Thaw-weakening period
Base	457	A-4	84	20-Nov	23-Apr	2-Apr	23-Apr	26-Apr	2-Apr to 26-Apr
Subgrade	737	A-6	85	21-Nov	26-Apr	16-Apr	> 30-May	—*	—
	1110	A-6	85	26-Nov	29-Apr	17-Apr	> 30-May	—	—
	1260	A-6	85	27-Nov	3-May	18-Apr	> 30-May	—	—
	1461	A-6	85	7-Dec	5-May	—	—	—	—
	1760	A-6	85	22-Dec	7-May	—	—	—	—
	2161	A-6	85	—	—	—	—	—	—

* Dashes indicates that there was no weakening at these depths, therefore, no critical period.

Layer	Depth (mm)	Length of period (days)				Average volumetric moisture content (%)			
		Freezing	Critical	Recovery	Thaw weakening	Non-frost	Freezing	Critical period	Recovered
Base	457	154	21	3	24	28	11	38	29
Subgrade	737	156	—*	—	> 44	37	22	41	—
	1110	154	—	—	>43	34	14	47	—
	1260	157	—	—	>42	35	20	42	—
	1461	149	—	—	—	38	25	—	38
	1760	136	—	—	—	39	26	—	39
	2161	None	—	—	—	40	—	—	40

* Dashes indicates that there was no weakening at these depths, therefore, no critical period.

Out of the five sites, the base courses mostly graded between an A-1-a and A-1-b. Although classified as granular material, the percentage of fines in the base varied between 8 and 15%. The exception to this was at East Glacier, where it graded out as an A-4. The subgrades at these sites were variable, ranging among A-1-b, A-2-4, A-4, and A-6. Water table locations were not available from these sites and we surmised that the water table was either deep or nonexistent at Wolf Point, Sweetgrass, and Scobey/Redstone.

Based on the moisture content, the base course layers at Dickey Lake, Wolf Point, Scobey/Redstone, and East Glacier are prone to thaw weakening. The length of thaw weakening varied from 4 days (Scobey/Redstone) to 3 weeks (East Glacier). The top of the subgrade at Dickey Lake and East Glacier are also prone to thaw weakening.

BACK-CALCULATION OF LAYER MODULI

The current pavement design procedure in the *AASHTO Guide for the Design of Pavement Structures* (AASHTO, 1993) requires the effective resilient modulus of the subgrade. This effective resilient modulus is a weighted mean of the monthly resilient moduli and is a function of the expected damage to the pavement structure. This effective resilient modulus is a single value that produces the same amount of damage to the pavement structure when compared with the damage obtained from the use of seasonal subgrade moduli.

The elastic moduli of the asphalt concrete pavement surface, base, and subgrade were computed using the back-calculation routine WESDEF. This program was developed by the U.S. Army Waterways Experiment Station (WES). Briefly, WESDEF is a five-layer system that uses all the measured surface deflections, initial layer moduli, and an iterative procedure to determine the moduli of the surface, base, and subgrade layers. The bottom layer is automatically set as a rigid layer of infinite depth. In early work, WES found that they were able to obtain closer agreement between measured and calculated deflections when an artificial rigid layer was placed at 6 m. The location of this rigid layer can be manually overridden, and any depth to bedrock can be used. Our experience has been that the best results are obtained when the number of unknown moduli layers is limited to three. A solution is obtained when the program matches the calculated to the measured deflection. The error between the calculated and measured deflections is indicated by an absolute arithmetic (AA) sum of the difference between the two. A zero error will indicate a perfect match. An acceptable AA sum error for this study was defined to be less than 20%.

Prior to the back-calculation process, a simple error check was conducted on the deflection data. The data were checked to see if the six deflections starting under the center plate to the last sensor located at 1.2 m (4 ft) followed a smooth, decreasing trend as the sensor spacing increased. This is based on the theory that the further sensors are more influenced by the deeper layers and the combined deflections decrease with distance from the point of loading. Points that did not follow the decreasing trend, as determined by visual observation, were not used in the analysis.

As mentioned earlier, deflection tests and measurements in 1996–1997 were obtained from the Road Rater. Surface deflections were generated by applying steady-state dynamic loads ranging from 9 to 22 kN. Deflections were measured at distances of 0, 203, 305, 610, 914 and 1219 mm from the center of the plate. In several cases, deflections were reported at four or five of the sensor spacings. Each load was applied one time at each of the 21 locations in the majority of tests, except when some re-tests were done. For the Road Rater testing in 1996–1997, only the deflections obtained from the 18-kN load were used in the back-calculation, as it was the only load common to all tests.

The 1997–1998 deflection tests and measurements were obtained using the JILS FWD. The deflections were generated by applying falling weight loads ranging from 27 to 62 kN (6000 to 16,000 lb). The deflections were measured at 0, 203, 305, 457, 610, 914, and 1219 mm (0, 8, 12, 18, 24, 36, and 48 in.) from the center of the plate. In several cases, deflections were reported for only four or five of the sensors. Each load was applied one time at each of the 21 locations in the majority of tests, except when some re-tests were done.

There are many ways to use a back-calculation tool. The process is sensitive to layer thicknesses and in some programs it can be sensitive to the initial layer moduli used to start the process. Our experience with WESDEF is that it is not sensitive to the initial seed moduli. For thin asphalt layers, less than 75 mm, the back-calculated surface modulus can be in error. The usual practice is either determining the modulus using other techniques, such as the spectral analysis of surface waves (SASW), or estimating the modulus from laboratory tests. Either of these values can then be used as a constant in the back-calculation process.

In this study all the layer moduli were back-calculated. The pavement structure was idealized as a three-layer system. A rigid layer was placed at a depth of 6 m, with the exception of Dickey Lake where bedrock existed at 1.5 m. The moduli and Poisson's ratio used in the process are given in Table 10.

Table 10. Initial and range of layer moduli used in WESDEF.

Material Type	Estimated initial modulus (MPa)	Minimum modulus (MPa)	Maximum modulus (MPa)	Poisson's ratio
Asphalt concrete	5516	1379	27579	0.35
Base or subbase	414	14	1379	0.35
Subgrade	140	14	1379	0.40

Other attempts were made to see if we could further reduce the error. For example, we tried assigning a surface elastic modulus and having WESDEF back-calculate only the base and subgrade moduli. The asphalt concrete modulus was estimated from the Asphalt Institute model (Asphalt Institute, 1982). This did not reduce the error; instead, it increased the error. Another attempt was to divide the subgrade into more than one layer based on changes in moisture content or between frozen and unfrozen layers. This attempt also did not reduce the AA error. The results presented in the following tables are from the first attempt at back-calculating all layers. Based on our experience, we found that the subgrade modulus is not significantly affected by any of the methods and thus can tolerate significantly higher error. The impact is usually on the base and the asphalt concrete layers.

The back-calculated base course and asphalt concrete moduli are presented in Tables 11 through 20. With respect to the base course, it is difficult to conclude the thaw weakening potential of the base course from the FWD deflections. Back-calculated base course moduli should be used with caution, as the error in the predicted modulus increases as one gets closer to the surface. The current results are limited and show some scatter, therefore a trend is difficult to formulate. However, the moisture measurements in the base course presented earlier suggests the possibility of thaw weakening. The authors suggest that an in-depth laboratory study on the resilient behavior of base courses be conducted and the results from the field FWD tests be correlated to the lab results before any relations are presumed from the back-calculated base course moduli presented in this report.

The results for the subgrade, base, and asphalt concrete layers from Dickey Lake, East Glacier, Bull Mountain, Livingston, Swan Lake, Alzada, Wolf Point, Scobey/Redstone, Loma, and Sweetgrass are presented in Tables 11 through 20 and in Figures B-1 through B-20.

It is apparent from reviewing the results that, in many cases, testing during the critical period was missed. This is illustrated in Figures 16 and 17 for the subgrade at Dickey Lake and in the base at East Glacier, respectively. However, based on the existing results, it is possible to surmise that at Alzada, Livingston, Loma, and Sweetgrass there is no thaw weakening of the base and subgrade. Thaw weakening may be a problem at Bull Mountain, Wolf Point (base), Swan Lake, and Scobey/Redstone (base). It is difficult to conclude whether thaw weakening is a critical problem based on the deflection data at Dickey Lake and East Glacier. Moisture data indicate that these two areas may be prone to thaw weakening.

In Tables 11 through 15, the headings include the temperature measured by the Vitel probes in the base course and the top of the subgrade. In Tables 16 through 20 there is only the back-calculated moduli, since the temperature and moisture measurement systems failed early in the test program.

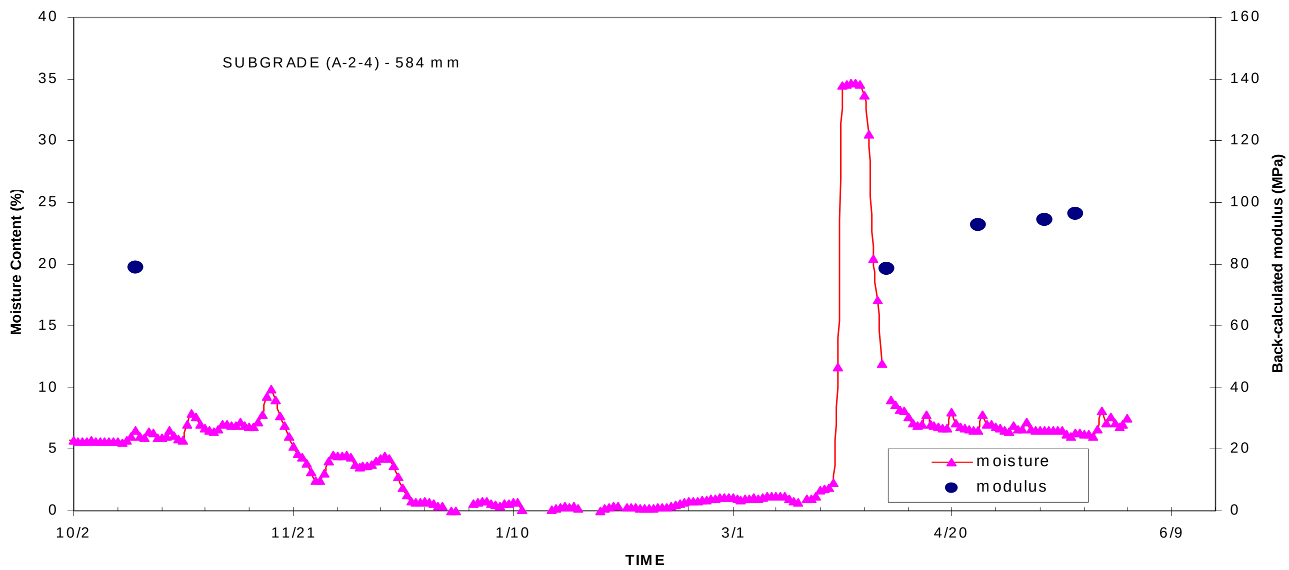

Figure 16. Back-calculated subgrade modulus and moisture content as a function of time at Dickey Lake.

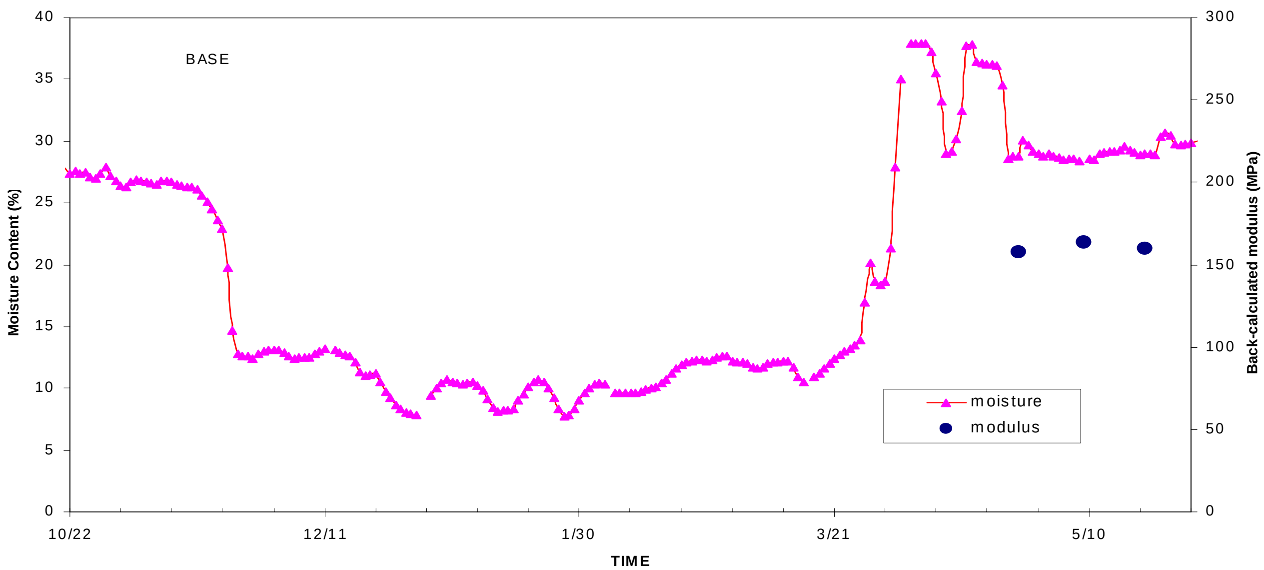

Figure 17. Back-calculated base modulus and moisture content as a function of time at East Glacier.

Table 11. Back-calculated layer moduli at Dickey Lake.

Thickness (mm)	127.0		426.7					919.5					AA
	AC		Base					Subgrade					
Date	Back-calculated modulus		Temperature		Moisture content	Back-calculated modulus		Temperature		Moisture content	Back-calculated modulus		
	(MPa)	(psi)	(ºC)	(ºF)	(%)	(MPa)	(psi)	(ºC)	(ºF)	(%)	(MPa)	(psi)	(%)
16-May-96	11659.5	1,691,006	—†	—	—	193.7	28,099	—	—	—	61.9	8,984	8.7
29-May-96	1692.8	245,518	—	—	—	287.8	41,744	—	—	—	53.4	7,740	14.7
18-Jun-96	9094.9	1,319,061	—	—	—	339.4	49,228	—	—	—	92.7	13,445	9.7
24-Jul-96	6398.1	927,933	—	—	—	459.4	66,624	—	—	—	133.6	19,380	25.9
17-Sep-96	8122.7	1,178,052	—	—	—	410.6	59,555	—	—	—	122.5	17,763	23
16-Oct-96	5779.5	838,222	7.9	46.2	5.3	528.3	76,615	9.1	48.4	6.5	79.1	11,468	33
5-Apr-97	10607.2	1,538,392	7.9	46.2	2.4	832.0	120,671	7.0	44.6	1.3	78.6	11,398	5.8
26-Apr-97	7915.1	1,147,942	7.1	44.8	8.3	287.0	41,629	6.4	43.5	6.5	92.9	13,475	5.4
11-May-97	3669.8	532,245	14.4	57.9	7.2	448.6	65,064	12.0	53.6	6.5	94.3	13,678	9.1
18-May-97	3360.0	487,312	15.6	60.1	6.7	502.0	72,800	14.7	58.5	6.3	96.5	13,991	29.1
22-Jun-97	1638.7	237,669	17.9	64.2	7.9	233.3	33,834	17.2	63.0	8.1	99.0	14,361	21.8
15-Jul-97	no solution*		7.3	45.1		no solution		19.2	66.6				no solution
12-Aug-97	4528.3	656,748	22.9	73.2	6.8	513.2	74,427	21.8	71.2	6.2	118.2	17,146	17.4
14-Oct-97	9737.6	1,412,268	7.0	44.6	6.7	481.0	69,767	7.7	45.9	6.2	121.0	17,543	7.3
26-Nov-97	14248.9	2,066,551	-1.5	29.3	4.9	251.1	36,415	-0.8	30.6	4.6	80.3	11,642	3.2
18-Feb-98	14289.3	2,072,413	-2.0	28.4	12.5	2285.8	331,511	-2.2	28.0	2.6	99.3	14,396	15.5
9-Mar-98	12602.4	1,827,763	-2.1	28.2	2.5	6477.7	939,483	-2.2	28.0	4.7	137.2	19,897	15.8
1-Apr-98	12324.9	1,787,513	4.7	40.5	7.5	182.5	26,470	3.7	38.7	9.1	48.9	7,099	2.6
1-May-98	9603.6	1,392,830	15.4	59.7	7.2	114.4	16,586	13.1	55.6	6.8	95.3	13,827	5.7
4-May-98	2628.6	381,227	16.6	61.9	7.0	242.7	35,203	14.6	58.3	6.7	85.9	12,463	4.9
19-May-98	5179.0	751,120	11.8	53.2	8.4	277.6	40,254	11.8	53.2	10.5	85.5	12,398	3.2
16-Jun-98	10187.5	1,477,513	—	—	—	203.6	29,531	—	—	—	79.5	11,526	4.1
27-Jul-98	2853.1	413,796	28.4	83.1	7.0	295.5	42,850	26.5	79.7	7.1	109.2	15,844	11.6
24-Aug-98	6306.6	914,668	—	—	—	281.2	40,785	—	—	—	98.1	14,225	4.7
28-Sep-98	8841.3	1,282,278	—	—	—	284.0	41,184	—	—	—	131.7	19,098	8.7
26-Oct-98	13218.9	1,917,176	—	—	—	251.1	36,414	—	—	—	58.2	8,435	3.3
18-Nov-98	9905.3	1,436,590	—	—	—	224.5	32,560	—	—	—	45.5	6,606	1.6

* Back-calculation program could not converge on a solution.
† No data were found in the record for the other parameters when the FWD tests were done (the FWD test generates the data for the back-calculation routine).

Table 12. Back-calculated layer moduli at Wolf Point.

Thickness (mm)	177.8		152.4					5588.0					AA
	AC		Base					Subgrade					
Date	Back-calculated modulus		Temperature		Moisture content	Back-calculated modulus		Temperature		Moisture content	Back-calculated modulus		
	(MPa)	(psi)	(ºC)	(ºF)	(%)	(MPa)	(psi)	(ºC)	(ºF)	(%)	(MPa)	(psi)	(%)
21-Oct-96	9498.8	1,377,637	2.5	36.5	45.7	79.1	11,477	4.5	40.1	38.8	84.2	12,215	4.7
4-Dec-96	1379.0	200,000	-8.5	16.7	11.0	13790.0	2,000,001	-6.6	20.12	26.3	329.3	47,758	114.6
3-Apr-97	4033.5	584,982	3.3	37.94	33.4	37.6	5,456	2.0	35.6	38.7	184.1	26,698	12.4
24-Apr-97	1379.0	200,000	7.0	44.6	50.4	486.4	70,546	5.6	42.08	40.1	89.5	12,980	8.4
8-May-97	1575.4	228,479	—*	—	—	391.6	56,800	—	—	—	65.3	9,473	1.3
18-Jun-97	1379.0	200,000	25.7	78.26	41.9	161.4	23,413	24.1	75.38	40.7	73.3	10,633	8.3
19-Aug-97	1379.0	200,000	22.3	72.14	39.4	178.7	25,922	21.6	70.88	40.3	64.2	9,305	17.7
16-Sep-97	1442.8	209,259	16.3	61.34	36.9	103.0	14,934	17.5	63.5	39.8	67.5	9,789	5.2
13-Nov-97	8459.8	1,226,952	-1.3	29.66	22.4	7351.4	1,066,194	0.2	32.36	38.0	89.8	13,030	1.5
27-Nov-97	11454.8	1,661,314	-2.5	27.5	19.1	7571.2	1,098,066	-1.7	28.94	31.8	115.6	16,769	1.3
24-Feb-98	4058.2	588,575	-0.2	31.64	31.3	58.0	8,415	-0.6	30.92	38.0	156.9	22,750	4.7
24-Mar-98	1454.1	210,898	0.5	32.9	31.4	88.1	12,777	-0.9	30.38	34.7	162.4	23,558	10.9
28-Apr-98	1420.9	206,079	14.1	57.38	34.3	70.9	10,283	11.7	53.06	39.1	110.7	16,052	1.7
20-May-98	1379.0	200,000	19.6	67.28	34.7	69.3	10,058	18.5	65.3	39.7	75.4	10,939	2.6
27-May-98	1379.0	200,000	23.2	73.76	35.6	34.2	4,957	21.9	71.42	40.1	75.3	10,921	19
16-Jun-98	2093.2	303,579	19.7	67.46	34.7	41.6	6,029	18.4	65.12	38.2	79.6	11,538	4.9
10-Jul-98	NO USABLE DATA†		—	—	—	NO USABLE DATA		—	—	—	NO USABLE DATA		
23-Sep-98	1379.0	200,000	—	—	—	94.7	13,741	—	—	—	71.9	10,431	5

* No data were found in the record for the other parameters when the FWD tests were done (the FWD test generates the data for the back-calculation routine).
† Absolute Arithmatic (AA) values exceeded 20.0.

Table 13. Back-calculated layer moduli at Sweetgrass.

Thickness (mm)	330.2		482.6					5588.0					AA
	AC		Base					Subgrade					
Date	Back-calculated modulus		Temperature		Moisture content	Back-calculated modulus		Temperature		Moisture content	Back-calculated modulus		
	(MPa)	(psi)	(ºC)	(ºF)	(%)	(MPa)	(psi)	(ºC)	(ºF)	(%)	(MPa)	(psi)	(%)
3-Apr-96	3,332.7	483,350	-1.9	28.6	0.1	1337.7	194,004	-2.2	28.0	15.8	379.6	55,060	12.4
13-May-96	3,043.2	441,358	8.6	47.5	4.0	593.3	86,046	7.3	45.1	—	66.9	9,700	3.9
30-May-96	1,379.0	200,000	18.1	64.6	5.0	401.4	58,219	14.1	57.4	20.6	68.9	9,993	18.4
19-Jun-96	3,446.1	499,794	19.9	67.8	5.0	311.7	45,203	18.8	65.8	30.9	78.9	11,442	5.0
24-Jul-96	1,679.9	243,644	25.1	77.2	5.4	129.6	18,796	22.7	72.9	30.4	121.2	17,574	5.4
18-Sep-96	3,709.6	538,009	—*	—	—	207.6	30,106	—	—	—	108.6	15,750	6.2
3-Oct-96	3,806.7	552,091	10.2	50.4	4.1	244.4	35,443	11.2	52.2	29.6	105.2	15,255	3.4
25-Apr-97	4,153.6	602,403	7.8	46.0	3.7	198.0	28,720	5.5	41.9	29.8	89.4	12,973	2.1
9-May-97	3,243.0	470,345	11.1	52.0	4.0	427.4	61,992	8.5	47.3	30.1	90.8	13,163	8.9
21-May-97	2,508.8	363,862	13.8	56.8	4.2	294.8	42,750	12.3	54.1	30.1	88.5	12,841	7.9
20-Jun-97	1,732.3	251,242	20.5	68.9	5.3	229.8	33,327	18.5	65.3	32.1	94.6	13,719	6.2
9-Aug-97	2,518.5	365,261	22.7	72.9	4.7	995.3	144,346	23.9	75.0	31.3	58.8	8,528	3.9
15-Oct-97	4,249.1	616,254	9.2	48.6	3.7	136.6	19,809	9.9	49.8	31.4	108.4	15,726	5.1
26-Nov-97	7,482.0	1,085,134	—	—	—	325.5	47,209	—	—	—	94.9	13,766	2.5
19-Feb-98	9,302.1	1,349,102	-1.4	29.5	2.8	140.0	20,299	-2.5	27.5	17.4	152.0	22,042	6.5
31-Mar-98	2,191.4	317,820	4.2	39.6	3.7	324.3	47,036	2.3	36.1	30.3	75.9	11,007	2.8
28-Apr-98	1,989.6	288,560	13.4	56.1	4.9	164.5	23,865	10.2	50.4	31.8	92.2	13,366	3.6
28-May-98	1,775.1	257,445	17.7	63.9	5.4	124.8	18,104	15.7	60.3	32.3	117.2	16,994	18
18-Jun-98	4,997.8	724,840	—	—	—	68.4	9,916	—	—	—	109.2	15,844	5.5
28-Jul-98	1,438.0	208,562	16.4	61.5	5.5	99.1	14,367	16.5	61.7	32.6	114.7	16,633	2.1
25-Aug-98	2,660.0	385,789	—	—	—	76.8	11,137	—	—	—	111.2	16,134	3
29-Sep-98	2,790.0	404,638	—	—	—	172.1	24,961	—	—	—	109.2	15,834	2.7
27-Oct-98	7,009.6	1,016,621	—	—	—	72.5	10,518	—	—	—	116.0	16,818	2.6
19-Nov-98	10,378.5	1,505,215	—	—	—	122.5	17,765	—	—	—	129.4	18,773	6.1

* No data were found in the record for the other parameters when the FWD tests were done (the FWD test generates the data for the back-calculation routine).

Table 14. Back-calculated layer moduli at Scobey/Redstone.

Thickness (mm)	228.6		139.7					5588.0					AA
	AC		Base					Subgrade					
Date	Back-calculated modulus		Temperature		Moisture content	Back-calculated modulus		Temperature		Moisture content	Back-calculated modulus		
	(MPa)	(psi)	(ºC)	(ºF)	(%)	(MPa)	(psi)	(ºC)	(ºF)	(%)	(MPa)	(psi)	(%)
15-Mar-97	27,580.00	3,999,998	-6.4	20.5	7.2	13,790.00	2,000,001	-6.7	19.9	12.3	1,488.40	215,868	54.1
3-Apr-97	4,212.50	610,944	3.3	37.9	21	26.3	3,818	1.8	35.2	33.7	237.5	34,439	9.3
24-Apr-97	3,937.50	571,065	—*	—	—	13.8	2,000	—	—	—	117.8	17,078	6.1
8-May-97	5,346.50	775,422	12.5	54.5	21.6	13.8	2,000	11.3	52.3	34.1	81.6	11,833	6.7
22-May-97	1,379.00	200,000	14.1	57.4	21.6	108.6	15,745	12.9	55.2	34	53.3	7,729	5.1
19-Jun-97	1,379.00	200,000	24.9	76.8	22.7	94.1	13,652	23.7	74.7	33.5	61.2	8,879	3.9
19-Aug-97	689.5	100,000	23.5	74.3	22.1	86.6	12,557	22.6	72.7	33	55.1	7,986	7.7
13-Nov-97	6,140.50	890,571	0.5	32.9	18.5	12,819.80	1,859,292	0.6	33.1	32.6	94.2	13,655	1.4
27-Nov-97	9,871.90	1,431,743	-0.9	30.4	11.7	5,922.50	858,959	-1.1	30.0	30.2	96	13,921	1.8
24-Feb-98	4,312.90	625,508	-0.5	31.1	20.8	333.8	48,419	-1.3	29.7	29	120.2	17,440	4.6
25-Mar-98	4,990.10	723,725	—	—	—	201.6	29,245	—	—	—	152.5	22,117	7
28-Apr-98	2,721.70	394,734	13.6	56.5	20.8	51.5	7,470	12	53.6	34.1	54.7	7,932	3.2
20-May-98	2,007.60	291,169	19.5	67.1	22.4	200.6	29,093	18.2	64.8	35.6	54.2	7,858	1.6
15-Jun-98	1,781.30	258,340	20.6	69.1	22.4	629.9	91,354	19.5	67.1	34.3	59.9	8,691	10.8
10-Jul-98	1,379.00	200,000	28.4	83.1	23.7	13.8	2,000	27.1	80.8	34.5	86.9	12,601	15.5
26-Aug-98	1,379.00	200,000	—	—	—	49.9	7,236	—	—	—	52.4	7,599	10.9
26-Aug-98	1,379.00	200,000	—	—	—	131.9	19,130	—	—	—	58.3	8,460	9.5
23-Sep-98	1,837.90	266,549	—	—	—	51.4	7,460	—	—	—	68.4	9,923	5.2
28-Oct-98	2,588.50	375,422	—	—	—	13.9	2,010	—	—	—	74.1	10,754	3.9
24-Nov-98	6,063.70	879,428	—	—	—	95.3	13,823	—	—	—	77.5	11,233	2.2

* No data were found in the record for the other parameters when the FWD tests were done (the FWD test generates the data for the back-calculation routine).

Table 15. Back-calculated layer moduli at East Glacier.

Thickness (mm)	76.2		584.2					5588.0					AA
	AC		Base					Subgrade					
Date	Back-calculated modulus		Temperature		Moisture content	Back-calculated modulus		Temperature		Moisture content	Back-calculated modulus		
	(MPa)	(psi)	(ºC)	(ºF)	(%)	(MPa)	(psi)	(ºC)	(ºF)	(%)	(MPa)	(psi)	(%)
15-May-96	34,475.00	4,999,998	7.3	45.1	35.6	134.5	19,509	5.1	41.2	40.6	202.9	29,428	19.9
29-May-96	27,580.00	3,999,998	—*	—	—	103.6	15,022	—	—	—	179.9	26,096	19.2
19-Jun-96	27,580.00	3,999,998	16.4	61.5	28.9	255.3	37,028	15.1	59.2	41.3	221.5	32,130	8.1
24-Jul-96	27,580.00	3,999,998	20.6	69.1	28.7	187	27,118	19	66.2	38.1	272.9	39,585	16.9
18-Sep-96	27,234.90	3,949,944	14.2	57.6	29.2	157.8	22,884	14.4	57.9	38.2	253.1	36,702	20.4
3-Oct-96	28,357.50	4,112,769	11	51.8	27.6	158.5	22,986	10.5	50.9	37.7	270.4	39,219	20.4
26-Apr-97	27,580.00	3,999,998	4	39.2	28.8	158	22,912	1.7	35.1	40.6	196.2	28,455	16.3
9-May-97	27,580.00	3,999,998	7.5	45.5	28.4	163.6	23,727	5.3	41.5	40.9	198.3	28,754	17
21-May-97	27,580.00	3,999,998	11.8	53.2	29	160.1	23,220	9.9	49.8	39	183.1	26,554	15.6
20-Jun-97	23,526.80	3,412,154	15.6	60.1	30.3	148	21,467	13.9	57.0	31.2	168.6	24,447	16.4
15-Jul-97	30,497.30	4,423,104	17.7	63.9	29.6	134.1	19,450	15.5	59.9	38.6	164.8	23,896	24.9
12-Aug-97	34,475.00	4,999,998	—	—	—	183.2	26,563	—	—	—	214.3	321,143	13.1
20-Aug-97	34,475.00	4,999,998	—	—	—	184.4	26,740	—	—	—	241	34,950	13.3
4-Feb-97	4,837.00	701,525	—	—	—	6,480.90	939,939	—	—	—	2,436.70	353,408	13.3
14-Oct-97	3,927.70	569,639	—	—	—	131.5	19,069	—	—	—	274.7	39,835	13.3
26-Nov-97	44,791.10	6,496,169	—	—	—	749.4	108,682	—	—	—	276.5	40,106	13.3
18-Feb-98	2,701.00	391,740	—	—	—	1,155.20	167,543	—	—	—	956.7	138,757	13.3
24-Feb-98	8,137.80	1,180,244	—	—	—	133.7	19,390	—	—	—	107.7	15,615	13.3
25-Mar-98	3,823.40	554,516	—	—	—	214.6	31,130	—	—	—	83.8	12,151	13.3
31-Mar-98	5,858.00	849,595	—	—	—	135.6	19,660	—	—	—	185.8	26,949	13.3

* No data were found in the record for the other parameters when the FWD tests were done (the FWD test generates the data for the back-calculation routine.

Table 16. Back-calculated layer moduli at Alzada.

Thickness (mm)	235.0		603.3		5588.0		AA
	AC		Base		Subgrade		
Date	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(%)
30-Apr-96	4,156.4	602,816	174.0	25,229	100.4	14,556	9.3
23-Jul-96	1,908.8	276,840	118.0	17,113	106.4	15,436	15.8
12-Aug-96	1,379.0	200,000	129.8	18,818	123.1	17,859	14.3
17-Sep-96	5,034.1	730,114	142.3	20,641	116.4	16,888	9.6
1-Oct-96	6,637.5	962,650	89.6	13,002	131.2	19,030	9.8
29-Oct-96	1,379.0	200,000	650.4	94,331	67.7	9,825	8.6
8-Jan-97	3,053.1	442,799	3,629.7	526,419	378.5	54,901	9.4
14-Mar-97	5,348.3	775,685	13,790.0	2,000,001	238.4	34,574	8.8
2-Apr-97	1,439.6	208,785	301.7	43,751	90.7	13,161	20.9
23-Apr-97	1,379.0	200,000	278.8	40,439	87.6	12,698	18.9
7-May-97	2,982.3	432,531	269.5	39,089	90.3	13,096	10.5
28-May-97	3,858.3	559,573	187.1	27,136	101.5	14,723	7.5
13-Jun-97	1,798.8	260,882	255.3	37,022	103.1	14,958	11.0
21-Jul-97	1,554.6	225,473	210.6	30,550	88.5	12,841	12.7
18-Aug-97	3,948.0	572,590	187.8	27,231	88.6	12,847	4.6
16-Sep-97	2,828.9	410,287	264.4	38,343	108.0	15,659	1.3
21-Oct-97	4,266.2	618,744	162.3	23,544	114.0	16,531	1.9
13-Nov-97	8,760.9	1,270,611	234.8	34,047	96.7	14,030	1.7
5-Jan-98	18,321.1	2,657,153	2,115.4	306,803	116.1	16,836	3.1
23-Feb-98	8,137.8	1,180,244	133.7	19,390	107.7	15,615	3.9
25-Mar-98	3,823.4	554,516	214.6	31,130	83.8	12,151	4.8

Table 17. Back-calculated layer moduli at Bull Mountain.

Thickness (mm)	254.0		431.8		5588.0		AA
Date	AC		Base		Subgrade		
	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(%)
23-Oct-96	1,905.3	276,324	2,049.9	297,306	142.3	20,632	10
13-Nov-96	1,379.0	200,000	5,813.6	843,169	322.2	46,736	50.4
13-Mar-97	2,625.6	380,793	1,282.3	185,975	152.6	22,129	5.2
1-Apr-97	1,671.5	242,415	872.0	126,472	162.8	23,608	18.8
22-Apr-97	1,379.0	200,000	400.3	58,051	186.1	26,991	16.2
6-May-97	3,830.2	555,498	356.0	51,625	200.5	29,083	5.7
23-May-97	2,576.4	373,666	332.4	48,204	204.5	29,655	17.4
16-Jun-97	11,518.8	1,670,599	715.6	103,783	196.3	28,466	6.8
21-Jul-97	3,666.1	531,706	157.6	22,850	216.2	31,350	11.6
18-Aug-97	2,491.1	361,290	372.3	53,993	211.4	30,657	1.3
15-Sep-97	3,748.6	543,666	320.4	46,464	268.0	38,869	2.6
27-Nov-97	15,771.6	2,287,397	75.3	10,925	256.4	37,187	1.8
5-Jan-98	16,176.0	2,346,041	959.5	139,153	167.9	24,349	1.2
2-Feb-98	4,873.7	706,844	263.5	38,221	148.6	21,559	2.9
23-Feb-98	7,619.3	1,105,044	195.2	28,317	148.5	21,535	8.1
30-Mar-98	7,357.3	1,067,042	112.7	16,345	159.8	23,169	5.7
16-Apr-98	12,576.3	1,823,978	266.5	38,656	151.2	21,923	5.6
27-Apr-98	2,815.9	408,393	148.0	21,461	194.3	28,179	2.5
28-Apr-98	1,971.4	285,921	248.0	35,974	123.9	17,966	2.6
30-Apr-98	10,129.8	1,469,148	33.7	4,891	487.7	70,736	3.0
21-May-98	4,455.1	646,136	206.4	29,937	175.8	25,502	5.2
26-May-98	1,919.6	278,409	144.1	20,902	243.6	35,332	17.1
17-Jun-98	12,154.1	1,762,740	55.5	8,055	374.4	54,303	5.5
27-Jul-98	2,008.1	291,246	212.1	30,755	187.0	27,125	4.1
27-Aug-98	4,744.2	688,058	167.0	24,217	173.7	25,191	3.3
22-Oct-98	9,662.9	1,401,441	562.9	81,635	134.5	19,506	2.3
25-Nov-98	10,031.8	1,454,942	533.4	77,364	161.6	23,440	5.0
25-Jan-99	19,280.2	2,796,263	2,801.7	406,343	165.9	24,058	1.0

Table 18. Back-calculated layer moduli at Livingston.

Thickness (mm)	152.4		518.16		5588		AA
Date	AC		Base		Subgrade		
	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(%)
26-Nov-96	6,188.9	897,597	241.8	35,072	121.4	17,600	12.6
12-Mar-97	1,844.1	267,452	171.3	24,843	110.6	16,047	18.4
1-Apr-97	5,280.1	765,792	131.9	19,130	129.2	18,738	3.9
22-Apr-97	5,538.2	803,216	122.2	17,726	130.1	18,873	1.4
6-May-97	1,379.0	200,000	158.1	22,923	123.4	17,894	9.9
23-May-97	2,463.1	357,228	157.1	22,785	133.8	19,406	9.1
16-Jun-97	2,295.6	332,943	136.6	19,807	164.9	23,920	10.1
24-Jul-97	1,624.4	235,586	148.7	21,570	121.4	17,600	4.4
18-Aug-97	3,564.7	517,001	130.1	18,870	124.0	17,986	6.9
8-Feb-97	21,364.6	3,098,570	3,557.3	515,923	288.4	41,834	26.3
23-Feb-98	7,896.9	1,145,307	115.6	16,769	92.1	13,357	5.5

Table 19. Back-calculated layer moduli at Loma.

Thickness (mm)	152.4		685.8		5588.0		AA
Date	AC		Base		Subgrade		
	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(%)
4-Apr-96	10,994.0	1,594,487	490.5	71,134	177.0	25,672	17.0
29-Apr-96	2,147.7	311,488	710.4	103,038	86.2	12,496	18.1
13-May-96	3,930.8	570,095	589.7	85,525	126.4	18,335	7.4
30-May-96	1,379.0	200,000	329.6	47,804	120.3	17,449	20.2
20-Jun-96	6,393.2	927,217	880.7	127,733	146.2	21,206	11.4
20-Aug-96	3,906.2	566,525	437.3	63,416	138.4	20,067	6.3
19-Sep-96	6,056.6	878,410	472.0	68,460	132.0	19,145	15.2
2-Oct-96	4,095.6	594,001	444.1	64,409	127.0	18,421	10.1
21-Oct-96	2,020.7	293,072	973.3	141,163	104.1	15,105	9.6
6-Dec-96	1,379.0	200,000	4,336.7	628,959	246.9	35,805	79.0
7-Jan-97	1,379.0	200,000	6,404.9	928,914	451.7	65,517	53.0
18-Mar-97	13,261.1	1,923,286	1,379.0	200,000	198.2	28,739	9.7
25-Apr-97	27,580.0	3,999,998	2,001.1	290,226	140.9	20,441	5.2
8-May-97	1,379.0	200,000	657.7	95,384	126.5	18,349	9.8
22-May-97	5,228.7	758,332	795.9	115,436	134.0	19,432	2.8
20-Jun-97	1,734.8	251,599	671.1	97,332	136.5	19,795	9.8
17-Jul-97	4,149.7	601,836	775.0	112,406	141.9	20,580	8.6
25-Jul-97	4,122.4	597,878	762.2	110,547	167.8	24,340	2.1
11-Aug-97	6,360.9	922,533	599.5	86,946	156.3	22,664	8.1
16-Oct-97	15,680.6	2,274,195	529.8	76,843	135.3	19,619	5.2
14-Nov-97	16,702.5	2,422,411	611.0	88,611	103.6	15,019	1.6
2-Feb-98	7,511.1	1,089,355	667.4	96,795	153.5	22,265	1.5
24-Feb-98	24,396.0	3,538,211	430.0	62,366	186.0	26,980	3.1
31-Mar-98	13,414.2	1,945,490	523.1	75,872	108.4	15,718	2.8

Table 20. Back-calculated layer moduli at Swan Lake.

Thickness (mm)	121.9		370.8		5588.0		AA
Date	AC		Base		Subgrade		
	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(%)
30-Apr-96	6,282.2	911,127	104.1	15,096	146.3	21,220	9.8
16-May-96	8,081.7	1,172,112	169.9	24,643	188.6	27,346	9.0
28-May-96	5,035.0	730,235	142.3	20,631	175.3	25,426	12.0
17-Jun-96	2,614.7	379,222	282.7	41,001	231.8	33,620	8.4
23-Jul-97	12,939.3	1,876,627	165.5	24,006	464.8	67,416	6.2
19-Aug-96	9,737.8	1,412,304	285.5	41,414	246.3	35,725	8.3
19-Sep-97	8,990.9	1,303,969	279.7	40,563	228.9	33,205	17.7
17-Mar-97	2,066.9	299,762	405.7	58,846	384.1	55,705	19.9
5-Apr-97	7,884.0	1,143,441	175.6	25,474	171.4	24,853	6.9
11-May-97	5,414.5	785,283	253.8	36,807	198.7	28,823	1.3
18-May-97	2,549.3	369,737	280.8	40,727	204.7	29,692	3.3
23-Jun-97	2,282.3	331,011	313.5	45,468	193.5	28,060	17.1
15-Jul-97	2,269.0	329,083	329.8	47,830	194.2	28,160	8.6
11-Aug-97	1,656.6	240,265	341.2	49,482	217.1	31,483	11.8
26-Nov-97	17,832.6	2,586,307	304.9	44,224	188.8	27,379	3.5
17-Feb-98	6,494.9	941,967	368.6	53,452	212.9	30,874	2.8
9-Mar-98	8,200.0	1,189,267	190.8	27,678	144.5	20,958	4.1
1-Apr-98	6,454.6	936,129	187.5	27,189	177.1	25,685	4.4

Using all the back-calculated data, we determined monthly subgrade and base course moduli. When more than one monthly back-calculated modulus was available, and if the data looked reasonable, average values were used for the month. These results are presented in Tables 21, 22, 23, and 24.

Table 21. Average monthly subgrade moduli (Sept. 1996–Aug. 1997 data).

	Dickey Lake		Wolf Point		Sweetgrass		Scobey /Redstone		East Glacier		Alzada		Bull Mtn		Livingston		Loma		Swan Lake	
Soil	**A-2-4/A-4**		**A-6**		**A-6**		**A-6**		**A-4**		**A-6**		**A-4**		**A-1**		**A-1**		**A-1**	
Month	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**
Sep	122.5	17,766	—*	—	108.6	15,751	—	—	253.1	36,708	—	—	—	—	—	—	132.0	19,144	228.9	33,198
Oct	79.1	11,472	84.2	12,212	105.2	15,257	—	—	270.4	39,217	142.3	20,638	142.3	20,638	—	—	115.6	16,766	—	—
Nov	—	—	—	—	—	—	—	—	—	—	322.2	46,730	322.2	46,730	121.4	17,607	—	—	—	—
Dec	—	—	329.3	47,759	—	—	—	—	—	—	—	—	—	—	—	—	246.9	35,809	—	—
Jan	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	451.7	65,511	—	—
Feb	—	—	—	—	—	—	—	—	2436.7	353,413	—	—	—	—	288.4	41,829	—	—	—	—
Mar	—	—	—	—	—	—	1488.4	215,867	—	—	152.6	22,132	152.6	22,132	110.6	16,041	198.2	28,745	384.1	55,707
April	85.7	12,429	136.8	19,840	89.4	12,966	177.6	25,758	196.2	28,455	174.4	25,294	174.4	25,294	129.7	18,811	140.9	20,435	171.4	24,859
May	95.4	13,836	65.3	9,471	89.6	12,995	67.4	9,775	190.7	27,658	202.5	29,369	202.5	29,369	128.6	18,651	130.2	18,883	201.7	29,253
Jun	99.0	14,358	73.3	10,631	94.6	13,720	61.2	8,876	168.6	24,453	196.3	28,470	196.3	28,470	164.9	23,916	136.5	19,797	193.5	28,064
July	—	—	—	—	—	—	—	—	164.8	23902	216.2	31357	216.2	31357	121.2	17579	154.9	22466	194.2	28166
Aug	118.2	17143	64.2	9311	58.8	8528	55.1	7992	214.3	31082	211.4	30661	211.4	30661	124.0	17984	156.3	22669	217.1	31488

* No FWD tests conducted.

Table 22. Average monthly base moduli (Sep. 1996–Aug. 1997 data).

	Dickey Lake		Wolf Point		Sweetgrass		Scobey/ Redstone		East Glacier		Alzada		Bull Mtn		Livingston		Loma		Swan Lake	
Month	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**
Sept	410.6	59,550	—*	—	207.6	30,109	—	—	157.8	22,886	142.3	20,638	—	—	—	—	472.0	68,455	279.7	40,566
Oct	528.3	76,621	79.1	11,472	244.4	35,446	—	—	158.5	22,988	370.0	53,662	2049.9	297,302	—	—	708.7	102,785	—	—
Nov	—	—	—	—	—	—	—	—	—	—	—	—	5813.7	843,176	241.8	35,069	—	—	—	—
Dec	—	—	13790.0	2,000,000	—	—	—	—	—	—	—	—	—	—	—	—	4336.7	628,963	—	—
Jan	—	—	—	—	—	—	—	—	—	—	3629.7	526,425	—	—	—	—	6404.9	928,920	—	—
Feb	—	—	—	—	—	—	—	—	—	—	—	—	—	—	3557.3	515,942	—	—	—	—
Mar	—	—	—	—	—	—	13790.0	2,000,000	—	—	13,790.0	2,000,000	1282.3	185,975	171.3	24,844	1379.0	200,000	405.7	58,840
Apr	559.5	81,146	262.0	37,999	198.0	28,716	20.1	2,915	158.0	22,915	290.2	42,088	636.1	92,255	127.1	18,434	2001.1	290,225	175.6	25,468
May	475.3	68,934	391.6	56,795	361.1	52,371	61.2	8,876	161.8	23,466	228.3	33,111	344.2	49,920	157.6	22,857	726.8	105,410	267.3	38,767
Jun	233.3	33,836	161.4	23,408	229.8	33,328	94.1	13,648	148.0	21,465	255.3	37,027	715.6	103,785	136.6	19,811	671.1	97,331	313.5	45,468
July	459.4	66,628	—	—	129.6	18,796	—	—	187.0	27,121	210.6	30,545	157.6	22,858	148.7	21,567	768.6	111,476	329.8	47,833
Aug	—	—	—	—	—	—	—	—	—	—	187.8	27,238	372.3	53,998	130.1	18,869	599.5	86,950	341.2	49,487

* No FWD tests conducted.

Table 23. Average monthly subgrade moduli (Sep. 1997–Aug. 1998 data).

	Dickey Lake		Wolf Point		Sweet-grass		Scobey/ Redstone		East Glacier		Alzada		Bull Mtn		Livingston		Loma		Swan Lake	
Soil	**A-2-4/A-4**		**A-6**		**A-6**		**A-6**		**A-4**		**A-6**		**A-4**		**A-1**		**A-1**		**A-1**	
Month	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**
Sept	—*	—	67.5	9,790	—	—	—	—	—	—	108.0	15,664	268.0	38,869	—	—	—	—	—	—
Oct	121.0	17,549	—	—	108.4	15,722	—	—	274.7	35,926	114.0	—	—	—	—	—	135.3	19,623	—	—
Nov	80.3	11,646	102.7	14,895	94.9	13,764	95.1	13,793	276.5	40,103	96.7	14,025	256.4	37,188	—	—	103.6	15,025	188.8	27,382
Dec	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Jan	—	—	—	—	—	—	—	—	—	—	116.1	16,838	167.9	24,352	—	—	—	—	—	—
Feb	99.3	14,402	156.9	22,756	152.0	22,045	120.2	17,433	532.2	77,189	107.7	15,620	148.6	21,552	190.3	27,600	169.8	24,627	212.9	30,877
Mar	137.2	19,898	162.4	23,553	75.9	11,008	152.5	22,117	134.8	19,551	83.8	12,154	159.8	23,176	—	—	108.4	15,722	144.5	20,957
Apr	48.9	7,092	110.7	16,055	92.2	13,372	54.7	7,933	—	—	—	—	239.3	34,706	—	—	—	—	177.1	25,685
May	88.9	12,893	75.4	10,935	117.2	16,998	54.2	7,861	—	—	—	—	209.7	30,413	—	—	—	—	—	—
Jun	79.5	11,530	79.6	11,545	109.2	15,838	59.9	8,687	—	—	—	—	374.4	54,300	—	—	—	—	—	—
July	109.2	15,838	—	—	114.7	16,635	86.9	12,604	—	—	—	—	187.0	27,122	—	—	—	—	—	—
Aug	98.1	14,228	—	—	111.2	16,128	52.4	7,600	—	—	—	—	173.7	25,193	—	—	—	—	—	—

* No FWD tests conducted.

Table 24. Average monthly base moduli (Sep. 1997–Aug. 1998 data).

	Dickey Lake		Wolf Point		Sweet-grass		Scobey/ Redstone		East Glacier		Alzada		Bull Mtn		Livingston		Loma		Swan Lake	
Month	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**	**(MPa)**	**(psi)**
Sep	—*	—	103.0	14,938	—	—	—	—	—	—	264.4	38,347	320.4	46,468	—	—	—	—	—	—
Oct	481.0	69,761	—	—	136.6	19,811	—	—	131.5	19,072	162.3	23,539	—	—	—	—	529.8	76,838	—	—
Nov	251.1	36,418	7461.3	1,082,132	325.5	47,208	9371.2	1,359,130	749.4	115,218	234.8	34,054	75.3	10,921	—	—	611.0	88,615	304.9	44,220
Dec	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Jan	—	—	—	—	—	—	—	—	—	—	2115.4	306,802	959.5	139,164	—	—	—	—	—	—
Feb	2285.8	331,516	58.0	8,412	140.0	20,305	333.8	48,412	644.5	93,477	133.7	19,391	229.4	33,270	115.6	16,766	548.7	79,579	368.6	53,459
Mar	6477.7	939,478	88.1	12,777	324.3	47,034	201.6	29,239	175.1	25,396	214.6	31,124	112.7	16,345	—	—	523.1	75,867	190.8	27,672
Apr	182.5	26,468	70.9	10,283	164.5	23,858	51.5	7,469	—	—	—	—	174.1	25,250	—	—	—	—	187.5	27,194
May	211.5	30,674	51.8	7,513	124.8	18,100	200.6	29,094	—	—	—	—	175.3	25,424	—	—	—	—	—	—
Jun	203.6	29,529	41.6	6,033	68.4	9,920	629.9	91,356	—	—	—	—	55.5	8,049	—	—	—	—	—	—
July	295.5	42,859	—	—	99.1	14,373	13.8	2,002	—	—	—	—	212.1	30,762	—	—	—	—	—	—
Aug	286.2	41,510	—	—	76.8	11,139	49.9	7,237	—	—	—	—	167.0	24,221	—	—	—	—	—	—

* No FWD tests conducted.

Discussion of weather data

The resilient modulus of a material is influenced by its moisture content. Precipitation, as well as thaw weakening, contributes moisture to the structure. Estimates of the M_r for materials determined from FWD measurements are also dependent on the timing of those measurements relative to weather phenomena. The National Climatic Data Center (NCDC) weather data that were used for the sites were from the nearest stations with sufficiently complete records to be useful. In no case were stations used that were more than 22 miles from the test sections.

Table 25 gives the weather data and compares the 96–97 season with the 97–98 season. At only two sites, Sweetgrass and Loma, was the 96–97 season drier than the 97–98 season.

Table 26 presents the M_r information. There are instances where the minimum M_r is lower during a drier season than the minimum M_r from a wetter season. In nine out of the ten sites studied, the minimum M_r was determined during the 97–98 season. The 97–98 season measurements were taken by the FWD. Only Wolf Point had a lower M_r value during the first, wetter season.

At five sites, the minimum M_r value occurred during the drier season. At two sites, the differences in M_r data are statistically insignificant; and at three sites the M_r data follow the precipitation pattern (i.e., the lower Mr was measured during the wetter season).

To determine whether a site's minimum resilient modulus is a function of spring thaw, or just excess precipitation, it is necessary to know whether the specific measurements were taken during periods of greater than average precipitation, average precipitation, or less than average precipitation, as well as whether the measurements were taken during the critical period or not. These relationships determine whether the back-calculated resilient modulus for a material is appropriate or needs adjustment. We have chosen to make no adjustments when the resilient modulus was taken during a "normal" or "drier" season. However, if the season was wetter than normal, then adjustments should be considered.

Critical periods could only be determined for five sites owing to data problems. Two of the five sites analyzed had M_r measurements taken during the critical period in both 1996–1997 and 1997–1998. A third site had measurements taken when only the subgrade was in the critical period, during the first winter/spring season, but the critical period could not be determined for the second winter/spring season. A fourth site had no critical periods, and data gaps prevented determination of the critical periods for the fifth site.

Table 25. Annual and seasonal precipitation effects on resilient modulus
(winter/spring precipitation is defined as occurring from October through April).

Location	Precipitation during test seasons compared to 1971-to-2000 (30-yr) normals — Full year values (January through December) (inches): 1971–2000 normals	1996	1997	1998	Winter/spring values (October through April Values) (inches): 1971–2000 normals	1996–1997	1997–1998	96-97 vs. 97-98 precipitation (numerically)	Comments (See Table 26 below)
Dickey Lake*	20.12	No Data	>9.85 Drier**	21.19 Wetter	10.30	9.82 Normal**	8.26 Drier	Wetter	Spring 97 M_r > Spring 98 M_r Should be other way because 96–97 is wetter than 97–98
Wolf Point†	13.05	12.41 Normal	12.89 Normal	13.16 Normal	3.50	5.23 Wetter	3.08 Drier	Wetter	
Sweetgrass	14.02	>6.39 Drier	10.63 Drier	12.57 Drier	3.53	1.13 Drier	3.41 Normal	Drier	
Scobey/Redstone	12.90	12.87 Normal	12.20 Normal	13.61 Wetter	3.26	4.82 Wetter	2.23 Drier	Wetter	Spring 97 M_r > Spring 98 M_r Should be other way because 96–97 is wetter than 97–98
East Glacier	29.38	>35.75 Wetter	>28.65 Normal	No Data	16.73	23.27 Wetter	13.19 Drier	Wetter	Spring 97 M_r > Spring 98 M_r Should be other way because 96–97 is wetter than 97–98
Alzada	14.00	14.52 Wetter	11.84 Drier	15.04 Wetter	4.95	4.46 Normal	3.40 Drier	Wetter	The M_r data are inconclusive
Bull Mountain	13.62	11.18 Normal	8.72 Drier	13.35 Normal	4.51	4.94 Normal	4.12 Normal	Wetter	The M_r data are inconclusive
Loma	13.08	12.26 Normal	10.01 Drier	11.91 Drier	4.59	3.41 Drier	4.16 Drier	Drier	
Livingston	15.65	14.37 Drier	17.71 Wetter	15.00 Normal	6.07	6.99 Wetter	5.47 Drier	Wetter	Spring 97 M_r > Spring 98 M_r Should be other way because 96–97 is wetter than 97–98
Swan Lake	25.93	32.68 Wetter	26.04 Normal	20.47 Drier	16.92	23.16 Wetter	10.90 Drier	Wetter	Spring 97 M_r > Spring 98 M_r Should be other way because 96–97 is wetter than 97–98

* Average of two stations, "Olney" and "Fortine 1N," that are on opposite sides of Dickey Lake.
† Normals are for period of record (POR), 1987–2000.
** ‘Normal’ is anything within ±10% or less of the 30-year mean for 1971 to 2000.

Table 26. Resilient modulus measurements and when they were taken relative to the critical period.

	Minimum subgrade M_r values*				Difference in M_r as % of larger minimum	Month of minimum M_r	Month of minimum M_r	Thaw-weakening (critical) period				Spring (critical period) M_r measurements were made in:						M_r measurement was made during critical period			
	96–97		97–98					1996–1997		1997–1998		1996–1997			1997–1998			1996–1997		1997–1998	
Location	**Mpa**	**psi**	**Mpa**	**psi**		**1996–1997**	**1997–1998**	**Base**	**Subgrade**	**Base**	**Subgrade**	**Feb.**	**Mar.**	**Apr.**	**Feb**	**Mar**	**Apr**	**Base**	**Subgrade**	**Base**	**Subgrade**
Dickey Lake	86	12,500	49	7,100	91.7	April 97	April 98	March 20 to April 13	March 25 to April 15; to April 3 to April 16 (depending on depth)	February 7 to March 15	February 15 to March 19; to March 14 to April 16 (depending on depth)	No	No	4/5/97 & 4/26/97	2/18/98	3/9/98	4/1/98	**Yes**	**Yes**	**Yes**	**Yes**
Wolf Point	65	9,400	75	10,900	72.2	May 97	May 98	April 21 to May 3	April 21 to April 25	February 14 to March 22	February 21 to March 27	No	No	4/3/97 & 4/24/97	2/24/98	3/24/98	4/28/98	**Yes**	**Yes**	**Yes**	**Yes**
Sweetgrass	89	12,900	76	11,000	87.6	April 97	March 98	None	None	None	None	No	No	4/25/97	2/19/98	3/31/98	4/28/98	No critical period	No critical period	No critical period	No critical period
Scobey/Red-stone	61	8,800	54	7,800	87.2	June 97	May 98	March 20 to March 24	April 19 to April 25	?[†]	?	No	3/15/97	4/3/97 & 4/24/97	2/24/98	3/25/98	4/28/98	No	**Yes**	ND**	ND
East Glacier	196	28,400	135	19,600	90.0	March 97	April 98	April 2 to April 26	?	?	?	2/4/97	No	4/26/97	2/18/98 & 2/24/98	3/25/98 & 3/31/98	No	No	ND	ND	ND

Location	Minimum subgrade M_r values* 96–97 Mpa	96–97 psi	97–98 Mpa	97–98 psi	Difference in M_r as % of larger minimum	Month of minimum M_r 1996–1997	Month of minimum M_r 1997–1998	Thaw-weakening (critical) period 1996–1997 Base	1996–1997 Subgrade	1997–1998 Base	1997–1998 Subgrade	Spring (critical period) M_r measurements were made in: 1996–1997 Feb.	1996–1997 Mar.	1996–1997 Apr.	1997–1998 Feb	1997–1998 Mar	1997–1998 Apr	M_r measurement was made during critical period 1996–1997 Base	1996–1997 Subgrade	1997–1998 Base	1997–1998 Subgrade
Alzada	89	12,900	84	12,200	86.3	April 97	March 98	No data available‡				—	—	—	—	—	—	—	—	—	—
Bull Mountain	153	22,200	149	21,600	85.9	March 97	February 98	No data available				—	—	—	—	—	—	—	—	—	—
Loma	130	18,900	108	15,700	88.0	May 97	March 98	No data available				—	—	—	—	—	—	—	—	—	—
Livingston	111	16,100	92	13,300	88.0	March 97	February 98	No data available				—	—	—	—	—	—	—	—	—	—
Swan Lake	171	24,800	145	21,000	87.7	April 97	March 98	No data available				—	—	—	—	—	—	—	—	—	—

* Minima are taken from Tables 11 through 20 above; and where more than one measurement was made during the month, values are the average for the month of minimum.
† Critical period did not occur or could not be determined.
** No data.
‡ Temperature and moisture contents not available.

Estimating Resilient Modulus Data

The missing monthly subgrade moduli could be estimated from trying to fit a model to the field data. Examples of this procedure are shown in Figures 18 and 19. The model attempted to account for the effect of temperature and moisture content on the resilient modulus of the subgrade at Dickey Lake and East Glacier. The model of the following form was used:

$$M_r = k_1(T_{ref} - T)^{k_2}(\omega_{vol})^{k_3}$$

where M_r = resilient modulus (MPa).

T_{ref} = reference temperature (20°C).

T = temperature (°C).

ω_{vol} = volumetric moisture content at top of subgrade (%)

k_1, k_2, k_3 = constants.

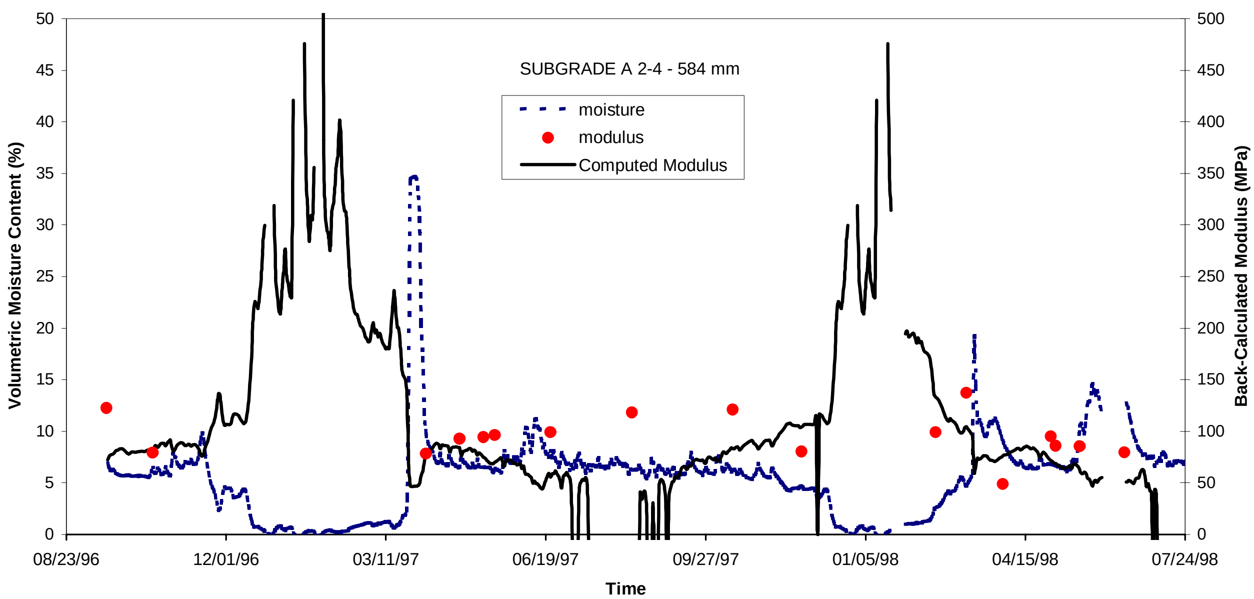

Figure 18. Results of prediction of subgrade modulus at Dickey Lake.

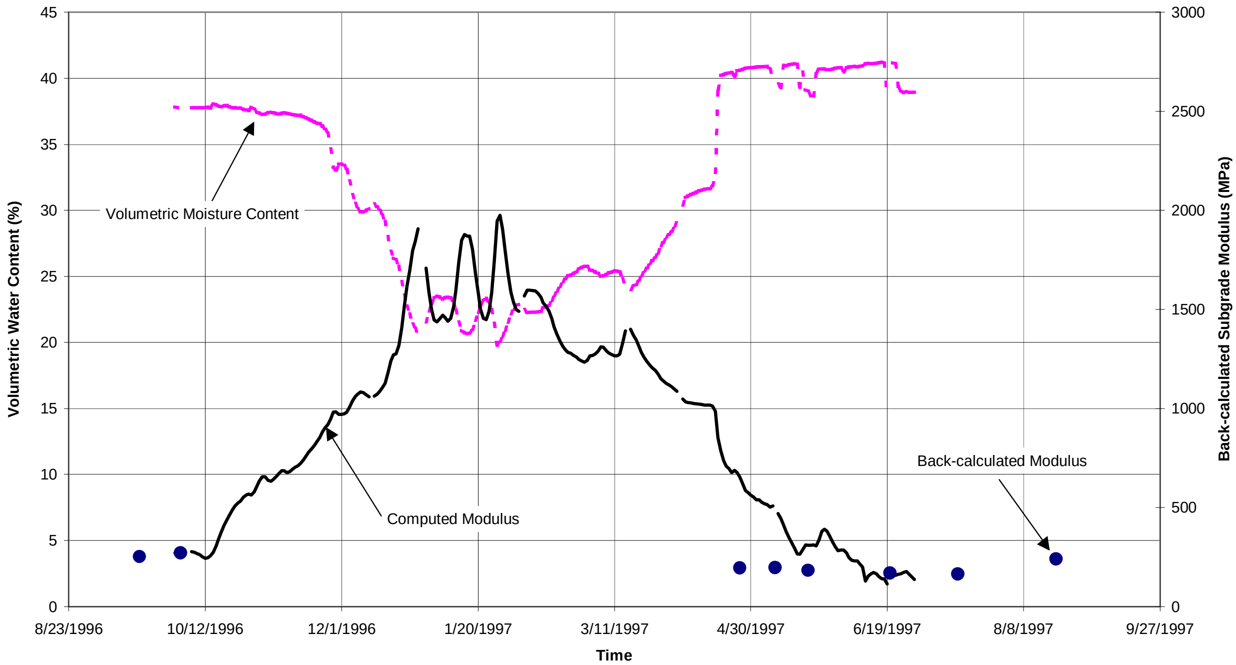

Figure 19. Results of prediction of subgrade modulus at East Glacier.

For Dickey Lake (A-2-4 soil), a good fit was found when the following constants were used: k_1 = 105, k_2 = 0.2, and k_3 = –0.4. Note that this model indicates a reduction in the subgrade modulus as the moisture content increases during the spring thaw period. The model predicts a subgrade modulus of approximately 47 MPa. The non-frost and recovered moduli are around 90 MPa. During the winter, the model predicts the subgrade modulus to average around 350 MPa. For East Glacier, the model also predicts a reduction in the subgrade modulus, as indicated by the field measurements (Figure 19). The reduction is approximately 50% of its non-frost value. For East Glacier (an A-6 soil), k_1 = 200, k_2 = 1.3, and k_3 = –0.7.

Similar models for other soils could be developed if sufficient data becomes available in the future.

The monthly subgrade modulus and relative damage for the test sites are presented in Tables 27, 28, 29, and 30. For the months where a back-calculated subgrade modulus is unavailable, a best guess is used, based on existing data and values from the models. We found that when the winter resilient modulus was increased by a factor of 5, the effect on the relative damage was insignificant.

Subsequently, the effective resilient modulus is only increased by approximately 10%. However, these results should be validated with additional FWD testing.

Based on our experience, we have adjusted the subgrade modulus downwards for sites where the precipitation data suggests that the subgrade was experiencing a drier than normal season. For design, the following effective subgrade resilient modulus can be used (see Table 31). These values are the seasonal average values, slightly rounded; and the recommended modulus is the average of the two seasonal values, except when only one season is available. The effective resilient modulus table is based on available data. The values look high, but the available data cannot support lower values. These values should be used with caution, and they should be validated with additional FWD testing.

Table 27. Effective subgrade resilient modulus.

Location	1996–1997 M_r		1997–1998 M_r		Recommended M_r	
	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)
Dickey Lake	2400	16500	1750	11900	2100	14300
Wolfpoint	1945	13300	2150	14600	2100	14300
Sweetgrass	2275	15700	2350	16200	2300	15900
Scobey/ Redstone	1650	11400	1600	11000	1650	11200
East Glacier	5750	39600	5800	40000	5800	39800
Alzada	2550	17600	2300	15600	2400	16500
Bull Mountain	4375	30200	3150	21700	3800	26000
Loma	3250	22400	2750	18800	3000	21000
Livingston	2925	20200	Insuficient Data		2950	20200
Swan Lake	5050	34800	3850	26500	4450	30700

Table 28. Monthly subgrade soil modulus and relative damages at Dickey Lake, Wolf Point, Sweetgrass, Scobey/Redstone and East Glacier (1996–1997).

	Dickey Lake			Wolf Point			Sweetgrass			Scobey/Redstone			East Glacier		
	M_r		u_f	M_r		u_f	M_r		u_f	M_r		u_f	M_r		u_f
	(MPa)	(psi)		(MPa)	(psi)		(MPa)	(psi)		(MPa)	(psi)		(MPa)	(psi)	
Sep	122	17,694	0.0163	67	9,717	0.0244	109	15,809	0.0216	_55_	_7,977_	_0.1043_	253	36,693	0.0030
Oct	79	11,458	0.0451	84	12,183	0.0450	105	15,228	0.0232	_55_	_7,977_	_0.1043_	270	39,159	0.0026
Nov	_96*_	_13,923_	_0.0287_	_200_	_29,007_	_0.0052_	_200_	_29,007_	_0.0052_	_200_	_29,007_	_0.0052_	_800_	_116,026_	_0.0002_
Dec	_159_	_23,060_	_0.0089_	329	47,716	0.0016	_300_	_43,510_	_0.0020_	_400_	_58,013_	_0.0010_	_1000_	_145,033_	_0.0001_
Jan	_287_	_41,624_	_0.0023_	_300_	_43,510_	_0.0020_	_300_	_43,510_	_0.0020_	_400_	_58,013_	_0.0010_	_2000_	_290,065_	_0.0000_
Feb	_271_	_39,304_	_0.0026_	_300_	_43,510_	_0.0020_	_300_	_43,510_	_0.0020_	_400_	_58,013_	_0.0010_	_2000_	_290,065_	_0.0000_
Mar	_193_	_27,991_	_0.0057_	_150_	_21,755_	_0.0102_	_235_	_34,083_	_0.0036_	1488	215,809	0.0000	_1500_	_217,549_	_0.0000_
Apr	86	12,473	0.0373	137	19,869	0.0126	89	12,908	0.0339	178	25,816	0.0069	196	28,426	0.0055
May	95	13,778	0.0007	65	9,427	0.0702	90	13,053	0.0337	67	9,717	0.0652	191	27,701	0.0058
Jun	99	14,358	0.0037	73	10,587	0.0537	95	13,778	0.0297	61	8,847	0.0816	169	24,511	0.0078
July	134	19,434	0.0133	_73_	_10,587_	_0.0537_	121	17,549	0.0167	_61_	_8,847_	_0.0816_	219	31,762	0.0042
Aug	118	17,114	0.0177	64	9,282	0.0732	59	8,557	0.0896	55	7,977	0.1043	231	33,503	0.0064
Summation			0.2338			0.3884			0.2633			0.5574			0.0306
Average			0.0195			0.0324			0.0219			0.0465			0.0026
M_r			16461 psi			13227 psi			15641 psi			11319 psi			39527 psi

* Data in italics are estimated values.

Table 29. Monthly subgrade soil modulus and relative damages at Alzada, Bull Mountain, Loma, Livingston, and Swan Lake (1996–1997).

	Alzada			**Bull Mtn**			**Loma**			**Livingston**			**Swan Lake**		
	M_r		**u_f**	**M_r**		**u_f**	**M_r**		**u_f**	**M_r**		**u_f**	**M_r**		**u_f**
	(MPa)	**(psi)**		**(MPa)**	**(psi)**		**(MPa)**	**(psi)**		**(MPa)**	**(psi)**		**(MPa)**	**(psi)**	
Sept	112	16,244	0.0050	268	38,869	0.0027	132	19,144	0.0137	*121*	*17,549*	*0.0168*	229	33,212	0.0038
Oct	99	14,358	0.0265	142	20,595	0.0115	77	11,168	0.0479	*121*	*17,549*	*0.0168*	*229*	*33,212*	*0.0038*
Nov	*150**	*21,755*	*0.0102*	322	46,701	0.0017	*130*	*18,854*	*0.0142*	121	17,549	0.0167	*350*	*50,761*	*0.0014*
Dec	*379*	*54,967*	*0.0012*	*325*	*47,136*	*0.0017*	247	35,823	0.0032	*300*	*43,510*	*0.0020*	*400*	*58,013*	*0.0010*
Jan	379	*54,967*	0.0012	*325*	*47,136*	*0.0017*	452	65,555	0.0008	*300*	*43,510*	*0.0020*	*400*	*58,013*	*0.0010*
Feb	*379*	*54,967*	*0.0012*	*325*	*47,136*	*0.0017*	*452*	*65,555*	*0.0008*	288	41,769	0.0000	*400*	*58,013*	*0.0010*
Mar	238	34,518	0.0035	153	22,190	0.0098	198	28,716	0.0053	111	16,099	0.0207	384	55,693	0.0010
Apr	89	12,908	0.0022	174	25,236	0.0072	141	20,450	0.0118	130	18,854	0.0143	171	24,801	0.0071
May	96	13,923	0.0288	202	29,297	0.0051	130	18,854	0.0142	129	18,709	0.0146	202	29,297	0.0027
Jun	103	14,938	0.0243	196	28,426	0.0055	136	19,724	0.0127	165	23,930	0.0082	193	27,991	0.0018
July	97	14,068	0.0277	216	31,327	0.0044	155	22,480	0.0095	121	17,549	0.0167	194	28,136	0.0032
Aug	106	15,373	0.0089	211	30,602	0.0046	147	21,320	0.0106	124	17,984	0.0159	217	31,472	0.0018
Sum-mation			0.2016			0.0576			0.1154			0.1469			0.0414
Average			0.0168			0.0048			0.0096			0.0122			0.0034
M_r			17546 psi			30121 psi			22315 psi			20113 psi			34730 psi

* Data in italics are estimated values.

Table 30. Monthly subgrade soil modulus and relative damages at Dickey Lake, Wolf Point, Sweetgrass, Scobey/Redstone and East Glacier (1997–1998).

Month	**Dickey Lake**			**Wolf Point**			**Sweetgrass**			**Scobey/Redstone**			**East Glacier**		
	M_r		**u_f**	**M_r**		**u_f**	**M_r**		**u_f**	**M_r**		**u_f**	**M_r**		**u_f**
	(MPa)	**(psi)**		**(MPa)**	**(psi)**		**(MPa)**	**(psi)**		**(MPa)**	**(psi)**		**(MPa)**	**(psi)**	
Sep	132	19,144	0.0138	_103_	_14,938_	_0.0244_	109	15,809	0.0213	68	9,862	0.0630	_275*_	_39,884_	_0.0025_
Oct	90	13,053	0.0338	_103_	_14,938_	_0.0244_	112	16,244	0.0200	74	10,732	0.0523	275	39,884	0.0025
Nov	63	9,137	0.0766	103	14,938	0.0246	112	16,244	0.0200	89	12,908	0.0341	277	40,174	0.0025
Dec	_99*_	_14,358_	_0.0268_	_157_	_22,770_	_0.0092_	_132†_	_19,144_	_0.0137_	_120_	_17,404_	_0.0171_	_532_	_77,157_	_0.0005_
Jan	_99_	14,358	_0.0268_	_157_	_22,770_	_0.0092_	_152_	_22,045_	_0.0099_	_120_	_17,404_	_0.0171_	_532_	_77,157_	_0.0005_
Feb	99	14,358	0.0266	157	22,770	0.0092	152	22,045	0.0099	120	17,404	0.0170	532	77,157	0.0005
Mar	137	19,869	0.0126	162	23,495	0.0085	76	11,022	0.0496	152	22,045	0.0098	135	19,579	0.0131
Apr	49	7,107	0.1371	111	16,099	0.0207	92	13,343	0.0316	55	7,977	0.1060	_135_	_19,579_	_0.0130_
May	89	12,908	0.0343	75	10,877	0.0504	117	16,969	0.0181	54	7,832	0.1083	_135_	_19,579_	_0.0130_
Jun	79	11,458	0.0445	80	11,603	0.0444	109	15,809	0.0213	60	8,702	0.0858	_135_	_19,579_	_0.0130_
July	109	15,809	0.0213	_80_	_11,603_	_0.0439_	_110_	_15,954_	_0.0210_	87	12,618	0.0362	_135_	_19,579_	_0.0130_
Aug	98	14,213	0.0273	_80_	11,603	_0.0439_	111	16,099	0.0204	55	7,977	0.1043	_135_	_19,579_	_0.0130_
Sum-mation			0.1242			0.2065			0.0614			0.1494			0.0075
Average			0.0414			0.0258			0.0205			0.0498			0.0025
M_r			11897 psi			14581 psi			16121 psi			10984 psi			39941 psi

* Data in italics are estimated values.
† This is a mid-point value between 112 and 152.

Table 31. Monthly subgrade soil modulus and relative damages at Alzada, Bull Mountain, Loma, Livingston. and Swan Lake (1997–1998).

Month	Alzada			Bull Mtn			Loma			Livingston			Swan Lake		
	M_r		u_f	M_r		u_f	M_r		u_f	M_r		u_f	M_r		u_f
	(MPa)	(psi)		(MPa)	(psi)		(MPa)	(psi)		(MPa)	(psi)		(MPa)	(psi)	
Sep	_114_	16,534	_0.0193_	_135_	19,579	_0.0130_	_135_	19,579	_0.0130_	Insufficient Data			_177_	25,671	_0.0069_
Oct	114	16,534	0.0193	134	19,434	0.0131	135	19,579	0.0130				_177_	25,671	_0.0069_
Nov	97	14,068	0.0282	209	30,312	0.0047	104	15,083	0.0241				189	27,411	0.0060
Dec	_116*_	16,824	_0.0185_	_167_	24,220	_0.0080_	_170_	24,656	_0.0076_				_189_	27,411	_0.0060_
Jan	116	16,824	0.0185	167	24,220	0.0080	_170_	24,656	_0.0076_				_213_	30,892	_0.0045_
Feb	108	15,664	0.0220	149	21,610	0.0104	170	24,656	0.0077	92	13,343	0.0316	213	30,892	0.0045
Mar	84	12,183	0.0394	160	23,205	0.0088	108	15,664	0.0217	Insufficient Data			145	21,030	0.0111
Apr	_114_	16,534	_0.0193_	239	34,663	0.0035	_135_	19,579	_0.0130_				177	25,671	0.0069
May	_114_	16,534	_0.0193_	210	30,457	0.0047	_135_	19,579	_0.0130_				_177_	25,671	_0.0069_
Jun	_114_	16,534	_0.0193_	374	54,242	0.0012	_135_	19,579	_0.0130_				_177_	25,671	_0.0069_
July	_114_	16,534	_0.0193_	216	31,327	0.0044	_135_	19,579	_0.0130_				_177_	25,671	_0.0069_
Aug	_114_	16,534	_0.0193_	211	30,602	0.0046	_135_	19,579	_0.0130_				_177_	25,671	_0.0069_
Sum-mation			0.0668			0.0309			0.0577						0.0129
Average			0.0223			0.0103			0.0144						0.0065
M_r			15540 psi			21668 psi			18734 psi						26479 psi

* Data in italics are estimated values.

SUMMARY AND RECOMMENDATIONS

Road Rater and FWD deflection, moisture, and temperature data were collected from several sites in Montana and were used to evaluate the potential for thaw weakening. The pavement structure consisted of variable thicknesses of asphalt concrete and base over different kinds of subgrade. The base courses mostly graded between an A-1-a and A-1-b. The exception was East Glacier, where the base course was classified as an A-4 soil. The percentage of fines in the base (except for East Glacier) varied between 8 and 15%. The subgrades at these sites were variable, ranging among A-1-b, A-2-4, A-4, and A-6. Water table locations were not available from these sites.

Because of instrumentation malfunction or problems with data collection, moisture and temperature data were limited to the northern half of the state. The deflection data taken were poor and appeared to miss the critical spring thaw period during both spring seasons. These poor data are a result of the limitations of the system's load application. The highest deflections in most cases were in the 6 to 8 mil range. The highest load used was 18 kN (4 kips).

Based on the moisture data, the base course layers at Dickey Lake, Wolf Point, Scobey/Redstone, and East Glacier are prone to thaw weakening. Deflection data indicate that the base at Bull Mountain, Swan Lake, and Scobey/Redstone may be prone to thaw weakening. The subgrade at Dickey Lake, East Glacier, Bull Mountain, Swan Lake, and Scobey/Redstone may also be prone to thaw weakening. The length of thaw weakening varied from 4 days (Scobey/Redstone) to 3 weeks (East Glacier).

Based on the limited deflection data, a tentative recommendation for effective subgrade modulus is provided. These values should be validated with additional Falling Weight Deflection (FDW) testing. These tests should be conducted using the Strategic Highway Research Highway (SHRP) protocol. In addition, prior to any testing, the Falling Weight Deflectometer should be calibrated. The numbers of sites could be reduced and more testing should be conducted during the spring thaw period. The authors suggest that an in-depth laboratory study on the resilient behavior of base courses be conducted and that the results from the field FWD tests be correlated to the laboratory results before any relations are presumed from the back-calculated base course moduli presented in this report.

In Appendix C, we have graphed the pertinent design data for all 10 sites as requested by MDT. Two sites have no plots for ground moisture content and soil temperatures, as the sensors for those sites failed early in the test period. The order of the graphs is: subgrade modulii, subgrade moisture contents, precipitation, and temperature. Each is presented as a function of the time of year; beginning in October and running through September to allow clear definition of the transition from frozen to thawing to thawed states. For each site, a table of the base and subgrade soil gradations and plasticity index follow the graphs.

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Janoo, V.C., R. Eaton, and L. Barna (1997) Evaluation of airport subsurface materials, CRREL Special Report 97-13.

Shepherd, K.L., and J.L. Vosen (1997) Spring thaw weakening: design impact and load restriction impact. MDT Research Project, August.

APPENDIX A: TEMPERATURE–MOISTURE DATA

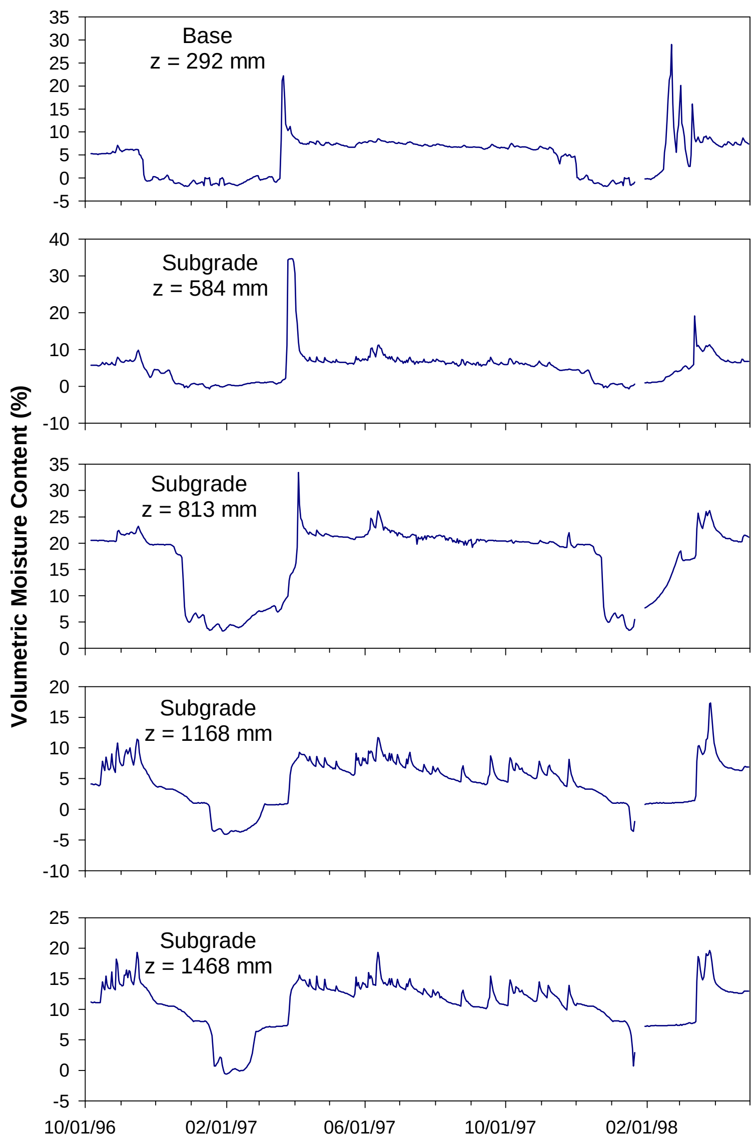

Figure A-1. Moisture plots for Dickey Lake.

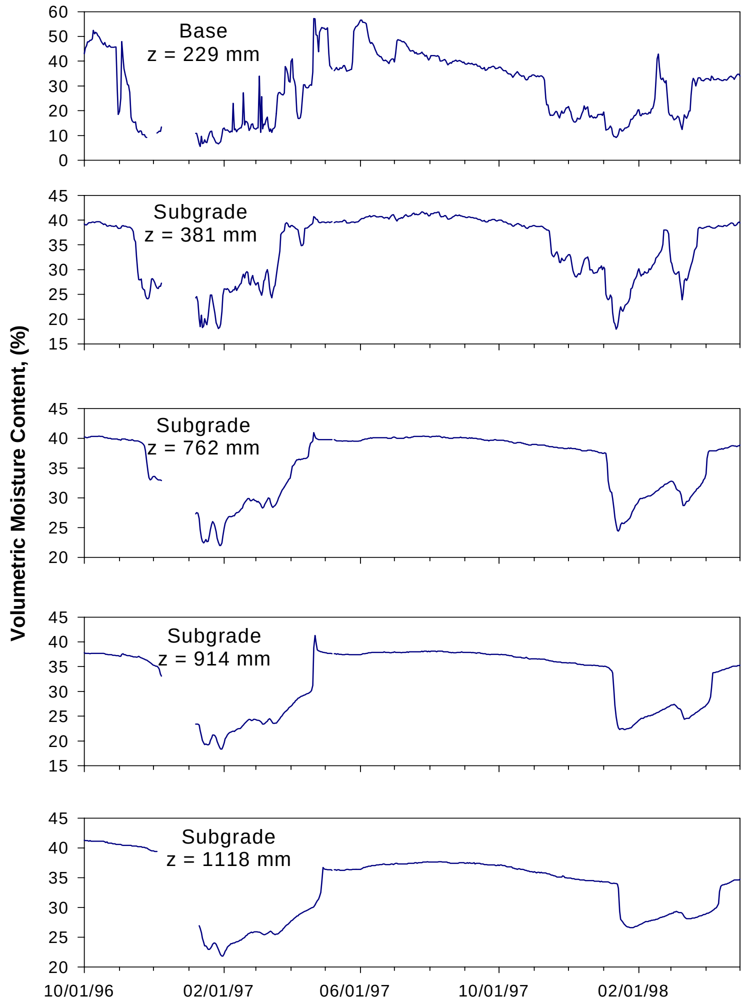

Figure A-2. Moisture plots for Wolf Point.

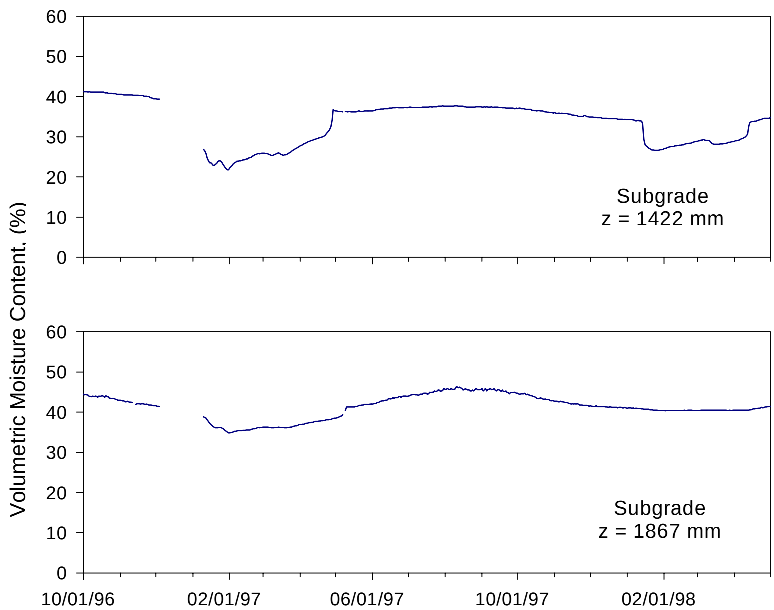

Figure A-3. Moisture plots for Wolf point.

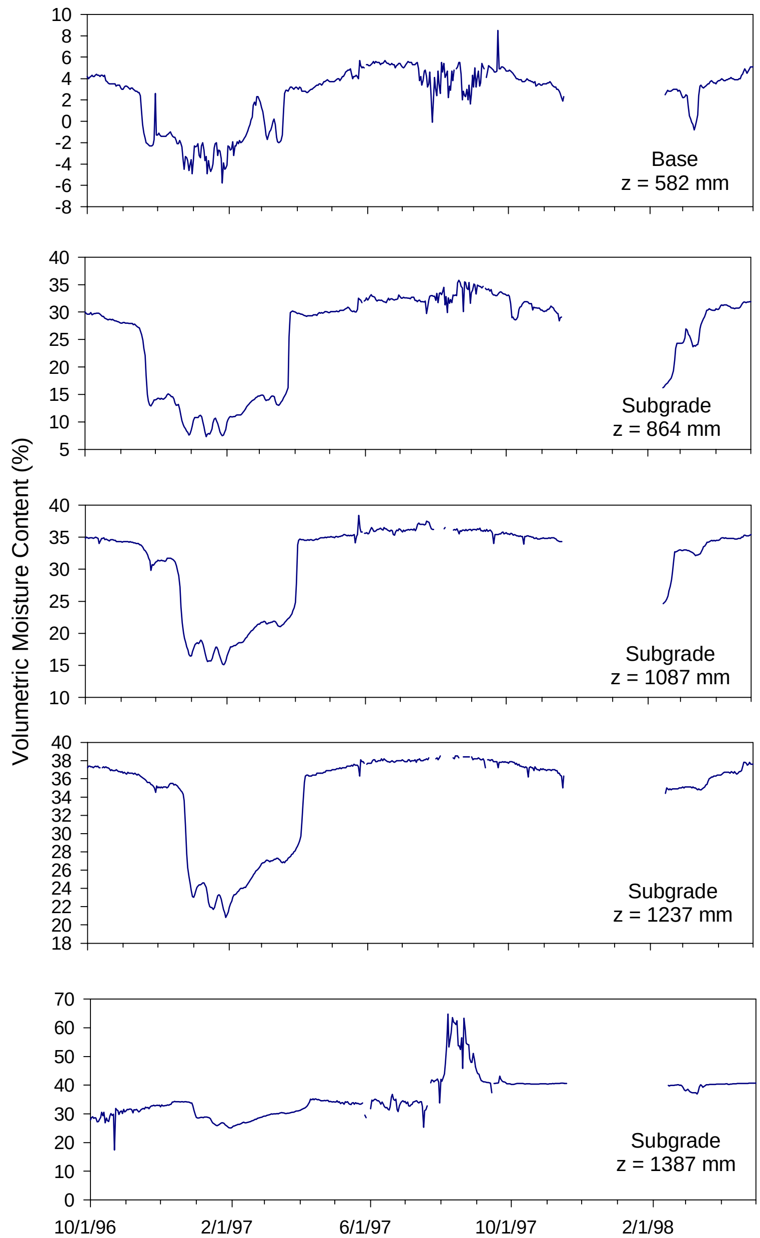

Figure A-4. Moisture plots for Sweetgrass.

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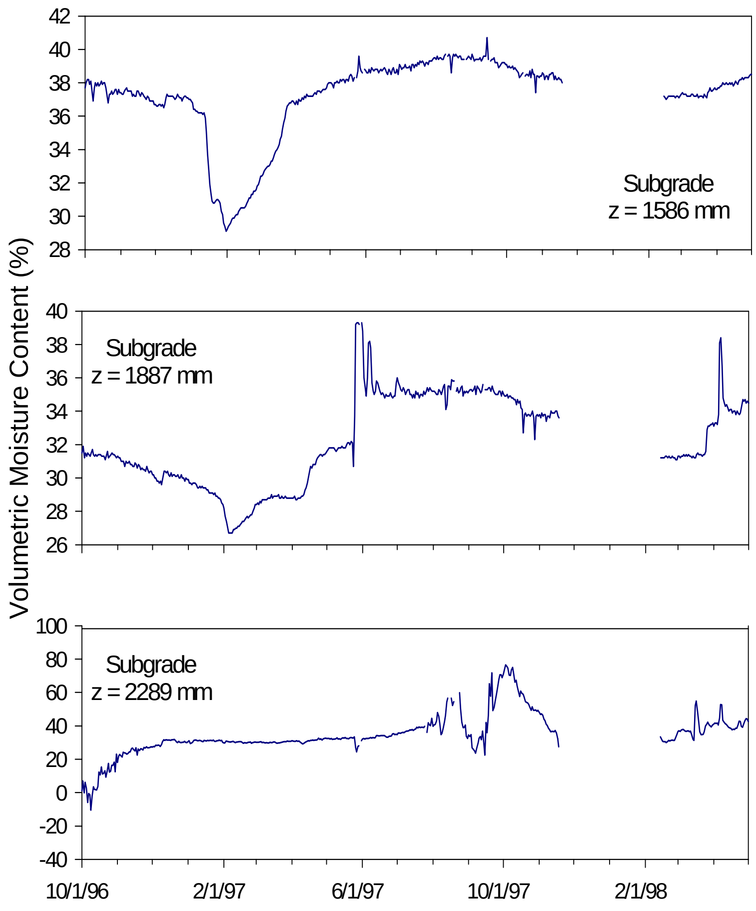


Figure A-5. Moisture plots for Sweetgrass.

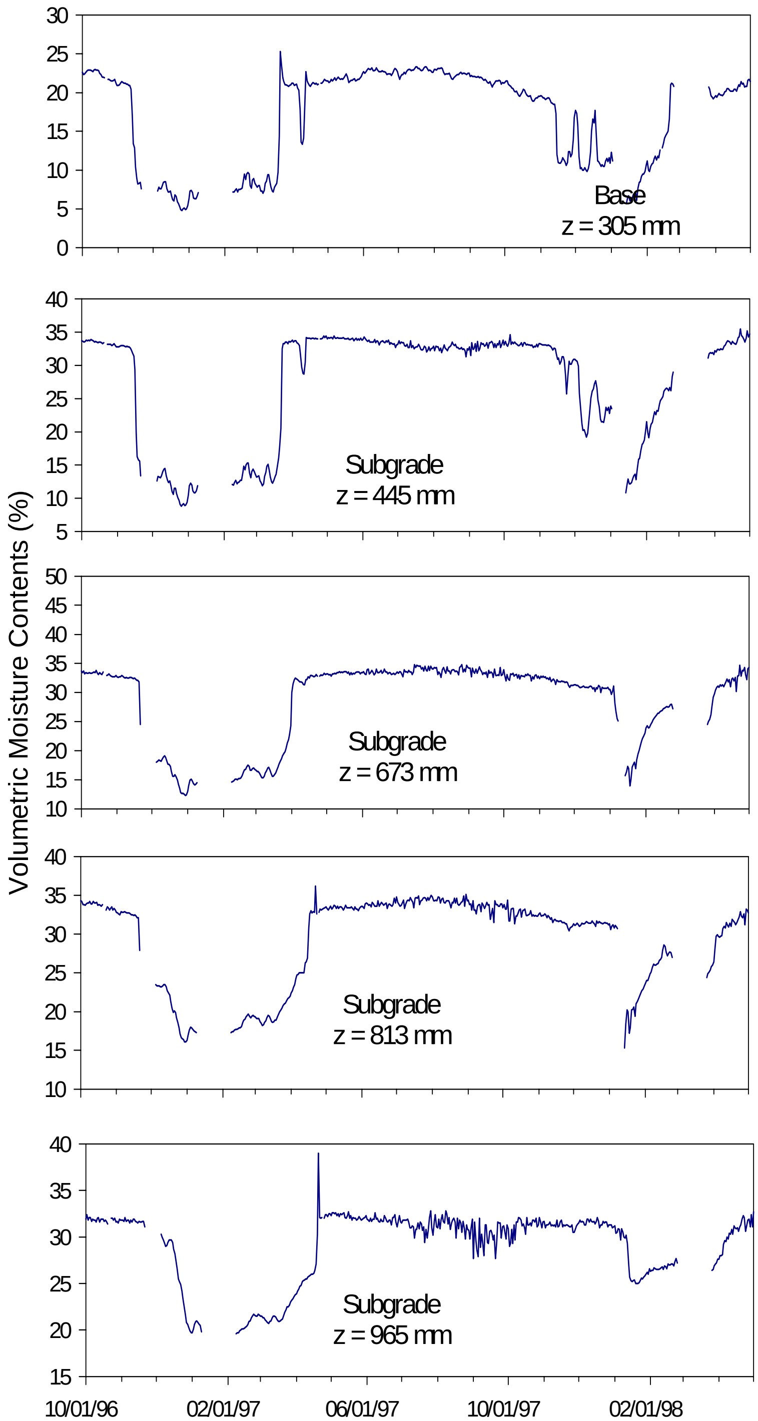


Figure A-6. Moisture plots for Redstone.

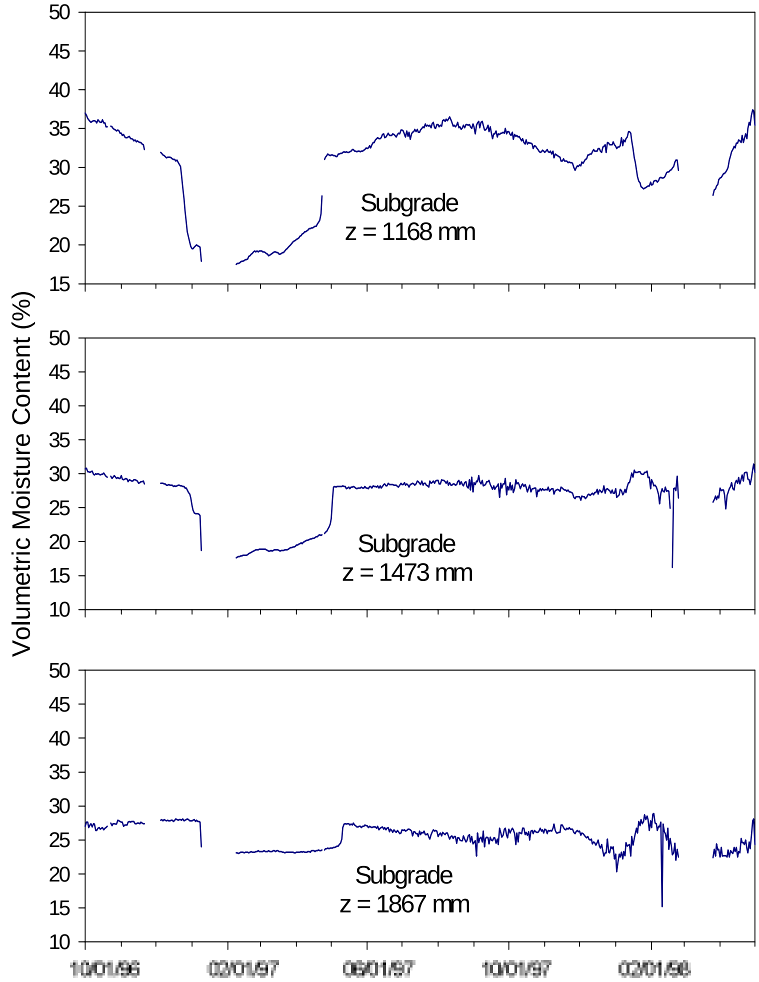


Figure A-7. Moisture plots for Redstone.

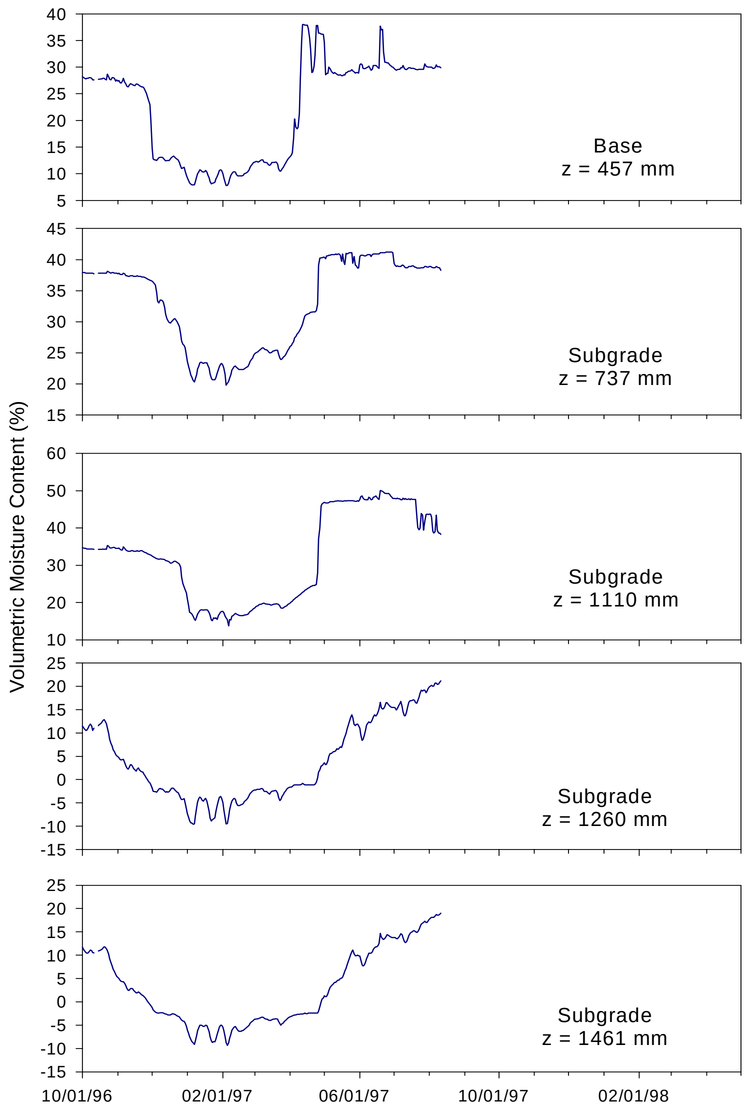


Figure A-8. Moisture plots for East Glacier.

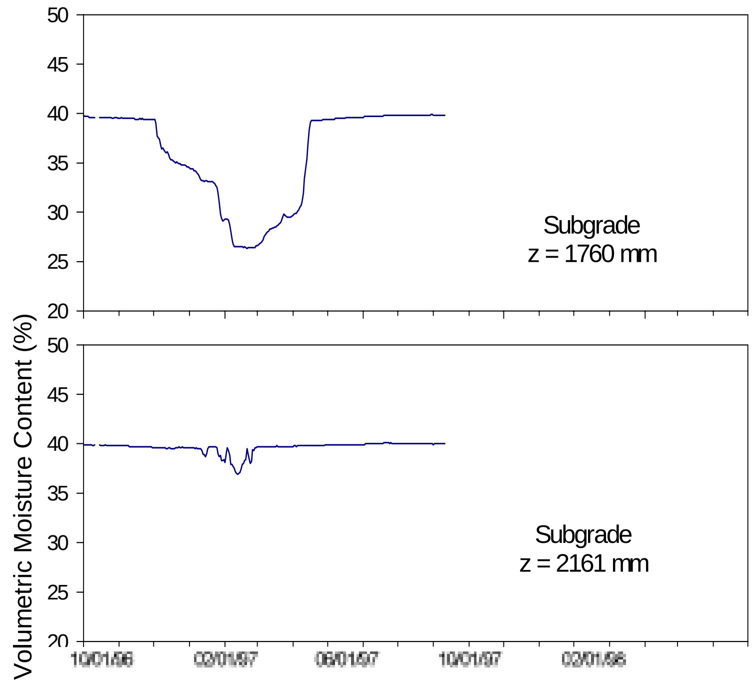


Figure A-9. Moisture plots for East Glacier.

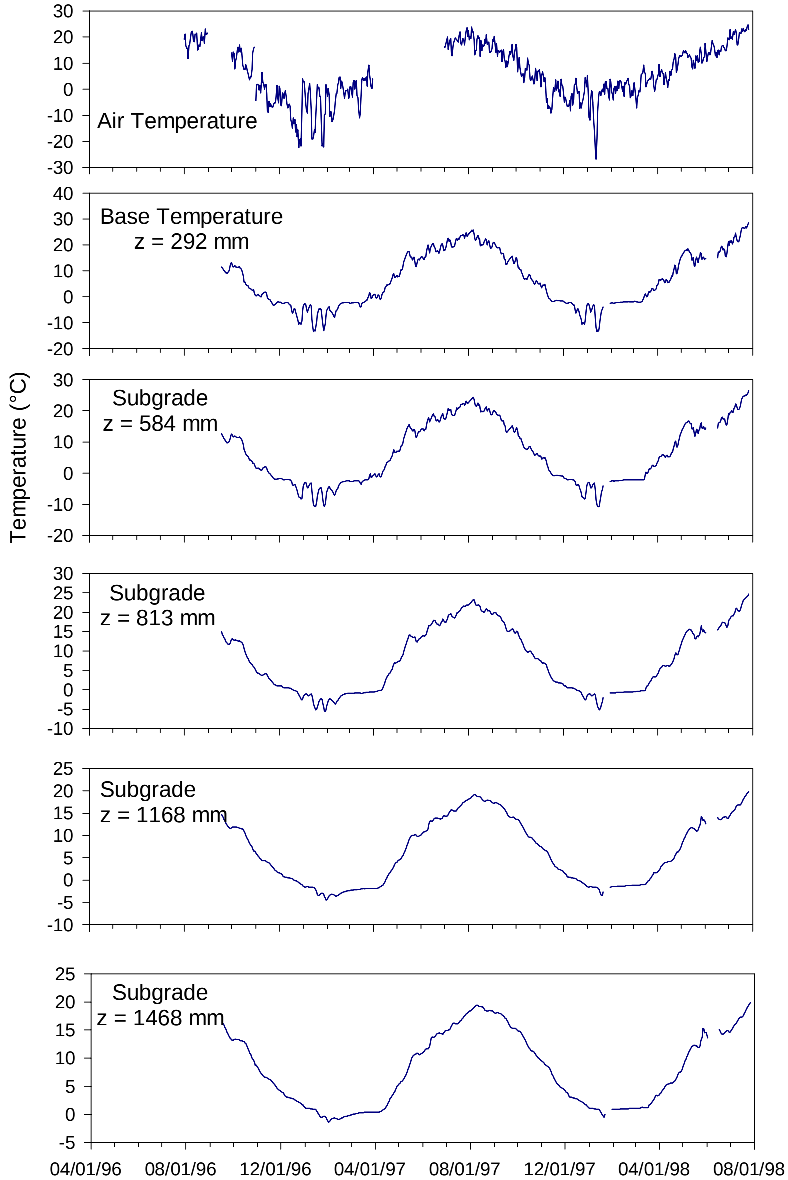


Figure A-10. Temperature plots for Dickey Lake.

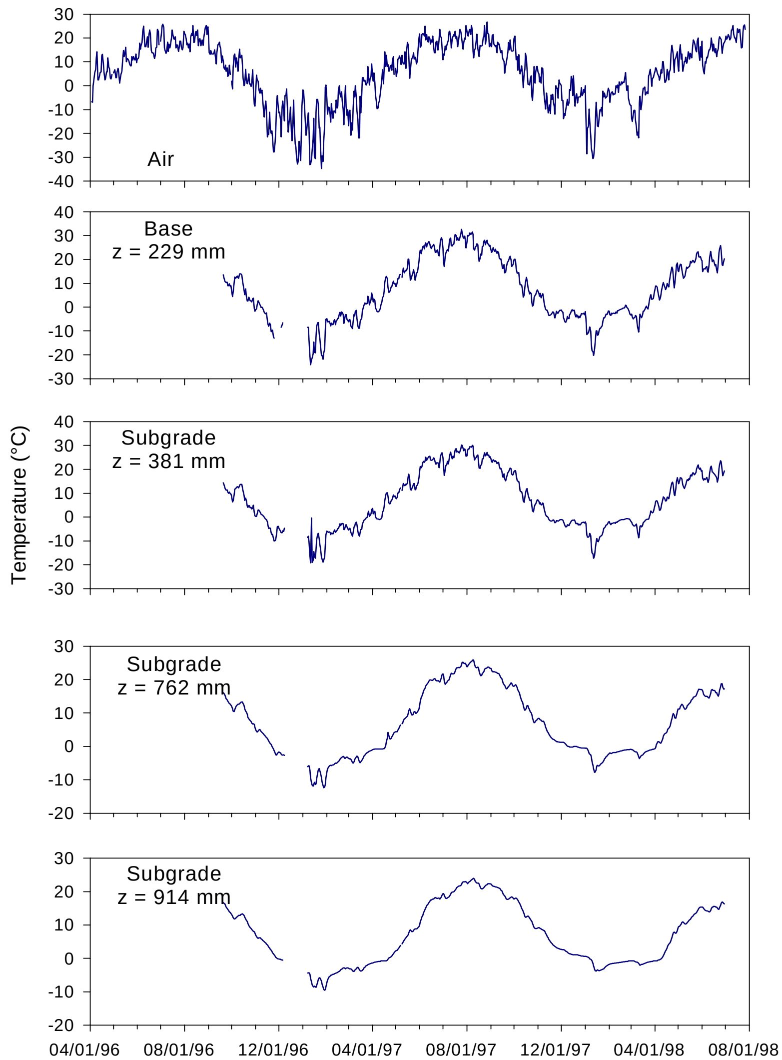


Figure A-11. Temperature plots for Wolf Point.

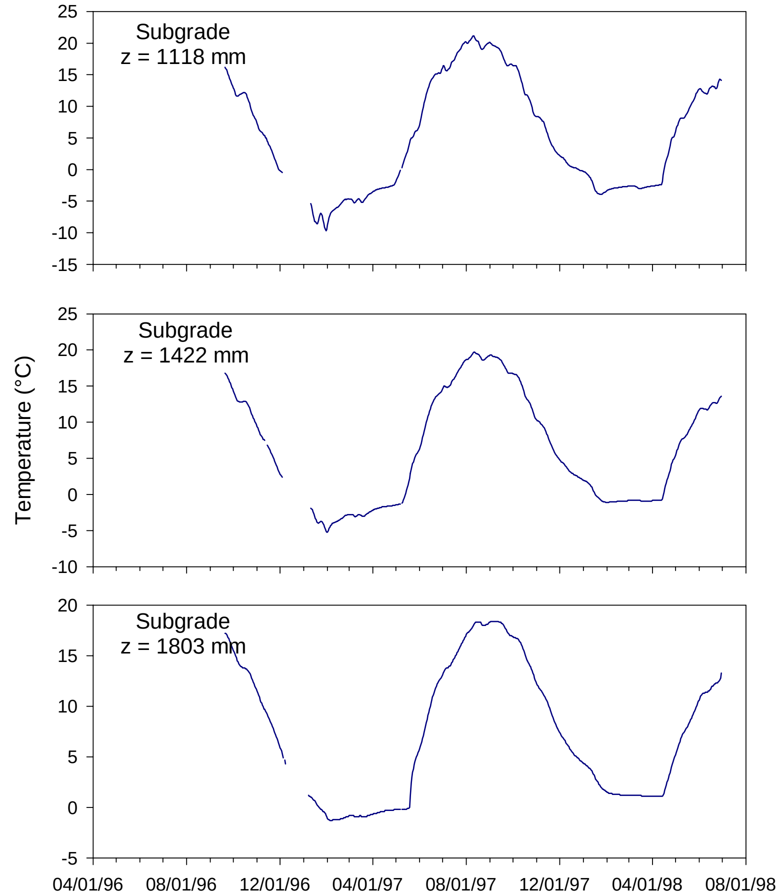


Figure A-12. Temperature plots for Wolf Point.

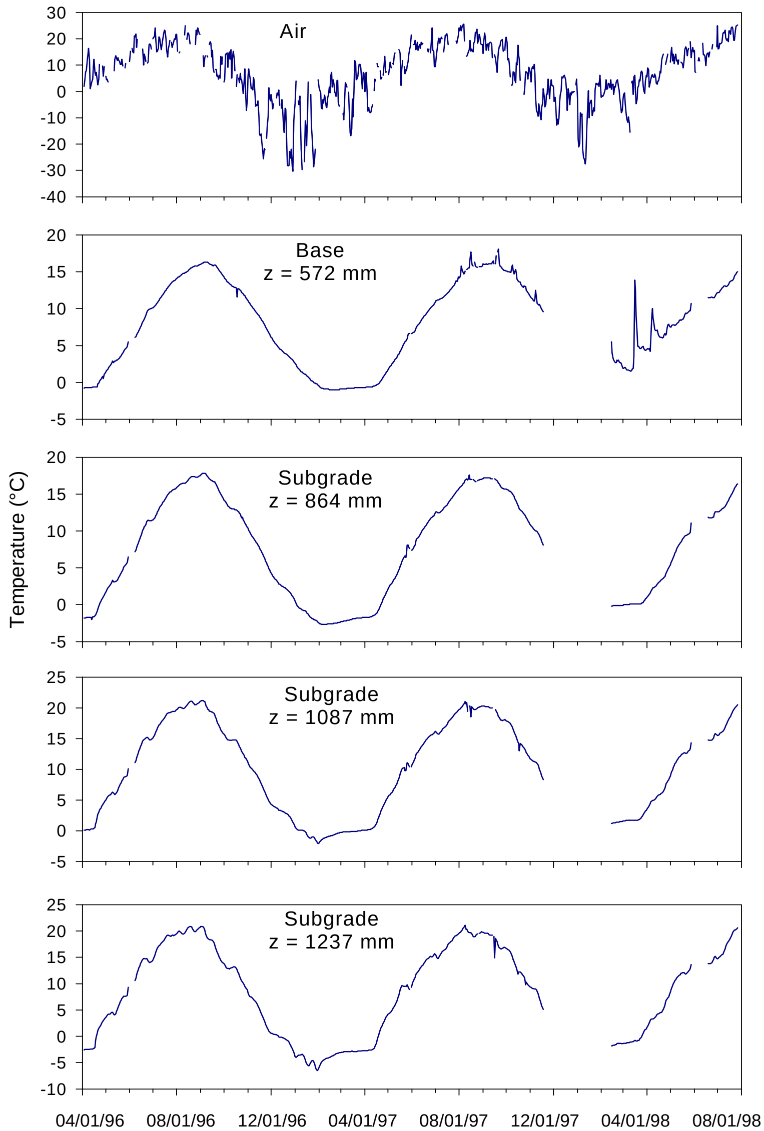


Figure A-13. Temperature plots for Sweetgrass.

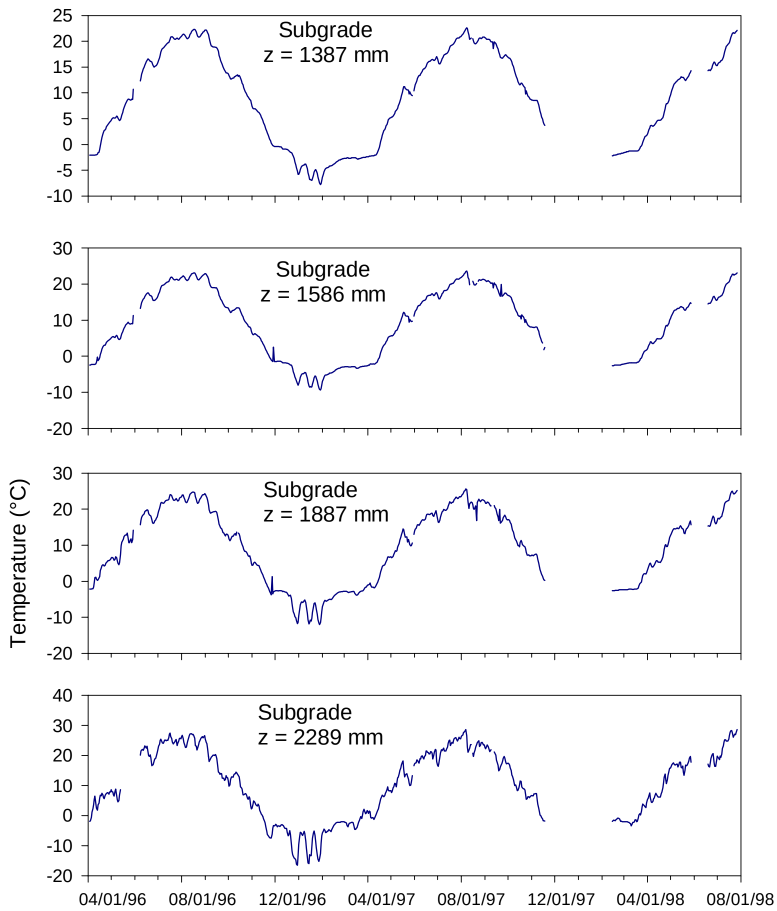


Figure A-14. Temperature plots for Sweetgrass.

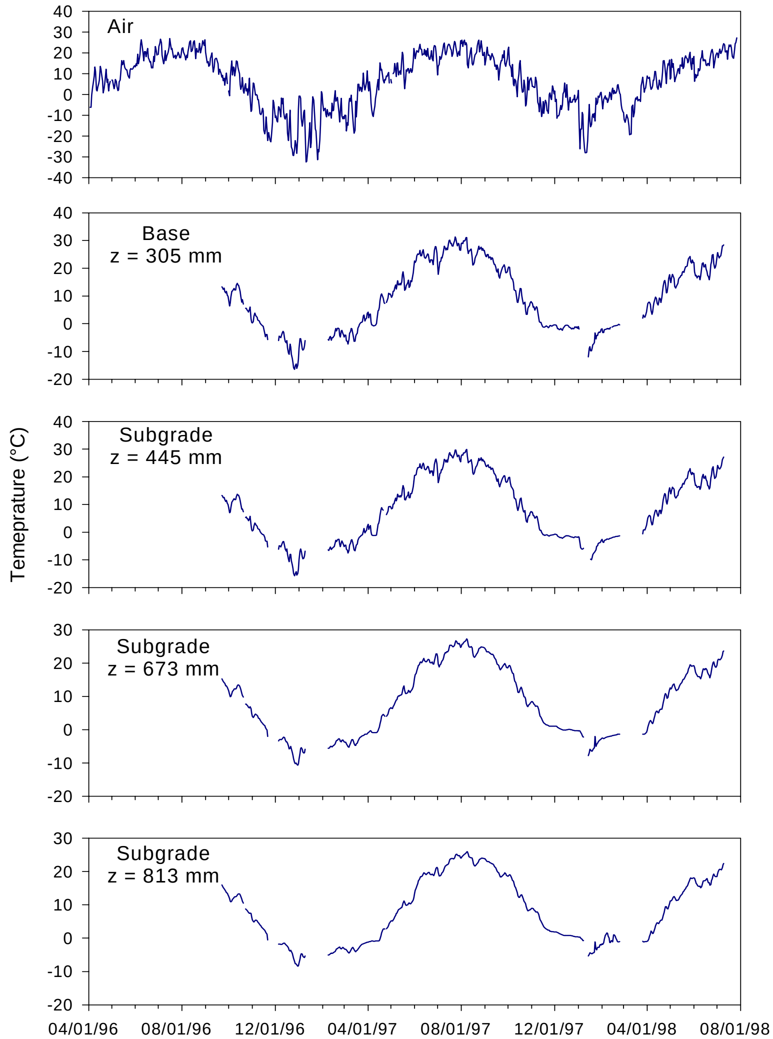


Figure A-15. Temperature plots for Redstone.

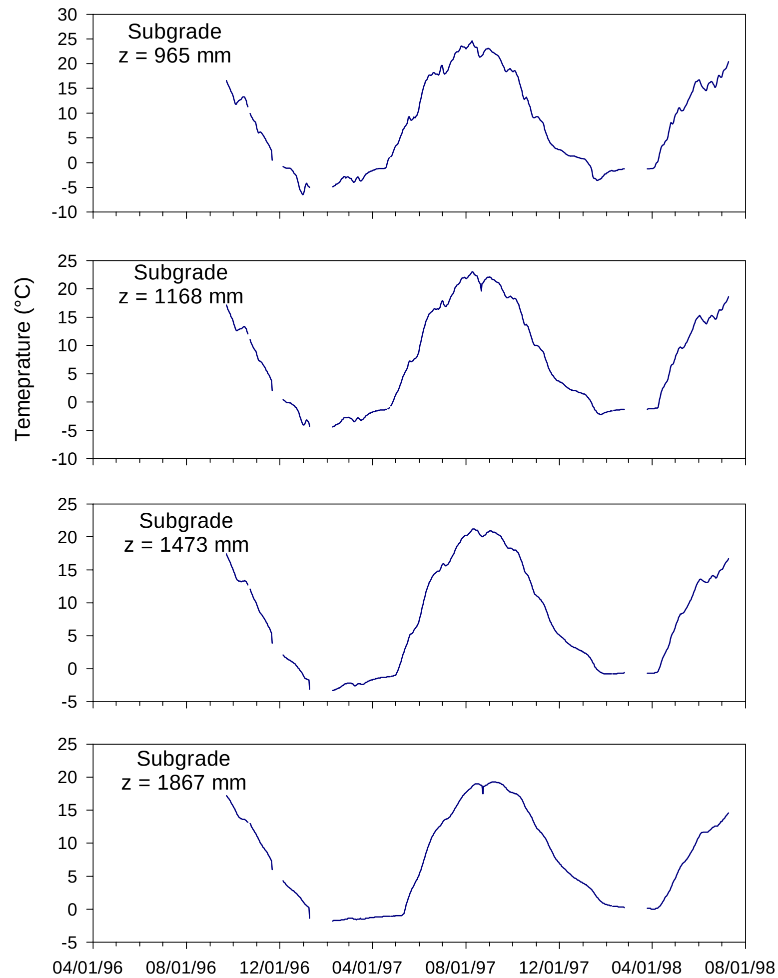


Figure A-16. Temperature plots for Redstone.

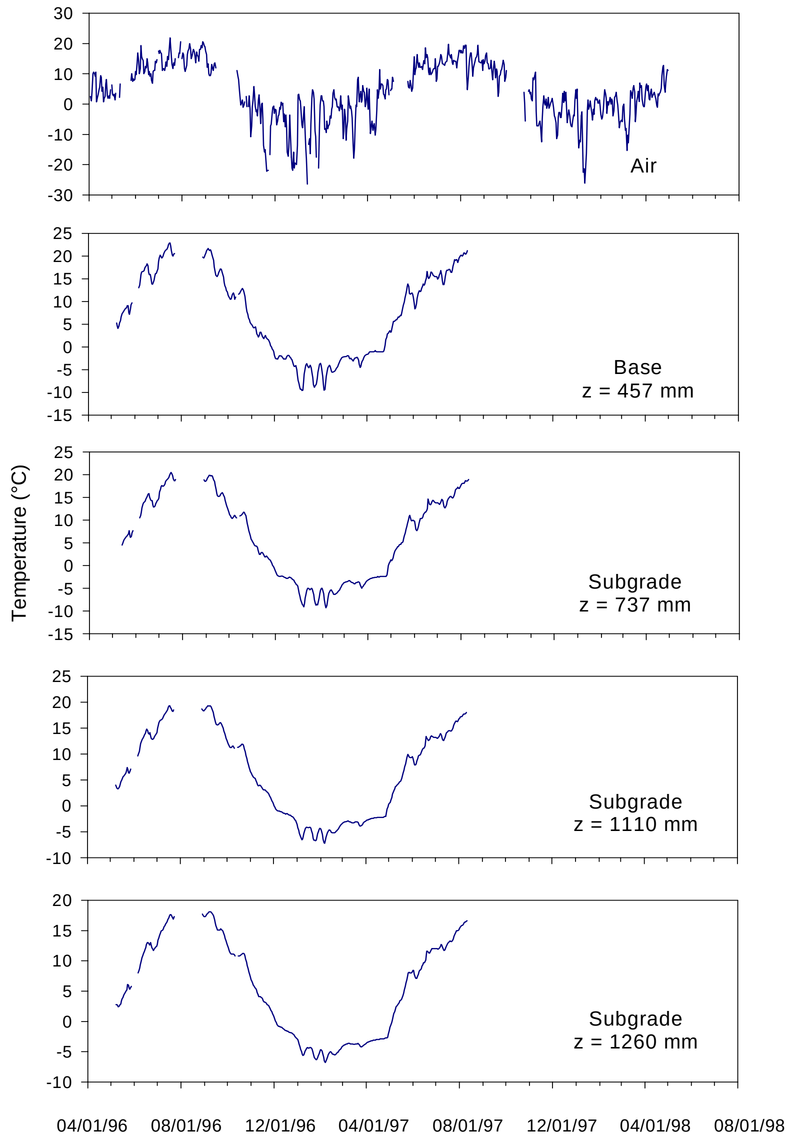


Figure A-17. Temperature plots for East Glacier.

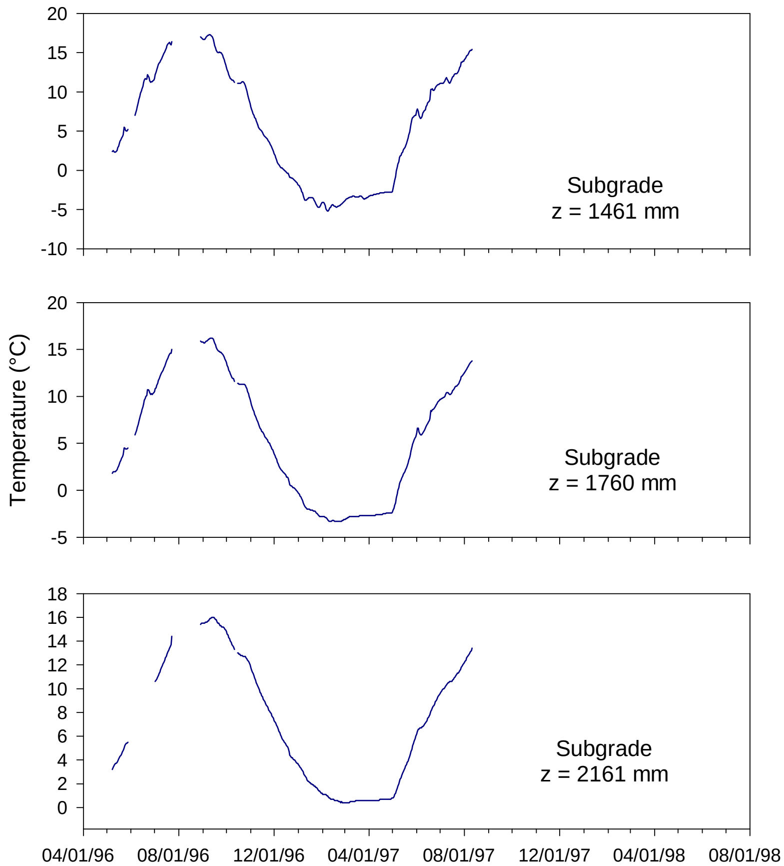


Figure A-18. Temperature plots for East Glacier.

APPENDIX B: BACK-CALCULATED MODULUS

Alzada

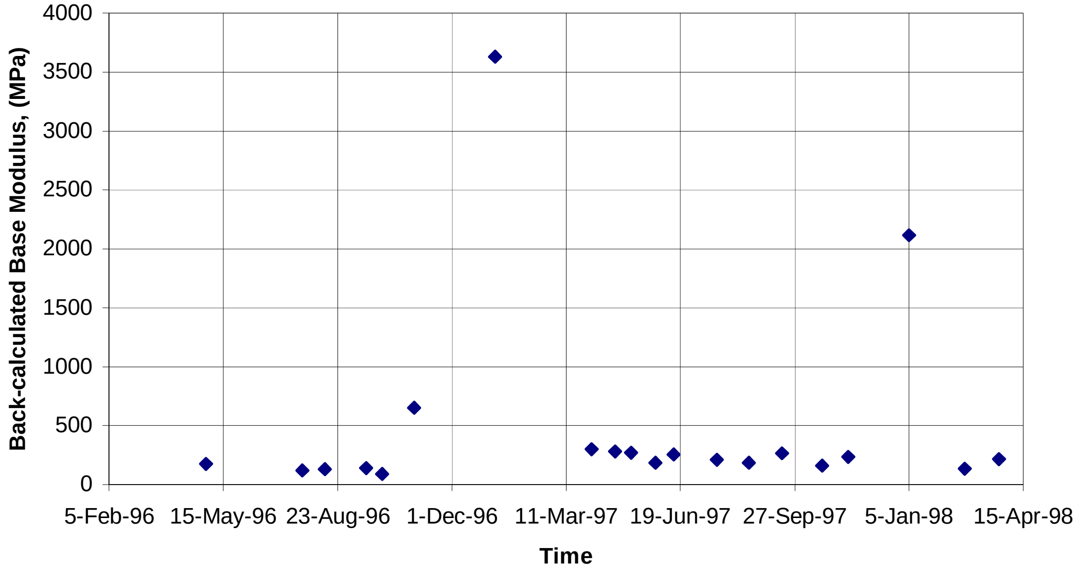


Figure B-1. Back-calculated base modulus as a function of time for Alzada.

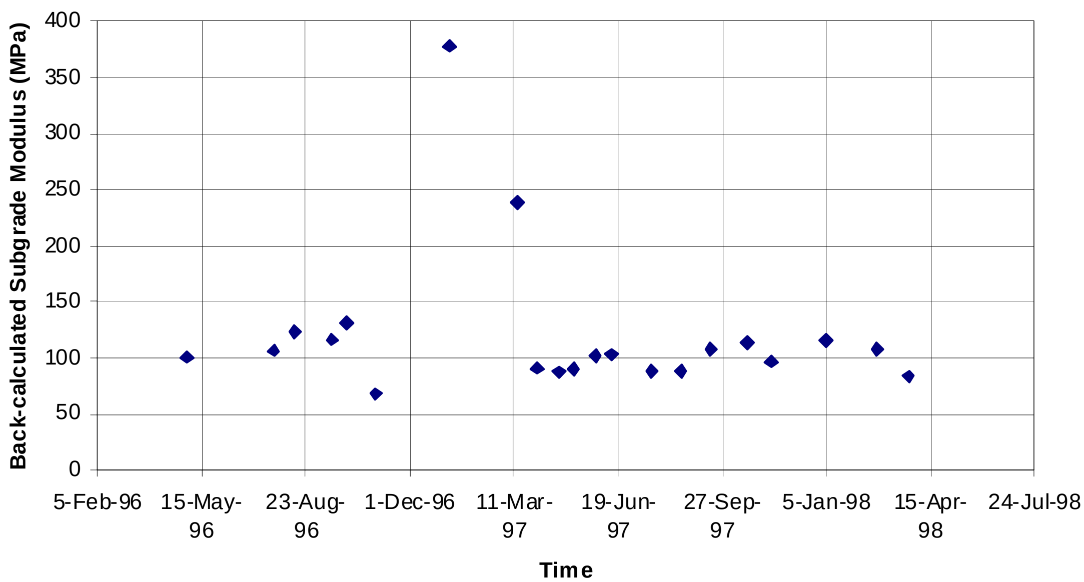


Figure B-2. Back-calculated subgrade modulus as a function of time for Alzada.

Bull Mountain

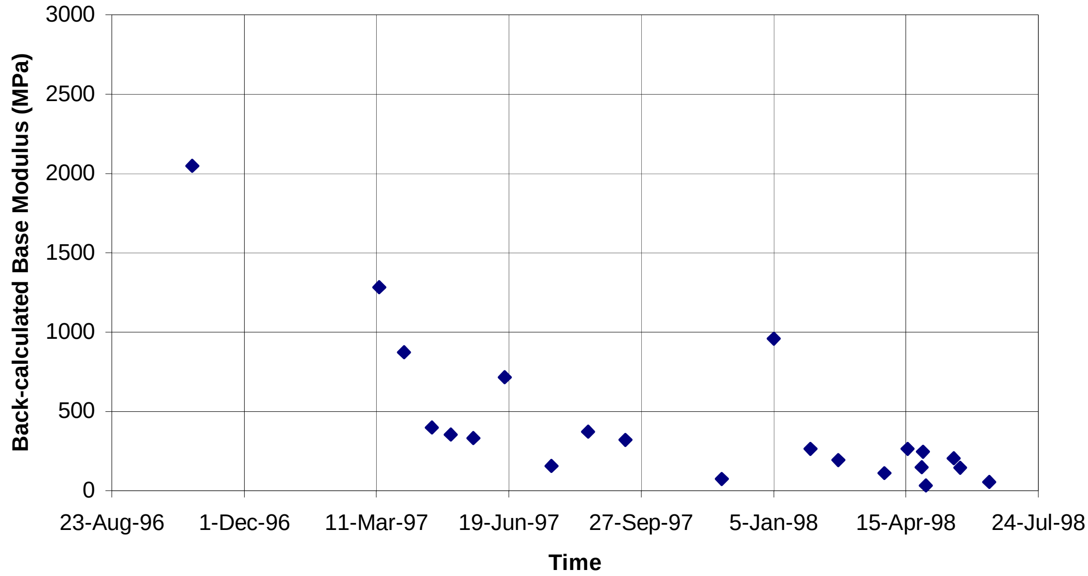


Figure B-3. Back-calculated base modulus as a function of time for Bull Mountain.

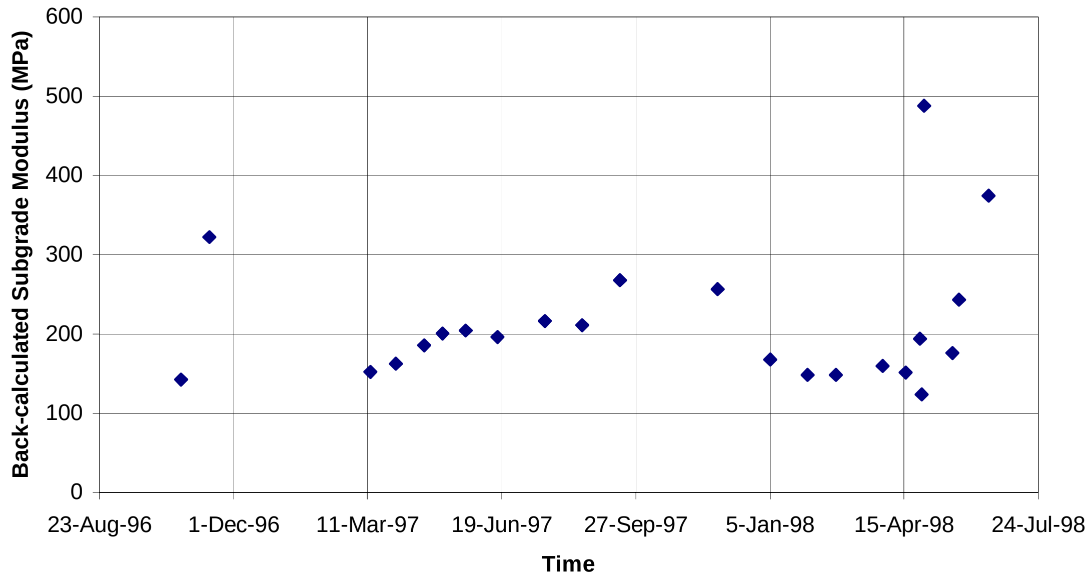


Figure B-4. Back-calculated subgrade modulus as a function of time for Bull Mountain.

Livingston

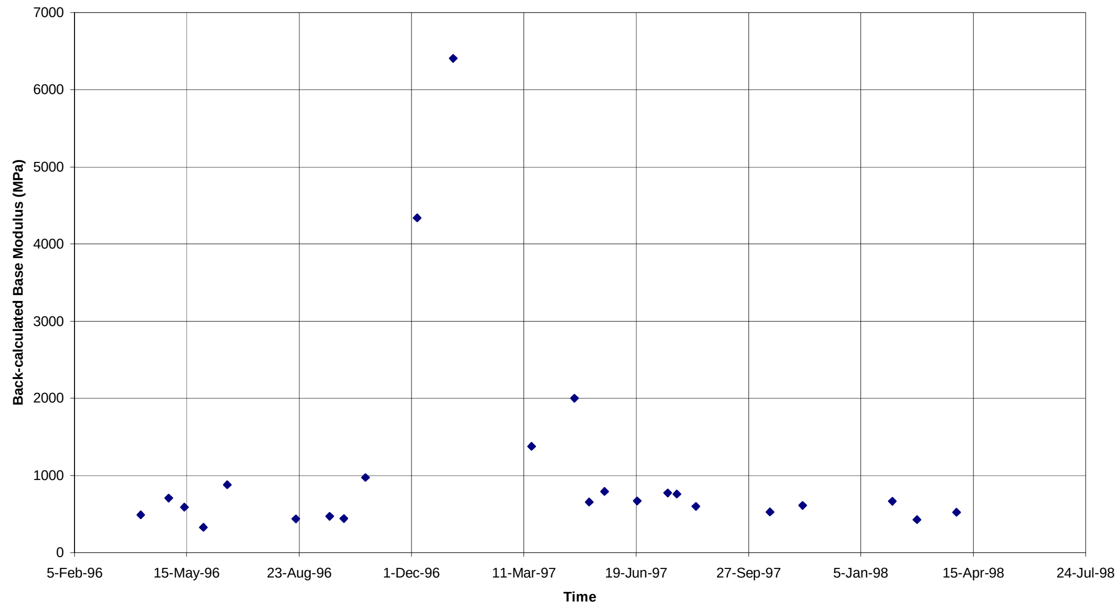


Figure B-5. Back-calculated base modulus as a function of time for Livingston.

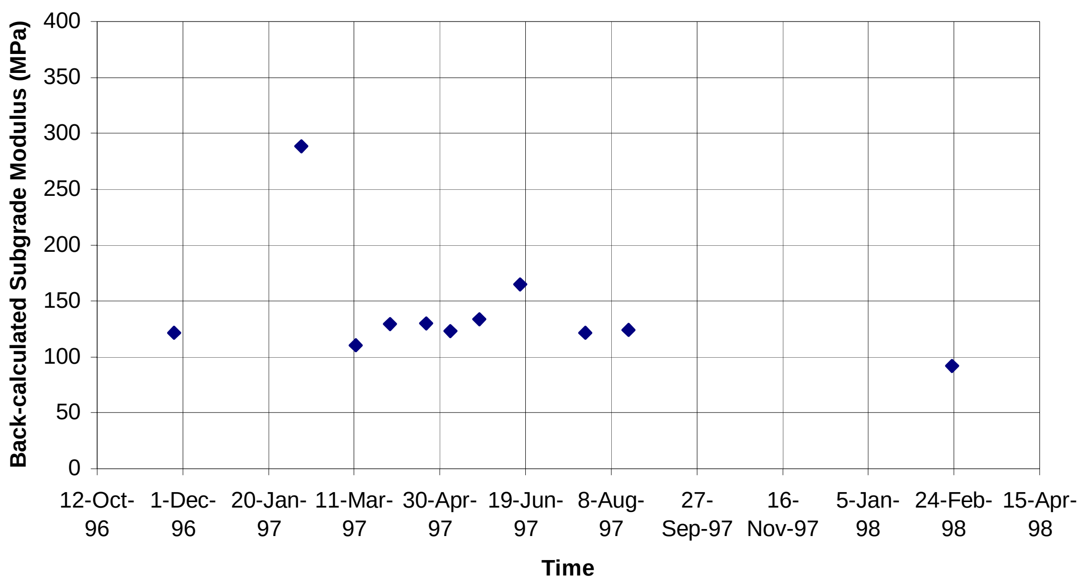


Figure B-6. Back-calculated subgrade modulus as a function of time for Livingston.

Wolf Point

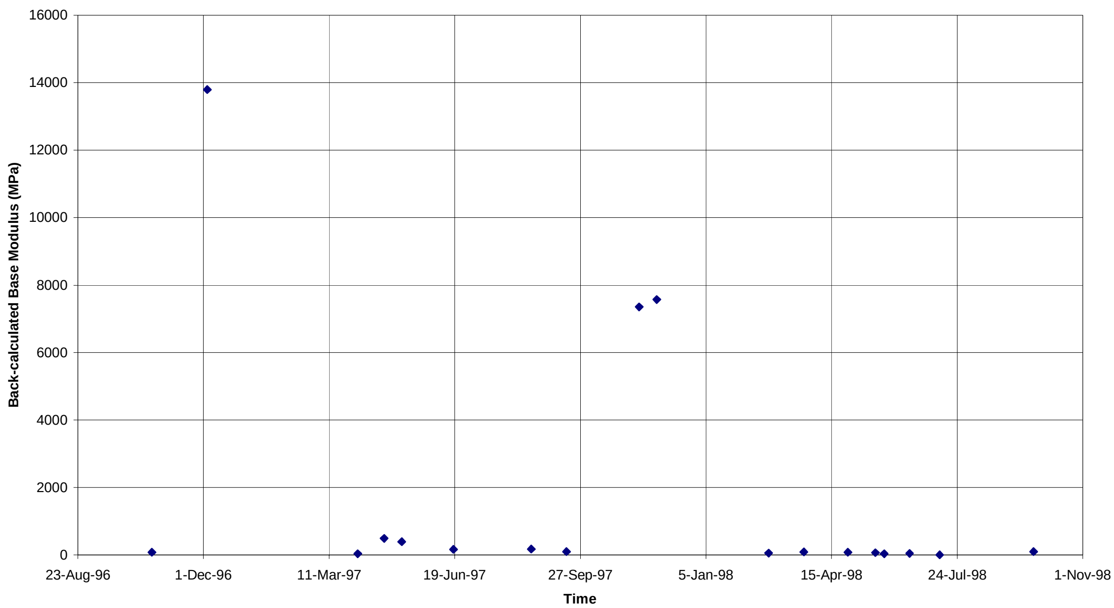


Figure B-7. Back-calculated base modulus as a function of time for Wolf Point.

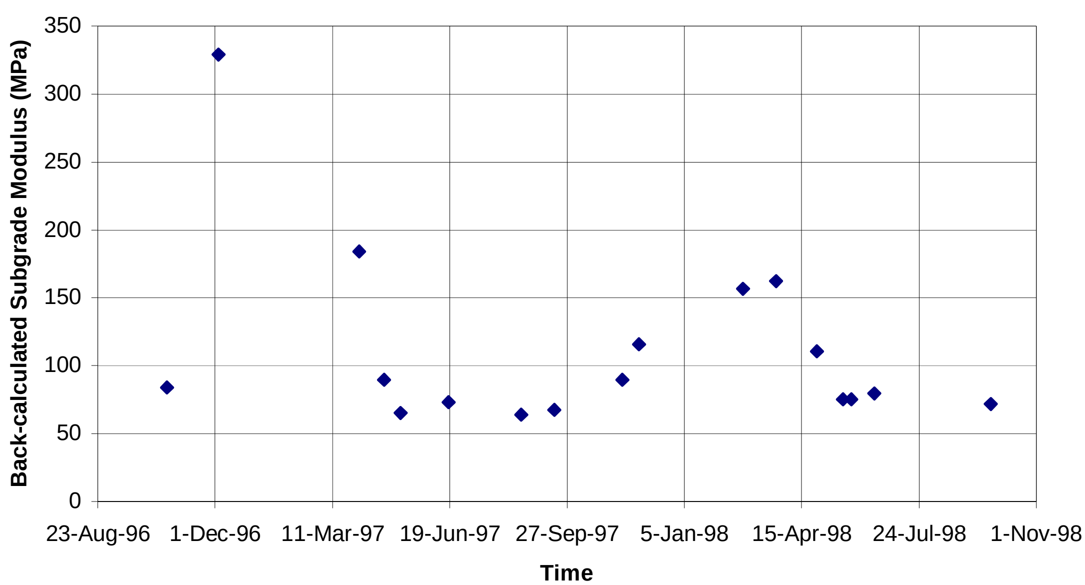


Figure B-8. Back-calculated subgrade modulus as a function of time for Wolf Point.

Swan Lake

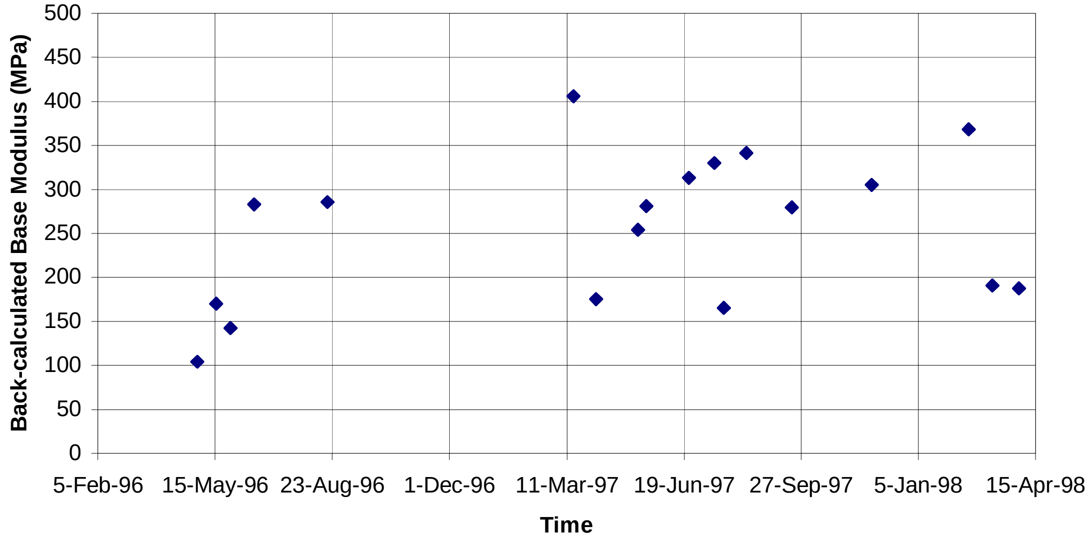


Figure B-9. Back-calculated base modulus as a function of time for Swan Lake.

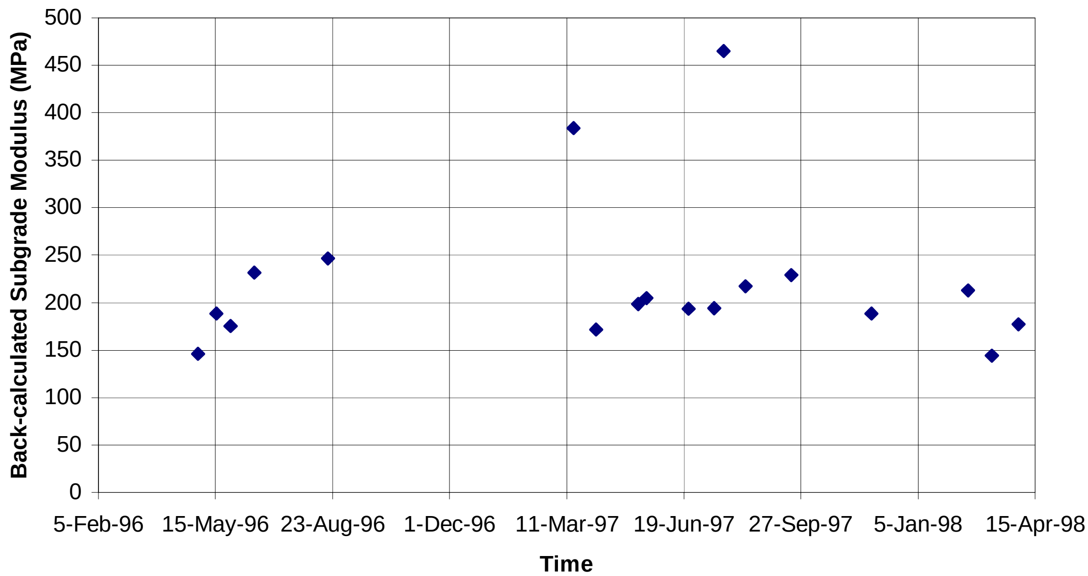


Figure B-10. Back-calculated subgrade modulus as a function of time for Swan Lake.

Loma

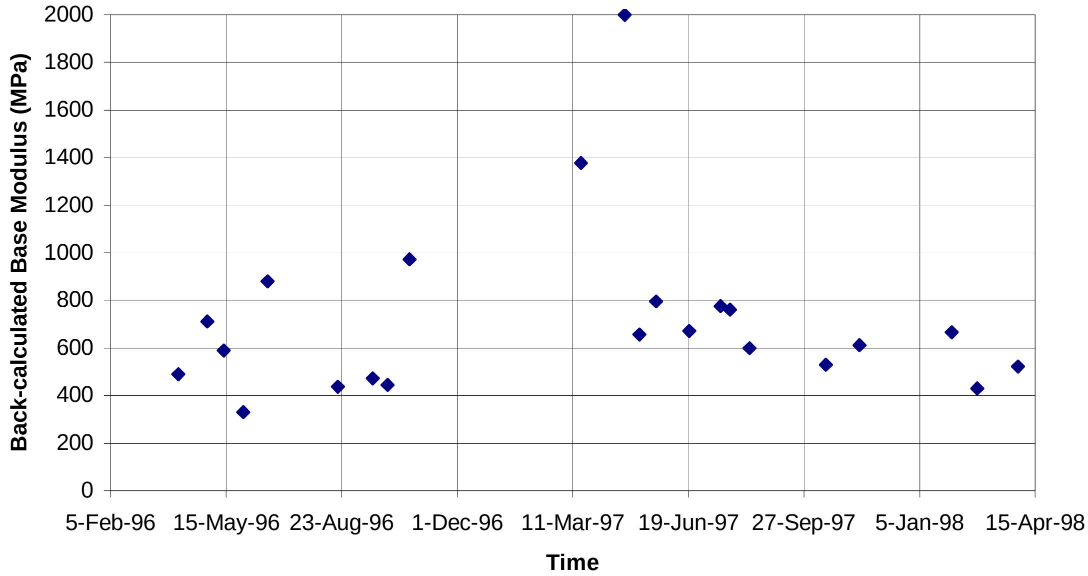


Figure B-11. Back-calculated base modulus as a function of time for Loma.

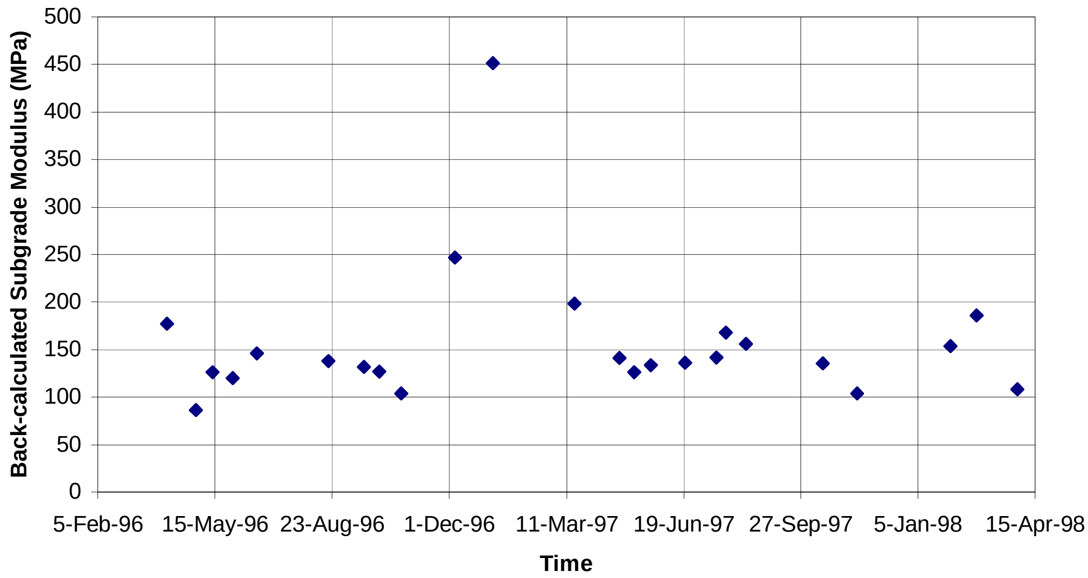


Figure B-12. Back-calculated subgrade modulus as a function of time for Loma.

East Glacier

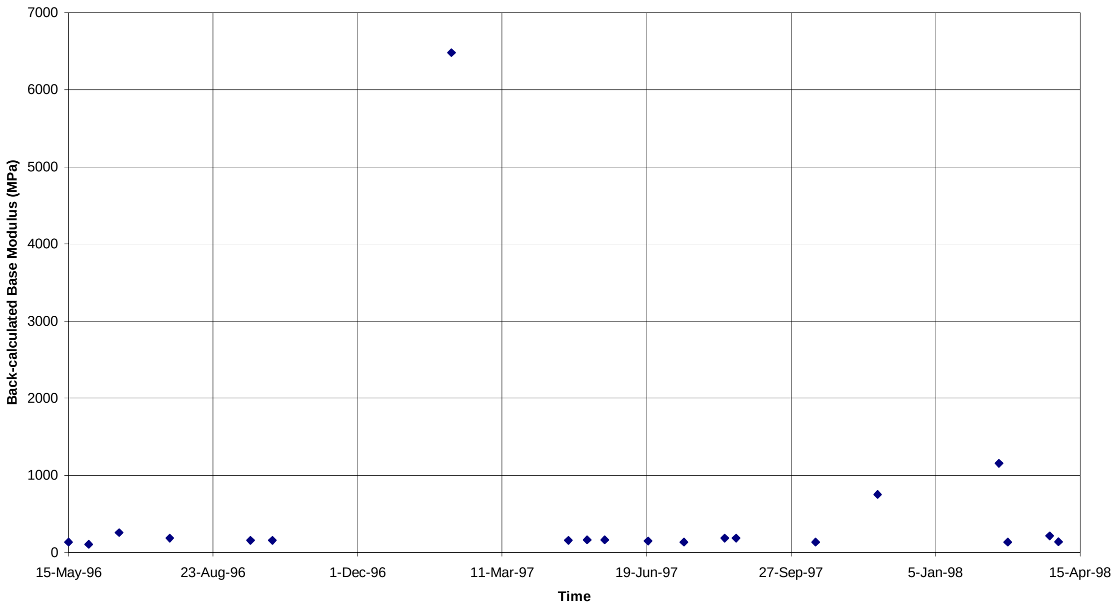


Figure B-13. Back-calculated base modulus as a function of time for East Glacier.

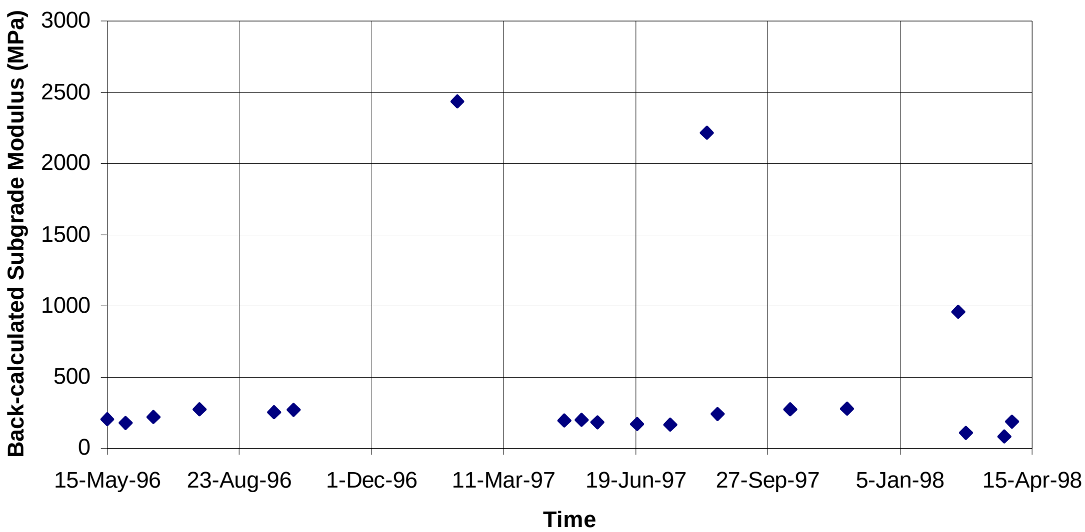


Figure B-14. Back-calculated subgrade modulus as a function of time for East Glacier.

Sweetgrass

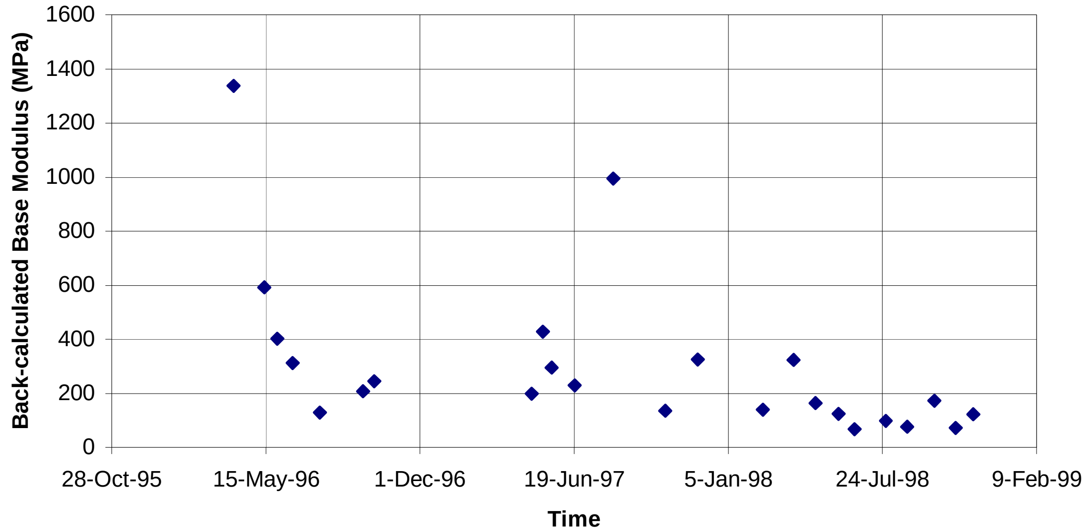


Figure B-15. Back-calculated base modulus as a function of time for Sweetgrass.

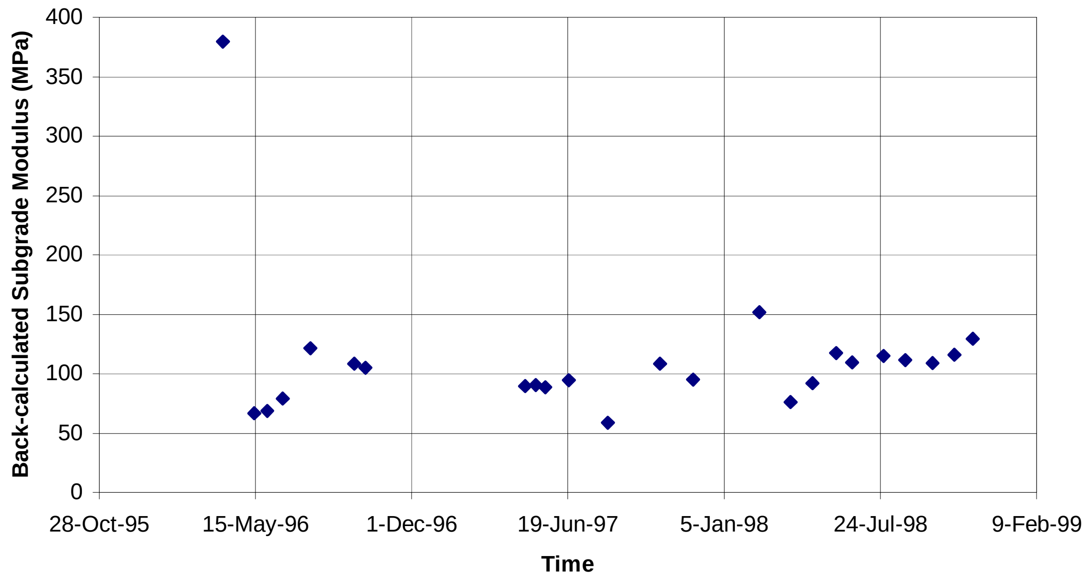


Figure B-16. Back-calculated subgrade modulus as a function of time for Sweetgrass.

Scobey/Redstone

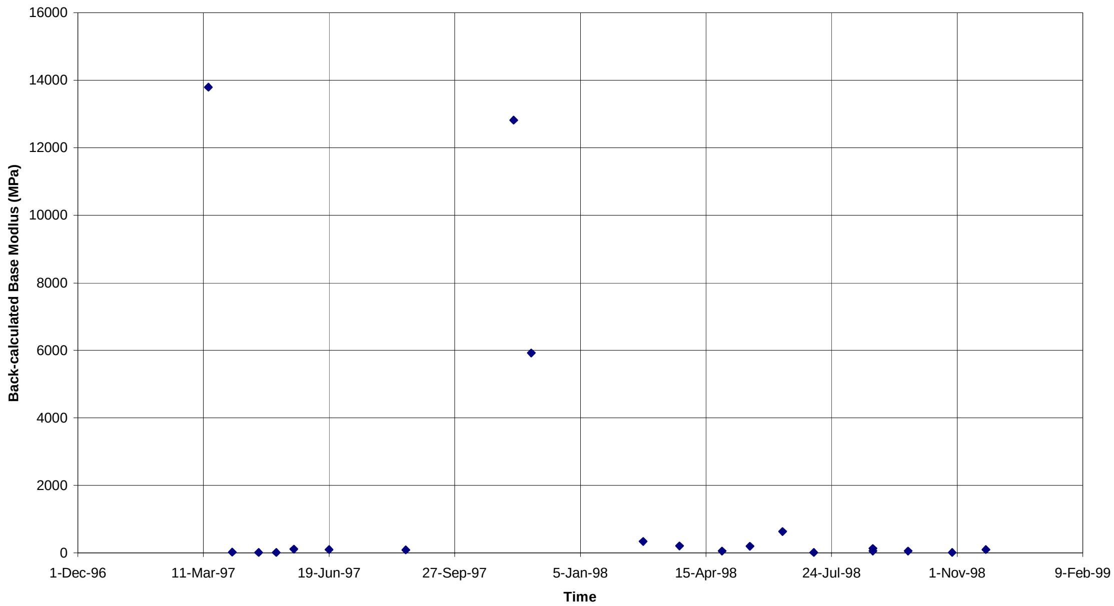


Figure B-17. Back-calculated base modulus as a function of time for Scobey/Redstone.

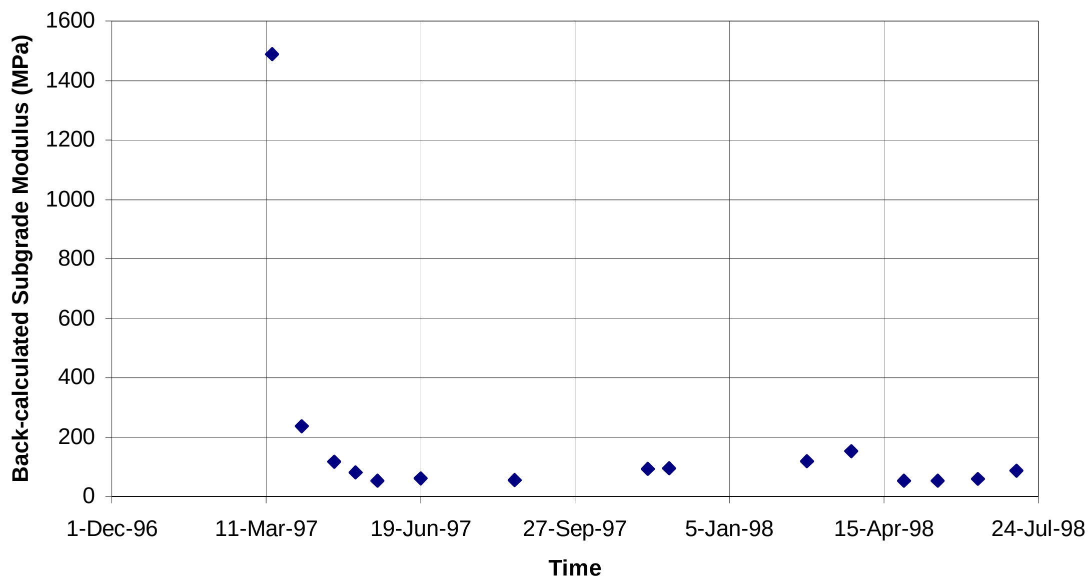


Figure B-18. Back-calculated subgrade modulus as a function of time for Scobey/Redstone.

Dickey Lake

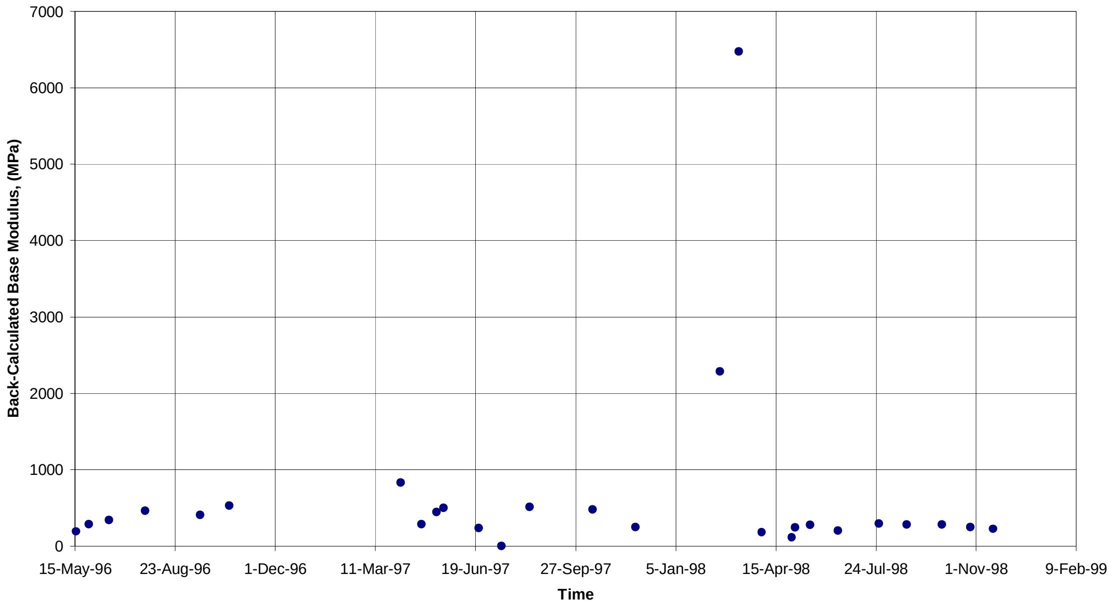


Figure B-19. Back-calculated base modulus as a function of time for Dickey Lake.

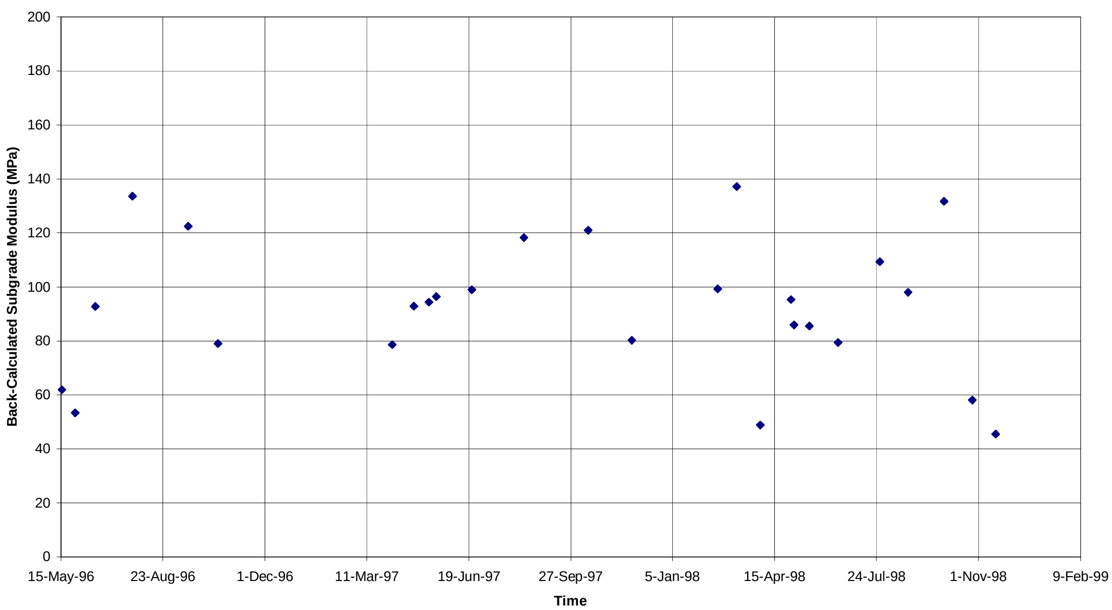
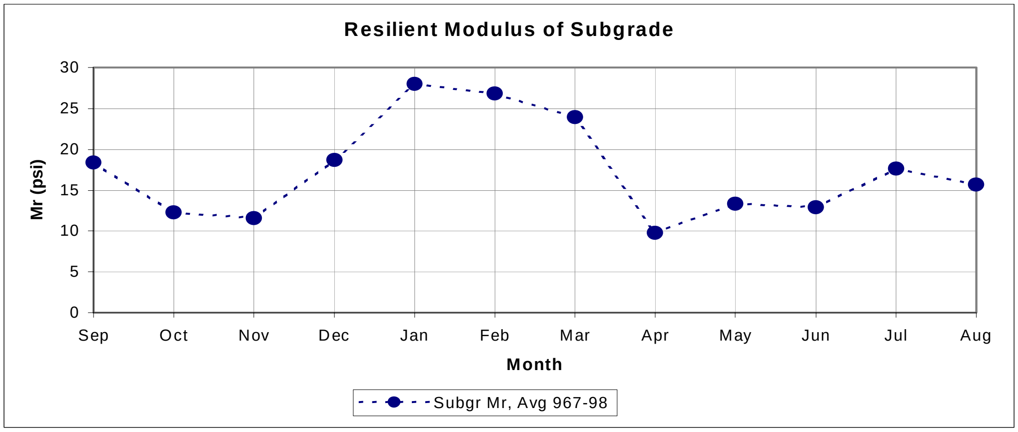


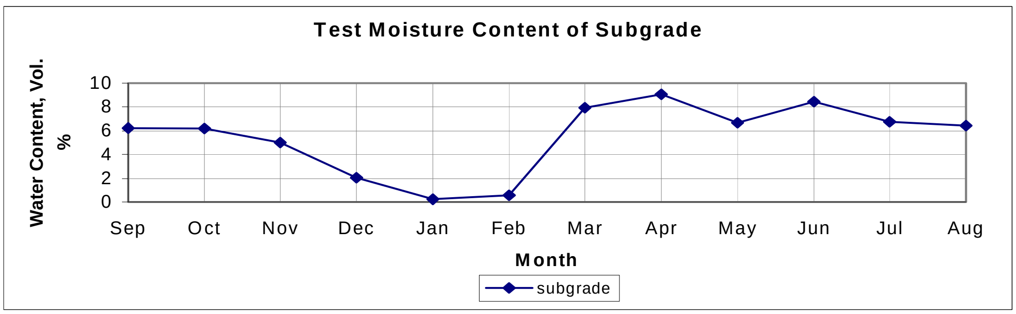
Figure B-20. Back-calculated subgrade modulus as a function of time for Dickey Lake.

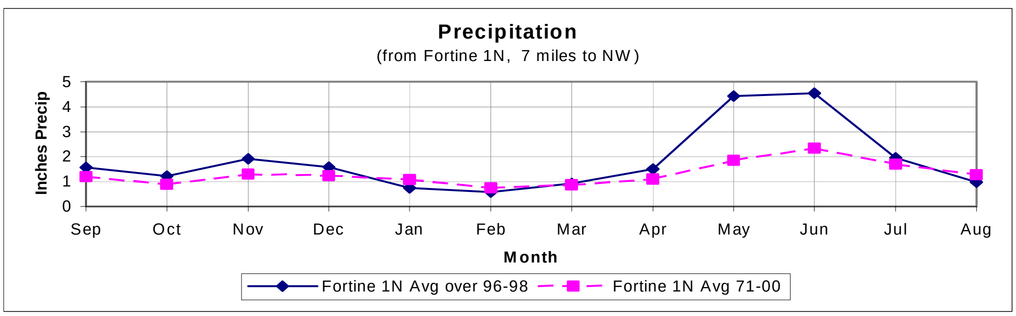
APPENDIX C: DESIGN INFORMATION

The volumetric moisture content on the following graphs can be converted to gravimetric moisture content by dividing the volumetric moisture content by the specific gravity of the material. Typical specific gravities are on the order of 2.70, plus or minus not more than 0.10.

Dickey Lake







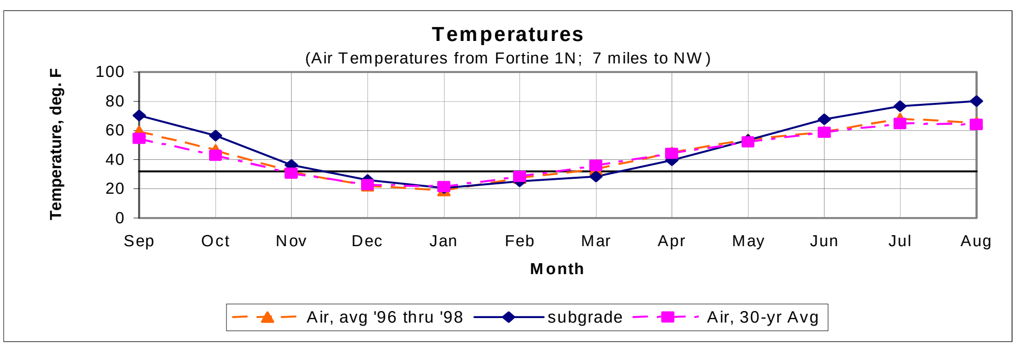


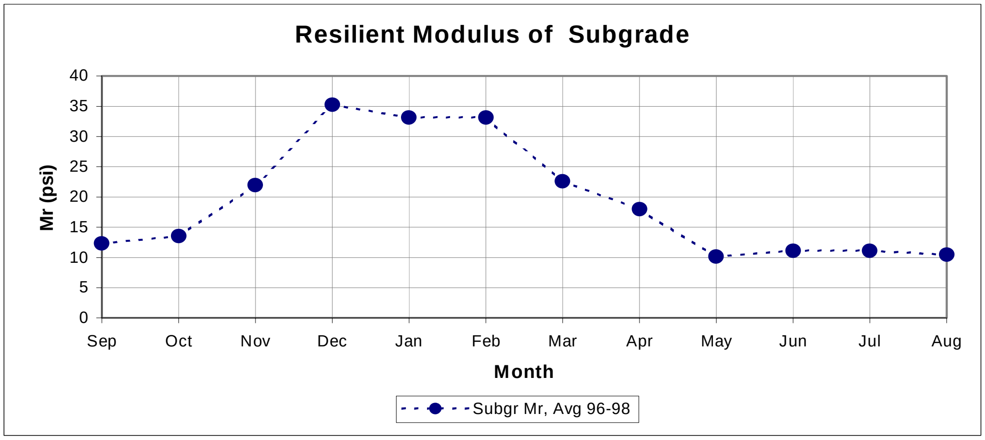
Figure C-1. Design data for Dickey Lake.

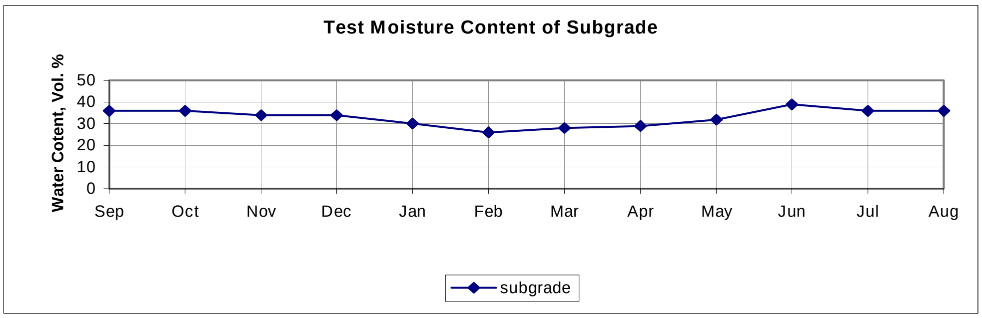
Table C-1. Gradation characteristics for base and subgrade at Dickey Lake

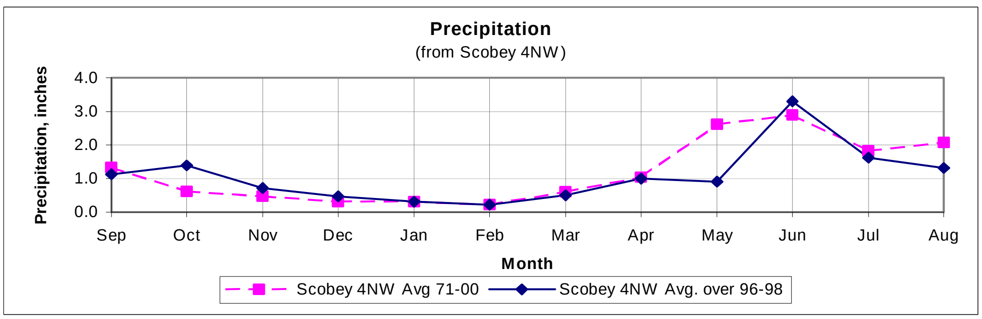
Structure:	5.0 in.	127 mm	AC						
	17 in.	432 mm	crushed BC						
Grain size	Subgrade						Base		
Depth (in.)		23	32	46	57.8	63	0 to 6	6 to 12	12 to 17
Depth (mm)		584	813	1168	1468	1600	0 to 152	152 to 305	305 to 432
US sieve designation	mm	Percent finer							
4	**101.600**	100	100	100	100	100	100	100	100
3.5	**88.900**	100	100	100	100	100	100	100	100
3	**76.200**	100	100	100	100	100	100	100	100
2.5	**63.500**	100	100	100	100	100	100	100	100
2	**50.800**	100	100	100	100	100	100	100	100
1.50	**38.100**	100	100	100	100	100	100	100	100
1.25	**31.750**	91	100	100	96	100	100	98	96
1.00	**25.400**	91	100	90	92	91	99	91	93
0.75	**19.050**	89	94	87	78	87	94	87	85
0.50	**12.700**	80	89	80	70	79	82	75	71
0.38	**9.525**	73	85	73	65	74	71	68	62
4	**4.750**	60	77	60	57	69	53	50	42
10	**2.000**	48	65	48	46	57	36	33	28
40	**0.425**	35	48	33	32	40	20	17	15
80	**0.190**	30	41	27	25	33	16	14	12
200	**0.075**	27.5	37.3	23.5	18.3	27.7	13.2	11.3	9.6
Liquid limit		19	22	22	22	20	NP*	NP	NP
Plastic limit		NP	20	20	19	18	NP	NP	NP
Plasticity index		NP	2	2	3	2	NP	NP	NP
AASHTO class		A-2-4 (0)	A-4 (0)	A-1-b (0)	A-1-b (0)	A-2-4 (0)	A-1-a(0)	A-1-a(0)	A-1-a(0)

* Non-plastic.

Wolf Point







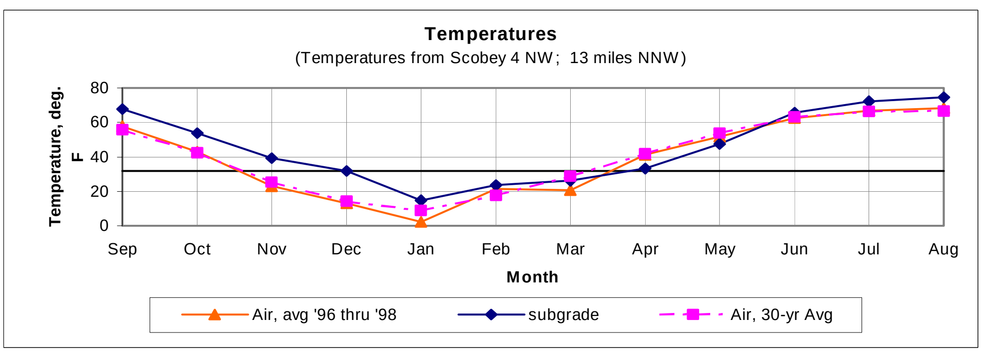


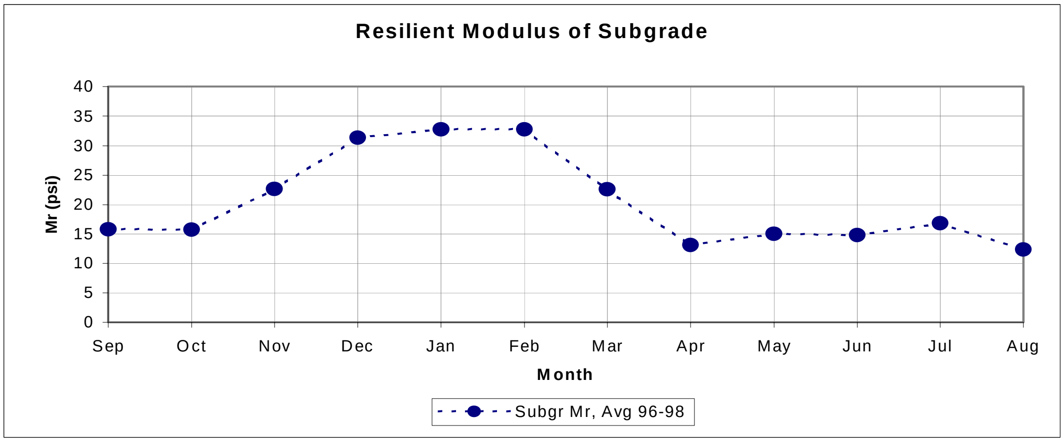
Figure C-2. Design data for Wolf Point.

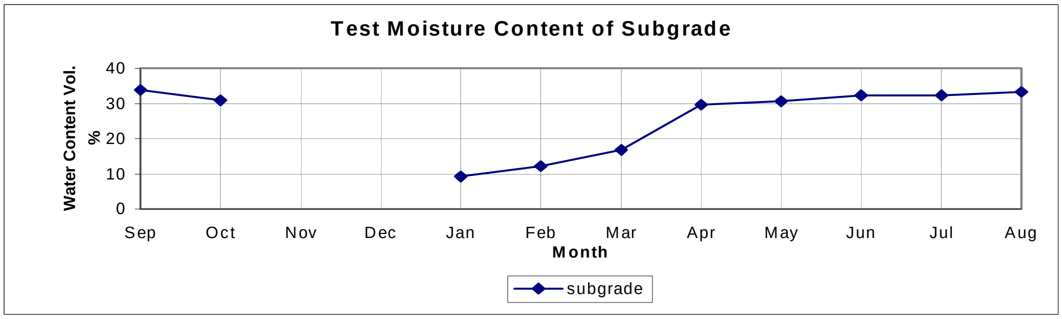
Table C-2. Gradation characteristics for base and subgrade at Wolf Point.

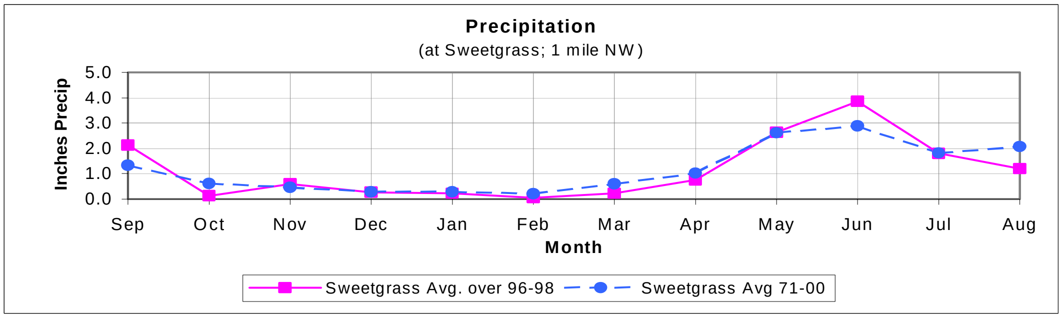
Structure:	**6 in.**	**152 mm**	**AC**				
	6 in.	**152 mm**	**crushed BC**				
Grain size		**Subgrade**			**Base**		
Depth (in.)		**Top 24**	**Below 24**	**60**	**Top 36**	**0 to 6**	**0 to 6**
Depth (mm)		**610**	**>610 mm**	**1524**	**914**	**0 to 152**	**0 to 152**
US sieve designation	**mm**	**Percent finer**					
4	**101.600**						
3.5	**88.900**						
3	**76.200**						
2.5	**63.500**			100			
2	**50.800**			98	100	100	100
1.50	**38.100**	100	100	98	99	100	97
1.25	**31.750**	99	100	95	99	100	95
1.00	**25.400**	98	99	93	97	99	92
0.75	**19.050**	98	99	92	96	92	87
0.50	**12.700**	97	97	90	94	80	75
0.38	**9.525**	96	97	89	93	68	65
4	**4.750**	95	95	87	91	50	47
10	**2.000**	92	93	86	89	42	39
40	**0.425**	87	89	82	85	33	32
80	**0.190**	78	78	71	72	16	22
200	**0.075**	64.8	65.2	61.2	56.2	11.9	15.4
Liquid limit		35	35	46	47	NP*	20
Plastic limit		16	16	19	21	NP	NP
Plasticity index		19	19	27	26	NP	NP
AASHTO class		A-6 (10)	A-6 (10)	A-7-6 (14)	A-7-6 (12)	A-1-b(0)	A-1-b(0)

***** Non-plastic.

Sweetgrass







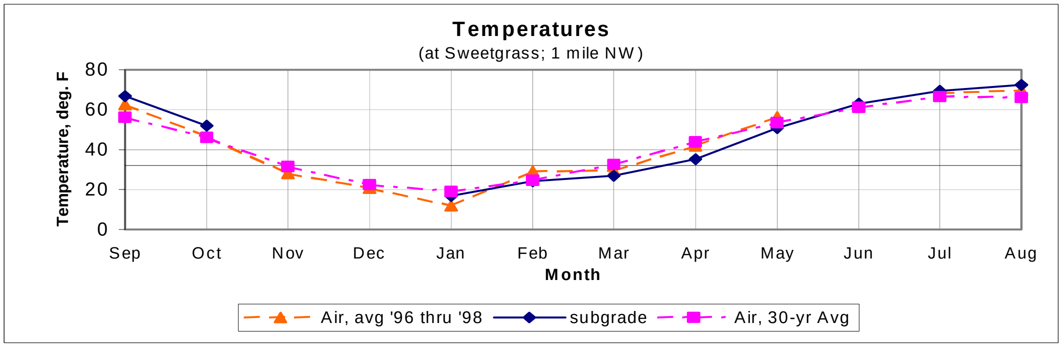


Figure C-3. Design data for Sweetgrass.

Table C-3. Gradation characteristics for base and subgrade at Sweetgrass.

Structure:	13 in.	330 mm	AC				
	19 in.	483 mm	crushed BC				
Grain size		**Subgrade**		**Base**			
Depth (in.)		**24 to 6**	**36 to 60**	**0 to 6**	**6 to 24**	**6 to 24**	**12 to 18**
Depth (mm)		**610 to 1600**	**914 to 1524**	**0 to 152**	**152 to 610**	**152 to 610**	**305 to 457**
US sieve designation	**mm**	**Percent finer**					
4	**101.600**						
3.5	**88.900**						
3	**76.200**						
2.5	**63.500**				100		
2	**50.800**	100	100		98		
1.50	**38.100**	99	99	100	94	100	100
1.25	**31.750**	99	98	99	92	95	93
1.00	**25.400**	99	96	96	86	88	88
0.75	**19.050**	99	94	88	79	77	82
0.50	**12.700**	98	92	76	68	69	70
0.38	**9.525**	97	91	71	62	63	65
4	**4.750**	96	89	56	50	50	52
10	**2.000**	92	79	42	42	40	42
40	**0.425**	85	69	20	26	19	33
80	**0.190**	80	62	11	18	12	16
200	**0.075**	68.2	46.7	7.5	13.4	8.8	11.8
Liquid limit		36	29	NP	27	NP*	21
Plastic limit		21	24	NP	23	NP	NP
Plasticity index		15	5	NP	4	NP	NP
AASHTO class		A-6 (9)	A-4 (10)	A-1-a(0)	A-1-a(0)	A-1-a(0)	A-1-b(0)

***** Non-plastic**.**

Scobey / Redstone

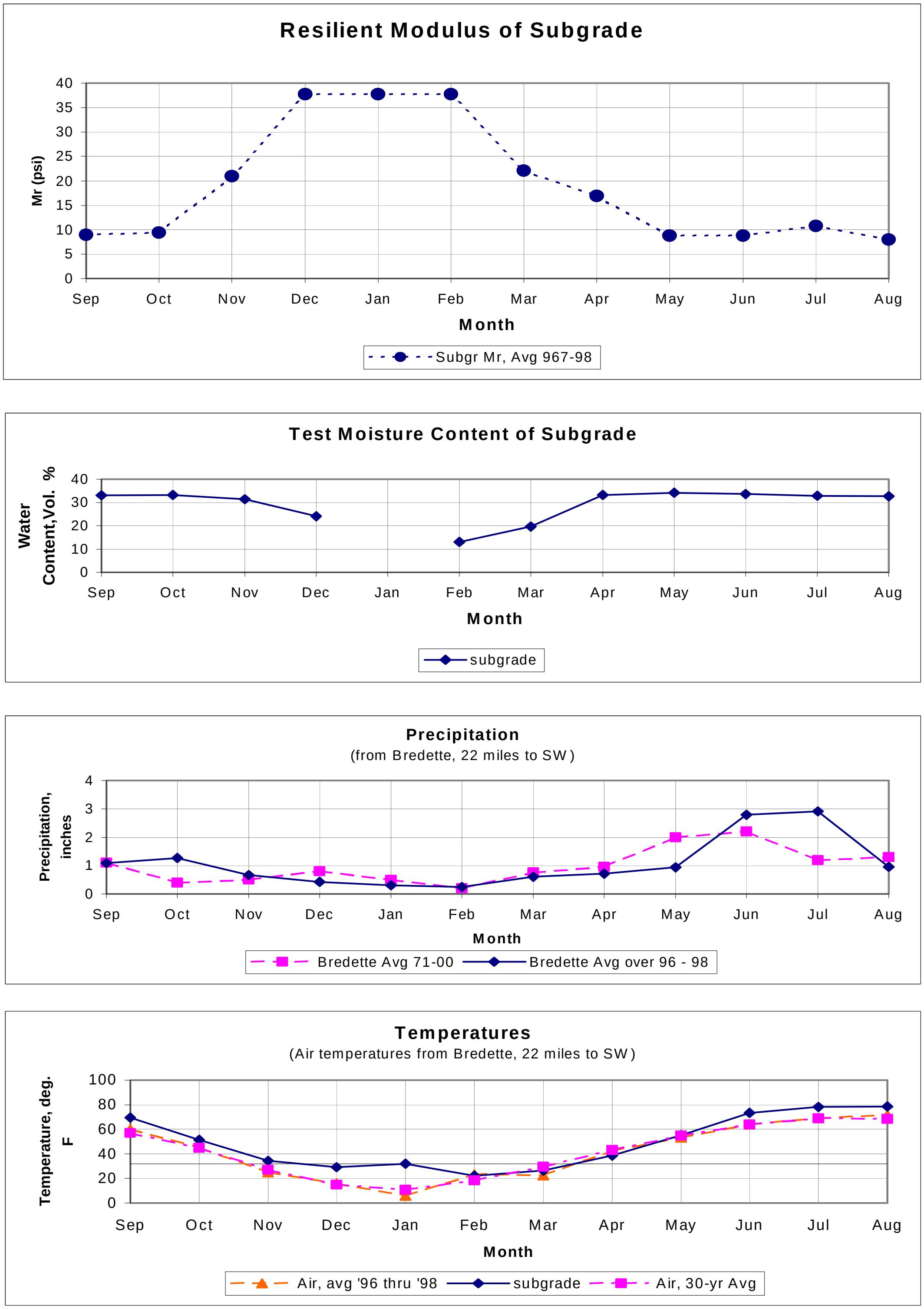


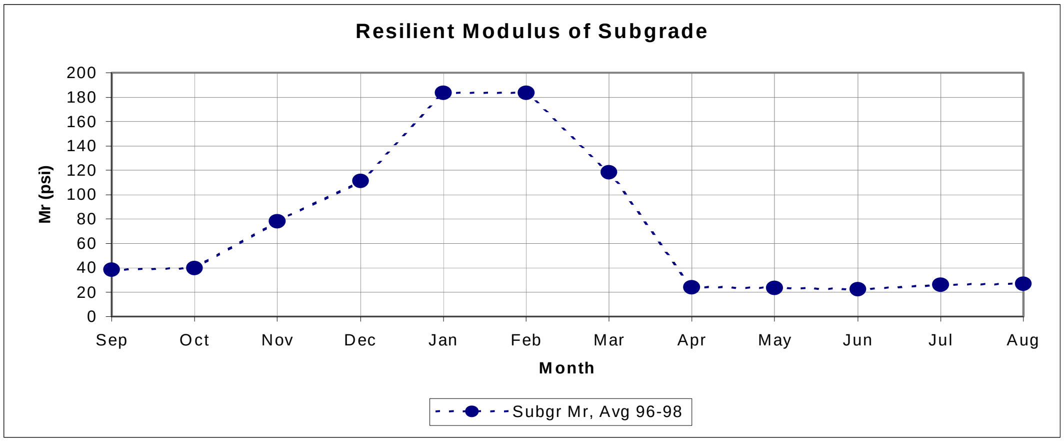
Figure C-4. Design data for Scobey/Redstone.

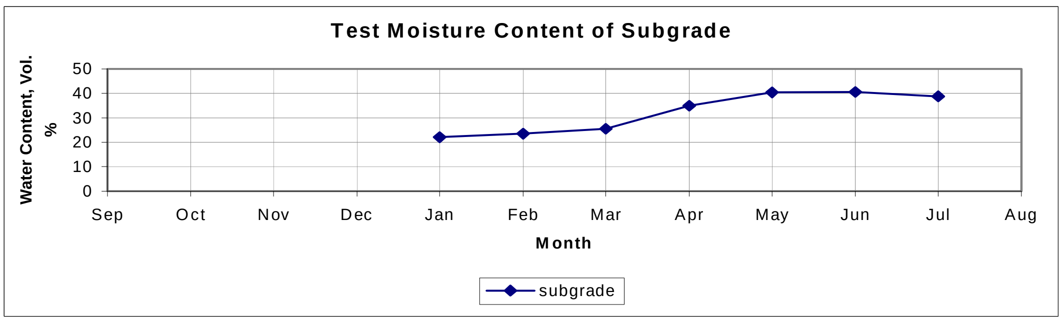
Table C-4. Gradation characteristics for base and subgrade at Scobey/Redstone.

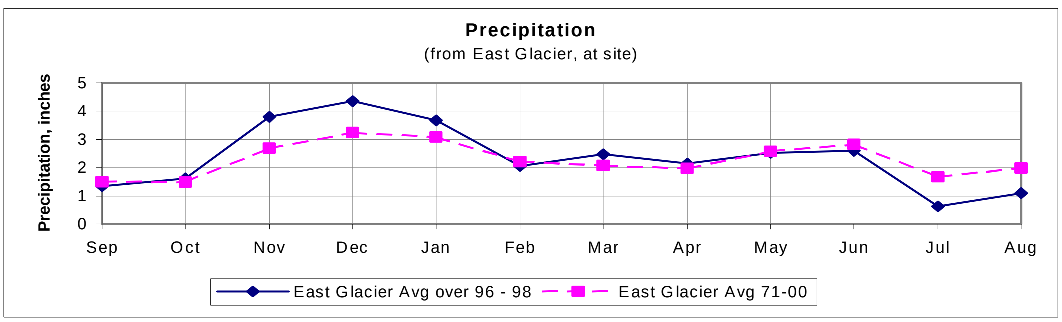
Structure:	6 in.	152 mm	AC	
	5.5 in.	140 mm	crushed BC	
Grain size		**Subgrade**		**Base**
Depth (in.)		**60±**	**12 to 36**	**6 to 12**
Depth (mm)		**610**	**813**	**152 to 305**
US sieve designation	**mm**	**Percent finer**		
4.00	**101.6**			
3.50	**88.9**			
3.00	**76.2**			
2.50	**63.5**			
2.00	**50.8**			100
1.50	**38.1**	100	100	97
1.25	**31.75**	100	99	95
1.00	**25.40**	99	98	92
0.75	**19.05**	99	98	87
0.50	**12.70**	97	97	75
0.38	**9.53**	97	96	65
# 4	**4.75**	95	95	47
# 10	**2.00**	93	92	39
# 40	**0.425**	89	87	32
# 80	**0.190**	78	78	22
# 200	**0.075**	65.2	64.8	15.4
Liquid limit		49	32	20
Plastic limit		28	22	NP*
Plasticity index		21	10	NP
AASHTO class		A-6 (10)	A-6 (10)	A-1-b (0)

* Non-plastic.

East Glacier







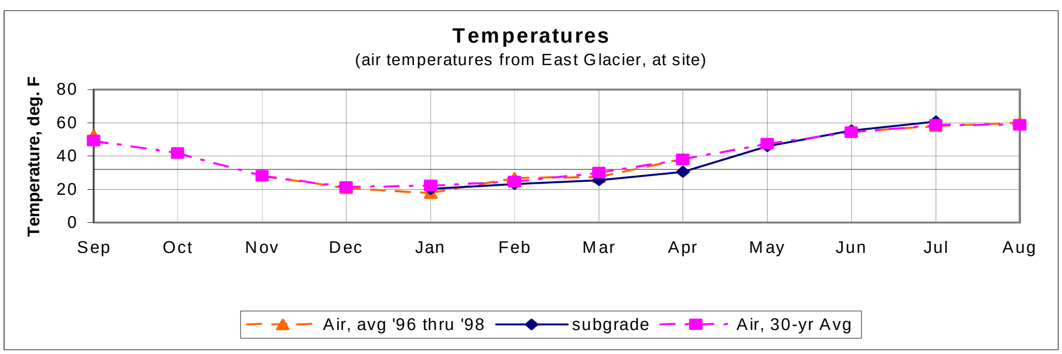


Figure C-5. Design data for East Glacier.

Table C-5. Gradation characteristics for base and subgrade at East Glacier.

Structure:	3 in.	76 mm	AC		
	8 in.	203 mm	CTB		
	15 in.	381 mm	crushed BC		
Grain size		**Subgrade**			**Base**
Depth (in.		**26 to 60**	**26 to 60**	**26 to 60**	**11 to 26**
Depth (mm)		**660 to 1524**	**660 to 1524**	**660 to 1524**	**279 to 660**
US sieve designation	**mm**	**Percent finer**			
4.00	**101.6**				
3.50	**88.9**				
3.00	**76.2**				
2.50	**63.5**				
2.00	**50.8**	100			
1.50	**38.1**	99			
1.25	**31.75**	98			
1.00	**25.40**	97			
0.75	**19.05**	96		100	
0.50	**12.70**	95		100	
0.38	**9.525**	94		100	100
# 4	**4.750**	93	100	99	99
# 10	**2.000**	89	94	98	93
# 40	**0.425**	84	89	97	88
# 80	**0.190**	80	87	96	87
# 200	**0.075**	73.6	82.2	88.4	84.2
Liquid limit		49	32	30	29
Plastic limit		28	22	20	21
Plasticity index		21	10	10	8
AASHTO class		A-7-6 (16)	A-4 (8)	A-4 (10)	A-4(6)

Alzada

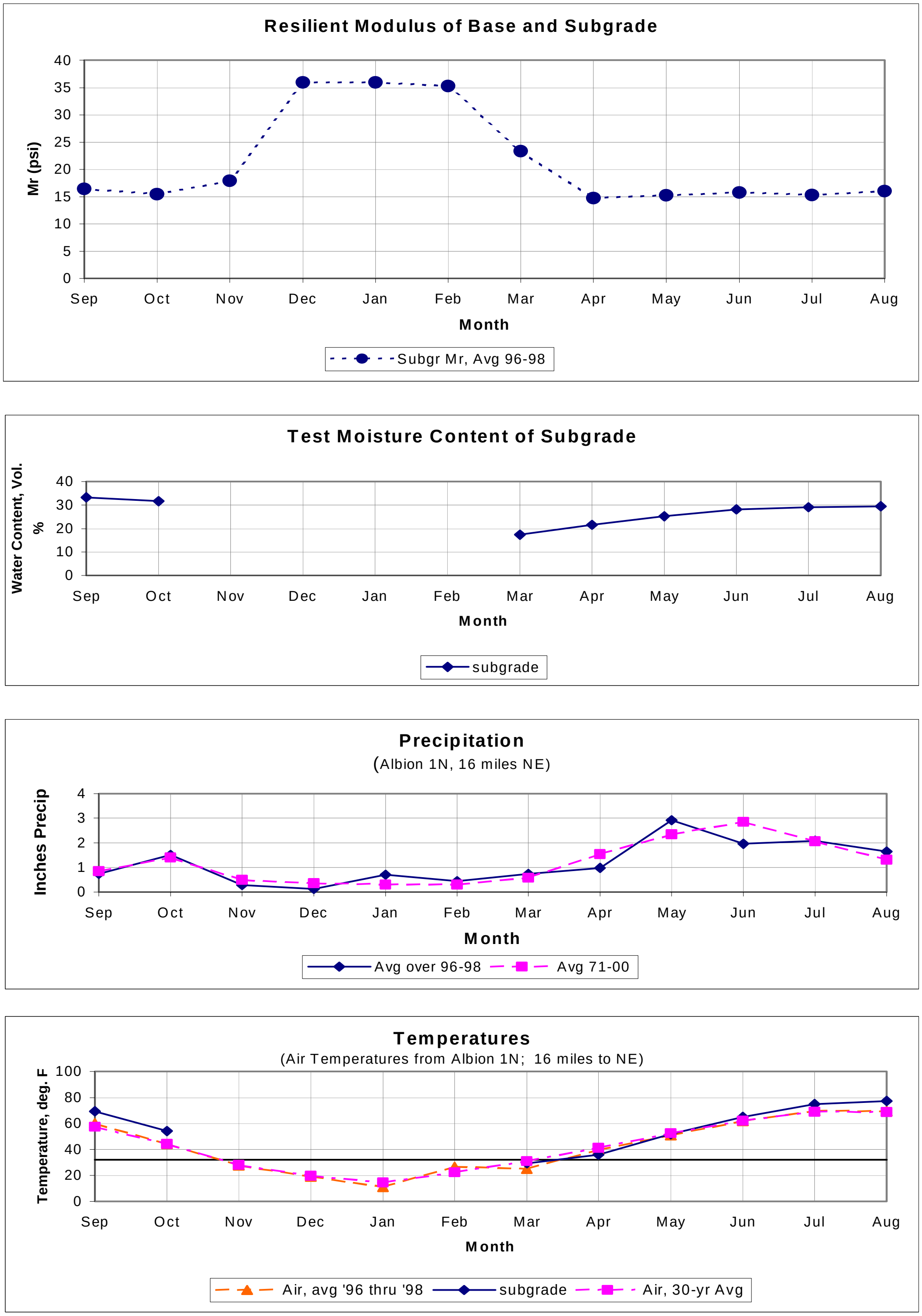
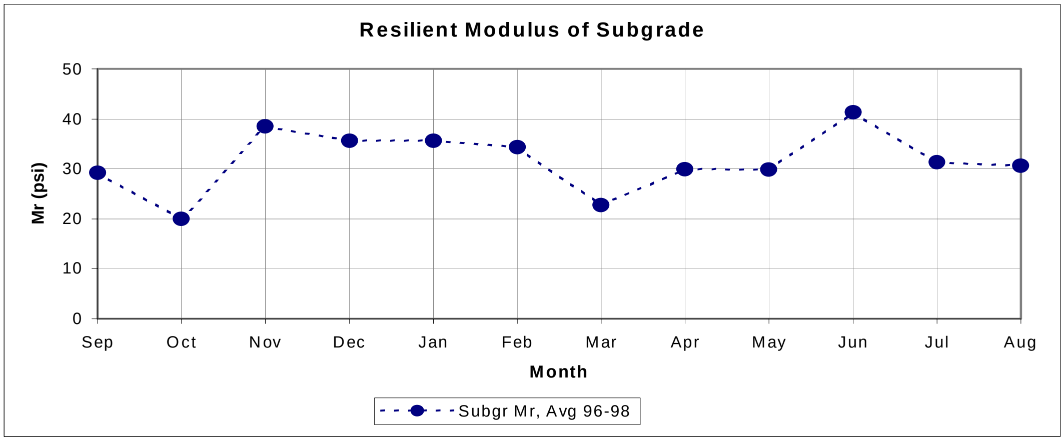


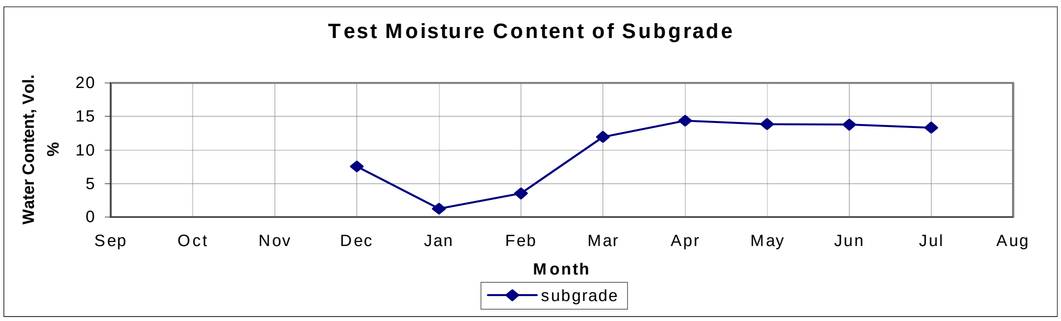
Figure C-6. Design data for Alzada.

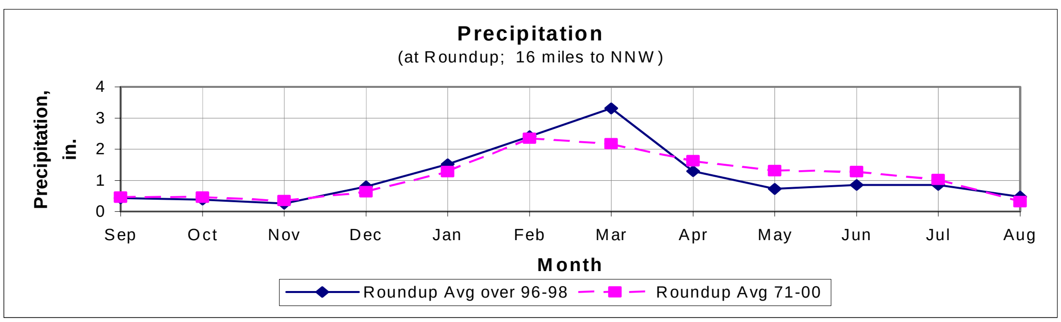
Table C-6. Gradation characteristics for base and subgrade at Alzada.

Structure:	**9.25 in.**	**235 mm**	**"PMS"**
	23.75 in.	**603 mm**	**granular base**
sum	**33 in.**	**838 mm**	
Grain Size		**Subgrade unreported**	**Base unreported**
Depth (in.)			
Depth (mm)			
US sieve designation	**mm**	**Percent finer**	
4.00	**101.6**		
3.50	**88.9**		
3.00	**76.2**		
2.50	**63.5**		100
2.00	**50.8**		99
1.50	**38.1**		99
1.25	**31.75**	100	97
1.00	**25.40**	99	96
0.75	**19.05**	99	93
0.50	**12.70**	97	89
0.38	**9.525**	96	86
# 4	**4.750**	93	78
# 10	**2.000**	88	64
# 40	**0.425**	78	27
# 80	**0.190**	69	18
# 200	**0.075**	57.7	12.6
Liquid limit		37	19
Plastic limit		18	18
Plasticity index		19	1
AASHTO class		A-6 (8)	A-1-b (0)

Bull Mountain







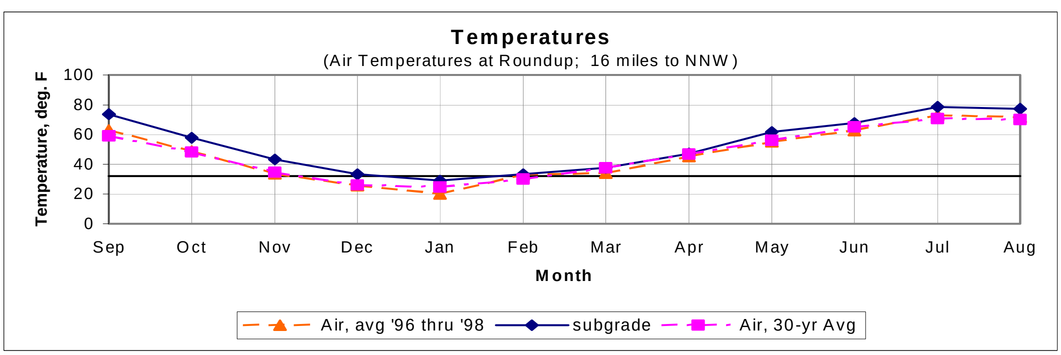


Figure C-7. Design data for Bull Mountain.

Table C-7. Gradation characteristics for base and subgrade at Bull Mountain.

Structure:	**7.4 in.**	**188 mm**	**AC**	
	13.8 in.	**351 mm**	**granular BC**	
sum	**21.2 in.**	**538 mm**		
Grain size	**Subgrade**			**Base Unreported**
Depth (in.)		**22 to 58**	**58 to 94**	
Depth (mm)		**559 to 1473**	**1473 to 2388**	
US sieve designation	**mm**	**Percent finer**		
4	**101.600**			
3.5	**88.900**			
3	**76.200**			
2.5	**63.500**		100	
2	**50.800**	100	99	
1.50	**38.100**	100	97	100
1.25	**31.750**	99	95	100
1.00	**25.400**	98	92	99
0.75	**19.050**	94	87	97
0.50	**12.700**	90	83	95
0.38	**9.525**	88	81	90
4	**4.750**	86	79	67
10	**2.000**	82	69	53
40	**0.425**	77	57	41
80	**0.190**	71	39	28
200	**0.075**	48.2	13.9	18.3
Liquid limit		NP*	NP	NP
Plastic limit		NP	NP	NP
Plasticity index		NP	NP	NP
AASHTO class		A-4 (0)	A-2-4 (0)	A-1-b (0)

* Non-plastic.

Livingston

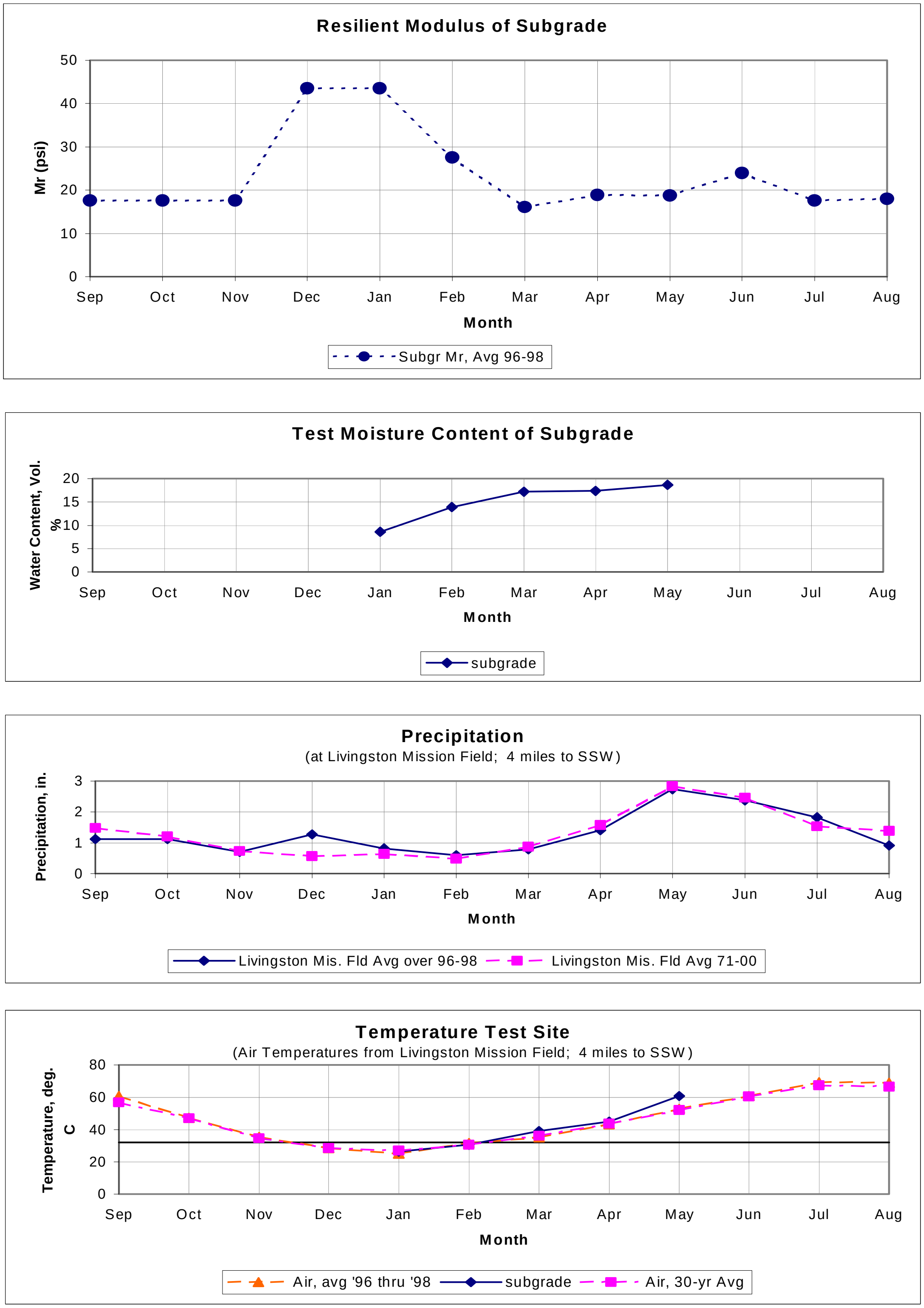
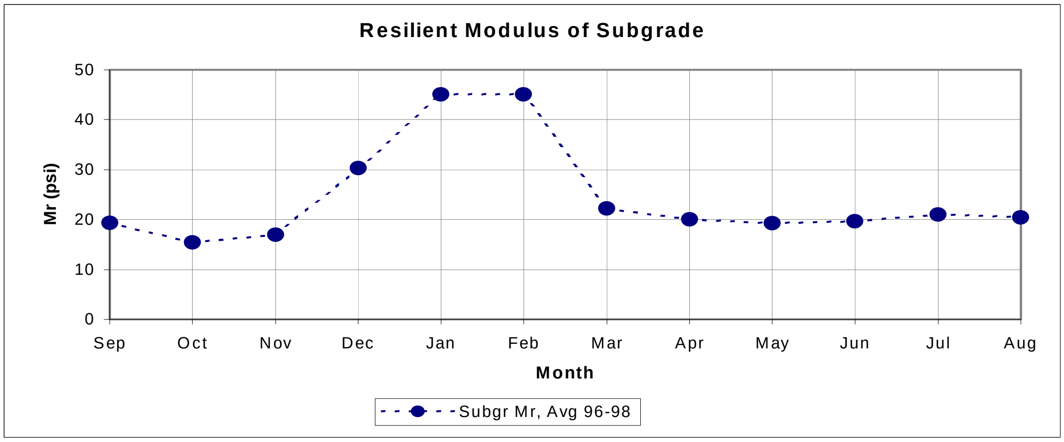


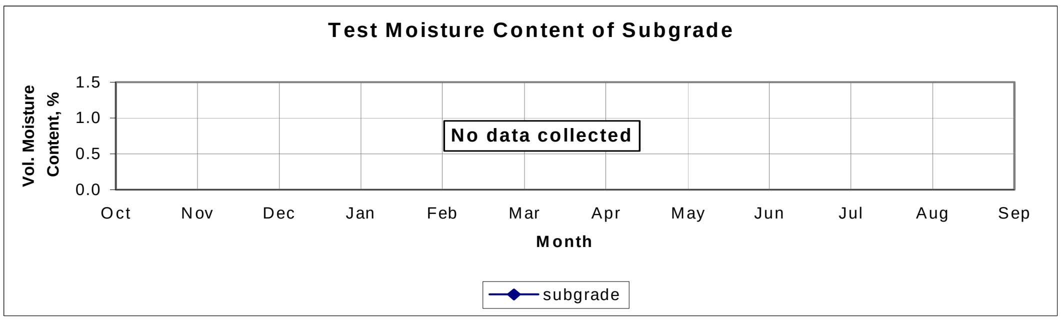
Figure C-8. Design data for Livingston.

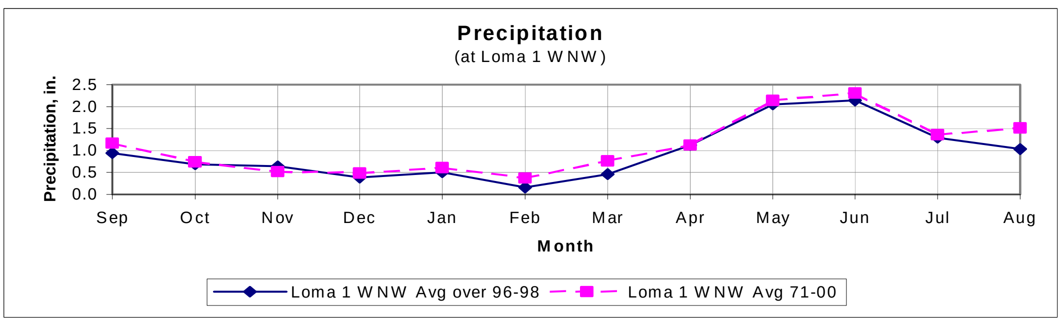
Table C-8. Gradation characteristics for base and subgrade at Livingston.

Structure:	1.8 in.	46 mm	AC	
	4.2 in.	107 mm		
	20.4 in.	518 mm	Granular BC	
sum	26.4 in.	671 mm		
Grain size	**Subgrade**			**Base**
Depth (in.)		**26 to 62**	**62 to 98**	**0 to 6**
Depth (mm)		**660 to 1575**	**1575 to 2489**	**0 to 152**
US sieve designation	**mm**	**Percent finer**		
4	**101.600**			
3.5	**88.900**	100		
3	**76.200**	96		
2.5	**63.500**	96	100	
2	**50.800**	91	95	100
1.50	**38.100**	82	90	92
1.25	**31.750**	80	87	88
1.00	**25.400**	77	81	79
0.75	**19.050**	71	72	69
0.50	**12.700**	62	59	59
0.38	**9.525**	58	52	53
4	**4.750**	51	43	41
10	**2.000**	45	38	35
40	**0.425**	37	30	18
80	**0.190**	29	22	9
200	**0.075**	20.3	16	5.5
Liquid limit		31	34	NP
Plastic limit		22	22	NP
Plasticity index		9	12	NP
AASHTO class		A-2-4 (0)	A-2-6 (0)	A-1-a (0)

Loma







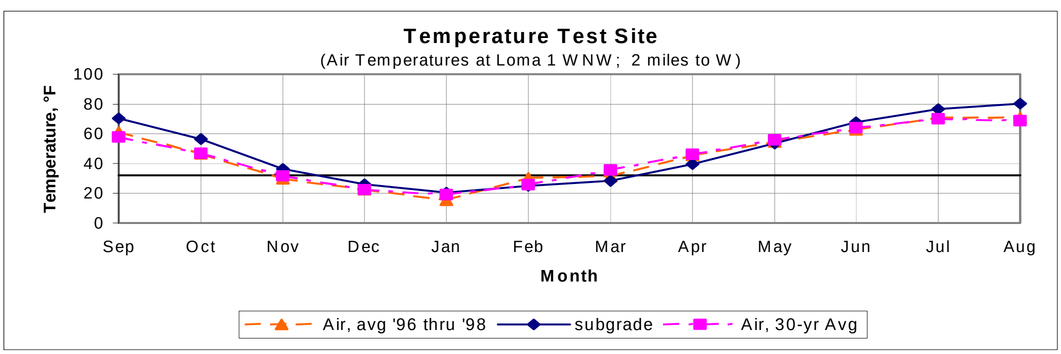


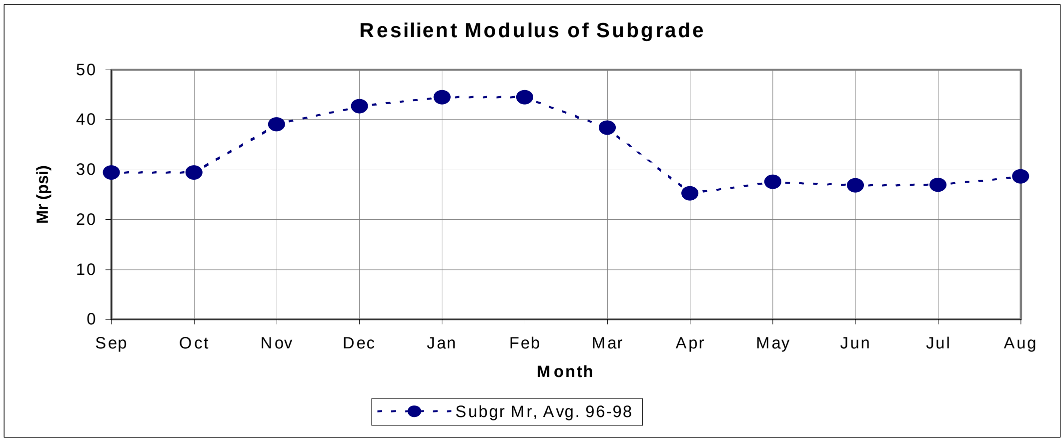
Figure C-9. Design data for Loma.

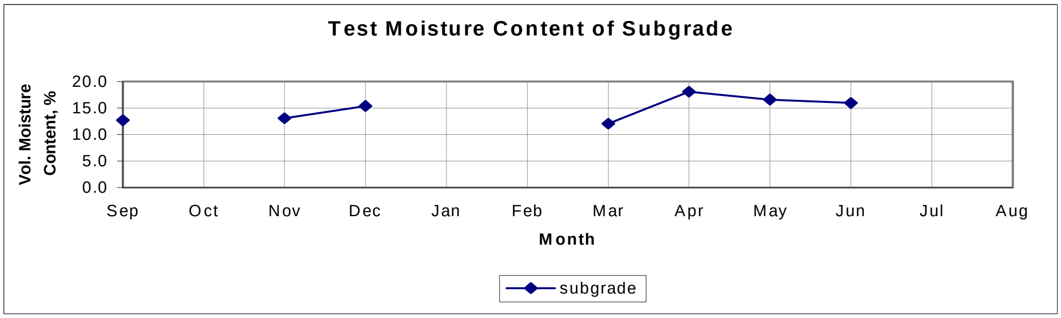
Table C-9. Gradation characteristics for base and subgrade at Loma.

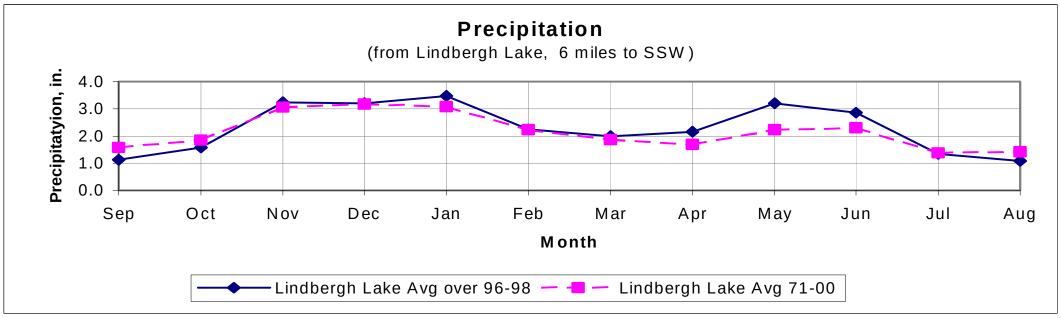
Structure:		6.0 in.	152 mm	AC	
		27.0 in.	686 mm	granular BC	
	Sum	33.0 in.	838 mm		
Grain size	Subgrade			Base	
Depth (in.)		30 to 60	Unreported	0 to 30	Unreported
Depth (mm)		762 to 1524		0 to 762	
US sieve designation	mm				
4	**101.600**				
3.5	**88.900**				
3	**76.200**				
2.5	**63.500**				
2	**50.800**				
1.50	**38.100**	100		100	100
1.25	**31.750**	99	100	96	97
1.00	**25.400**	98	100	88	90
0.75	**19.050**	96	100	76	77
0.50	**12.700**	94	99	62	64
0.38	**9.525**	93	99	55	58
4	**4.750**	91	99	44	47
10	**2.000**	90	99	40	42
40	**0.425**	85	98	23	23
80	**0.190**	79	92	13	11
200	**0.075**	51.7	22.7	9.4	7.3
Liquid limit		24	NP*	NP	NP
Plastic limit		21	NP	NP	NP
Plasticity index		3	NP	NP	NP
AASHTO class		A-4 (0)	A-2-4 (0)	A-1-a (0)	A-1-a (0)

* Non-plastic.

Swan Lake







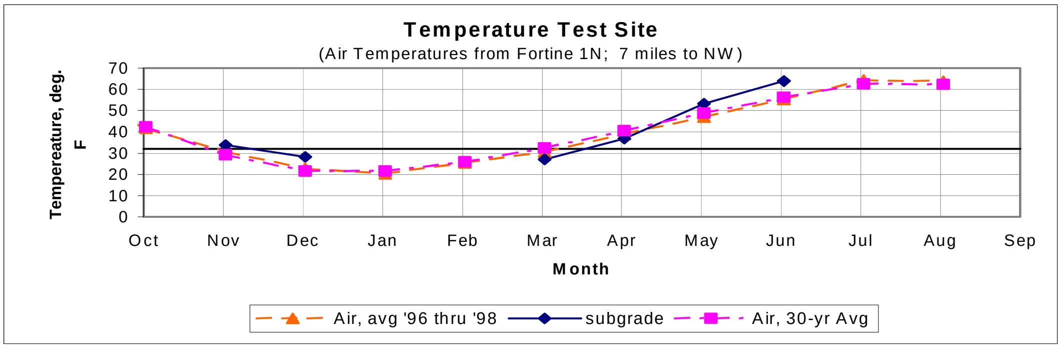


Figure C-10. Design data for Swan Lake.

Table C-10. Gradation characteristics for base and subgrade at Swan Lake.

Structure:	**4.8 in.**	**122 mm**	**AC**						
	4.8 in.	**122 mm**	**Pulverized AC**						
	5.0 in.	**127 mm**	**granular BC**						
Sum	**14.6 in.**	**371 mm**							
Grain size		**Subgrade**						**Base**	**Pulverized AC**
Depth (in.)		**26.5**	**32.0**	**38**	**46**	**58**	**73.5**	**10 to 15**	**5 to 10**
Depth (mm)		**673**	**813**	**965**	**1168**	**1473**	**1867**	**254 to 381**	**127 to 254**
US sieve designation	**mm**								
4	**101.600**								
3.5	**88.900**								
3	**76.200**								
2.5	**63.500**								
2	**50.800**					100	100		
1.50	**38.100**		100			94	83		100
1.25	**31.750**	100	85		100	94	76	100	98
1.00	**25.400**	92	73		93	85	73	99	98
0.75	**19.050**	92	67	100	90	74	66	98	96
0.50	**12.700**	86	52	92	79	65	56	87	83
0.38	**9.525**	80	45	86	71	57	50	77	71
4	**4.750**	73	38	72	59	46	38	55	55
10	**2.000**	59	29	57	48	34	23	35	38
40	**0.425**	38	18	36	32	19	7	15	17
80	**0.190**	30	14	28	23	12	4	9	12
200	**0.075**	25.1	11.7	22.9	18.8	8.6	2.4	6.5	9
Liquid limit		NP*	NP	NP	NP	NP	NP	NP	NP
Plastic limit		NP	NP	NP	NP	NP	NP	NP	NP
Plasticity index		NP	NP	NP	NP	NP	NP	NP	NP
AASHTO class		A - 2 - 4 (0)	A - 1 - a (0)	A - 1 - b (0)	A - 1 - b (0)	A - 1 - a (0)	A - 1 - a (0)	A - 1 - a (0)	

* Non-plastic.