Design, Construction, Maintenance, and Performance of Qinghai-Tibet Plateau Highway

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Qinghai-Tibet highway, the highway with the highest elevation in the world, was originally built in the 1950s without detailed design. It is about 860 km in length and goes through the center part of the Qinghai-Tibet Plateau with an average elevation of 4100 m. A number of permafrost engineering problems have been experienced since an asphalt surface layer was placed over the entire highway during the mid-1970s. Typical pavement damage and distress included large amounts of thaw settlement of embankments, unequal deformations of pavement structures, low-temperature cracks, and frost heaving. The traffic operation on this highway has been seriously affected by this pavement damage and distress. Based on 3 years of field observations and experimental tests of behavior, this paper emphasizes the proper design and construction of embankment and pavement with asphalt surface in permafrost regions of the Qinghai-Tibet Plateau. The minimum height of the pavement structure required for each pavement condition in permafrost areas is discussed. It involves study of the changeable patterns in the upper boundary of the permafrost table under different pavement structures, estimation of thaw settlement due to the construction of the asphalt pavement, and the seasonal change of structural capacity of the pavement. The minimum thickness of a pavement structure in permafrost regions of the Qinghai-Tibet Plateau is dictated by the type of pavement surface, condition of frozen soil above the permafrost table, annual air temperature, fill materials, and the criteria required for pavement performance. Pavement strength during a thaw can be determined by using the Benkelman beam deflection test. Tests show that the reduction in pavement strength during the thawing season is about 40 to 75 percent of the value during the freezing season. Finally, a practical evaluation procedure for pavement design and maintenance in permafrost regions of Qinghai-Tibet Plateau is presented.

Permafrost is present in approximately 2.14 million km^2 of China, which is over 22 percent of the total area of the country. In the extensive area of the Qinghai-Tibet Plateau, the so-called Roof of the World, there are large areas of continuous permafrost between the Himalayan and Kunlun mountains. The Qinghai-Tibet Plateau has the highest altitude, largest area, greatest thickness, and the lowest temperature among all the low-latitude continuous permafrost areas of the world. Its area is about 1.49 million km^2 and represents nearly 70 percent of the total area underlain by permafrost in China. Figure 1 shows the distribution of different types of permafrost and their areas in China. It also indicates the geographic location of the Qinghai-Tibet highway. Each type of permafrost is further classified into the following categories: continuous, discontinuous, isolated and alpine permafrost, as well as seasonally frozen ground (shown as the lightly shaded area).

Qinghai-Tibet highway, which is 860 km long, is one part of China's National Highway 209. It is a two-lane

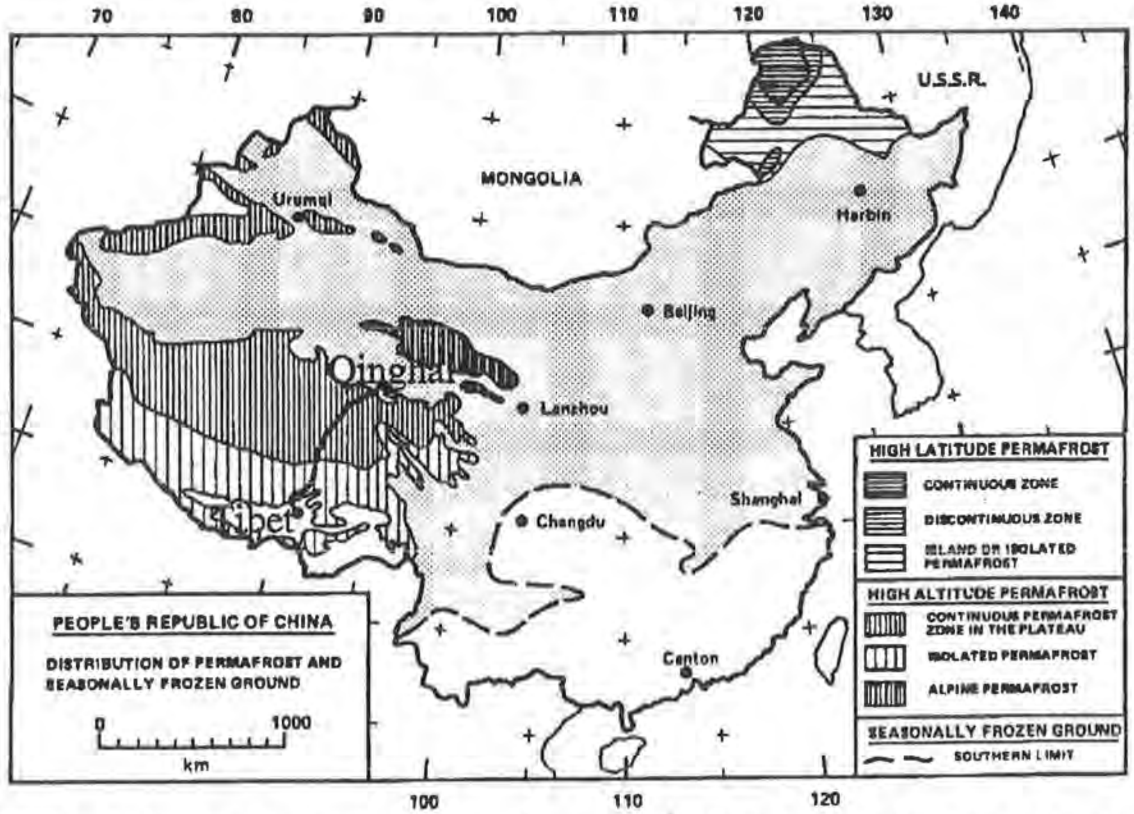

FIGURE 1 Outline map showing Qinghai-Tibet highway and distribution of permafrost type and area in China.

road with pavement widths of 9.5 to 12 m and is classified as a low-traffic-volume road with no more than 1,000 vehicles per day. The average elevation along the highway is approximately 4120 m. Certain sections have elevations of more than 5000 m, where the percentage of oxygen in the air needed for human activities is seriously deficient.

The large areas of perennially frozen ground at mid-latitude on the Qinghai-Tibet Plateau exist because the general altitude is 4000 m or more above sea level. Another major reason is that the frozen period of the ground surface in most regions of the plateau is as long as 7 to 8 months (*1,2*) Even in the warm season (from May to September), the ground surface freezes at night. For instance, in the area of the Kunlun Mountains, where the elevation is approximately 4700 m, during the warmest month of July, the highest temperature in the day is 17.6°C, while the lowest temperature at night is −8°C. Table 1 gives information on the climate in some of the permafrost regions of the Qinghai-Tibet Plateau, in which the permafrost table and thickness were investigated during the 1970s by Lanzhou Research Institute of Glaciology and Cryopedology of China (*3*) and the temperature was recorded by the Highway Bureau of Qinghai and the local meteorological bureau over a period of 20 years.

In the extensive permafrost areas of the Qinghai-Tibet Plateau, there exists a depth below the ground surface where the highest value of the ground temperature is zero. The ground above that depth thaws in the summer and freezes in the winter; hence, it is usually referred to as the "active layer." The ground below that depth is perennially frozen. The depth is then the thickness of the seasonally thawed layer, or the depth of the upper limit of the perennially frozen ground. The distance between the upper and lower limits of the perennially frozen ground is its thickness as shown in Table 1.

The highway was originally surveyed and built in the 1950s without detailed design to meet the urgent transportation need. There was very little research into the cost of permafrost engineering problems in the construction of the highway. In 1973 an asphalt surface layer was initiated; it took about 7 years to complete the resurfacing of the entire highway. However, some serious pavement damage or distress occurred immediately after the construction in the early 1980s. These problems included large amounts of thaw settlement of

TABLE 1 Principal Climate Factors in Some Regions of Qinghai-Tibet Plateau

Location of Permafrost	Elevation of Permafrost (m)	Thickness of Permafrost (m)	Depth of Active Layer (m)	Average annual air temperature (°C)	Average annual ground surface temperature (°C)
Tanggula Mt.	4950	164	1.2	-5.2	-2.1
Fenghuo Mt.	4700	120	1.1	-4.9	-3.7
Kunlun Mt.	4780	175	0.95	-5.7	-4.0
Qilian Mt.	4500	65	1.41	-5.5	-1.5
Bayan Shan	4430	78	1.61	-4.8	-2.7

embankments, unequal deformation of pavement surfaces, different types of cracks, and frost heaving, resulting in normal traffic operation being seriously affected. Consequently, a large-scale rehabilitation was required in the middle 1980s, which included raising the heights of embankments, clearing drainage systems, and resurfacing the pavement with asphalt concrete, which took about 3.5 years. Even with the rehabilitation, many permafrost engineering problems need to be resolved due to the original improper design and construction. These pavement maintenance problems from inadequate design and construction have been described (*4*).

To understand the factors that lead to the severe distress noted, a number of field experiments in four permafrost regions of the Qinghai-Tibet Plateau along the highway have been conducted since 1987 by the Highway Bureau of Qinghai. The purpose of these tests and observations was to determine the minimum height of a pavement structure under a specific condition in the permafrost regions of the plateau, including an analysis of factors that influence thaw settlement of the embankment, estimation of thaw settlement in quantitative terms, seasonal change of structural capacity during thawing and freezing cycles, and special evaluation of the pavement structure in the Qinghai-Tibet Plateau. Detailed discussions of these items is provided in the following sections.

Basic Considerations for Road Design and Construction

Climate Features

A preliminary investigation of geology and climate along the highway in the Qinghai-Tibet Plateau was conducted by the Highway Bureau of Qinghai and Lanzhou Institute of Glaciology and Cryopedology of China during the 1970s. The results of this investigation are shown in Tables 1 and 2. It has been found that most of the perennially frozen ground occurring along the Qinghai-Tibet highway is relatively stable (*2*). Therefore, any construction projects planned for this area should be based on the principle of preserving the permafrost, not increasing or even reducing the depth of the active layer. In addition, every effort should be made to leave the natural vegetation cover undisturbed (*5*). Except for the south area of the highway, the distinguishing features in these regions are (a) an annual evaporation three to five times greater than annual precipitation, meaning it is a very dry area; (b) a mean annual air temperature of less than −5.0°C; and (c) a high altitude with an average elevation of over 4500 m above sea level. Both the altitude and thickness of permafrost in the plateau obviously increase with a decrease in latitude (as the region approaches the highway mountains). Also at the same altitude, with each degree of decrease in latitude to the south, the average ground temperature was observed to increase by 0.7°C to 0.9°C.

There are essentially three types of soil in most permafrost regions of the Qinghai-Tibet Plateau: gravelly soil, sandy soil, and silty soil. Although the ground soil is basically sandy and gravelly in the Fenghuo Mountains and Tanggula region, clayey soil is extensively distributed in the Kunlun Mountains and Qilian region. The data obtained in these regions indicated that the gravelly soil in dry sections along the highway collects no water, consequently there is no serious frost heaving in the Fenghuo Mountain region, but thaw settlement is still a major problem in all regions of the plateau. Clayey soil, on the other hand, accumulates additional

TABLE 2 Thickness of Permafrost in Some Regions of Qinghai-Tibet Plateau

Location or Region	Latitude	Mean Annual Air Temp.(°C)	Annual Precipitation (mm)	Annual Evaporation (mm)	Period of Test
Liandao He	31°52'	-1.1	892.5	1626.2	1986-89
Tanggula Shan	32°51'	-5.4	476.1	1897.2	1975-82
Fenghuo Shan	32°45'	-5.1	324.7	1427.9	1978-82
Kunlun Shan	35°29'	-6.2	434.7	1600.1	1982-87
Qilian Shan	38°17'	-5.3	644.5	1626.8	1984-89
Jiang Cang	38°21'	-3.1	619	1624.2	1984-89

water when it is in a frozen state, hence frost heaving will always occur in the cold season due to volume expansion.

Distribution of Temperature Under Soil

Since asphalt pavement absorbs more solar radiation than gravel road surfaces, the ground soil under a newly paved asphalt highway will thaw earlier and freeze later than it had before the asphalt surfacing. The upper boundary of the permafrost will decline downward by depths ranging from about 120 to 750 mm, depending upon the thickness of asphalt surface, the number of years it has been paved, the annual air temperature above the ground soil, the height and orientation of embankment, and the embankment materials. The increased depth of the active layer will, in turn, result in a greater thaw settlement of the pavement structure.

Figure 2 shows the seasonal changes in thawing and freezing depths of the ground soil in the Qinghai-Tibet Plateau. The field tests were done in the Fenghuo Mountain region on two different pavement sections. One section was paved with a 40-mm thickness of asphalt, while the other section was a gravel surface. Both had the same total thickness of 520 mm. The test sections were instrumented with thermocouples and resistivity gauges to determine the location of the 0°C isotherm and the location of the freezing or thawing front, respectively. Data were collected during the 3-year period from 1988 to 1991. The results indicate that there is a general pattern of temperature distribution in ground soil under different pavement conditions in the permafrost area of the plateau. It should be noted that the thawed depth varies with the thickness of pavement structure, especially the thickness of the asphalt concrete surface; annual temperature; climate; and type of subgrade soil under the surface. The following facts can be deduced from Figure 2.

1. Ground soil with an asphalt surface could result in a maximum of about 1 month of thawing with a delay of 20 to 30 days for freezing, depending on the thickness of the asphalt concrete surface, the annual aboveground temperature, and the age of the asphalt surface. Generally, in the initial 2 years, this phenomenon is more marked; in subsequent years, the difference becomes gradually smaller. When a new asphalt surface is applied as a routine maintenance, this phenomenon again emerges.

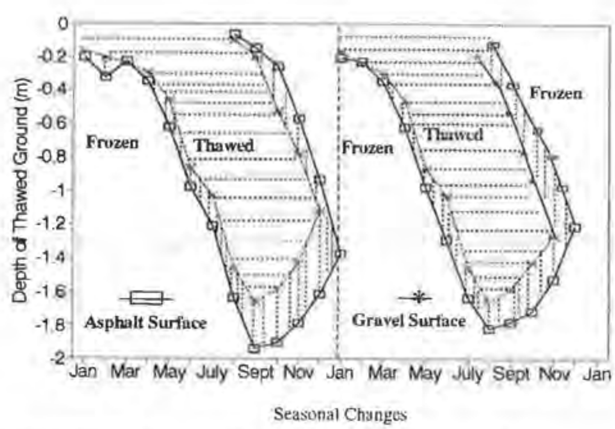

FIGURE 2 Seasonal changes in freezing and thawing depth of frozen ground soils underlying asphalt surface and gravel surface in Fenghuo Mountain region.

2. The maximum thaw depth caused by the asphalt surface is about 200 to 700 mm deeper than that of the gravel surface, depending on the thickness of asphalt surface, the width of pavement, annual air temperature, orientation of the embankment, and content of water or ice in the newly thawed soils. The maximum thawing depth of the ground with asphalt surface will decrease with age, while the maximum thawing depth of the ground with gravel surface will not significantly change with age provided the mean annual air temperature remains approximately the same each year.

3. The frozen time can also be delayed 15 to 30 days by the asphalt surface. The completion of the freezing is normally in mid-December under the gravel surface, while it can be shifted to mid-January under the asphalt surface.

4. In late August or early September of each year, the ground soil starts to freeze from both the upper side, where the air temperature is below freezing, and the lower side, where it is close to the frozen upper boundary of the permafrost table. The entire ground soil freezing process will be completed in December or January of the following year.

In addition, the relationship between thaw depth and ground temperature for three different pavement conditions has been observed in the same permafrost area. The tests were performed in May and August, in which the average air temperature is the lowest and highest, respectively. The test results are shown in Figure 3. It is obvious that the thaw depth increases when an embankment is constructed. The tests also indicate that thaw depth under an embankment with an asphalt surface will increase much more than that of an embankment with gravel, although the total heights of the embankments are approximately equal. In this field experiment, the total increased depth by the embankment with asphalt surface is about 850 mm in the first year and 700 mm in the second year, compared with the natural ground (no embankment).

Thaw Settlement and Shift of Permafrost Table

The main problem in this area was to maintain the stability of the roadbed through the permafrost zone. Over 200 km of the highway crosses an area containing significant amounts of ground ice. A key question was how to keep the paved highway from being damaged when the ground ice melts. Other important issues included protecting the highway from frost heaves and frost boils and accurately determining the optimum embankment elevation because over 90 percent of the damage occurring to the old Qinghai-Tibet road was caused by insufficient embankment elevation and poor drainage.

Generally thaw settlement is the differential downward movement of the ground surface resulting from the melting of excess ice in the soil and the thaw consolidation of the soil mass under its own weight and external loadings. A one-dimensional finite element model was developed to estimate thaw depths and subsequent settlement of an embankment in a permafrost terrain (6). In permafrost regions, the main cause of damage to highways is thaw settlement, which can be classified as sudden or gradual in terms of duration and process.

Sudden Thaw Settlement

Sudden thaw settlement occurs when roads are built in a region where the upper portion of the permafrost gen-

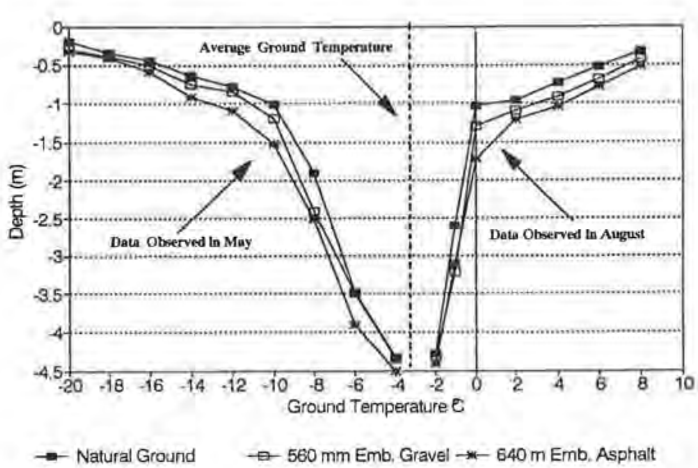

FIGURE 3 Comparison of temperature in ground soils under different heights of embankment.

erally contains a thick clayey, ice-rich soil. When the ice melts, the soil reaches a supersaturated state, and the pavement structure may lose almost its entire bearing capacity. The result is a large amount of subsidence under external loads and its own weight. In addition, when the depth of thaw is unequal on both sides of the embankment, a slanting, frozen slip plane is formed beneath the subgrade. Under these conditions, the vibrations and loads of passing traffic may force the supersaturated clayey soil to be squeezed out along the frozen slip plane so that a sudden slump will occur in an embankment that had been gradually subsiding during a warm period. Sudden settlement can cause drivers to lose control of their vehicles.

Gradual Thaw Settlement

Gradual thaw settlement follows sudden thaw settlement. Gradual settlement is dictated by the density of the frozen soil, height of the embankment, fill materials, loading, and traffic. In addition, when water infiltrates the road embankment and accumulates on top of the permafrost table during the rainy season, ground ice in this area will thaw slowly but steadily; this, in turn, can cause the pavement to gradually subside. Subsidence of a pavement surface from this type of thaw settlement makes road maintenance work very difficult and costly. For example, thaw settlement of an embankment of 1.15 m in height has been observed in the Kunlun Mountain region. Records of accumulated thaw settlement showed that the process of gradual thaw settlement of an embankment has continued for 12 years since the construction of the road, although at a declining rate.

A general movement of thaw depth or shift of the permafrost table after construction of the embankment and then the asphalt surface layer is illustrated in Figure 4. When the embankments constructed above the natural ground are greater than a minimum (critical height) thickness, the permafrost table will rise, by certain amounts, depending on the height of embankment. Figure 4 is representative only when the height of the embankment is greater than a minimum height required in a specific permafrost region. If the height of an embankment is less than the minimum value, the level of Boundary Line 3 (upper boundary after paving with asphalt surface) could be below Boundary Line 1 (depth of permafrost table under natural conditions), which means the upper portion of the permafrost table will melt in the warm season. Some field observations of change in permafrost table were conducted in the Fenghuo Mountain region for a period of 3 years. Table 3 contains the observed data. The value of the raised upper boundary after construction of the embankment is directly propotional to the height of the embankment (see Figure 4), and the amount of the reduced thaw depth is the difference between Boundary Line 2, which is raised due to construction of the embankment, and Boundary Line 3, which has moved down because of paving with an asphalt surface.

Since the prediction of thaw settlement is considered a critical element in pavement structure design and the thickness calculation of each layer, some empirical equations for estimating the thaw settlement of a pavement structure in each specific permafrost region of the Qinghai-Tibet Plateau have been developed by means of regression analysis. It is beyond the scope of this paper to describe the detailed procedures and equations of the regression analysis. Figure 5 shows the observed thaw settlements for a period of 3 years on three different thickness of pavement structure in the Fenghuo Mountain region. It illustrates that the thaw settlement could be controlled if the height of embankment is adequate and the quality of fill materials is good.

Frost Heaving of Pavement

Frost action is a complex physical and chemical process. The physical component is the dominant one and includes the transmittal of heat, the phase change of water, water migration, and various mechanical processes under certain conditions of loading, temperature, and moisture.

The mechanics of the frost heaving phenomenon include (a) frost-susceptible soil, (b) slowly depressed air temperature, and (c) water supply. The amount of frost heave is defined as the increment in the vertical direction. Increase of the ice volume is a necessary condition for producing frost heave (7). If water from an external source is supplied to the subgrade, there will be a conspicuous increase in the water content of all the soil comprising the subgrade and subbase. When water contained in the subgrade soil freezes, it expands in volume. The expansive force generated by the freezing of the subgrade soil will push the pavement surface upward

According to observations in some permafrost regions of the Qinghai-Tibet Plateau, frost heaving of the highway subgrade usually occurs when the embankment is low and built on grassy, water-logged marshland. These types of soils are generally sandy or clayey and frequently have a high moisture content. When this moisture freezes, pavements are very easily elevated to different heights, disrupting highway traffic. Consequently, the problem of frost heave in permafrost areas can be reduced to a great extent by preventing external water from entering the pavement structure.

Table 4 contains data for the maximum frost heave of the pavement surface under different conditions along the Qinghai-Tibet highway in the Tanggula and

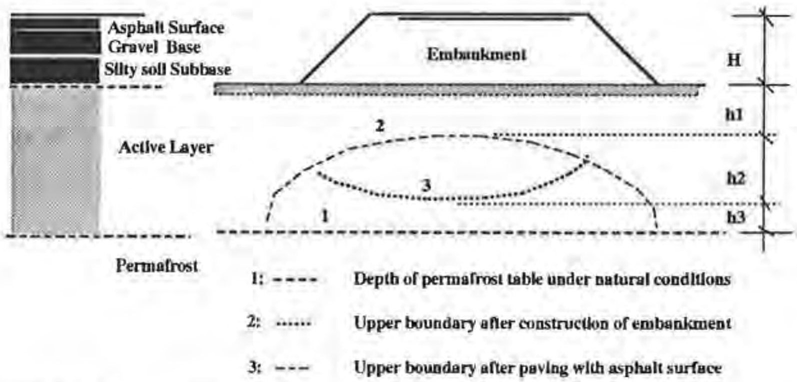

FIGURE 4 General movement of permafrost table after highway construction in Fenghuo Mountain region of plateau.

TABLE 3 Maximum Frost Heave Observed in Roads Under Different Conditions of Frozen Soil and Water Supply

Observed Experimental Section No.	Depth Under Natural Condition H_1 (cm)	Height of Embankment (cm)	Depth Predicted After Road Construction (Estimated by Empirical Formulas), H_2 (cm)	Depth Observed After Paving Asphalt Surface, H_3 (cm)	Decline of Upper Boundary of Permafrost (cm)
T100+1F.Shan	2.23	84	56	22	32
T100+2F.Shan	2.56	75	42	19	23
T100+3F.Shan	1.86	115	78	57	21
T100+4F.Shan	1.34	120	84	62	22
T100+5F.Shan	3.10	64	32	-7	39
T100+6F.Shan	3.58	52	28	-10	38

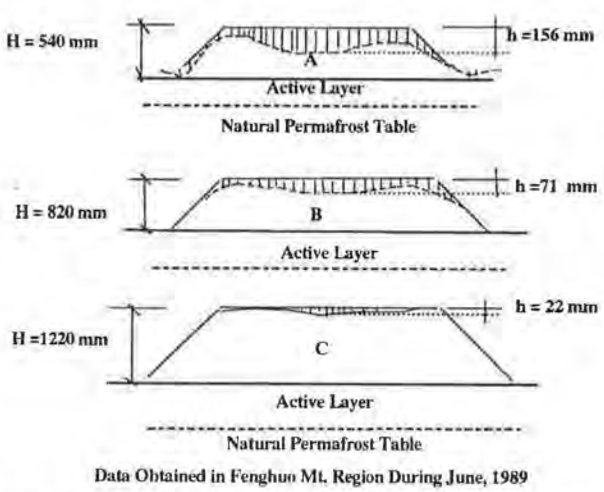

FIGURE 5 Deflection measurements by Benkelman beam through a year in Fenghuo Mountain region of the Qinghai-Tibet highway.

Fenghuo Mountain regions. The amount of ground heaving is clearly related to the level of the water accumulating beside the road or to the level of the groundwater table before freezing. Both of the two largest frost heaves obtained from the observation took place in the areas where the extra water can be supplied from the pool along the roadside.

Pavement Evaluation in Permafrost Areas

Deflection Measurements

Benkelman beam deflection measurements were conducted in the Fenghuo Mountain region for a period of 3 years (1989–1992). As shown in Figure 6, the result of the deflection measurement indicated that the reduction in bearing capacity was strongly dependent on the

TABLE 4 Change of Upper Boundary of Permafrost in Fenghuo Mountain after Asphalt Road Construction

Observed Regions of Road section	Pavement Structure and Thickness of Each Layer	Condition of Frozen soil above Permafrost Table	Height of Road Surface Above the Level of Pool Water Along the roadside (m)	Difference Between Road Surface and Ground Water Before Freeze-up (m)	Maximum Frost heave observed within 3 years (mm)
Test #1 (Fenghuo Mt.)	38 mm asphalt 220 mm gravel base 280 mm sandy soil	Ice-rich frozen soil	0.35	0.86	131
Test #2 (Fenghuo Mt.)	47 mm asphalt 300 mm stabilized gravel 380 mm sandy soil	Ice-saturated frozen soil	0.53	0.92	74
Test 3# (Fenghuo Mt.)	47 mm asphalt 350 mm binder and gravel 450 mm sandy soil	Ice-saturated frozen soil	1.25	1.04	42
Test #1 (Tanggula Mt.)	52 mm asphalt 150 mm gravel 35 mm old asphalt 350 mm binder and gravel 450 mm clayey soil	Ice layer with soil inclusions	0.65	1.10	55
Test #2 (Tanggula Mt.)	40 mm asphalt 250 mm gravel 35 mm old asphalt 300 mm stabilized soil 380 mm clayey soil	Silty soil with vegetation cover removed Ice layer with soil inclusions	0.85	0.75	97
Test #3 (Tanggula Mt.)	40 mm asphalt 300 mm binder and gravel 450 mm clayey soil	Ice-saturated frozen soil	0.46	0.87	145

thickness of pavement structure if other conditions were equal. The lowest strength of pavement structure took place in June or July when full thaw had occurred. For example, the pavement section on clay subgrade (55 cm in height) had a maximum deflection in June almost four times larger than that measured in January. For the other two conditions, the values of the maximum deflection are two to three times greater than that tested in January or February, when the pavement strength is highest. Additional work is required to determine the correlation between the freezing index and thaw depth.

Minimum Height of Pavement Structure

The minimum height of pavement structure in a permafrost area should be sufficient to prevent the natural permafrost table from declining. If ice-rich frozen soil is considered the basic condition of the ground soil, a certain amount of height should be added or reduced if the frozen soil is classified as having a higher or lower water content. For example, the minimum thickness of pavement structure constructed on three different frozen soils in the Fenghuo Mountain region of the Qinghai-Tibet highway is shown in Figure 7. Observations from experimental sections in the Fenghuo Mountains, Wudaoliang, and Tanggula Mountains showed that the upper limit of the permafrost underlying the newly paved asphalt roads fell to a level that was 450 to 750 mm lower than the upper limit of permafrost lying beneath nearby roads with a gravel surface.

"More filling and less excavating" is the principle derived from extensive design and construction experience in the permafrost area of Qinghai-Tibet Plateau. When the climate is sufficiently cold, the thaw period is short, and hence the depth of annual thaw is shallow. In the permafrost area of the Qinghai-Tibet Plateau, the annual average air temperature is −6.7°C; therefore, complete protection against the detrimental effects of frost action—especially of permafrost degradation—can be achieved by using nonfrost-susceptible materials for fill to a proper height.

The natural upper boundary of the underlying permafrost may change after road construction because the thermal equilibrium of the original frozen ground might be disturbed. To ensure that the upper boundary of the permafrost does not change after an asphalt surface has been applied, the road embankment should be elevated to a height 0.7 m higher than that of the old road.

Since ground ice is a major component of frozen soils in the plateau area, it has tremendous influence on the

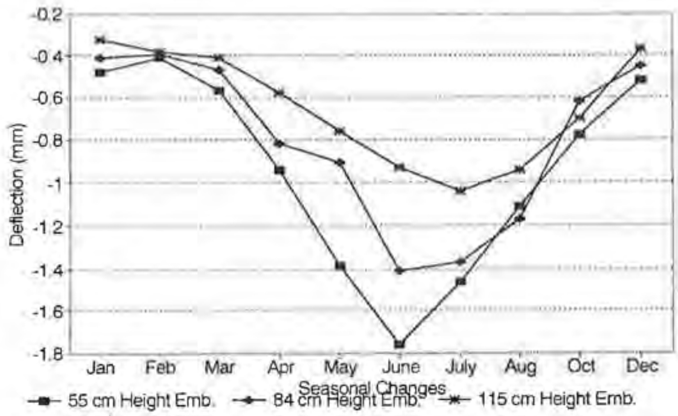

FIGURE 6 Measured thaw settlements of pavement structure under different conditions in south permafrost areas of Qinghai-Tibet Plateau.

stability of the pavement structural capacity during seasonal thawing and freezing. The water migration and the different types of segregation ice during the freezing period were observed in 35 boreholes and 27 test pits. In these regions, three types of segregation ice in terms of structure were found through a microscopic analysis: granular segregation ice, cementation ice, and laminar segregation ice. The ice content of segregation varies with different types of ground soils and geographic location.

Experiments conducted in the Fenghuo and Tanggula Mountains indicate that thaw settlement resulting from an asphalt pavement surface may be prevented by raising the embankment. However, other problems will appear if the embankment is too high, such as compaction, stability, safety, construction, and so on. In other words, both the minimum height and maximum height of an embankment in a permafrost area must be considered.

Proposed Model for Pavement Evaluation in Permafrost

A performance evaluation of a pavement structure in the permafrost areas of the Qinghai-Tibet highway includes not only criteria on riding comfort, structural capacity, skid resistance, and so on but also thaw settle-

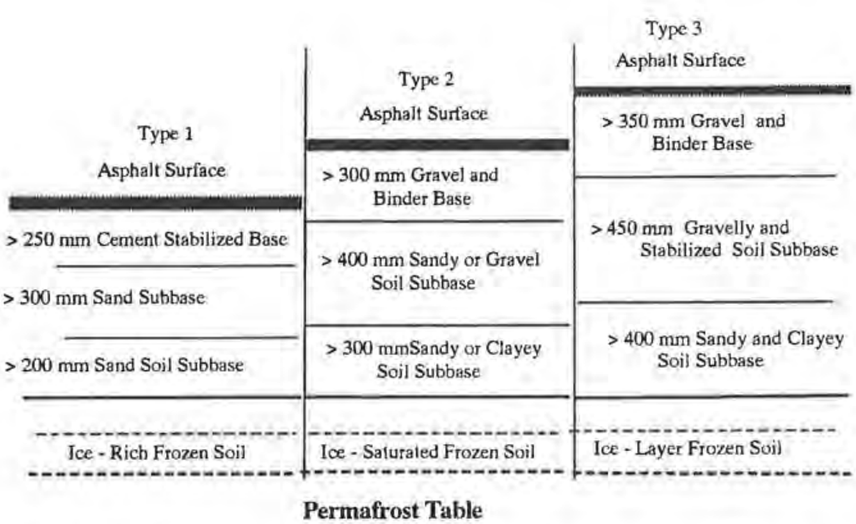

FIGURE 7 Recommended height of embankment under three different ground soils in permafrost regions of Qinghai-Tibet Plateau.

ment and frost heave criteria. Like roads built in many other permafrost areas of the world, pavement roughness caused by the uneven settlements due to thawing is the major problem in the Qinghai-Tibet Plateau. The highway design and construction in continuous permafrost areas should be predicated on the principle of soil in its frozen state needing to be preserved.

Figure 8 is a schematic diagram of the proposed model for evaluating pavement structure in the permafrost areas of the Qinghai-Tibet Plateau. The key components and considerations for pavement design are described by three sets of criteria: permafrost criteria, distress criteria, and performance criteria. Under each set, there are four levels of assessment on the structure design. For example, under the permafrost block criteria, all factors related to permafrost conditions (permafrost table, thickness of pavement, type of frozen soil, and water supply) are evaluated. Condition of water (either in the form of ice crystals or free water state) in the soil may be determined by the temperature of the permafrost soil; the bearing capacity of the soil can be decided by the amount of ice crystals in the permafrost soils.

For the purpose of assessing the engineering characteristics of frozen soils, a geotechnical classification of permafrost in the plateau and some major considerations in pavement design should be carried out. A simple classification was based mainly on many natural soil laboratory experiments and a few field experiments. A statistical relationship between thaw settlement and groundwater content was evidenced in the thawing and freezing processes in frozen soil. It is helpful to analyze the principal factors in highway construction failures, such as thaw settlement, frost heave, and seepage of water. Some other considerations and methods associated with the design and construction of pavement structures in the Qinghai-Tibet Plateau are summarized in the following paragraphs.

When a pavement initially built of gravel materials is paved with asphalt, much more heat is absorbed from sunlight through the asphalt layer. Therefore, the upper boundary of the permafrost table will decline, and new thaw settlement has to be considered again. Even if the old pavement has already been surfaced with asphalt, any maintenance operation (i.e., a resurfacing treatment with asphalt) will shift the upper boundary of the permafrost table down to a certain magnitude of depth.

Orientation of highway geometric alignment design is a very important factor affecting thawed depth of a permafrost embankment. For instance, two sections of highway with different orientations (one is east-west; the other one is south-north) in the Fenghuo Mountains were observed; the difference of thaw settlement between the two sides of embankment was found to be 200 to 500 mm.

Elevating the grade line sufficiently to ensure that the sides of the roads are above the groundwater table—or above the level of the water accumulating beside the road—is important. To keep frost boils and frost heaves from occurring as a result of the infiltration of

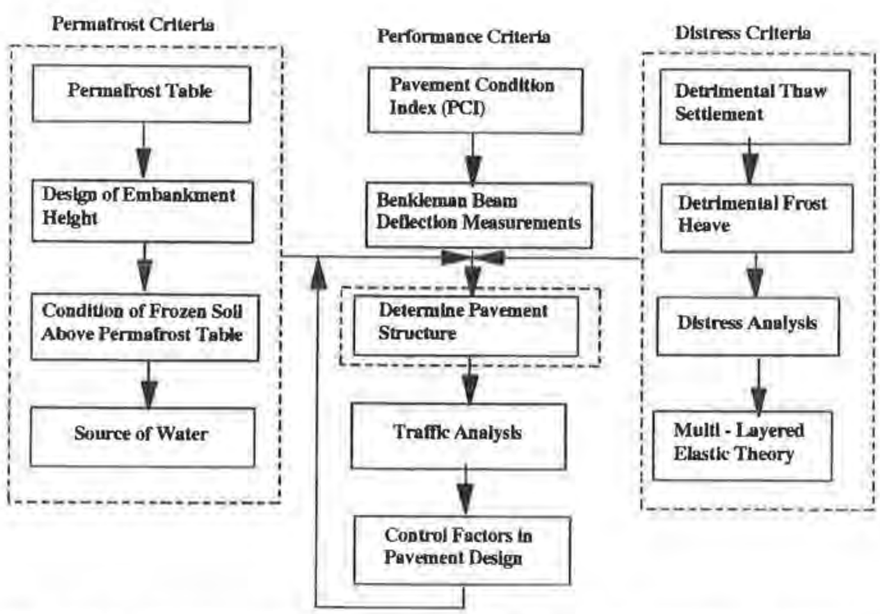

FIGURE 8 Proposed pavement evaluation procedure in permafrost regions of Qinghai-Tibet Plateau.

surface water, the asphalt pavement must be impermeable to water, and the shoulder of the road should be strengthened to ensure good drainage.

Adjusting the properties and thicknesses of each layer of the pavement structure to ensure the predicted stresses, strains, and deflections are within allowable limits is another major consideration. The mechanistic approaches provide flexibility in modeling a material, and drainage conditions in the field may be incorporated in the analysis.

The formation of cracks in the pavement surface not only depends upon the air temperature but is also influenced by thaw settlement of the subgrade. Hence, the amount of settlement of the pavement surface depends on the distribution of ice in the frozen soil and the swelling characteristics of the skeleton of the thawed soil. The amount and distribution of ice and the stress-deformation behavior of the thawed soil depend upon a variety of factors, including the stress, thermal, and moisture change histories of the material.

CONCLUSIONS

In the extensive permafrost areas of the Qinghai-Tibet Plateau, pavement maintenance or rehabilitation is greatly affected by the original design and construction of the highways. It is very important to consider all major factors that influence the basic performance of the pavement structure before starting road construction on ground with permafrost. Otherwise, some severe damage or distress of the pavement structure may result immediately after construction; in some cases, maintenance may be impossible because the original design and construction were improper. The 20-year experience of pavement maintenance along the Qinghai-Tibet highway has generated the following information.

1. Thaw settlement of a highway subgrade is directly related to the construction of the embankment and the type of frozen ground soil (ice-rich frozen soil, ice-saturated soil, or ice layer with soil inclusions) above the permafrost table. Therefore, under each type and condition of frozen ground soil, the amount of thawing settlement of the pavement structure can be determined by the height of embankment, the fill materials of each layer, the orientation of the center line of the embankment, and the annual air temperature.

2. There exists a minimum height of embankment that could prevent the upper boundary of permafrost from shifting upward or downward for each situation in a permafrost area. For instance, in Fenghuo Mountain permafrost regions of the Qinghai-Tibet Plateau, the minimum height of an embankment is estimated to be 0.7 m when the pavement structure is a 42-mm asphalt surface; the subbase and base filling material is composed of sandy or gravelly soil, respectively; and the orientation is 15°24′ northeast. If the height of the embankment is less than the critical height, the depth of the permafrost table will decline and result in thaw settlement.

3. When asphalt concrete or even asphalt seal is to be used to resurface the existing pavement (even if the old surface is asphalt) during routine maintenance, the existing permafrost table will shift downward because asphalt can absorb and conduct much more heat from sunlight.

4. Frost heave along the Qinghai-Tibet highway is mainly the result of water seeping in through the cracks in the pavement surface and being stored in the upper layers during the warm season and freezing with volume expansion in the cold season. This distress can be minimized by sealing cracks in the pavement surface and providing a good drainage system.

5. Defection measurements indicate that the bearing capacity of the pavement structure in the warm season (June and July) in some permafrost regions of the plateau will lose 20 to 70 percent of its value compared to the cold season.

6. The behavior of asphalt surface pavements in permafrost areas can be predicted by evaluating the three sets of criteria for pavement structural design: thaw settlement criteria, frost heave criteria, and performance criteria. The proposed pavement evaluation procedure for the Qinghai-Tibet highway in the permafrost regions is practical. The performance evaluation in permafrost areas should include, in addition to the common requirements, a cumulative damage procedure due to thawing and freezing cycles.

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