Determination of the Critical Thaw-Weakened Period in Asphalt Pavement Structures

JAMES A. MCBANE AND GORDON HANEK

Preliminary results of a soil-temperature monitoring program beneath asphalt-surfaced forest roads in northwest Montana indicate that the critical spring thaw-weakened period of a pavement structure can, in most cases, be identified by temperature alone. At all monitored locations, thawing below the pavement did not commence until the average soil temperature above a depth of 36 in., excluding the asphalt mat, had risen to approximately 30°F. Initial subpavement thawing was indicated by temperatures above the freezing point of local soilwater as measured at the asphalt–base course interface. Pavement strength values were equal to or greater than those recorded the previous fall when the depth of thaw had progressed to approximately 48 in. below the asphalt mat in areas underlain by nonplastic soils. This relationship was less clear in plastic soils. Utilizing this soil-temperature monitoring program, road managers have the means to forewarn facility users of the possible imposition of vehicle load restrictions. This program provides accurate identification of the onset of spring thaw weakening and allows an evaluation of the strength recovery as the critical period wanes.

Unseasonably warm weather in January 1984 resulted in the early development of a thaw-weakened state in the asphalt pavement structure of the Yaak 92 Forest Highway, Kootenai National Forest, Montana (Figure 1). The subsequent decision to impose vehicle load restrictions 3 to 4 weeks before the historical placement of such limits evoked adverse comments from local timber company representatives and construction contractors who regularly use the facility. Comments generally reflected an acceptance of the inevitability of spring closures; however, complaints of insufficient forewarning to allow equipment removal from the field or to plan springtime mill operations were universal. Concern was frequently expressed by the users that the road condition evaluations leading to the imposition of load restrictions were based on incorrect procedures and subjective judgments and that the shutdowns were premature.

Although the controversy lessened to a great extent when visible signs of pavement distress developed within days of the closure, it was apparent that to avoid similar problems in the future, the concerns expressed by the road users should be addressed. A program of monitoring temperatures throughout the pavement structure was devised in response to the stated concerns. The system described in this paper was developed by combining the results of published research projects covering various aspects of the thaw-weakening phenomenon with the practical instrumentation and monitoring experience of agencies such as the Alaska Department of Transportation and Public Facilities. At the time of this writing, the instrumentation system had been operational on the Kootenai National Forest for one complete year.

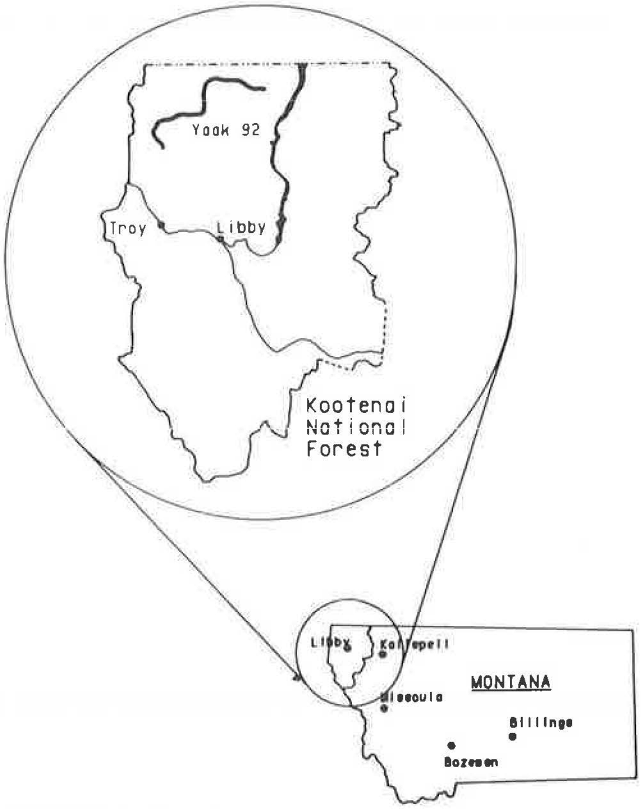


FIGURE 1 Location map.

Past research efforts aimed at developing methods for the identification of thaw-weakened conditions in pavement structures have resulted in procedures that were complex, expensive, labor intensive, or all three and that were difficult to implement in commonly encountered field settings. Public acceptance of road closure decisions based on these methods has been generally skeptical because of the lack of trust in systems not easily understood. The interrelation between temperature and thaw weakening has proven more readily apparent to most individuals than methods that must address soil moisture and excessive pore-water pressures.

The system components are inexpensive. Road networks can

J. A. McBane, Engineering Branch, Kootenai National Forest, Route 3, Box 700, Libby, Mont. 59923. Current affiliation: USAFEA-K, Building and Grounds Division, APO San Francisco, Calif. 96301-0082. G. Hanek, U.S. Bureau of Reclamation, Denver Federal Center, Box 25007, D-1542, Denver, Colo. 80225.

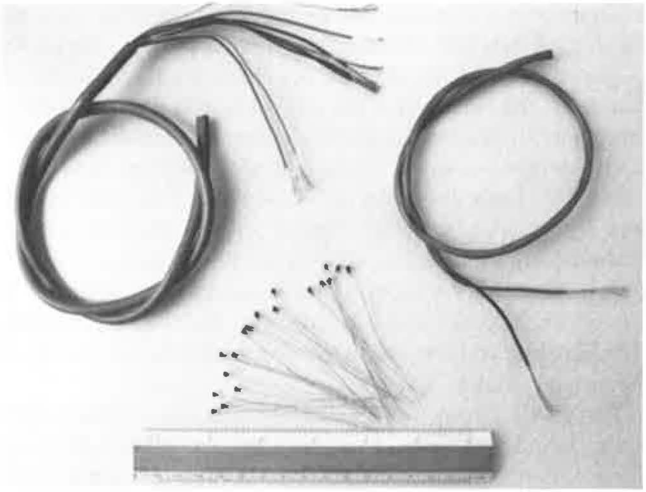


FIGURE 2 Instrumentation components: thermistors, eight-conductor cable, and two-conductor cable.

be completely instrumented at a very low cost, allowing individual road segments to be managed separately. Responsible personnel can determine whether portions of a road system may be left open to commercial use while other portions of the same system remain closed because of thaw-weakened conditions. Conversely, a road system may be reopened in segments as the instrumentation indicates strength recovery in specific areas. The duration of the closures may be shortened by the use of this system.

Finally, and most important, this system makes possible the accurate determination of the limits of the critical thaw-weakened period. Potentially destructive vehicle loads can be restricted during this more accurately defined time period, resulting in a reduction of typical spring thaw damage. A large savings in current yearly maintenance expenditures on asphalt-paved forest roads is anticipated as well as an extension of their serviceable lifetimes by years.

In short, this instrumentation system has proven to be accepted by the public and the industry and is inexpensive to install and maintain, accurate, and simple for nontechnical personnel to operate. The conservative management approach based on subjective methods can be replaced by an objective, accountable management approach easily understood by the road users. It provides increased flexibility to road managers and promises future savings in road maintenance and reconstruction expenditures.

INSTRUMENTATION

The system consists of a series of thermistors used to monitor temperature variations above, within, and below the asphalt mat. Thermistors are semiconductors consisting of epoxy-encapsulated metal oxides whose electrical resistance varies with fluctuations in temperature (Figure 2). These devices were selected because of their low cost and high degree of accuracy and interchangeability and because no special calibration or circuitry conditioning is necessary for operation. Instrumentation at each site consists of a minimum of eight sensors (Figure 3). The air temperature is monitored by a thermistor placed approximately 4 ft above the ground surface. Air probe thermistors are inserted into the center of opaque plastic tubes and mounted in the shade to prevent inaccurate readings due to direct sunlight (Figure 4). The mat temperature is obtained by a thermistor sealed within a saw cut 1.5 in. deep made in the asphalt surface. This depth represents the approximate midpoint of the new 2.5- to 3.0-in. thick hot-mix asphalt pavement recently completed on a large portion of the Yaak 92 Forest Highway (Figure 5). Each site is instrumented with a thermistor located immediately at the base of the mat. Spacing of succeeding thermistors follows a consistent sequence of 4, 9, 15, 21, and 33 in. below this sensor. At five sites, sensor strings include two additional thermistors 45 and 57 in. below the base of the asphalt. The exact depths of the temperature sensors are

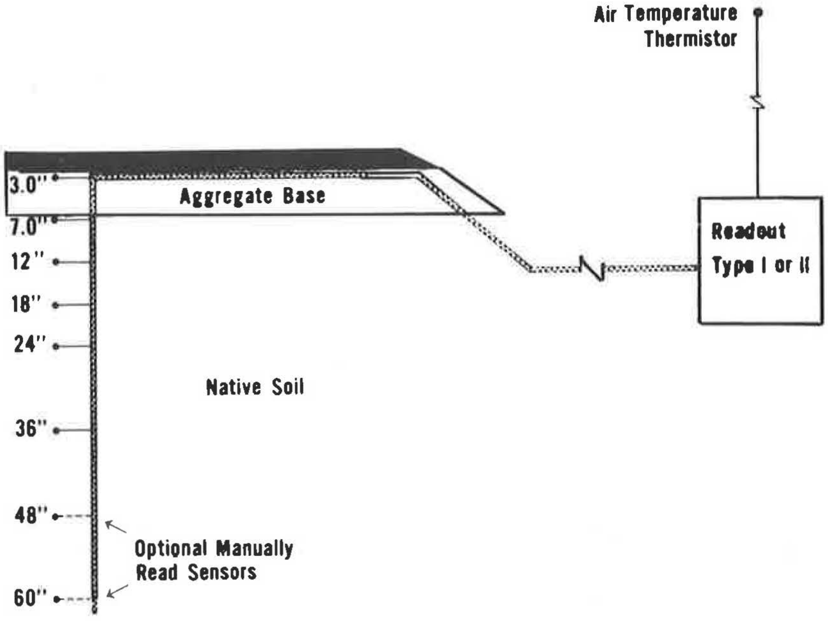


FIGURE 3 Instrumentation schematic.

FIGURE 4 Air probe, Site D2-92-38.0.

FIGURE 5 Yaak 92 Forest Highway: view south from Milepost 38.0.

governed by the thickness of the mat. Figure 3 shows thermistor depths for an idealized 3-in.-thick asphalt structure.

Ground thermistors are soldered into a multiconductor cable consisting of eight 22-gauge, multistrand, polyvinylchloride-(PVC-) insulated copper wires. One wire serves as a common ground for all sensors. Each remaining wire is connected to the second lead of the individual sensors (Figure 6). Air probe thermistors and the two bottom sensors at the five extended sites are wired into two conductor cables. The eight-conductor ground cable and the two-conductor air probe cable end at a 10-pin electrical connector placed within a junction box located near the shoulder of the road (Figure 7).

Monitoring is accomplished by removing the cover plate of the junction box and attaching the 10-pin connector (Figure 8) to one end of a switching unit. An electronic thermometer is attached to the other end of the unit (Figure 9). The thermometer operates by measuring the line resistance, converting resistance to temperature, and displaying the temperature in degrees Fahrenheit. Each thermistor on the string can be sequentially read by rotating the dial selector on the switching unit. Extended strings are equipped with two phono jacks within the junction box, one connected to the 4-ft sensor, the other to the 5-ft sensor. The electronic thermometer is detached from the switching unit and coupled to the phono jacks to monitor these thermistors (Figure 10).

The Yaak highway was divided into segments, each of which could be independently closed without significantly affecting the use of remaining segments. Within each division a minimum of two sites was selected for instrumentation. These represented areas anticipated to enter the critical thaw-weakened state early (locations exposed to direct sunlight for a large portion of the day) and areas expected to lag behind (shaded locations). In addition, instrumentation was installed in most major soil types and elevation extremes encountered along the Yaak highway. Seventeen instrument sites at an approximate density of one site every 3.5 mi were installed during the fall of 1984 along the Yaak 92 Forest Highway and adjacent paved roads.

TESTING AND MONITORING

The presence of dissolved minerals depresses the freezing point of water below the laboratory distilled value of 32°F; thus it was necessary to determine the actual soil moisture freezing point to use while the critical period was being monitored. Tests were performed on soil samples obtained from 8 of the 17 sites to determine the freezing point of local soil moisture. This testing is important because if too high a freezing value was assumed during monitoring, a significant amount of time could elapse, with thawing and associated damage to the pavement structure.

Soil samples were placed into glass test tubes. A thermistor was imbedded within the soil and the sample immersed in an ethylene glycol solution that had been cooled to +17°F. The temperature change of the soil was monitored by an electronic thermometer attached to the thermistor leads (Figure 11).

Cooling progressed through four distinct phases (Figure 12). The temperature of the sample decreased as the soil moisture

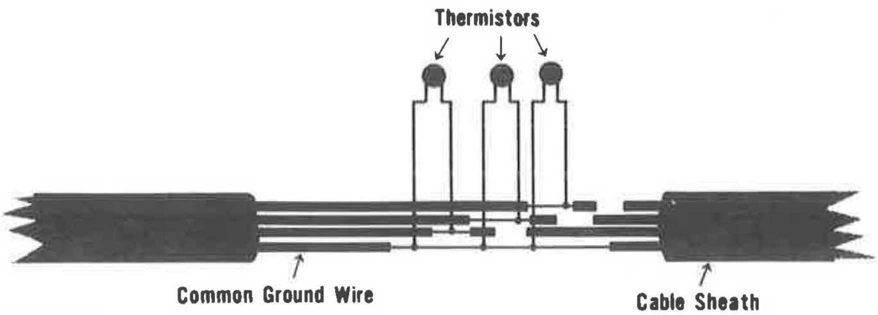


FIGURE 6 Generalized thermistor string wiring diagram.

FIGURE 7 Junction box, Site D2-92-38.0; note air probe on branch slightly above and left of junction box.

FIGURE 9 Electronic thermometer and switching box, Site D2-92-45.2.

system cooled. At the point of ice nucleation (the time when ice crystals begin to form) the temperature rose rapidly as heat was released during the phase change from water to ice. The temperature of the sample rose to a plateau where it remained constant while the moisture in the sample froze. This was recorded as the soil moisture freezing point. When all the soil moisture had been converted into ice, the temperature of the sample again decreased as the soil-ice system moved toward thermal equilibrium with the cold bath.

Test results indicated that the freezing point of soil moisture throughout the project area was 31.7 to 31.8°F. The conservative value of 31.7°F was used in all subsequent analyses.

Beginning in October 1984, air, pavement, and soil temperatures were recorded at least weekly at each site. This increased to approximately three times per week per site as ground and air temperatures rose immediately preceding the commencement of spring thaw in March. Accessibility problems caused by heavy snows and unplowed roads limited the frequency of monitoring at four of the sites to once per week throughout the winter and spring.

Pavement strength was measured by a series of Benkelman beam deflection tests (Figure 13). Testing began in late fall of 1984, ceased during the winter months, and was resumed in the spring of 1985. Deflection data were obtained at least weekly at

FIGURE 8 Ten-pin electrical connector at instrument string terminus and phono jacks for reading the 4- and 5-ft sensors, Site D2-92-23.95.

FIGURE 10 Electronic thermometer reading the 4-ft sensor, Site D2-92-45.2.

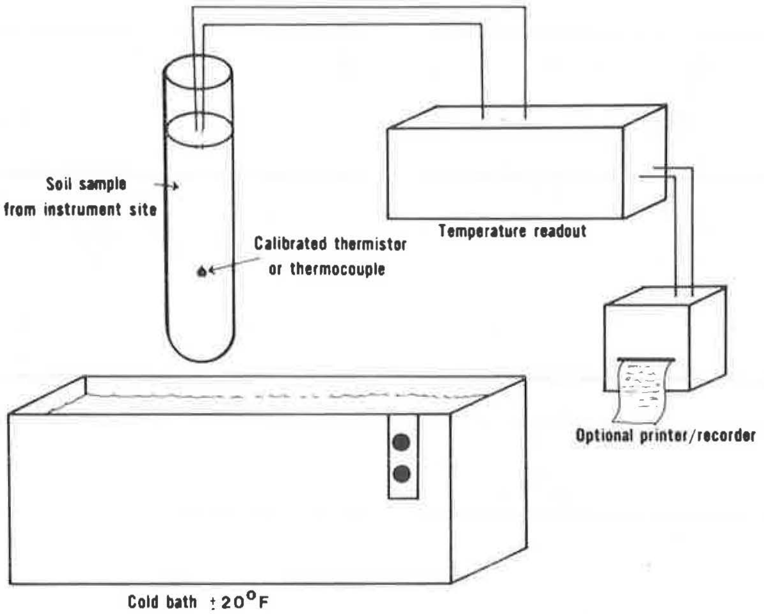
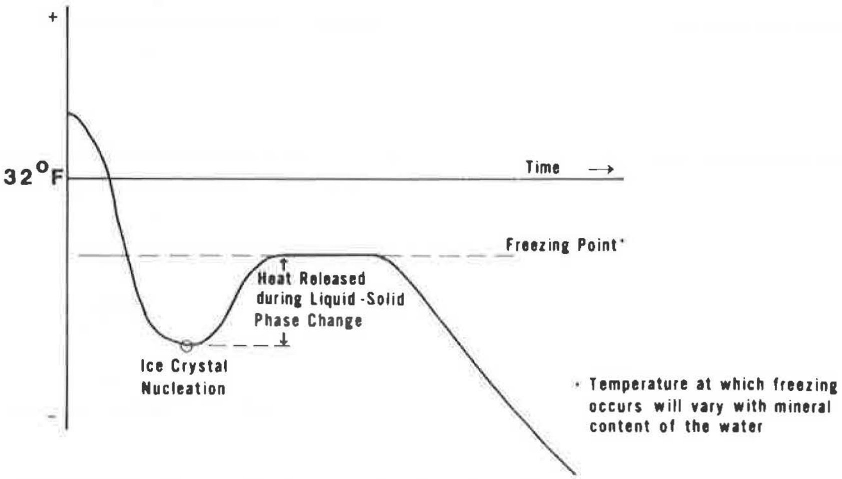


FIGURE 11 Laboratory setup for determination of groundwater freezing point.

accessible sites throughout the critical thaw-weakened period. The test vehicle was a three-axle, 8-yd^3 capacity dump truck loaded with 20,000 lb of steel railroad rails. The gross vehicle weight was 48,000 lb. A pressure of 70 psi was maintained in all ten 11.00×7-size tires. Testing was performed by placing the tip of a 12-ft-long Benkelman beam at the mid-point between the rear dual-wheel sets. Measurements were obtained at each site within the driving lane anticipated to carry the heaviest vehicle loads with a deflection reading obtained for each wheel track within that lane. Measured deflections for each given site and date were analyzed for each wheel track and then combined to obtain a site average deflection for entry into the *E*lastic *L*ayer *SY*ste*M* (ELSYM5) computer program.

The ELSYM5 computer program was used to compute stress and strain values at various points within the pavement structure from assumed and measured surface deflections. This program was selected because of its input option of up to 10 uniform loadings on the pavement, permitting deflections obtained from the nonstandard test vehicle to be analyzed. During the computer reduction of deflection measurements, four loads were input per deflection, one for each wheel load immediately adjacent to the Benkelman beam measurement point. Computer runs that included more than 4 of the test vehicle's 10 wheels as input provided results not significantly different from a four-load model and therefore were not attempted beyond the program testing. Additional program inputs include a description of the pavement structure to be analyzed (the number and thickness of layers), the material properties of each layer (modulus of elasticity and Poisson's ratio), and the spatial coordinates of points within the structure where data are desired. The program outputs values for stresses, strains, and displacements at the designated locations.

The program was used by attempting to match computer-generated surface deflections with field-measured deflections.



* Temperature at which freezing occurs will vary with mineral content of the water

FIGURE 12 Generalized curve for freezing of water.

FIGURE 13 Benkelman beam deflection testing, Site D2-92-45.2.

The physical dimensions of the pavement structure and the material types present at each site were directly determined from drill corings. The test vehicle load magnitude and load spacing were also directly measured, leaving only the properties of the materials making up the structure as unknowns. Published values for resilient modulus and Poisson's ratio were input into the program for each structure layer to determine reasonable strength boundaries for the materials. The asphalt, base course, and subgrade soils were assumed to be drained and computer trials continued until the output deflection values matched actual deflections measured for each site in the fall.

Parametric studies performed using ELSYM5 to model a thaw-weakened pavement condition indicated that changes in the resilient modulus and Poisson's ratio of the thawing layer had the greatest effect on the calculated deflections. Variations in the asphalt parameters and the parameters of the frozen soil had very little effect. During the spring thaw period, input asphalt values were held approximately constant with only minor variations to account for differing pavement temperatures. Similarly, the frozen soil parameters varied only slightly to account for the warming ice. The thawing layer could then be incrementally analyzed for resilient modulus and Poisson's ratio values as its thickness increased throughout the critical period. When a satisfactory match was obtained between computer-generated and field-measured deflections for a given test date at a given site, the calculated horizontal strain value at the base of the asphalt mat was recorded (Table 1) and later used to develop a pavement strength parameter, the road damage factor, for presentation to the public.

The purchase of a diametral testing apparatus by the Forest Service Region I Materials Testing Laboratory early in the summer of 1985 provided the opportunity to determine the actual resilient modulus of the pavement asphalt. This allowed a comparison with the assumed values used in the computer analyses during the preceding spring thaw-weakened period. A total of 24 asphalt core samples with 3-in. diameter were obtained from 6 of the 17 sites. The cores were tested as received; no moisture conditioning was attempted. Tests were performed on samples cooled to 41°F and again at 77°F. Results are summarized in Table 2. Assumed resilient modulus values entered into the ELSYM5 program were within the range of test values obtained. Substitution of the measured values into the computer program did not affect the magnitude of resilient modulus changes calculated for the thawing layer as the critical weakened period progressed. It was the relative magnitude of the resilient modulus changes and their rate of occurrence, not the absolute values, that were of primary importance to this study.

RESULTS

The weighted average soil temperature was calculated from readings obtained from the six thermistors beginning with Thermistor 2, at the base of the mat, through Thermistor 7, located approximately 36 in. below the road surface for each site for each monitored date. The change in this average temperature from early October 1984 through late April 1985 at Site D2-92-30.6 is shown in Figure 14. This plot is representative of all noninsulated (plowed) sites. Thawing commenced when temperatures of 31.7°F occurred at the base of the asphalt. This value of 31.7°F at the base of the mat did not

TABLE 1 SAMPLE DATA: ELSYM5 INPUT AND OUTPUT, SITE D2-92-23.95, 1985

Date[a]	Pavement Deflection (in.)	Resilient Modulus (ksi)[b] by Layer 1	2	3	4	5	Strain (E-03)[c]
March 4	0.011	150	125	150	150	4.7	0.1007
March 12	0.028	100	3.5	125	150	4.7	0.6967
March 22	0.108	100	4	0.4	125	4.7	0.9913
March 29	0.086	80	7	0.83	125	4.7	0.9246
April 5	0.044	75	11	4.5	125	4.7	0.6823
April 8	0.042	60	11	6	125	4.7	0.7423
April 11	0.040	75	11.2	7	125	4.7	0.6478
April 17	0.040	75	11.2	8	10	4.7	0.6419
April 22	0.040	80	11.2	8	10	4.7	0.6267

[a] On March 4 the structure was totally frozen. On April 17 the structure was totally thawed.

[b] Layer 1 = 5.5 in. of asphalt. Layer 2 = 7.0 in. of base course [GP-GM, Unified Soil Classification System (USCS)]. Layer 3 = 15.0 in. of silt (ML USCS). Layer 4 = 22.0 in. of gravels and cobbles (GP, USCS). Layer 5 = silt (ML, USCS).

[c] Strain = maximum horizontal strain at the bottom of the asphalt mat.

TABLE 2 RESULTS OF DIAMETRAL TESTING

Site No.	No. of Asphalt Samples	Resilient Modulus (ksi) 41°F Range	Avg	77°F Range	Avg
92-23.95	3	—[a]	—[a]	—[a]	—[a]
92-30.6	6	394–2,557	1,274	144–367	267
92-35.55	3	1,863–2,010	1,921	234–288	254
92-38.0	3	600–855	699	315–380	355
92-45.3	3	793–1,079	936	350–400	372
92-49.4	3	447–1,089	742	304–423	373

[a] All samples failed during testing.

occur, as is shown by Figure 15, until the average soil temperature rose to approximately 30°F. This is an apparent consequence of the frozen material's efficiency in distributing incoming heat until sufficient energy has accumulated in the pavement structure to permit thawing of the base course. These initial results suggest that by developing graphs similar to Figure 14 through the late winter and early spring, it will be possible to project warming soil temperatures to determine the approximate date by which soil temperatures will reach the 30-degree threshold and predict within close limits when spring thawing will begin. The specific time can be identified by thawing temperatures recorded at the base of the asphalt. Road users can be notified in advance of impending load restrictions, and the commencement of spring thaw can be objectively demonstrated. In addition, the effects on instrumented roads of short-term weather changes such as the so-called "January thaw" of northwestern Montana can be accurately evaluated.

A relationship between depth of thaw and pavement strain was identified that allows the utilization of the soil temperature profile to monitor strength recovery near the end of the critical period. Figure 16 shows this relationship at Site D2-92-23.95. To better present strength loss and gain in a pavement structure to nontechnically oriented individuals, strain values derived from the ELSYM5 computer reduction of Benkelman beam deflection measurements were used to calculate road damage factors. A factor of 1.0 was assigned to the 18-kip equivalent axle loading value of the test vehicle when the pavement structure is in its fully recovered state, that is, in late summer. Damage factors other than 1.0 indicate the increased or decreased loading in 18-kip equivalents required under summer conditions to duplicate the calculated horizontal strain at the base of the asphalt for a given test date. The horizontal strain values were derived from the ELSYM5 computer analysis of measured Benkelman beam deflections. Values above 1.0 indicate a progressively weakening structure; below 1.0 they indicate increasing strength due to the presence of frozen ground directly beneath the mat. For example, a factor of 1.0 would indicate the relative impact on the road caused by a passing vehicle during the period of the pavement's maximum unfrozen structural strength in late summer. A factor of 10.0 indicates strength loss is such that the same vehicle has 10 times the pavement impact (damage potential) when compared with late summer values. The peak value in Figure 16 indicates that when the pavement at this specific site was at its weakest observed state, the foregoing vehicle would cause 17.6 times the impact relative to the recovered road condition. Calculations of the damage factor were based on the 48,000-lb three-axle Benkelman beam test vehicle using AASHTO 18-kip equivalent axle loads.

The rapid pavement strength loss accompanying the onset of thaw in the base course was typical for all sites tested and monitored. Within a very short time the load-carrying capacity of the pavement had dramatically decreased. The importance of placing vehicle restrictions at the beginning of base thawing is graphically illustrated by Figure 16 because even short delays will result in heavy vehicular loads traveling over a substantially weakened structure. Findings of the present study are consistent with conclusions reached in past research projects that indicated that pavement strength loss progresses swiftly as the base course begins to thaw *(1-4)*.

Strength recovery for all sites occurred with the same general pattern: an initial rapid strength gain followed by a period of more gradual improvement. At sites underlain by nonplastic soils, the change from the rapid primary recovery to the slower secondary recovery occurred when pavement strain values had returned to approximately prefrozen fall values. Thaw depths at the point of this change had progressed to between 3 and 4 ft below the asphalt mat. The conservative 4-ft value was used to

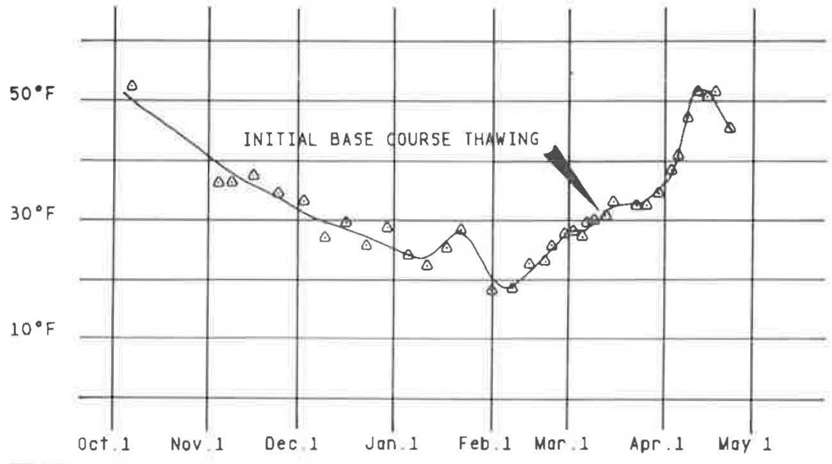


FIGURE 14 Average soil temperatures from base of asphalt to depth of 3 ft, Site D2-92-30.6.

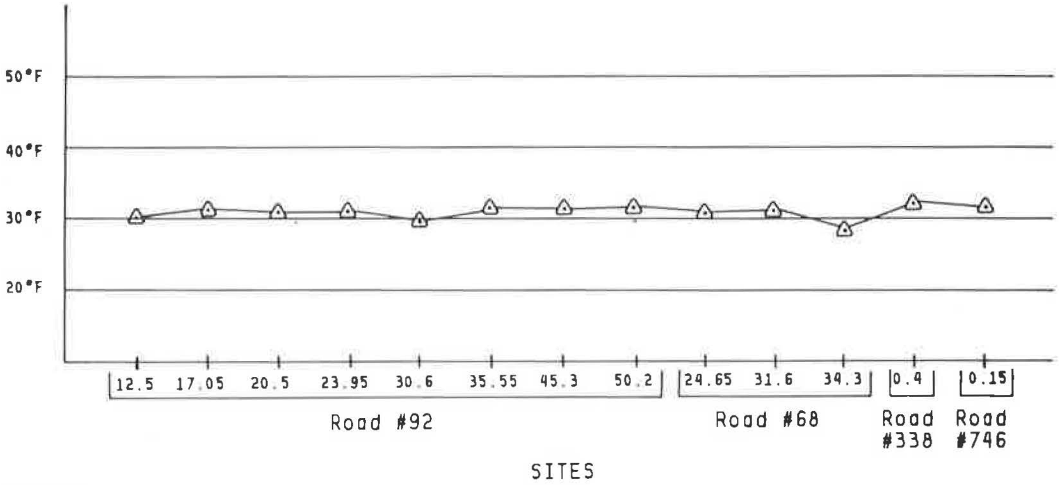


FIGURE 15 Average soil temperatures at commencement of base course thawing.

indicate recovered pavement strength for the purposes of this study (Figure 16). Data gathered after the first season of instrument monitoring strongly indicate that for pavements underlain by nonplastic soil adequate strength recovery has been achieved to allow removal of load restrictions when thawing reaches a depth of 4 ft. This is in close agreement with the results of similar studies performed by the Alaska Department of Transportation and Public Facilities (B. Connor, unpublished data).

At sites underlain by soils exhibiting plastic properties (Table 3), the change from primary to secondary recovery rates occurred at some strain value greater than the prefrozen fall value. Data to establish a reliable correlation between pavement strength recovery and depth of thaw under these conditions are currently insufficient.

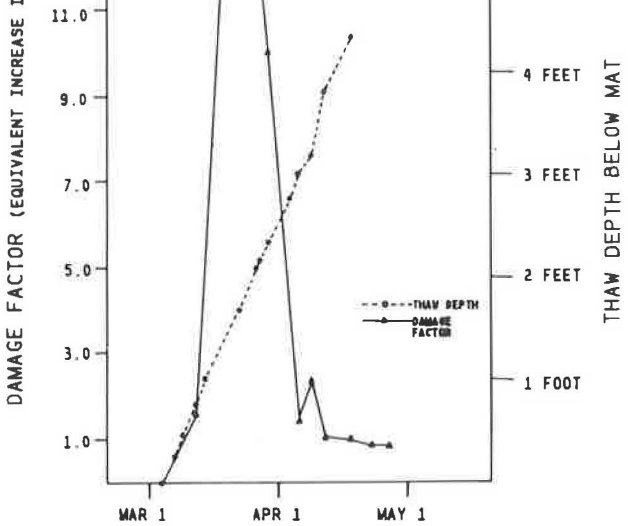


FIGURE 16 Damage potential versus thaw depth, Site D2-92-23.95.

CONCLUSIONS

Results obtained from one season of monitoring asphalt and soil temperatures as indicators of pavement structural strength during the spring thaw period suggest that road managers now possess a tool with which to address past problems involved with the imposition of seasonal load restrictions. Monitoring warming soil temperatures through the late winter and early spring allows a reasonable prediction to be made of the expected onset of pavement weakening. Road users have the opportunity to remove equipment from the field and to plan their springtime activities. Commencement of spring thaw can be accurately and objectively confirmed by the occurrence of temperatures above the freezing point of local soil moisture measured at the base of the asphalt mat. In areas of nonplastic soils the recovery of pavement strength can be indirectly determined by monitoring the depth of thaw. When thawing progresses to approximately 4 ft below the base of the asphalt mat, vehicle load restrictions can be removed. Finally, this method can be used to evaluate the effects of short-term weather fluctuations on pavement load-carrying capacity. Large decreases in annual maintenance costs and extended road ser-

TABLE 3 PROPERTIES OF PLASTIC SOILS ALONG YAAK 92 FOREST HIGHWAY, KOOTENAI NATIONAL FOREST, MONTANA

Unified Soil Classification System Symbol	Plastic Limit (%)	Liquid Limit (%)	Plasticity Index	Percent Passing No. 200 Sieve
ML-CL	22	29	7	87.5
ML-CL	20	26	6	56.5
GM-GC	21	27	6	43.0
GC	19	28	9	35.1

viceability are anticipated from the implementation of this inexpensive system. Cost of installation per site in 1984 was approximately $240, which includes all parts, equipment, and labor.

Additional work is currently under way to confirm the correlation between depth of thaw and pavement strength recovery in geographical areas outside northwest Montana, to check the reliability of projecting average soil temperature, to predict the onset of the spring-thaw period under a wider variety of climatic conditions than was possible in the present program, to test the results obtained from variations in the thermistor spacing on the instrument strings, and to evaluate the long-term survivability of the system. In addition, the relationship between thaw progression and pavement strength recovery in areas underlain by plastic soils is being investigated.

REFERENCES

1. R. N. Stubstad and B. Connor. *Prediction of Damage Potential on Alaskan Highways During Spring Thaw Using the Falling Weight Deflectometer.* Report AK-RD-83-11. Alaska Department of Transportation and Public Facilities, Juneau, 1982, 22 pp.
2. H. L. Jessberger and D. L. Carbee. "Influence of Frost Action on the Bearing Capacity of Soils." In *Highway Research Record 304,* HRB, National Research Council, Washington, D.C., 1970, pp. 14–26.
3. T. C. Johnson, D. M. Cole, and L. H. Erwin. "Characterization of Freeze/Thaw-Affected Granular Soils for Pavement Evaluation." In *Proc., Fifth International Conference on Structural Design of Asphalt Pavements,* University of Michigan, Ann Arbor, 1982, pp. 805–817.
4. T. C. Johnson, R. L. Berg, and C. W. Kaplar. *Roadway Design in Seasonal Frost Areas.* Technical Report 259. U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory, Hanover, N.H., 1975.

Publication of this paper sponsored by Committee on Flexible Pavements.