Seasonal Nondestructive Evaluation of Frost-Heave Prevention Layers in Asphalt Pavements

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In cold and snowy regions, road pavements are greatly affected by frost heaving in the ground. The frost heave damages the ground in two ways. The first is because of the frost heaving itself, and the second is because of the decrease in the bearing capacity on the subgrade soil and the subbase courses during spring thaw. A number of methods are available to protect pavement from frost-heave damages. The most popular method used in Japan is the replacement of frost-susceptible soil with local materials such as sand, volcanic ash, and unscreened gravel. In the investigations, the bearing coefficients of the materials generally used in cold regions for subgrade, frost-preventing layer, and subbase course are obtained from the buried plate-loading apparatus on each layer of pavement before freezing and after thawing. From these coefficients, the moduli of deformation for the layers of these materials were calculated using the approximate calculating method of multilayer-displacement, and the structures of pavements were theoretically analyzed. The performance of pavements at the "Bibi Test Road" was analyzed on the basis of the assessments on the test road through traffic loads.

In cold and snowy areas, road pavements, concrete tunnels, and retaining walls are greatly affected by the freezing and thawing of the ground. Especially in Hokkaido, northern Honshu, and mountainous areas—even in warmer areas of Japan—frost heave in road pavement has serious consequences.

Frost heaving occurs when ice crystals grow in a freezing front and cause the earth surface to rise (*1*). This phenomenon causes damage in two forms: one because of the frost heave itself, and the other from the decrease in the bearing capacity of the subgrade and subbase in pavement during spring. The latter damage occurs in winter, when a large amount of water moves into the icy layers from the groundwater. Many heavy vehicles cause partial ruts and alligator cracks to form in the asphaltic pavements, and the drainage is obstructed by the frozen layers in the spring (*2*). To protect pavements from frost-heave damage, displacement, chemical treatments, heat insulation, and installation of impermeable layers have been selected as countermeasures, for experimental and for practical purposes (*3*).

For reasons of economy, performance, and experience, the replacement method is generally used for road pavements in Japan. This method consists of replacing frost-susceptible soil with coarse materials to about 70 percent of the maximum frozen ground depth in winter. On the basis of many experiences in northern Japan, this method has been applied as the standard design for all classes of roads in various regions without any actual defects.

However, in cold and snowy regions, the present design method, which is mainly based on experience, is not necessarily appropriate for the changes in traffic situation, layer composition, and the selection of new subgrade and subbase materials. Therefore, it has become necessary to evaluate analytically the asphaltic pavements constructed by the conventional method to prevent frost heave and to establish a rational pavement design method capable of adapting to the conditions brought on by new materials and situations.

The theoretical structural analysis of asphaltic pavements is extremely difficult because the mechanical properties of the component materials in pavement are not completely understood and because the stress-strain relationship in various layers of pavements in the actual road have not been investigated. As for the mechanical properties of the subgrade and subbase materials subjected to frost action in cold regions, the moduli of elasticity coefficients (deformation coefficients) for structural layers that are essential to theoretical calculations are discussed only in relation to the California bearing ratio (CBR) of the materials (*4*).

For this reason, the deformation coefficients of subgrade, subbase, and all of the pavement layers subjected to the repetition of freezing and thawing under the conditions in the actual road should be determined. On the other hand, deformation coefficients of asphaltic mixtures have previously been satisfactorily obtained for pavement structures, temperature changes, and loading time (*5*). The fatigue properties of asphaltic mixtures should also be considered because frost-heave damages to pavements is mainly evaluated from cracks in the road surface. Many experimental test results are available for this purpose. However, it is important to determine how they relate to the performance of the actual pavements.

The Bibi Test Road was established on National Highway 36 in the Tomakomai district of Hokkaido, Japan, for conducting systematic studies on the countermeasures against frost-heave damage in cold areas and also for theoretical analysis (*6*). The replacement method, as a frost-heave countermeasure was evaluated by determining the plate-bearing coefficients on the layers of pavements of different thickness and types of replacement materials and by investigating the relationship between traffic loads and crack damages in pavements of the test road.

With the coefficients in the subgrade and subbase layers of this road, the authors attempt to calculate the deformation

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coefficients and to evaluate a frost-heave prevention method by analyzing the pavement structures. The performance of the pavements in the test road was also investigated.

MEASUREMENTS OF PLATE-BEARING CAPACITY AT BIBI TEST ROAD

The Bibi Test Road was planned by the Civil Engineering Research Institute of the Hokkaido Development Bureau for the systematic establishment of frost-heave prevention methods; the investigations have continued since 1960. The construction of the test sections, as shown in Figure 1, started in May 1967 and was completed in October 1968, whereupon the investigations started immediately.

The subgrade of this test road was frost-susceptible soil. There were 16 kinds of pavement structures consisting of different materials and thicknesses that were adopted by the design standard of the Hokkaido highway specifications. Each experimental test section was 30 m long; the total length was 480 m. The properties of the materials used in the subgrade, frost-prevention layer, and subbase course are presented in Table 1.

Rigid loading plates 30 cm in diameter were buried on the subgrade and subbase layers as shown in Figure 2 and were isolated from the upper layers with a double pipe. Testing

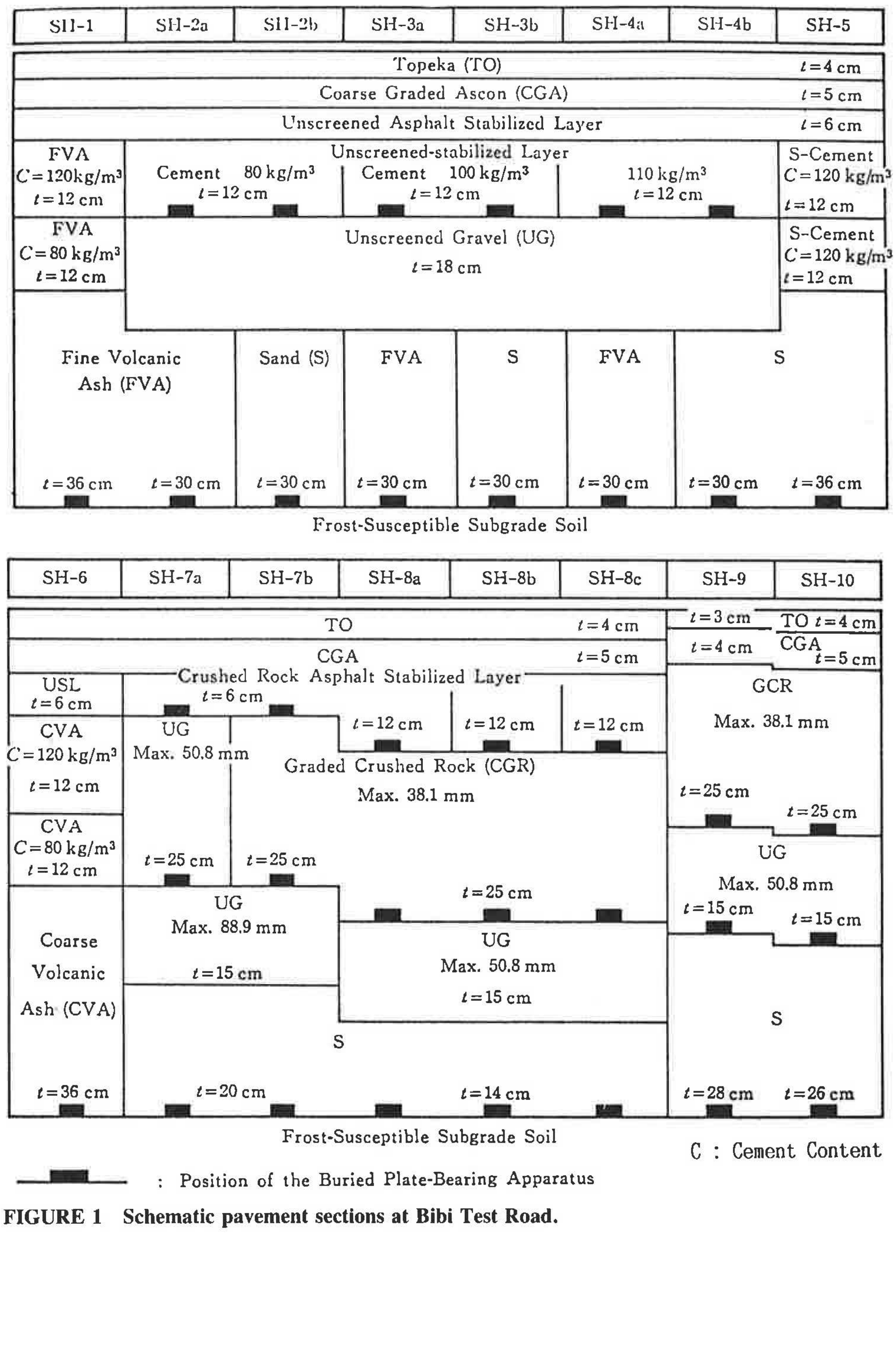

FIGURE 1 Schematic pavement sections at Bibi Test Road.

TABLE 1 Engineering Properties of Subgrade and Replacement Materials

Subbase, Frost Preventing Layer or Subgrade	Gradation (Passing Weight %)														Modified CBR (%)	Remarks
	88.9 mm	50.8 mm	38.1 mm	25.1 mm	19.1 mm	9.52 mm	4.76 mm	2.38 mm	2.00 mm	590 μ	297 μ	149 μ	74 μ	5 μ		
Graded Crushed Rock			100	84	74	60	45	30	—	17	12	8	4	—	90	
Unscreened Gravel (Max. 88.9 mm)	100	92	80	—	57	33	21	16	—	7	—	—	1	—	68	
Unscreened Gravel (Max. 50.8 mm)		100	97	87	79	62	49	42	—	14	4	1	1	—	68	
Sand							100	95	—	43	15	2	1	—	12	
Fine Volcanic Ash				100	—	—	91	—	82	—	—	—	25	—	53	
Subgrade Soil (Frost-Susceptible)									100	99	92	80	62	13	8	LL=68% PI=20%

loads were applied to the bearing plate with an oil jack and load-reflecting tractor. The deflection of the bearing plate was measured with dial gauges that were set up on a rod horizontal to the pavement surface. The buried plate-bearing capacities on each layer were measured every year (in November) immediately before freezing of the pavement, again in the thawing period, and once in the middle of every month from March to May. From 1968 to 1971, when the investigations were carried out, 835,000 heavy vehicles passed over this test road (open to traffic from October to May). The relationship between the total number of vehicles and the performance of pavements on the basis of cracking ratios was also investigated.

Table 2 presents the plate-bearing coefficients obtained on the subgrade and subbase courses for the 3-year period of investigations, before freezing and during the thawing period. The freezing depth of the test sections varied, depending on the severity of the cold in winter and the pavement structures; it ranged from 95 to 105 cm from the top of the pavement. Frost heavings in the subgrade soil ranged from 4 to 14 cm.

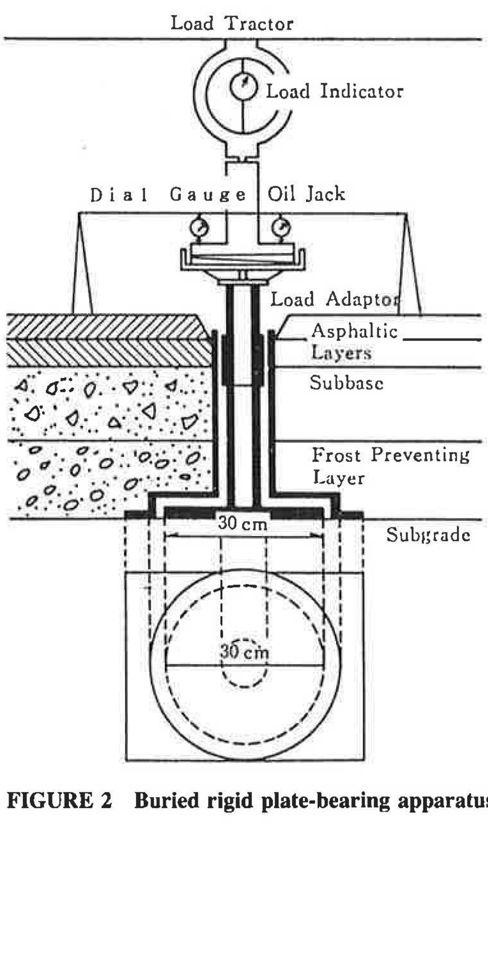

FIGURE 2 Buried rigid plate-bearing apparatus.

CALCULATION OF DEFORMATION COEFFICIENTS AND DISCUSSION OF RESULTS

Determination of the deformation coefficients before freezing and during thawing was tried for each of the following materials in the layers: (a) most frost-susceptible subgrade soil in Hokkaido; (b) fine volcanic ash and sand used as the materials of the frost-prevention layer; (c) unscreened gravel with maximum grain sizes of 88.9 and 50.8 mm used in the subbase course; and (d) graded crushed rock used as the base course in southern areas. By using the plate-bearing coefficients observed for each layer of the 16 test sections, the deformation coefficient of the layers of these materials was calculated using the approximate method of multilayered replacement proposed by Ueshita (*7*).

In the case for which a rigid loading plate is placed on a multilayered pavement as shown in Figure 3, the following equations are derived by Ueshita's theory:

$$d_{2)\ 1} = d_1 + K_1T_1,\ d_{3)\ 1} = d_{2)\ 1} + K_2T_2, d_{4)\ 1} = d_{3)\ 1} + K_3T_3$$

$$K_1 = f(E_1/E_2),\ K_2 = f(E_2/E_3),\ K_3 = f(E_3/E_4)$$

$$E_{01}d_1 = E_{12}d_{2)\ 1} = E_{23}d_{3)\ 1} = E_{34}d_{4)\ 1}$$

$$E_4 = 17.7K_{30\ (4)},\ d_{4)\ 3} = 30K_{30\ (3)}/K_{30\ (4)}$$

where

$E_{01}, E_{12}, E_{23}, E_{34}$ = equivalent deformation coefficients for the layers under Layer 1, Layer 2, and so forth ($E_{34} = E_4$);
$d_1, d_{2)\ 1}, d_{3)\ 1}, d_{4)\ 1}$ = diameters of loaded area on the layer (d_1 = 30 cm);
E_1, E_2, E_3, E_4 = deformation coefficients for each successive layer from the top; and
$K_{30\ (3)}, K_{30\ (4)}$ = plate-bearing coefficients on Layers 3 and 4, respectively.

TABLE 2 Plate-Bearing Coefficients of Each Layer

Kinds of Material	Measured Position [a]	Period [b]	Plate-Bearing Coef. (kg/cm³)		
			Number	Range of Values	Average [c]
Subgrade (Frost-Susceptible)	Subgrade	A	40	9.2–17.5	11.9
		B	40	5.2–15.2	9.8
Sand (Frost Preventing Layer)	Sand	A	6	23.6–27.2	25.6
		B	6	19.6–24.8	22.1
	Subgrade	A	6	10.8–15.2	13.8
		B	6	9.2–14.8	12.7
Unscreened Gravel (U. G.) Max. 50.8 mm	U. G. Max. 50.8	A	6	30.4–39.2	34.5
		B	6	23.6–34.4	29.1
	Sand	A	6	23.6–27.2	25.6
		B	6	19.6–24.8	22.1
Unscreened Gravel (U. G.) Max. 88.9 mm	U. G. Max. 88.9	A	8	25.2–32.0	29.0
		B	8	21.2–30.8	25.4
	Subgrade	A	8	10.4–12.4	11.4
		B	8	8.8–12.4	10.5
Graded Crushed Rock (G. C. R.) Max. 38.1 mm	C. G. R. Max. 38.1	A	10	40.8–54.8	47.7
		B	10	33.6–44.4	38.7
	U. G. Max. 50.8	A	10	23.2–33.2	28.8
		B	10	16.8–30.8	25.1
Fine Volcanic Ash (Frost Preventing Layer)	U. G. Max. 50.8	A	10	30.0–40.0	33.8
		B	10	22.0–30.4	26.7
	Subgrade	A	10	10.0–16.0	12.0
		B	10	8.0–15.2	10.8

a Measured on Each Layer.
b A means Values of Nov., and B means Min. Values of March-May.
c Average of Three Years from 1968 to 1971

The plate-bearing coefficients are obtained from the buried plate loading apparatus. On the basis of the plate-bearing coefficients, the deformation coefficient in the lowest layer (subgrade) is calculated first, and then the deformation coefficient for the frost-preventing layer on the subgrade can be calculated, and then the subbase course, and so on for each layer. The deformation coefficient for the materials in the frost-susceptible subgrade soil, the frost-preventing layer, and the subbase course of pavement structures and their decrease in the thawing period are presented in Table 3.

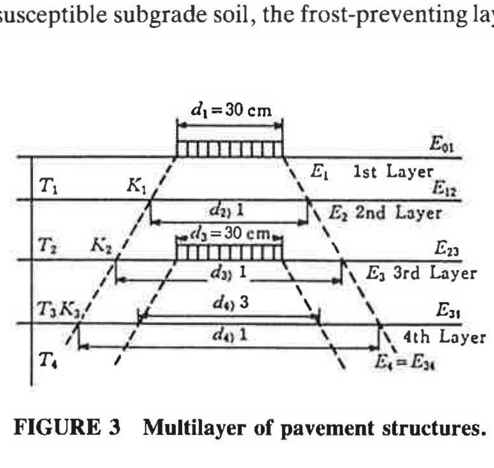

FIGURE 3 Multilayer of pavement structures.

There should be some discussion about the deformation coefficient for the various materials that constitute pavement structures. The icy layers in the frost-susceptible subgrade soils melt in the spring and cause a decrease in the bearing capacity of the subgrade and subbase courses, which eventually leads to pavement damage. Table 3 shows the reduction in bearing capacities of various materials of subbase, the frost-preventing layer, and the subgrade in relation to changes in the deformation coefficient. According to the results, the deformation coefficient in the spring thaw decreased 16 to 35 percent compared with that before the freezing. The coefficients for the fine volcanic ash and graded crushed rock layers show particularly large reductions of 35 and 31 percent, respectively. The reason for these large reductions is considered to be the relatively high proportions of particles finer than 74 μm. The graded crushed rock may show a high deformation coefficient before freezing, and its use in the base course in cold areas is indeed questionable in light of the large decrease in the coefficient in the thawing period. These relations between replaced materials and reduction ratios are in agree-

TABLE 3 Deformation Coefficients of Pavement Layers

Materials of Each Layer	Deformation Coef. (kg/cm^2)		
	Before Freeze E_A	After Thaw E_B	Reductive Rate (%)*
Subgrade Soil (Frost-Susceptible)	210	170	19
Fine Volcanic Ash	830	540	35
Sand	950	770	19
Unscreened Gravel (Max. 88.9 mm)	2,080	1,750	16
Unscreened Gravel (Max. 50.8 mm)	2,120	1,560	26
Graded Crushed Rock (Max. 38.1 mm)	2,630	1,820	31

* Reductive Rate of Coef. = $\frac{E_A - E_B}{E_A} \times 100$ (%).

ment with the experience on replaced materials in cold areas.

Therefore, these results would make possible the structural analysis of pavements considering the reduction in bearing capacities of various component materials in the thawing period.

CONCLUSIONS

On the basis of the measurements of the plate-bearing capacities on the subbase and subgrade of the Bibi Test Road at Tomakomai, Hokkaido, the moduli of deformation (deformation coefficients) for the pavement layers have been calculated to evaluate the frost-prevention replacement method for pavements in cold and snowy regions. Using these coefficients and the elastic theory, the analysis of the pavement structures was conducted. The main conclusions from these investigations are as follows:

1. The decrease in bearing capacity on the various pavement structures in the thawing period was observed by plate-bearing coefficients on the subgrade and subbase of the pavements with a specially designed rigid loading plate.
2. On the basis of these coefficients, the deformation coefficients for the layers of these materials were calculated using the approximate calculating method of multilayered replacement. By these calculations, deformation coefficients and their changes are given for all the materials generally used in subgrade and subbase courses in cold regions before freezing and during thawing. It is clear that the deformation coefficient decreases in the thawing period by 16 to 35 percent and that the extent of decrease varies among the materials. The materials containing fine volcanic ash and graded crushed rock show an extraordinarily large decrease.

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