Frost Considerations in Highway Pavement Design: West-Central United States

F.C. FREDRICKSON, Assistant Materials and Research Engineer, Minnesota Department of Highways

•ASSESSING the harmful effects of frost action on highways and adjusting highway design to eliminate the harmful effects is a major effort in frost areas. The problems are roughness resulting from freezing, weakening of road structures on thawing, and the deterioration of materials and structures resulting from freeze-thaw. The number of problems, their seriousness, and the nature of corrective action depend on the severity of the frost action which is related to geographic location.

The area considered in this report includes Arkansas, Oklahoma, Missouri, Kansas, Nebraska, Iowa, South Dakota, North Dakota and Minnesota.

GENERAL INFORMATION

This area involves regions of diverse climate and topography, ranging from the forest and lake region of northern Minnesota through the vast plains and lowlands to the Ozarks in Missouri and Arkansas. It can generally be subdivided into three physiographic provinces: the Great Plains, Central Lowlands, and the Ozark Plateau region (Fig. 1).

The Great Plains region is part of the high Piedmont area located at the foot of the Rockies. Elevations gradually rise from 1,000 ft in the east to 5,000 ft in the west. Grazing and winter wheat farming reflect the moisture deficiency of the area.

Elevations in the Central Lowlands are fairly uniform ranging from 500 to approximately 1,500 ft. This province, trending north-south through the area, forms the basis for the rich agricultural economy of the Cotton Belt, Corn Belt, and the Spring Wheat regions in the Dakotas.

The Ozark Plateau, located in the southeast portion of the study area, stands at 1,500 to 2,000 ft elevation. The plateau is composed primarily of sedimentary rocks. Early settlement occurred here because of a good supply of timber and spring water leading to a small farm type of agriculture. Today the area produces fruit and truck farm products.

The Rocky Mountains, located west of the study area, have a direct influence on the climate of the area, especially in regard to precipitation. Precipitation and temperature seem to have a more direct bearing on soil formation and frost problems than does topography, and for this reason climatic relations will be discussed more fully than topography. W. Koppen and R. Geiger in "Hanbuch der Klimatologie" (1936) devised a climatic classification based on temperature and precipitation measurements (Fig. 2). Their climatic zones serve as convenient divisions for the discussion of frost conditions in the nine-state area.

Climatic Region BS_w

In western North Dakota, South Dakota, Nebraska, Kansas, and in the Oklahoma Panhandle (at the eastern foot of the Rockies) is a semi-arid "Steppe Climate" classified by Koppen as BS_w (Fig. 2). This type of climate normally occurs in continental interiors where mountain barriers shut off rain-bearing winds. This region suffers from a precipitation deficiency, a high evaporation rate, and in addition, has a severe

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daily temperature range which causes it to have the highest frequency of freeze-thaw cycles of any of the four regions discussed (Fig. 3). Generally, the Rockies depress the growing season by 40 days and the mean annual temperature by 10 to 15 degrees. Soils formed in this semi-arid climate are lime-accumulating Chestnut and Brown soils of the Pedocal group which develop under a grassland cover. These soils are arranged in north-south belts in Central United States succeeding one another from east to west as aridity increases, until desert soils replace them west of the study area (1). The A horizon is thin; decreasing or increasing with annual precipitation. Zones of lime accumulation usually occur 3 to 5 ft below the surface in the upper part of the B horizon. Due to aridity of the soils and a high evaporation rate, but in spite of a high freeze-thaw frequency, frost damage is not as serious here as in the areas of higher precipitation farther east. Oklahoma and Kansas report frost is not a very serious problem.

Climatic Region Cfa

Farther east, away from the Rockies, the Gulf of Mexico has a moderating effect on temperatures. It also increases precipitation and lengthens the frost-free season by 30 days (3, p. 16). This is the zone of Koppen's "Cfa Humid Sub-tropical Climate" which extends from the coast inland almost to Iowa (Fig. 2). It includes most of Kansas, Missouri, Oklahoma, and all of Arkansas. The climate is warm and temperate with rain occurring in all seasons. Mean annual precipitation ranges from 24 to 56 in. (Fig. 4). Frost occurs during 5 to 7 months of the year, with the soil freezing 1 to 4 in. in the south and 6 to 18 in. in the north (Fig. 3). Soils located in this zone are least affected by frost. Missouri and Arkansas report few or no frost problems. Due to a high annual precipitation, non-lime-accumulating soils of the Pedalfer group developed in this zone. The Prairy soils in the southern Central Lowlands formed under grasslands from parent material of decomposed limestones. The Ozarks, because of higher precipitation (52 in.) developed Red and Yellow soils under a heavy forest cover. The A and B horizons are relatively thick and strongly leached.

Climatic Region Dfa

Iowa, southern Minnesota, southeastern South Dakota, eastern Nebraska, and small parts of Kansas and Missouri are included in the Dfa Climate, differing only from the Cfa Climate in that it has colder winters. Black soils of the Pedocal group are found in South Dakota, but Prairy soils of the Pedalfer group developed in Iowa and southern Minnesota. The west boundary of the Prairy soils shows a definite correlation with annual precipitation and generally follows the north-south 24 in. precipitation isoline, despite divergent parent material and topography. A large part of this area was heavily glaciated, generally north of the Missouri River. In the glaciated area, Prairy soils developed on the older transported glacial tills and wind-blown loess deposits associated with the Nebraskan, Kansan, Iowan, and Wisconsin glacial advances. Directly south of the Missouri River, similar residual soils developed on unglaciated parent material. Mean annual precipitation for the Dfa region ranges from 24 to 32 in. The soil normally freezes 18 to 36 in., with only 3 to 4 months without frost (Fig. 3). Freeze and thaw cycles based on the difference between the annual number of nights with frost and the number of days continuously below freezing, range from 90 to 100 per year (3, p. 135). Frost problems are more complex in this area because glaciation has produced a high diversity of soil types and poor drainage. All states involved report frost problems.

Climatic Region Dfb

The Canadian Climate (Dfb) dominates North Dakota, northern Minnesota, and northeastern South Dakota. This area includes large dairying and spring wheat agricultural regions. It has snowy, cold winters and moderately warm summers. Mean annual precipitation ranges from 16 to 28 in. with most falling during the crop season (Figs. 4 and 5). Freeze-thaw cycles, based on the frequency of a temperature of 28° or lower followed by one of 32° or higher, range from 68-91 per year (Fig. 3). All states in the area report difficult frost problems with extensive studies being made. In 1941, F. C.

Figure 1. Major physiographic provinces (1, Fig. 448, p. 650).

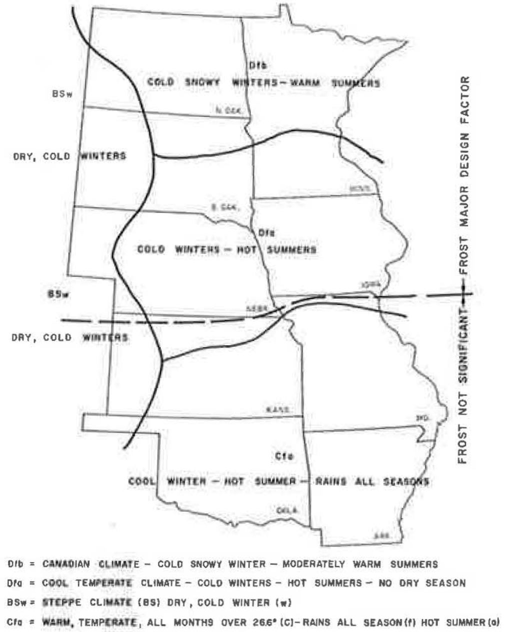


Figure 2. Climatic regions (3, Fig. 981).

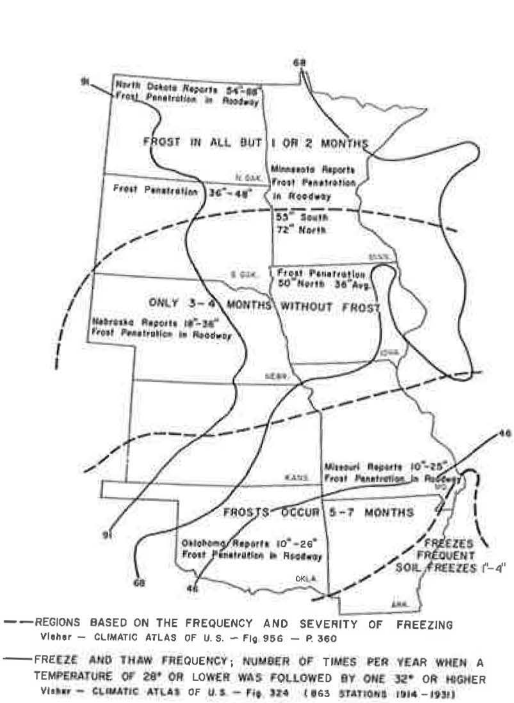


Figure 3. Freeze and thaw data.

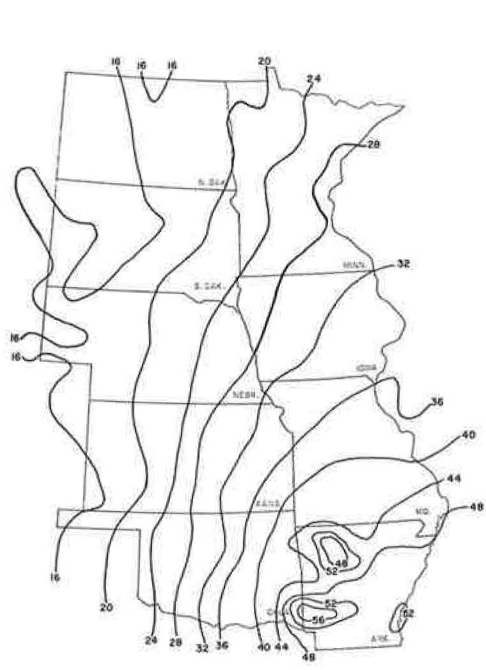


Figure 4. Mean annual total precipitation, in inches (U. S. Weather Bureau).

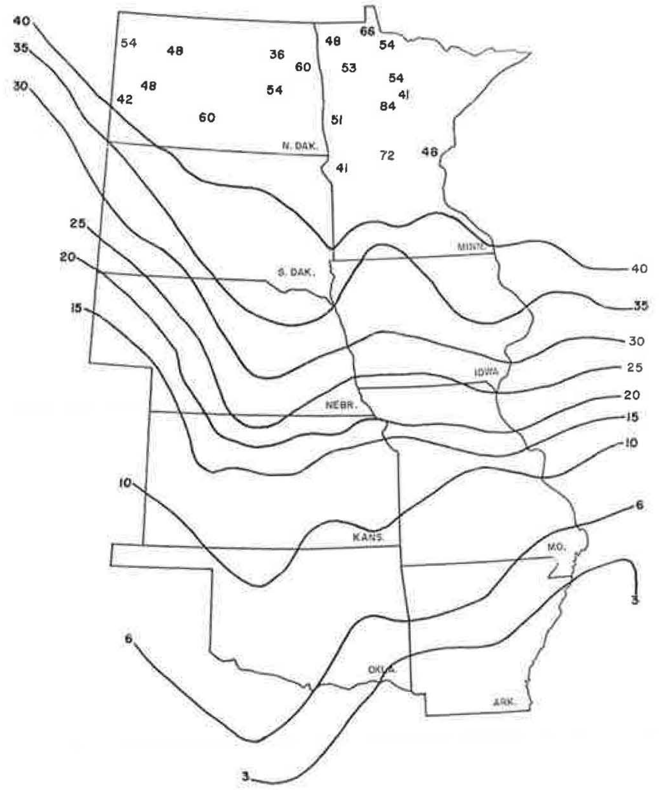


Figure 5. Average depth of frost penetration, in inches, in normal terrain not in roadway, 1899 to 1938 (4).

Lang (2) reported on frost penetration and freeze-thaw cycles occurring in a concrete slab and subbase section exposed to the elements in Minneapolis, Minn. This showed a total frost penetration in excess of 60 in. Freeze-thaw cycles for the winter observed varied from 43 at the surface of the 7-in. slab to 14 at the bottom. Only one cycle was recorded at the 60-in. level (2).

Soil types in the Dfb region range from the infertile Podzols in heavily-wooded northern Minnesota, to the rich Black soils of the Pedocal group developing on the lacustrine deposits of glacial Lake Agassiz. The area was glaciated during the late Wisconsin ice advance and the topography reflects the youthful features of this recent glaciation: massive terminal moraines, young soils, numerous swamps and poor drainage. Minnesota has the most complex glacial history, receiving successive invasions from the Keewatin (grey drift) and Patrician (red drift) ice centers.

PROBLEMS ASSOCIATED WITH FROST ACTION

Because frost problems are related to depth of frost penetration, the problems caused by frost action are most numerous and serious in the northern portion of the West Central States where the penetration is deep, but become less significant southward as frost penetration decreases. Frost damage is also related to the moisture content in the freezing zone. Without moisture there would be little damage, but as moisture increases, the damage increases. Frost enters the roadway from the top and penetrates downward. In the spring, thawing progresses from both top and bottom.

A seasonal fluctuation generally occurs in soil moisture with the moisture content greatest in the spring. Scientific studies attribute much of the increase to the transfer of film and vapor moisture from the warm soil below the zone of seasonal temperature change toward the cooling soil in the temperature change zone where it collects and increases the total moisture content. During the summer, when the temperature of the upper zone increases, the movement is reversed. It is probable that periodic recessions of temperature, caused by the release of latent heat of fusion and the time required to dissipate the heat, results in a fluctuating frost line during the freezing period. Warming periods contribute to temperature recession. During sunny winter days, thawing can occur to depths of more than 6 in. below the top of bituminous surfaces. A fluctuating frost line is conducive to moisture gain.

The percentages of contained water which freeze at normal freezing temperatures vary widely for different soils. In general, these percentages vary inversely with the clay content of the soil. Normally, soil does not freeze until the temperature of the soil reaches about - 4 C.

When freezing, moisture moves from small capillaries and thick films around the soil particles to larger capillaries. When drawn into the larger capillaries this moisture assumes the properties of lubricating moisture. Physically combined and loosely chemically combined water exists in the colloids. On freezing, the colloids coagulate and the combined water is liberated. The capillaries are destroyed by freezing and additional unfree water is liberated. With each cycle of freezing and thawing, more free water is liberated which freezes at normal temperatures. During the summer months the above processes are reversed.

In relation to the bearing value of a soil, moisture may be divided into two classifications: lubricating or free moisture and adhesive moisture. A soil is stable when the absorbed or adhesive moisture is the dominating influence. As lubricating water increases in proportion to adhesive moisture, the bearing value decreases.

Laboratory tests were conducted by the Minnesota Highway Department in 1948. After sealing to prevent moisture change, soils were subjected to freezing and thawing. Bearing tests made before and after freezing and thawing indicated losses in bearing value ranging from 18 to 39 percent.

Plate bearing tests made in the field indicate losses in bearing value of 50 to 62 percent in early spring. It appears the loss of strength in the spring is only partially caused by total moisture increase. Because water expands 9 percent in volume when becoming solid, there is a disrupting effect when materials containing water become frozen.

The gain in moisture on freezing is not necessarily confined to soil materials. This occurrence was observed numerous times in granular (sand gravel) bases. The moisture gain in base material is more evident in aggregates with a high content of soil fines than in aggregates low in fines. When the base thaws, "bleeding" of water through the surface occurs if the moisture gain is substantial.

The moisture gain in a bituminous surface is difficult to detect because it is rare and does not appear to occur in any detectible amount in properly constructed surfaces. When it does happen, stripping of the bituminous material from the aggregate sometimes results. Moisture can be considered a related frost action problem.

Arkansas, Oklahoma, Kansas and Missouri report that frost does not penetrate sufficiently into the subgrade and the frost action is not of sufficient duration or severity to create problems requiring special design considerations for the subgrade, base or surfacing. Occasionally some frost damage does occur, but it is not a major problem. Therefore, few data on frost design practices are available from this area. Missouri reports some subgrade frost problems in the northern counties, but their only frost design consideration relates to the durability of portland cement concrete in pavements and bridge decks. Oklahoma does consider frost penetration in the determination of base thickness, but frost damage is not indicated as a major factor. The deepest frost penetration is in the northwestern part of Oklahoma, but frost damage is unlikely because of low rainfall and the presence of low frost-susceptible soils.

The following are area problems that include Nebraska, South Dakota, Iowa, North Dakota and Minnesota.

Subgrade Problems

Frost heaves and frost boils were among the first highway defects caused by frost action to be recognized by highway engineers. Because these problems have been recognized for a long time and have a long history of study, corrective action has succeeded in practically eliminating objectionable defects of this nature from modern highways. They are still a major consideration in design, and in the maintenance of the older roads.

Differential frost heaves (bumps) occur when there are pockets or layers of highly capillary soils in sections predominantly composed of moderately capillary or granular soils, or where cohesive soils have ready access to localized moisture. The heaving can occur as a single bump in a cut, as a series of bumps, or as general irregularity (Fig. 6). The heaving is caused by ice crystal growth in the soil, and its severity varies with the depth and rate of frost penetration, availability of moisture, and the nature of the soil. The height of heaving above surrounding areas varies from one year to the next for the same heave, and, in some cases the height of the same heave will increase with age. The maximum height of heaving in this area varies from 12 in. in northern Minnesota to 4 or 5 in. in Nebraska. Differential frost heaves are a much more serious problem in the northern portion of this area than in the south portion.

In the northern portion, frost penetration is so deep that general surface roughness occurs where soils and moisture are variable. The problem is not always serious, but it is costly to correct and the offending materials or conditions are difficult to detect.

Frost boils are localized areas where there is almost complete loss of soil strength during thawing. The loss of strength is caused by the large accumulation of moisture that occurs as ice crystal growth during freezing. Boils occur when there is insufficient cover of frost-free material to bridge the weakened frost-susceptible material. Frost boil areas do not always develop detrimental heaving, nor do frost heaves necessarily boil in the spring.

A great effort is made by the states in this area to identify materials subject to frost heaves and boils, and to assess conditions that contribute to the problems. Detailed soil surveys are performed prior to design to visually classify the various soils present and evaluate other conditions that influence this performance. Representative samples are physically tested in the laboratory for classification.

Most cohesive soils are frost-susceptible to some degree depending on their physical and chemical composition. If less than 20 percent of the material passes the No. 200 sieve, it is considered a coarse-grained soil and normally is not subject to frost heaves

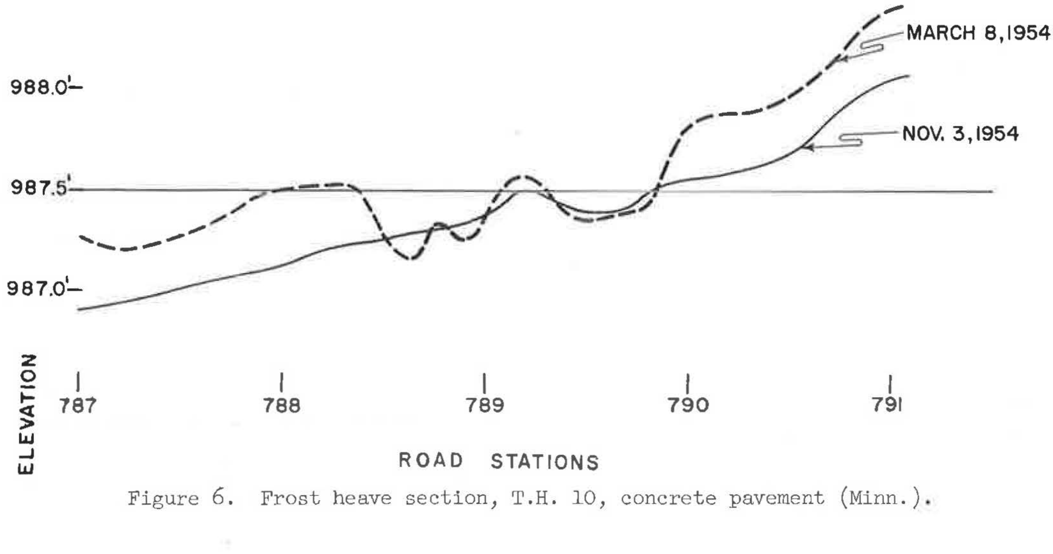


Figure 6. Frost heave section, T.H. 10, concrete pavement (Minn.).

or boils, although very fine sands will heave and boil under adverse moisture conditions. There are no available recognized limiting test values for assessing the degree of susceptibility for various soils, but it is generally recognized that silty soils (A-4) are the most susceptible to boils and heaves. Other cohesive soils may heave or boil when in a non-uniform, pocketed or layered condition, or when adjacent to ledge rock or coarse-grained soil material. Moisture conditions that are recognized to contribute to these problems are springs, seepage areas, high ground water table, perched water, restricted drainage, or underground water supplied by faulty utility installations. Detrimental frost action can be expected where these conditions occur. When encountered in the soils survey, they receive special consideration.

Reduction in soil strength in subgrades during the spring period is a critical problem particularly in connection with flexible pavements. The strength loss in the general subgrade soils for the area varies from 30 to 62 percent of the fall season strength. Because frost penetration is less in the south portion of this area than in the north, there is correspondingly less strength loss. This loss of stability is a result of a reduction in cohesion and internal friction in the soil caused by the loosening effect of freezing, a reorientation of the contained moisture into free moisture, and a possible moisture increase. This strength loss can be expected in all soils including granular material.

The period from spring break-up to substantial recovery in strength of cohesive soils averages approximately three months. There is some variation from year to year. It is believed that coarse-grained materials recover substantially in a much shorter time, and because the strength is still comparatively high during the weakest period, the loss related to granular subgrades is not significant.

Contraction of frozen subgrade soil after a drop in temperature is not considered a serious problem in this area. Contraction cracking occurs in sand subgrades as well as in cohesive soil subgrades during the winter. Both transverse and longitudinal cracks occur, although longitudinal cracking is generally limited to cohesive soil subgrades (Fig. 7). When the cracks carry through the base and surface courses, some damage from spalling or break-down of the crack may occur. The occurrence of this problem appears to be limited in extent.

Base Problems

Granular bases lose strength as the base thaws in the spring, but the duration of the reduction strength is estimated at only one week. Granular base materials become mealy and appear slightly loosened during this period, but regain firmness in a short time under traffic. The reduction in strength is very difficult to measure in the road,

Figure 7. Large crack caused by shrinkage of dense clay subgrade following deep frost penetration (Minn.).

therefore no test data are available. The loss is primarily the result of the disruptive stresses produced by the freezing expansion of the contained moisture, combined with the reduced stability contributed by any increase in moisture. Seasonal moisture content fluctuation in the sand-gravel base on a section of flexible pavement in Minnesota is shown in Figure 8. Moisture migrates upward in vapor form to the cold surface. As freezing occurs, moisture collects, and fluctuations of temperature in the freeze-thaw range promote accumulation. In bases containing excess fines, additional moisture could also be supplied by capillary migration of moisture from the subgrade. Coarse, well-graded bases containing a minimum of fines accumulate less moisture than finer-graded bases containing excess cohesive fines, and consequently are less affected by frost action. Loss of stability in granular base covered by bituminous surfacing is evidenced, if failure occurs, by alligator cracking or breaking of the surface without appreciable displacement. The deflections involved are usually relatively small because there is no reflection of deflection in the frozen subgrade. The base usually regains firmness before substantial thawing developes in the subgrade.

Data on loss of density are limited, but it has been observed that in coarse, well-graded base aggregates, the loss of density is negligible but finer aggregates show some loss. Any losses in density that occur are usually recovered under traffic during thawing.

Substantial loss in strength on thawing can be expected in subbase and base materials that exceed the general limits for gradation and unsound particles indicated under design practices for bases.

In general, materials used for base courses are sampled and their suitability determined by gradation tests, shale tests, Los Angeles rattler tests and Atterberg limits. The locations of representative portions to be sampled are determined by visual examination.

Bituminous stabilized and treated bases are not appreciably affected by frost action. Contraction cracking does occur in bituminous bases, but because of the relatively short period of experience with these bases, it is not recognized as significant. Little is known about detrimental effects, but this could become a future

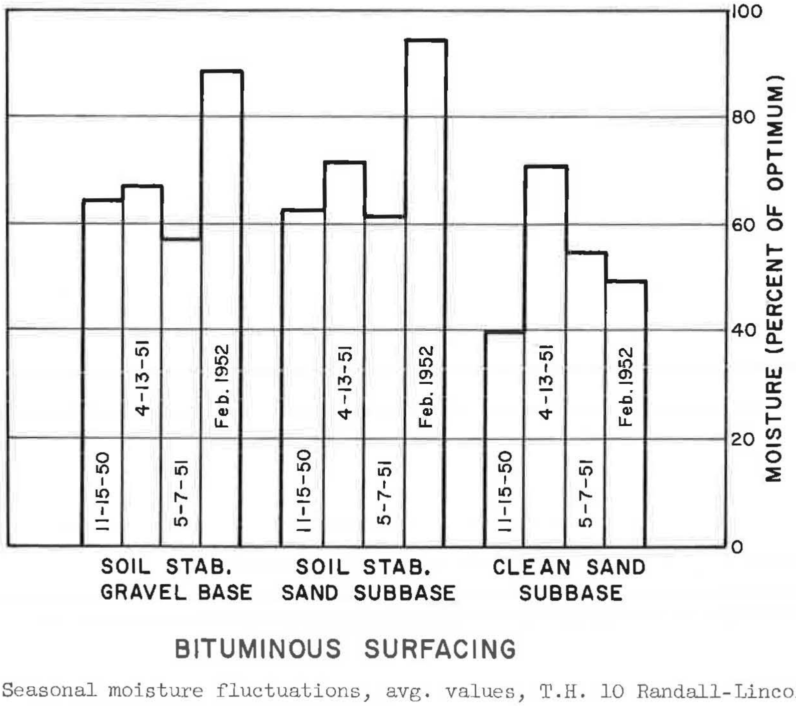


Figure 8. Seasonal moisture fluctuations, avg. values, T.H. 10 Randall-Lincoln, Minn.

problem. Because there is no history of bituminous bases being frost-susceptible, there is little knowledge regarding methods of determining the susceptibility of materials of mixtures; consequently, limiting values are unavailable.

Soil-cement and cement-treated bases are not significantly affected by frost action except for contraction cracking. Contraction cracking is a problem, especially in the northern portion of the area where winter cracking causes considerable maintenance crack filling. Otherwise, these bases appear durable and structurally sound.

Considerable contraction cracking can be expected when fine-grained soil material is used in the soil-cement mixture. Considerable reduction can be obtained if granular materials are used in place of soil. In general, the cracking increases in proportion to the increase in cement used.

Structures and Pavements

Heaving of approach fills adjacent to bridges and culverts is a problem in the northern portion of the area (Fig. 9). The causes and detection procedures are the same as previously described for frost heaves. Pronounced heaving can be expected where frost-susceptible soil is placed in relatively shallow fills adjacent to structures if there is water readily available for ice crystal accumulation. Heaving is rare in the higher fills. In the extreme northern portion of the area where frost penetration is deep, shrinkage can occur in "fat" clay fills causing a slight bump at the culvert.

Culvert heaving is a problem in the northern half of the area where there is less than approximately 5 ft of cover over the culvert top (Fig. 10). The heaving is caused by ice crystal accumulation in the soil under the culvert. The occurrence can be suspected for culvert placement on most non-granular soils where moisture is readily available and there is no protection to prevent freezing below the culvert. Unfrozen water in the culvert or heavy snow cover will prevent freezing under the culvert. The heaving will vary from year to year depending on the amount of freezing protection from snow cover. On rare occasions, fill shrinkage occurs in conjunction with culvert heave causing a more pronounced bump (Figs. 11 and 12).

Permanent uplift (jacking-out) of culverts is a problem associated with culvert heaving. Not all heaved culverts are subject to permanent uplifts. Jacking appears to oc-

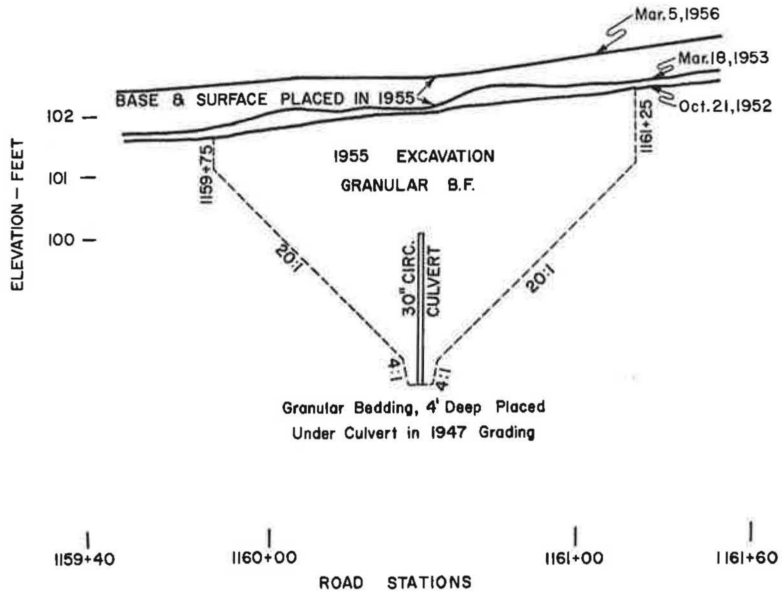


Figure 9. Pipe culvert fill heave and treatment (Minn.).

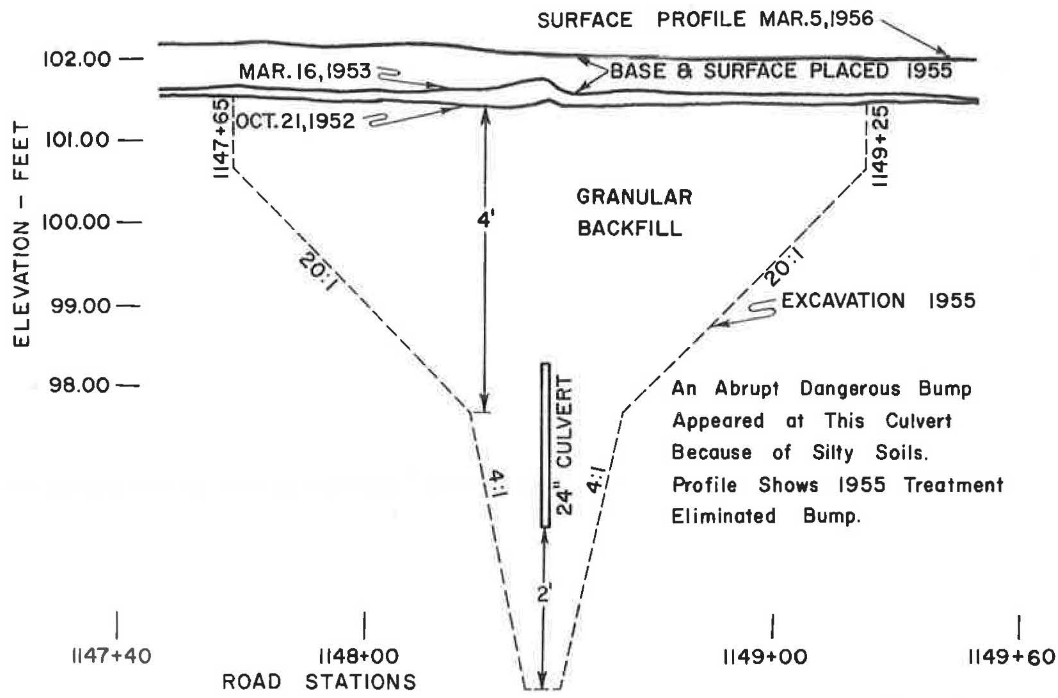


Figure 10. Typical culvert heave treatment--longitudinal section (Minn.).

Figure 11. Combination culvert heave and fill shrinkage causing dangerous bump (northern Minn.).

cur where there is shallow fill over the culvert in areas of "lean" clay loam or cohesive sandy loam soil. The jacking occurs during the spring thaw when soil below the culvert thaws more rapidly than the adjacent fill soil, thus creating a void under the culvert which is prevented from subsiding by the adherence of the frozen fill. Small amounts of loose soil fall under the culvert each year resulting in a progressive uplift.

Portland cement concrete pavement warp (high joints) caused by frost action is a

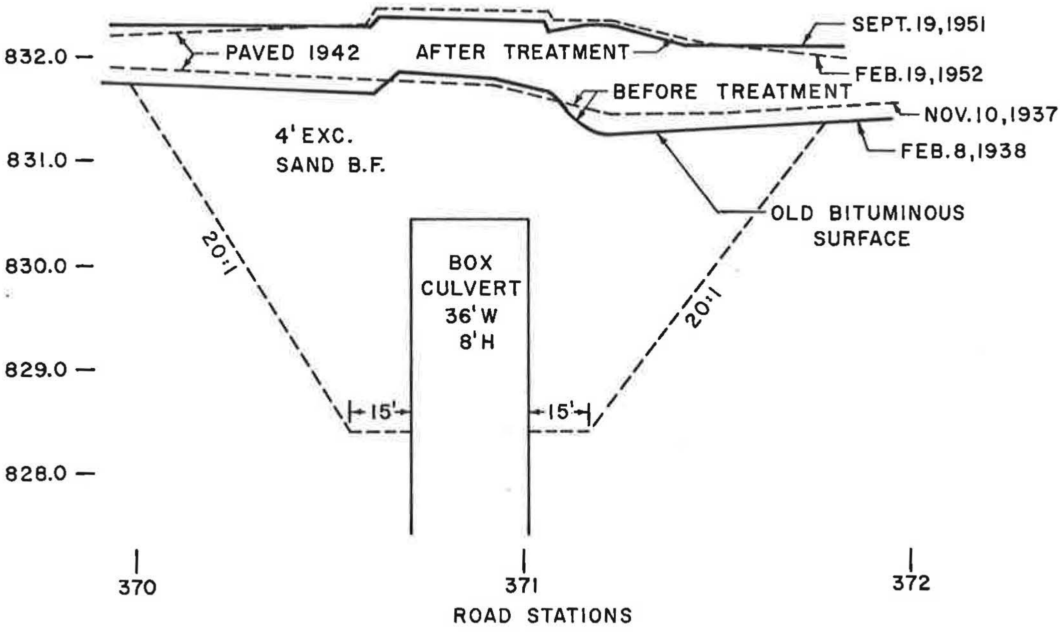


Figure 12. Combination culvert heave and fill shrinkage (low density gumbo clay, northern Minn.).

problem in South Dakota and Minnesota. It is considered an inconvenience to traffic in the form of a slightly rough-riding surface during the frozen period and only occurs occasionally. The roughness is much more noticeable and distressing to trucks than to passenger cars. The high joints, which subside in the early spring period, are primarily caused by the formation of ice lenses in the soil at the joint. The moisture is supplied by water leaking through joints that open during contraction. High joints can be expected in pavements constructed on relatively dry subgrades composed of plastic lacustrine soil of clayey glacial till from the grey drift. Moisture and density control in the subgrade and tightly sealed joints can reduce and sometimes prevent the warp.

Cracking caused by differential subgrade heaving is a problem in the northern portion of the area. This does not occur in newer pavements because of corrective action taken when constructing the subgrade. Consequently the problem is minor in extent. It occurs more in older pavements causing roughness, and in some cases, pavement failure during the spring break-up.

Progressive increase in the permanent roughness of rigid pavements can be partially attributed to subgrade movement caused by freezing where substantial frost penetrates the subgrade. Surface irregularities caused by frost movement are not likely to return entirely to original smoothness after thawing especially if cracks develop. Cracks never close entirely, but become progressively open after repetitive movement. This progressive roughening of the pavement is not serious, but is objectionable and leads to shortening of the pavement life. It is not as evident in bituminous pavements because of the flexible nature of the structure and the dampening effect of substantial subbase and base thicknesses.

ROAD LOAD TESTS—FLEXIBLE PAVEMENTS

Plate Bearing Tests

The loss of load-carrying capacity as related to frost action is considerable. With no increase in moisture, the loosening effect of freezing and the character change of the contained moisture reduce the internal friction and cohesion sufficiently to cause an appreciable loss in stability. In addition, subgrade soils normally increase in moisture content because of moisture migration to the freezing zone. This is dependent on frost penetration, temperature fluctuation, precipitation and chemical properties of the soil.

By plate bearing tests (Fig. 13), Minnesota has derived an average curve showing the loss of load-carrying capacity from fall to spring and the rate of recovery through the summer. Bearing values, measured at various times during spring and summer, are adjusted to maximum fall values by multiplying the value obtained by the factors in Table 1. Spring strengths are generally estimated by applying a 50 percent reduction to the fall value. The 50 percent was selected as an average year-to-year value for all roads.

In the plate bearing test, load-carrying capacity is evaluated by loading a 12-in. diameter steel plate in uniform increments and determining the unit pressure at 0.2-in. deflection. The plate bearing test is used in Minnesota for research, evaluating the strength of existing road structures, and to assist in establishing spring load restrictions. The test is not used directly for design purposes, but the information developed is considered and influences design. Figure 14 shows typical loss and recovery curves developed by Minnesota, Nebraska and Iowa. Nebraska's plate bearing study confirms that flexible pavement strengths are lowest in the first few weeks after spring thaws, and the loss of strength is not as great for subgrades composed of sand as for subgrades of silt-clay materials. Their curve indicates that average strength loss is not as great in Nebraska as in colder Minnesota. Iowa's curve is very similar to that of Minnesota.

Figure 15 shows average strength loss and recovery curves developed by Minnesota for various bituminous-surfaced base structures on various subgrade soils. Test loads were applied to the surfacing. Sand subgrades lose considerably less strength than do

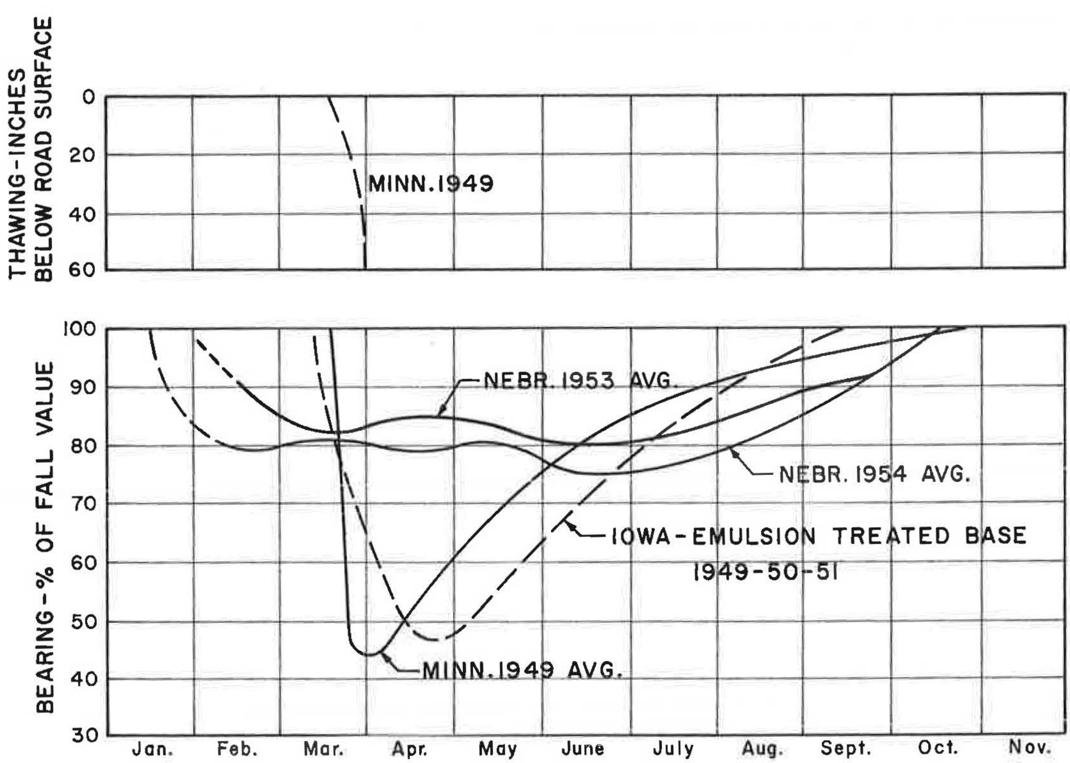


Figure 13. Typical plate bearing test curves showing loss of road strength and recovery.

cohesive soil subgrades. Similarly, road structures consisting of hard semi-rigid bases such as soil-cement on cohesive soil subgrades lose considerably less strength than do structures of more flexible bases such as gravel on cohesive soil subgrades. The strength loss and rate of recovery also varies moderately from year to year.

Table 2 gives the average values of retained strength for several combinations of subgrade soils and bases as a percent of fall load-carrying capacity.

Loss of road structure strength because of frost action varies with the type of subgrade soil, type of base, and depth of frost penetration.

TABLE 1

MULTIPLICATION FACTORS TO OBTAIN FALL BEARING VALUE

Test Period	Cohesive Soil Subgrade	Sand Subgrade
June 1-15	1.370	1.176
16-30	1.284	1.149
July 1-15	1.221	1.125
16-31	1.176	1.099
Aug. 1-15	1.135	1.077
16-31	1.095	1.055
Sept. 1-30	1.042	1.022
Oct. and Nov.	1.000	1.000

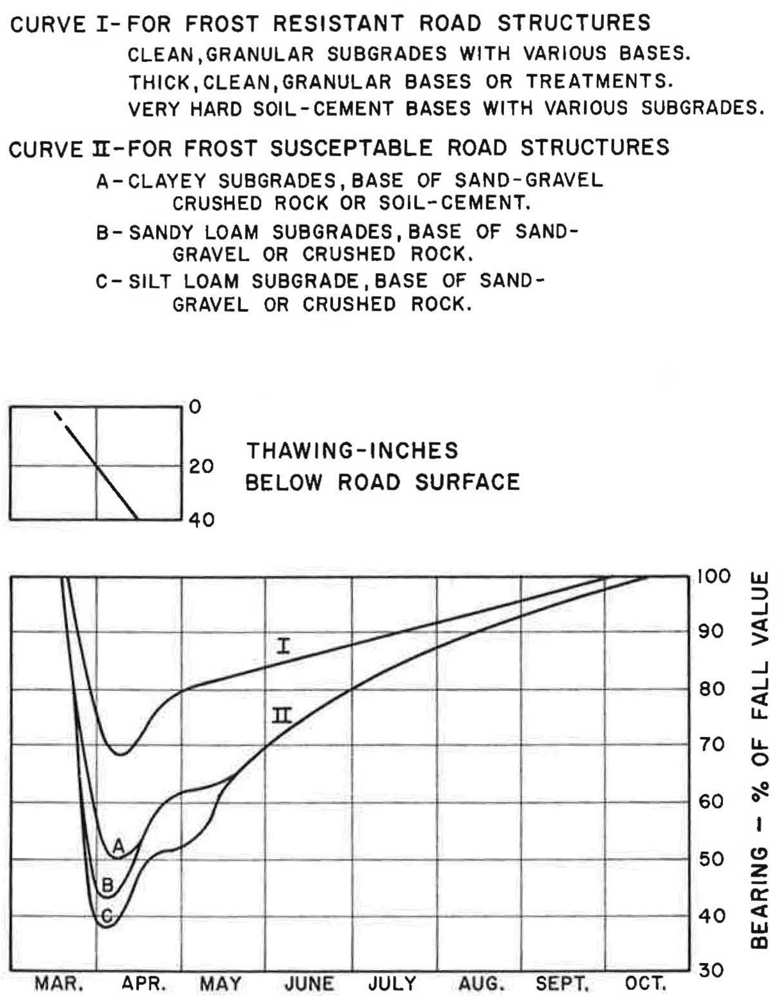


Figure 14. Average strength loss and recovery curves (Minn., 1956-57).

Loaded Vehicle Pavement Deflection Tests

The Benkelman beam test has been used in research work by both Minnesota and Nebraska (Fig. 16).

Minnesota is conducting research using both plate bearing and Benkelman beam procedures. This study is being made in cooperation with the counties. Roads in 50 counties are included. A correlation between the two tests is needed to develop a procedure that will permit use of the Benkelman beam test in place of the more expensive plate bearing test.

Nebraska is using the Benkelman beam test in a study which began in 1960 and is still in progress. The study is based on road condition and the deflection measured using a 9,000-lb wheel load. The arithmetic means and standard deviations were calculated and a limiting value of deflection was selected for several flexible pavement designs. Benkelman beam tests have also been used to check deflections on highways with load restrictions.

Figure 15. Plate bearing truck—trailer.

TABLE 2

AVERAGE VALUES OF RETAINED STRENGTH AS PERCENT OF FALL CAPACITY

Base	Subgrade	Strength Retained in Spring (%)
Sand and gravel	Silt loam	38
Sand and gravel	Sandy loam	43
Sand and gravel	Clayey	48
Sand and gravel	Sand	66
Crushed rock	Clayey	49
Soil-cement (soft)	Clayey	53
Soil-cement (hard)	Clayey	71

DESIGN PRACTICES ASSOCIATED WITH FROST ACTION

The following design practices pertain only to the area covered by Nebraska, Iowa, South Dakota, North Dakota, and Minnesota.

General

The design of good roadway drainage, which is common practice in planning most highway construction, deserves special attention in frost problem areas when attempting to prevent high subgrade moistures and reduce frost damage potential. Springs, perched water, seepage areas and low areas are drained as much as possible. Underground drainage systems are provided in areas where free water may be a problem. Minimum ditch depths vary from 3 to 5 ft below the finished shoulder for rural sections.

Figure 16. Benkelman beam and truck.

General practice is to provide a grade line over low wet areas of sufficient height to insure against penetration of frost into unstable foundation soils that are likely to create problems. The minimum elevation of the top of the subgrade above natural ground varies from 2 to 4 or 6 ft depending on moisture conditions and the nature of the foundation soil. Base and surface thicknesses are additional.

Maximum legal loads for the area are uniformly 9 tons per axle. Primary highways are designed to withstand this loading during the low strength period. Highways not constructed to this standard are usually restricted to lower axle weights in the spring period. These restrictions are usually placed in late February or early March and remain in effect until the latter part of May. Minnesota designs some secondary routes to support maximum axle loads of 7 tons during the weakest period. These routes are restricted to the design loadings during the spring, but are expected to support 9-ton axle loads the remainder of the year.

Restrictions on construction work during the freezing season prevail throughout the area, resulting in the suspension of most construction from freeze-up time until there is sufficient stability recovery in the spring to support construction equipment.

Grading with frozen soil or placing embankment on frozen ground is generally not permitted. Swamp excavation is permitted in the winter in Minnesota, but backfill with frozen material is not permitted. Base construction with frozen material or on frozen subgrade is generally not permitted. Surfacing construction is generally restricted to temperatures well above freezing.

Subgrades

The design of treatment for frost boil and frost heave sections consists of excavating the offending soil from the subgrade to depths of 1 to 3 ft in the southern portion of the area and 2 to 4 ft in the northern part. The exact depth of excavation is governed by conditions determined by soil borings and prevailing frost penetration. Base and surface thicknesses are additional, and in the extreme north, result in a maximum total depth of 6 ft from pavement surface to bottom of treatment. The width of excavation generally includes the shoulder width of the finished surface. Seepage trench outlets or perforated drain pipes are provided as needed in sections where there is a danger of water accumulations. Sand or gravel backfill is usually provided, although suitable mineral soil material may be provided in sections where water is not a problem. In Minnesota, suitable soil is used when feasible for backfill in the interest of economy and because it offers more resistance to frost penetration than do granular materials. Granular materials are used where there are adverse moisture conditions.

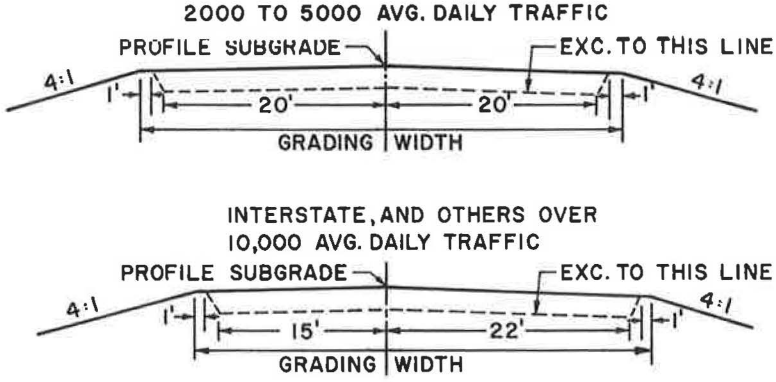
Adequate tapers, ranging from 1 ft to 10 to 1 ft in 20, are provided at the ends of all treatments and subcuts to avoid abrupt changes in soil. Figure 17 shows typical standard designs for frost heave treatment as practiced in Minnesota.

Soil selection is practiced in grading throughout the area. Topsoils, silty soils and other unsuitable soils are placed below the upper 3 ft of the subgrade. The better soils are reserved for the upper 3 ft of the subgrade for uniformity and to minimize frost susceptibility. Where sufficient granular materials are available, they are selected for the upper portion of the subgrade. Unless deeper treatments are provided, cuts are generally subcut 1 to 2 ft for soil selection and compaction to obtain uniformity. Figure 18 shows typical standard subcut designs used in Minnesota. When previously unknown areas of unsuitable soil are discovered during grading construction, they are removed and replaced with selected suitable material. Any necessary underground drainage systems are installed.

It is the practice to provide underground drainage systems of perforated drain pipe to intercept the infiltration of seepage or spring water into the subgrade or to depress the elevation of free water. Trenches filled with open-graded granular material or special ditches are sometimes used. When free water exists in the roadway, an underground drainage system is installed in the subgrade excavation. Gravel-filled trench outlets are usually provided for gravel-filled excavations if ditches are sufficiently deep to provide run-offs.

In rock cuts, the rock is removed 12 in. below the bottom of finished surface and backfilled with suitable soil material or sand-gravel. South Dakota uses bituminous-treated material for this purpose. Soil is removed from pockets to a depth of at least 3 ft at the ends of the rock. Adequate tapers are provided and sand-gravel materials are used for backfill.

Although compaction and moisture control are primarily to develop stability and are not considered a positive treatment for frost effects, they do promote uniformity in subgrade construction and contribute some resistance to strength loss. Nebraska requires that the upper 6 in. of the subgrade soil be compacted to not less than 90 percent of maximum density. For flexible pavements the moisture content of the upper 6 in. of subgrade must not be more than 4 percent above or below a value which is 90 percent of optimum, and for rigid pavements, not more than 3 percent above or below optimum

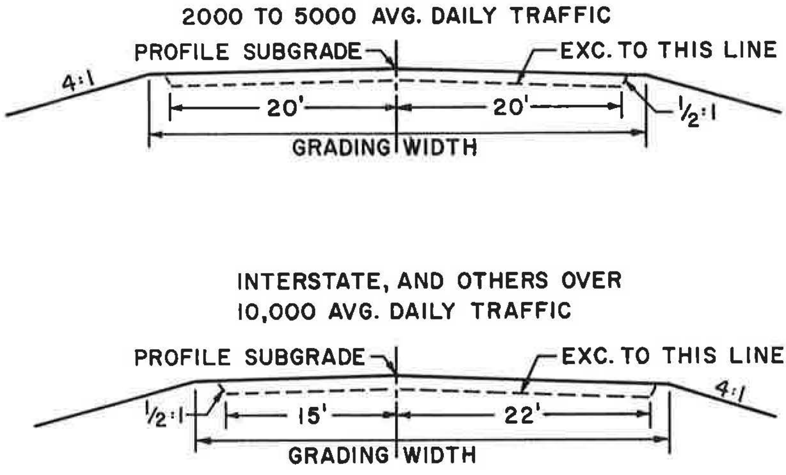


NOTE: TAPER EACH END OF SUBGRADE EXCAVATION 20:1 SLOPE UNLESS OTHERWISE RECOMMENDED. BACKFILL MATERIAL TO BE SUITABLE SOIL OR GRANULAR MATERIAL AS RECOMMENDED. PROVIDE DRAINAGE FOR ALL SUBGRADE CORRECTIONS DURING CONSTRUCTION. PROVIDE SEEPAGE TRENCHES WHEN BACKFILLED WITH GRANULAR MATERIAL. PLACE PERFORATED PIPE DRAINAGE AND OUTLET PIPE AS REQUIRED. WHEN THE PROPOSED SUBGRADE CORRECTION IS LOCATED WHERE THERE IS BASE AND BITUMINOUS SURFACING OR CONCRETE PAVEMENT INPLACE, THE ENDS OF THE TAPERS SHALL BE VERTICAL FOR THE DEPTH OF THE BASE AND BITUMINOUS OR CONCRETE PAVEMENT. DEPTH OF SUBCUT, AS RECOMMENDED BY SOILS ENGINEER, VARIES FROM 3' TO 4.5' BELOW TOP OF SUBGRADE.

Figure 17. Subgrade correction or treatment (Minn.).

moisture. Optimum moisture and maximum density are determined by AASHO Designation T 99. North Dakota specifies that embankments are to be constructed in layers not to exceed 12 in. and must contain not less than 75 percent of optimum moisture when being compacted. Compaction of embankment material to a density of not less than 95 percent of maximum density is required for the upper foot and to not less than 90 percent below the upper foot. Optimum moisture and maximum density is determined by AASHO Designation T 180. South Dakota requires compaction of fill material to 95 percent of maximum density with moisture controlled to within 2 percentage points below and above optimum moisture as determined by AASHO Designation T 99. Iowa requires compaction of the lowest lift of fill to 90 percent of maximum density (AASHO T 99) and to 95 percent for subsequent lifts. The control of moisture is also specified. Minnesota requires embankment materials to be compacted in layers not to exceed 6 in. at moisture contents between 65 and 102 percent of optimum moisture for the upper 3 ft and at not more than 115 percent for material below the upper 3 ft. The lower limit of 65 percent does not apply to granular materials, and the upper limit of 102 percent may be increased slightly for "fat" clay. In areas where pavement warp is prevalent, the moisture in the upper 12 in. of clayey subgrades is limited for 80 to 100 percent of optimum. Compaction of embankment materials to a density of not less than 100 percent of maximum density is specified for the upper 3 ft and to not less than 95 percent below that. Optimum moisture and maximum density are determined by AASHO Designation T 99.

In recent years Nebraska used hydrated lime to stabilize the upper 6 in. of the sub-



NOTE: PROVIDE DRAINAGE FOR ALL SUBCUTS DURING CONSTRUCTION. BACKFILLED WITH MATERIAL AS RECOMMENDED BY SOILS ENGINEER. DEPTH OF SUBCUT VARIES FROM 1' TO 2'.

Figure 18. Typical subcut for compaction (Minn.).

grade in weak areas. The addition of 3 to 6 percent has been effective in adding bearing strength to the subgrade, but because of the high cost, it is only used in areas where there is a shortage of granular materials. Hydrated lime, cement, and a combination of hydrated lime and cement have been used in Nebraska to stabilize the upper subgrade on experimental construction projects. The results have been satisfactory, but it is too early for definite conclusions on the permanency of this type of treatment. South Dakota has recently treated some subgrades with lime, but results have not been evaluated.

Bases

Because of strength loss in the subgrade during the spring period, it is the practice to provide adequate thickness of subbase and base to withstand traffic loads during the weak period. No data are available on the added thickness used to compensate for frost effects, but it is believed this is in the order of 30 to 40 percent of the total thickness required on cohesive soil.

Granular materials used for base are generally limited to a maximum of 10 percent of material passing the No. 200 sieve, 35 percent passing the No. 40 sieve, and 65 percent passing the No. 10 sieve. A limiting value of 7 percent rather than 10 percent is considered more appropriate in the portion of the area where freeze-thaw cycles are numerous. Subbase materials are generally limited to a maximum of 10 percent passing the No. 200 sieve. These limiting gradation values are subject to variation in relation to other characteristics of the base aggregate. An excess of soft, deleterious or unsound particles in the aggregate, such as shale, soft limestone and soft limey sandstone, contributes to strength loss. The limiting values in the area vary from a maximum of 7 percent shale in high quality base materials to a maximum of 10 or 15 percent in subbase aggregates and lower quality base aggregates. For both subbase and base, plastic limits are restricted to a maximum of six and liquid limits to a maximum of 25. Iowa specifications permit soil-aggregate subbase and base materials to contain soil fines and soft particles in considerable excess of these limits, but these materials are seldom used. Iowa base courses on primary roads are usually asphalt or bituminous treated to add resistance to frost action. It is becoming common practice in flexible pavement design to provide a granular subbase plus a base composed of granular material stabilized with bituminous material or portland cement to develop added strength and resistance to frost action. They are placed full width of the subgrade. The aggregates used in the base are sand or gravel with gradation deficiencies compensated for by the increase in the amount of stabilizing agent. Bituminous-stabilized bases are used extensively on the high-traffic roads.

Soil-cement bases are used primarily on secondary roads in areas where satisfactory base aggregates are not economically available. Sand materials are generally preferred in place of cohesive soil for cement treatment. Cement factors are determined by the freeze-thaw durability tests and wet-dry durability tests. Density to 98 or 100 percent of maximum density (AASHO T 134) is required.

The following are limiting values for freeze-thaw durability tests on soil-cement mixtures performed in accordance with AASHO Designation T 136-57 (values established by Portland Cement Association):

AASHO Soil Classification	Maximum Allowable Loss (%)
A-1, A-2-4, A-2-5, A-3	14
A-2-6, A-2-7, A-4, A-5	10
A-6, A-7	7

These maximum allowable loss values are the same for the wet-dry durability test, AASHO Designation T 135-57.

Stabilization of aggregate bases by the use of additives other than bituminous material and cement, such as lime, calcium chloride, or sodium chloride, is not standard practice although they have been tried experimentally. Subbase and base for portland cement concrete pavement is not generally predicated on the basis of frost effect.

Minnesota relates flexible pavement quality and thickness to the traffic loads and subgrade soil. The thicknesses have been established on the basis of experience and performance studies. The following are three typical design standards for A-6 soil subgrade and 9-ton axle loads related to heavy commercial average daily traffic count:

150-300 H. C. A. D. T. —Single-Roadway Type

10-in.	sand-gravel subbase	Full width
5-in.	crushed gravel base	Full width
1-in.	road-mixed bituminous base using crushed gravel	26 ft wide
3-in.	hot-mixed bituminous surfacing	24 ft wide

600-1, 100 H. C. A. D. T. —Two-Roadway Type

6-in.	sand-gravel subbase	Full width
6-in.	sand-gravel subbase, high type	Full width
5-in.	high-type crushed gravel base full with or 4 in. of bituminous-treated lower type crushed gravel	28 ft wide
3-in.	hot-mixed bituminous base	26 ft wide
4-in.	asphaltic concrete surface	24 ft wide

Interstate or Over 1,100 H.C.A.D.T.—Two-Roadway Type

8-in. sand-gravel subbase	Full width
6-in. sand-gravel subbase	Full width
4-in. bituminous-treated crushed gravel	28 ft wide
4-in. hot-mixed bituminous base	26 ft wide
4-in. asphaltic concrete surface	24 ft wide

For granular subgrade, the base structure is reduced by 50 percent. For A-4, A-5, A-7-6 and A-7-5 soils, the base structure is increased up to 20 or 30 percent. Compaction to 100 percent of maximum density (AASHO T 99) is required for granular subbase, granular base and bituminous-treated gravel base. The lower limit for the moisture content of granular subbases and bases at the time of compaction is 90 percent of optimum (AASHO T 99), except when vibrating compactors are used and this may be reduced to 75 percent. Hot-mixed bases must be compacted to 90 percent of Marshall density determined when the mixtures are placed on the road.

Nebraska requires soil-aggregate base courses and granular subbases to be compacted to 100 percent and 95 percent, respectively, of maximum density (AASHO T 99). No moisture limits are required. Iowa and South Dakota provide for density control in the compaction of base courses.

Flexible Pavement Surfaces

There is no general practice for the determination of the quality and thickness of bituminous surfaces in relation to frost effects. North Dakota has adopted the criteria and formulas developed by the AASHO Test Road Staff, and Minnesota is studying this approach for application to design. The primary consideration is traffic loading.

Frost effects do have an influence on the design of bituminous surfaces in Minnesota, except that selection of the kind of bituminous mixture used is predicated on traffic volume. Thicknesses were increased an estimated 30 percent because of frost effects on the aggregate base courses.

Rigid Pavements

Frost action is not presently recognized as a design factor in rigid pavement thickness determination. The design of steel reinforcement in pavements is not related to frost action except where reinforced panels are used over culverts where heaving is a possibility.

To control pavement warp in certain areas, Minnesota provides for the compaction of the upper 12 in. of clayey subgrades to 100 percent of maximum density (AASHO Designation T 99) at moisture content between 80 and 100 percent of optimum. Nebraska generally provides granular subbase under rigid pavements to promote even moisture distribution in the subgrade for the control of joint heaving. South Dakota reports the use of thicker subbase to improve riding qualities.

The effectiveness of subbase under rigid pavement and the thickness needed are controversial. It was observed in Minnesota that pavements placed on aggregate base do not become as rough as pavements placed without base. Iowa reports an increased use of subbase under rigid pavements. South Dakota spokesmen indicate that the best riding pavements are those with thicker subbases. They believe the thicker subbases provide better protection against frost uplift. This writer believes that in cohesive soil sections and where frost penetration is deep, the use of good quality and properly consolidated bases of substantial thickness will result in pavements that remain smooth longer, perform better, and last longer than those placed on thin bases.

Bridges and Culverts

The treatment of bridge approaches and culverts is confined to the northern portion of this area. Iowa places wedge-shaped granular backfill adjacent to abutments in bridge approaches, but does not provide placement treatment for culverts. South Dakota intends to study the effects of frost on structures and methods of placement.

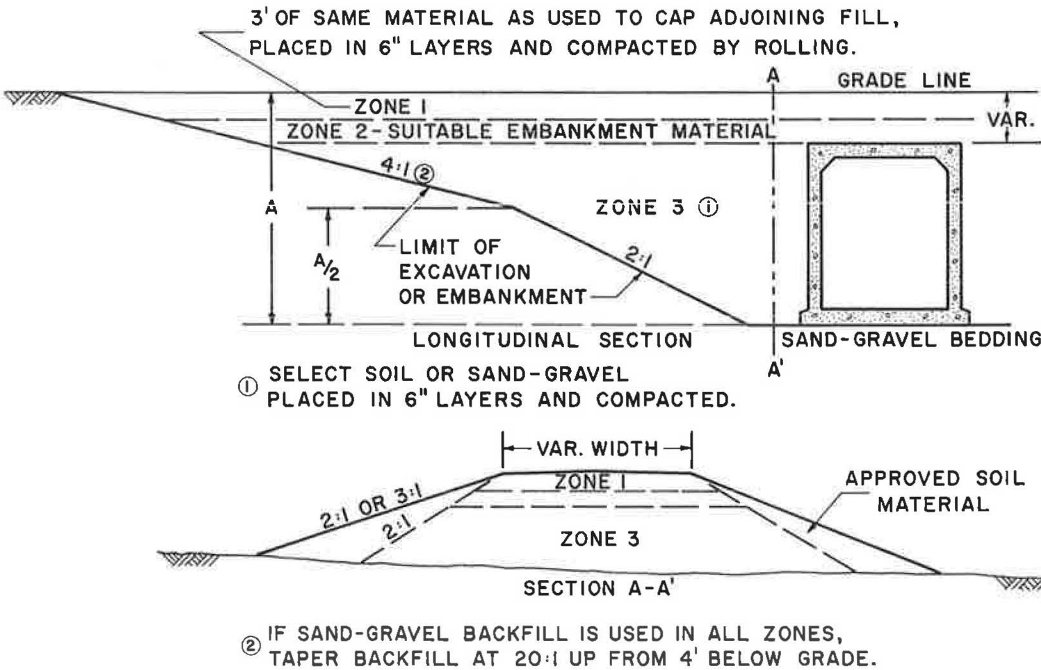


Figure 19. Box culvert approach fill treatment (Minn.).

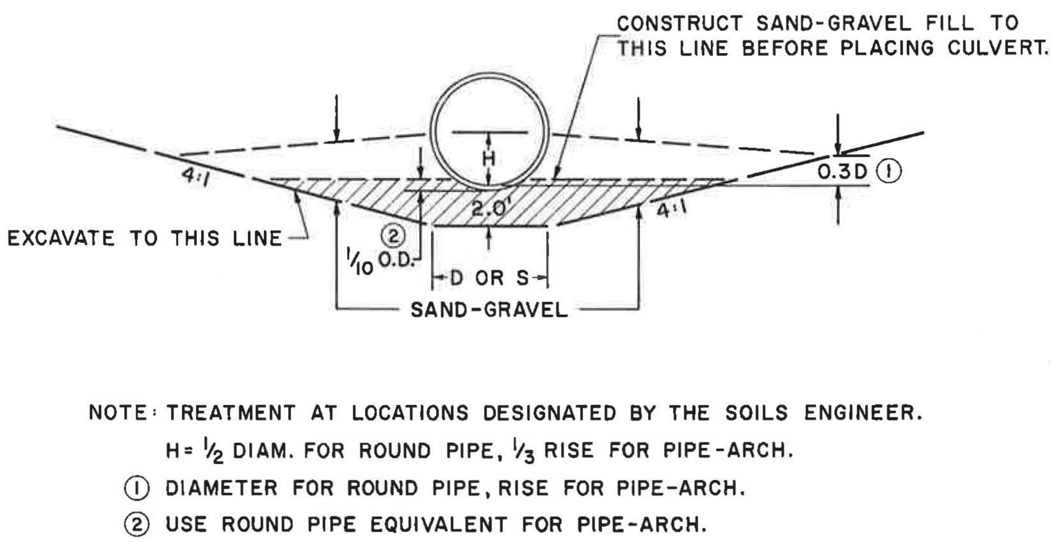


Figure 20. Treatment for centerline culvert in cohesive soils (Minn.).

North Dakota uses pit run gravel, well drained, behind the abutments of overhead structures. The bottoms of abutments are generally placed 4 ft or more below ground, and pier footings 5 to 7 ft below ground. Drainage culverts are bedded in one to several feet of gravel where foundation soils are questionable, but this has not completely solved the heave problem where fills are shallow over the culverts.

In Minnesota, wedge-shaped granular fill is often used adjacent to bridge ends, and the bottoms of pier and abutment footings are placed at sufficient depth below ground to avoid frost complications.

Foundation soils below box culverts are subcut sufficiently to provide space for 1 to 2 ft of granular material below the floor. The approach fills are generally designed with suitable local soil. If only silty soils are available, granular materials are selected for a tapered fill adjacent to the culvert. Figure 19 shows a typical design for box culvert treatment. Minnesota's bedding design for pipe culverts with less than 10 ft of cover provides for excavation to 2 ft below the culvert with 4 to 1 tapers (Fig. 20). Granular backfill is placed up to the center of the culvert. The remainder of the fill consists of suitable grading soil. This is a relatively new practice and is being observed to evaluate its effectiveness. This type of installation is not required where natural soils are sand and gravel.

SUMMARY

There are no significant frost problems in the southern portion of the West Central States other than the deterioration of portland cement concrete which is not discussed herein. Progressing northward, the base courses and subgrade soils become successively involved in frost action resulting in more numerous deep-seated problems. Design and construction practices used in severe frost areas cannot be applied in less severe areas without adjusting to local conditions.

General frost design practices used in states where problems exist have been quite effective in overcoming or minimizing most of the problems. A few are not fully solved and improvements are possible in the area of base design for rigid and flexible pavements, culvert placement, and a number of others. The greatest advances have been made in solving subgrade and base problems through improved design, grading, and base construction procedures.

Future research is suggested as follows:

1. Cheaper and more effective stabilization of subgrade soil.
2. More effective treatment of low-quality aggregate for base courses.
3. Development of chemicals for combination with soils to neutralize frost effects, and more effective methods of injecting them into foundation soils to correst existing problems.
4. Evaluation of the loss of density in base courses and subgrade soil as a result of frost action.

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Discussion

E. B. MCDONALD, Materials Engineer, South Dakota Department of Highways—The following, presented in the order that the various points are given in this report, is written to add to the information presented by Mr. Fredrickson rather than as a critique. Others should have a more complete study made before definite conclusions are made or criteria set up in design.

Topography is quite important, especially in glaciated areas where kettle-holes are found in combination with the A-4 and A-5 soil groups. Serious frost boils have developed in such areas where pockets of these types of soils were not detected on soil surveys and were also passed up on construction.

Recent studies made on several roads built in the past five years bear out the moisture transfer theory associated with freezing and also the loss of subgrade support. A difference as great as 10 percentage points has been found between the soil 18 in. below the subbase as compared to the soil 6 in. under the subbase.

Subgrade problems, as described, are typical of what has happened on many South Dakota roads; namely, differential heaves—some permanent and others reverting to a nearly normal condition in spring and summer. Some permanent roughness remains in all of the affected areas. It is believed that in the expansive soils the alternate freezing and thawing causes the moisture vapors to gradually accumulate in the subgrade soil and over a period of years a permanent uplift develops due to the expansive nature of the soil, even though no free-water ice lenses were formed and the system does not have access to any moisture other than that presented by rainfall. It has been found that many South Dakota roads located in the highly expansive soil areas react like a solid and many transverse and longitudinal cracks develop during the winter. Also, there have been transverse cracks only that were so evenly spaced it appeared they were built into the road.

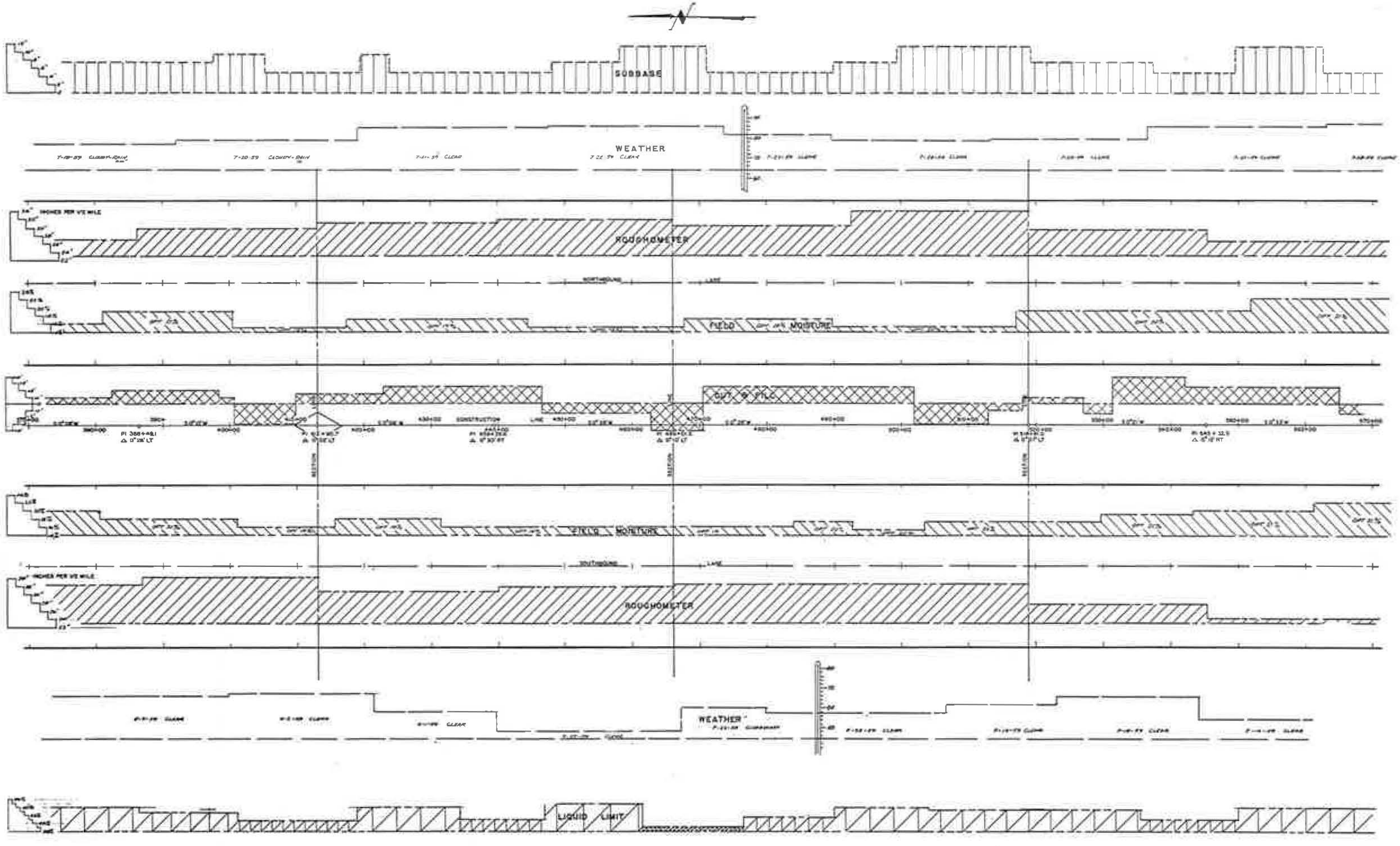
The problems listed in the report as associated with base courses are essentially the same as have been found in South Dakota. It is planned to treat the upper 6 in. of expansive soil with lime and lime-asphalt, and phosphoric acid to see if reflected cracking due to contraction can be prevented and also to reduce the expansion due to moisture accumulation associated with freezing.

The structure and pavement approach fill problems, as submitted, are certainly typical of the South Dakota area. A study of this problem is being made to determine, if possible, the cause or causes of the uplift. It is suspected in some instances, that lack of proper control has resulted in some of the roughness connected with approaches to structures.

High joints have been the object of a rather intensive study made in the past two years. Figures 21 and 22 were made in connection with this study, and also a summary of the conclusions. Study of the figures tends to conclude that where moisture contents were not held at or slightly above optimum, a higher roughometer count was noted.

An extremely rough portion of the pavement project studied does not completely recover in the spring. Some portions are extremely rough. A highly saturated condition exists in the area of subgrade directly below the subbase. The soil has a rather high organic content and is quite plastic resulting in some expansion which has contributed to the permanent rough condition.

Plate bearing tests on 34 projects throughout South Dakota showed a reduction in the bearing capacity of the soil in the spring as compared to the bearing capacity in the fall. These tests were made during the spring and fall of 1961 and 1962. The per-


SUBBASE
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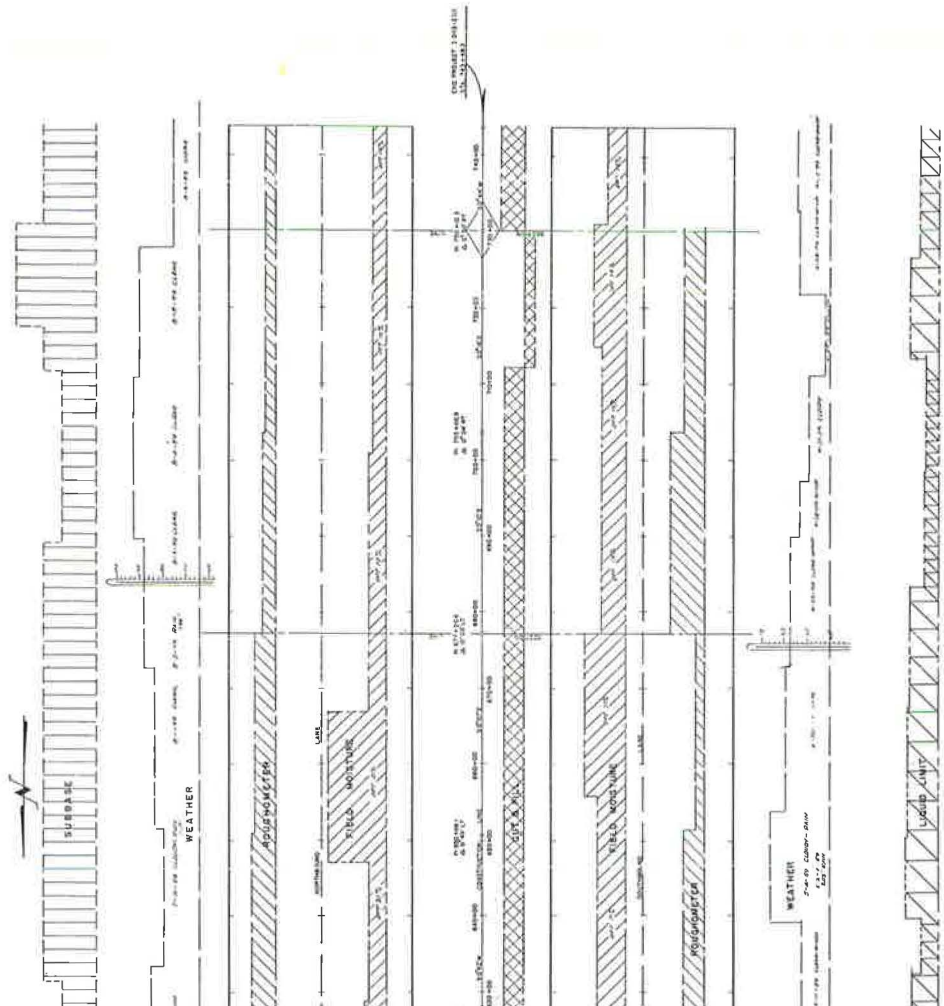
FIELD MOISTURE
CUT & FILL
FIELD MOISTURE
ROUGHOMETER
WEATHER
LIQUID LIMIT

Figure 21.


SUBBASE
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FIELD MOISTURE
CUT & FILL
FIELD MOISTURE
ROUGHOMETER
WEATHER
LIQUID LIMIT

Figure 22.

centage of loss was not as large as noted in Minnesota. The average loss for all projects was only 13 percent. However, some projects did show as much as 43 percent loss. A few showed a higher bearing in the spring than in the fall. This latter finding points up the extreme difficulty in trying to predict exactly what will happen in any given year on the same project.

Benkelman beam tests were run on all of the projects where plate bearing tests were made. Results of the two tests did not correlate very well. A comparison of deflections between the spring and fall readings shows that, on the average, the spring reading is only 6 percent less than in the fall.

Recent studies of subgrade conditions on some of the projects built in South Dakota in the past five years indicate that if moisture is held closer to the optimum less roughness will develop due to frost. This appears to be especially true in subgrades that contain higher liquid limit soils (Figs. 21 and 22). More study is needed to determine just how closely the moisture content should be controlled on construction.

South Dakota has one Interstate project in which the upper 6 in. of subgrade has been treated with 3 percent lime to reduce the P.I. This project is the next project south of the one that has shown much warping and roughness. To date, the lime-treated project has not shown any roughness or warping, even though it is located in the same area of subgrade soil, terrain and moisture conditions that exist on the rough project. This is the second winter for the lime-treated project which is being closely watched to see if any roughness develops.

One Interstate project in the highly expansive soil area has a 4-in. bituminous-treated base course along with a standard 4-in. base and 4-in. mat. It is now in its third year and seems to be standing up quite well. It does not appear that the quality or thickness of the wearing surface or base in flexible pavements would be a factor in design criteria, insofar as frost action is concerned. The overall total thickness of frost-free material is believed to be the most important factor. Total thickness in South Dakota is usually two-thirds of the expected frost penetration.

Although there is presently no design factor in rigid pavement thickness determination, South Dakota experience indicates that a thicker subbase generally provides a better riding surface. It appears that this is an area where more research should be made to determine to what degree roughness could be reduced in pavement.

The design of beddings under culverts and approaches to bridges, as described in the report, appears to be the proper approach to the problem of uplift and heaving at the structures. As mentioned previously, it appears that possible lack of control in placement of these items on construction may be a factor. Indications are that this may be true because on some projects several of the culverts and approaches will be very smooth while others placed in the same soil will be rough.

There is no doubt that all the roughness is not due to frost. It is true that compaction on berms is rather difficult to achieve on the slope and possibly some special equipment could be developed for this purpose. Also, it is rather difficult to eliminate all of the internal differential settlement, especially in the higher fills.

Figures 21 and 22 were developed in an analysis of the causes of rough joints. Several factors, along with the roughness index have been placed on an abbreviated profile, in graph form, to see if there was any definite correlation that might determine the causes of rough joints.

It should be pointed out that the roughness index is general in that there may be areas within the sections marked rough that were fairly good. This is indicated by some of the tests that seem to contradict the average or general trend in these sections. To have made a more accurate study of what actually happened it would have been necessary to set up special instrumented test sections so that a before and after record could have been made for comparison.

Test data indicate that several factors were involved in causing the joint roughness.

1. Natural inherent curl in the concrete due to temperature and moisture differential;
2. Low grade heights, especially in the areas of high water table;
3. High-plasticity soil combined with moisture differential; and
4. Frost action.

The fact that water moved back into the test hole after being channeled out to the edge of the pavement indicates that the top of the subbase material was not in contact with the bottom of the slab.

Figures 21 and 22 as plotted on the abbreviated plan, seem to indicate that generally where the grade line is in shallow cut or on a shallow fill, the roughness index increases. This appears to be especially true in the low, poorly drained areas.

The graph depicting the field moistures, as measured at the time of construction, tends to indicate that when the moistures were from 2 to 4 percent below optimum the roughness index increases. The fact that moistures are presently over 2 percent above optimum at these same depths would indicate that the additional moisture which has collected would cause expansion in the high-plasticity soils.

There is no doubt that frost action caused some of the roughness. Heaves were visible in a few short areas and were responsible to a certain degree in other areas. The recovery of the joints to a relatively smooth condition, early this spring, would indicate that the frost had contributed to the rough condition.

In conclusion, it would appear that the following changes in design and construction methods would tend to reduce roughness.

1. Construct shorter slab lengths. Several sections of concrete should be laid down with the joints constructed in the manner adopted by New York State. This type of joint provides for a channel of specified width and depth, usually $^3/_4$ in. wide and $^1/_2$ in. to $^3/_4$ in. deep, to be cut through just above the normal sawed joint. This channel, when filled with sealing compound, allows the compound to move with the slab and prevents separation between the compound and the slab.

2. It does not appear that the earth subgrade should be less than 2.0 to 2.5 ft above the original ground line on any portion of a project. All grades should be built to this minimum even if it is necessary to bring in borrow material from outside the right-of-way.

3. Indications are that the moisture contents of the soil should be held to a closer tolerance, than is now allowed, for optimum moisture control. It appears that it would be better to hold the moisture slightly above optimum.

4. Sufficient time has not elapsed since stabilizing additives have been added to the subgrade soils on some South Dakota projects. Preliminary tests indicate that the waterproofing will retard the action of frost in the material directly below the slab. On the basis of these tests it may be desirable to include some type of stabilization in the soils prior to placing the subbase. It may also be desirable to treat the subbase material to reduce the plasticity index.

Observations and studies will be made of all of the projects built between Sioux City and Sioux Falls in order to determine if the changes, that have been made, have corrected the rough joints to any appreciable degree.

In conclusion, Mr. Fredrickson has covered the subject of frost problems as related to design very well. Many of the problems associated with frost action have been eliminated or at least reduced to a point where the ridability of present roads is quite good.

Economy seems to be a big factor in eliminating completely the effects of frost. Most of the personnel connected with surfacing design are familiar with methods of design which could almost completely eliminate all frost problems throughout an entire project. However, on some projects where frost-susceptible soil is practically the only soil available and the water table and terrain are such that sufficient grade height is difficult to maintain, the cost of design to eliminate all effects of frost is prohibitive.