Polystyrene Foam as a Frost Protection Measure on National Roads in Sweden

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Polystyrene foam boards have been used as a frost protection measure on roads in Sweden for about 20 years. Different qualities have been tested regarding their long-term function as an insulation. Properties such as bacterial, chemical, and mechanical durability in roads and preserved low-heat conduction have been continuously followed. In the specifications of the National Road Administration in 1976, the extruded polystyrene skinboard, type HI 50 from the Dow Chemical Company, was recommended for use in an insulated road base. For skid resistance, the depth of insulation was changed from 50 cm, according to the 1976 specifications, to 40 cm below road surface in the specifications of 1984. This change was based on experience from the Swedish Road and Traffic Research Institute test field. It was observed that a conventional crushed rock roadbase showed the same icing risk potential as a base with 40 cm of sandy gravel above the insulation board. Recommended insulation thicknesses are related to average freezing index at the site. A new procedure is being developed making it possible to calculate the frost heave when the frost penetrates below the base into underlying frost-susceptible soils. The procedure is based on determination of the frost heave properties of soils by a direct freezing test. This make it possible to optimize the frost-protective base construction in relation to local climatic, geological, and hydrological conditions at the site.

Extruded polystyrene skinboard and molded bead polystyrene board have been used as a frost damage protection measure for about 20 yr on a number of national and other roads in Sweden. In the Swedish Road Administration specifications of 1976 and 1984, the insulated road base consisted of three main layers: the overlying bearing course upon the plastic foam layer; the plastic foam layer itself; and, as a bottom layer, non-frost-susceptible soil material (e.g., sand or old roadbase material). Figure 1 illustrates both this construction and bases with gravel and sand, tree bark, lightweight aggregates, and a conventional base. All of these bases were frost protected to the same degree. The layers above the plastic foam had a thickness of at least 40 cm. The thickness of the plastic foam layer depends on the mean freezing index at the site and also on the thickness of the underlying non-frost-susceptible layers. Table 1 shows the design table for insulation with polystyrene foam used on Swedish roads *(1)*.

The type of plastic foam used in insulating Swedish roads is predominantly made up of different qualities of extruded polystyrene skinboard foam from the Dow Chemical Company. The recommended quality is Styrofoam HI 50. The investigation of this product and other varieties of polystyrene foam started in 1966 and has been continued for many years. The results have led to the conclusion that polystyrene foam can also function in the long run as an efficient measure against the detrimental effects of frost.

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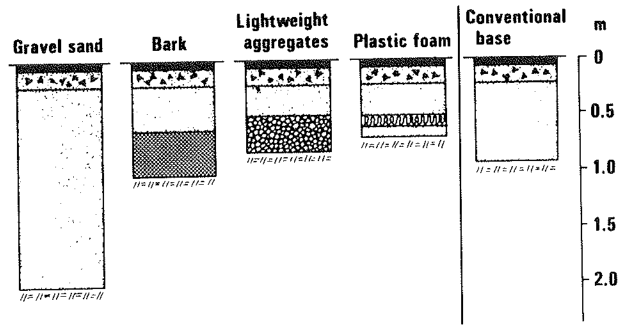

FIGURE 1 Thickness of road bases for same frost protection degree and different frost protection methods.

INVESTIGATIONS OF THERMAL BEHAVIOR ON TEST ROADS

When the Swedish Road and Traffic Research Institute (VTI) was asked to test polystyrene foam built into a roadbase in 1965, the frost-insulation properties of this type of foam were practically unknown. The tests therefore had to be both intensive and extensive. In Sweden, frost problems affect every part of the country. The climatic conditions can simply be described by the distribution of the freezing index, see Figure 2. The increasing values of the freezing indices toward northern regions indicate a greater need for frost protection in these parts of the country. Compare the frost heave shown in the three columns in the table in Figure 2.

The first test road was constructed in 1966, and was of an introductory type. The next year, 1967, the main test roads were constructed. These test roads, Edsvalla 1967 A and B in the western part of Sweden, contained sections with two types of polystyrene foam and different designs of the base. For comparison, a number of test sections with lightweight aggregates and tree bark were included. The total number of sections was 44. Some sections are to be found in Figure 3. Among other test roads, one in central Sweden is of special interest: Lasele 1972. The test road is situated in a part of Sweden where frost protection measures must always be considered. It contains sections with two different types of plastic foam: extruded polystyrene skinboard and molded bead polystyrene.

TABLE 1 DESIGN TABLE USED BY THE NATIONAL SWEDISH ROAD ADMINISTRATION FOR ROAD BASES INSULATED WITH PLASTIC FOAM *(1)*

Average Freezing Index	Insulating Bed[a] (mm) by Foam Layer Thickness (m)						
(°Cd)	100	200	300	400	500	600	700
<500	35	30	25	20			
500–600	40	35	30	25	20		
600–700	50	40	35	30	25	20	
700–800	60	50	40	35	30	25	20
800–900	70	60	50	40	35	30	25
900–1000	80	70	60	50	40	35	30
1000–1100	90	80	70	60	50	40	35
1100<	90	90	80	70	60	50	40

[a]Non-frost-susceptible material.

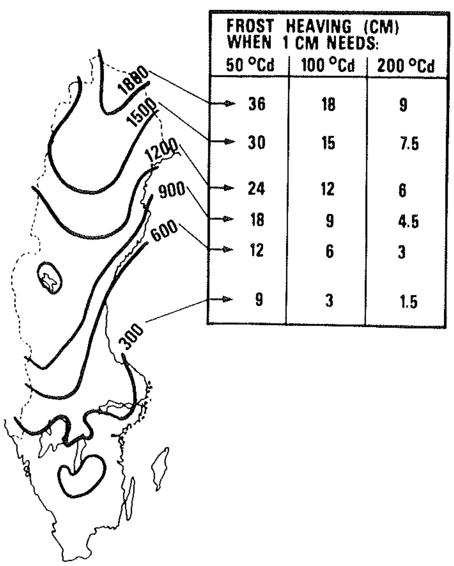

FIGURE 2 Average freezing index (°Cd) and corresponding frost heave for the frost heave quotients 50, 100, and 200 °Cd/cm.

At all the test roads mentioned, the water takeup of the plastic foam has been determined. Several specimens of the foam from the test roads have also been tested for heat insulation properties. Thermal conductivity has been determined on samples directly after being taken up from the road. The water takeup registered on the test roads at Edsvalla and Lasele is shown in Figure 4. The two Edsvalla curves represent two kinds of polystyrene foam: an expanded type (cut cell molded bead polystyrene) and an extruded type. As can be seen from the curves, the rate at which the expanded type takes up water is very high, with a water content of about 16 percent by volume after 5 yr. Consequently, this type of polystyrene foam is not recommended for frost insulation. At Lasele, one extruded polystyrene foam (extruded polystyrene skinboard) and one expanded polystyrene foam (molded polystyrene foam) have been tested. The curves show that the increase in water content is low for the extruded polystyrene foam and higher and somewhat irregular for the expanded polystyrene foam.

Of more direct interest, however, is the thermal conductivity, which has been determined on certain occasions (see Figure 5). The curves describe the development of the thermal conductivity with time from the same test roads as in Figure 4. The superiority of the extruded foam over the expanded is clearly recognized. In fact, after 12 yr at the Lasele test road, the thermal conductivity value for the expanded foam exceeds that of the extruded foam by a factor of nearly 1.5. This result has been applied by dimensioning the plastic foam layer (see design table, Table 1). The thickness of the foam layer in the table is related to the extruded polystyrene foam at Lasele (Styrofoam HI 50). When the bead-board type of polystyrene foam of the Lasele quality is to be used, the thickness in the design table must be increased by 50 percent.

The mechanical behavior of polystyrene foam material has also been investigated, but not to the same extent as the thermal behavior. Attaining sufficient mechanical strength of the polystyrene foam presents no difficulty today as the producers of the foams have all the knowledge necessary to manufacture the foam boards to the desired strength.

INVESTIGATION OF ICING IN THE TEST FIELD

When the investigation of the test roads previously mentioned was started, it was well known that icing on the road surface could occur earlier in autumn on heat-insulated sections than on uninsulated sections. Therefore, measurements of the skid resistance and surface temperature were performed along the test roads during autumn and winter. From these investigations, it was clearly apparent that there was a somewhat greater risk of icing on heat-insulated sections in comparison with uninsulated ones. This risk was strongly influenced by the construction type of the road base (see Figure 3), which shows the variation of the coefficient of friction for one special occasion on a number of the test sections on the Edsvalla test road. The friction values for the various insulated sections are related to the values of the uninsulated sections, which are given the value 1.

To study icing as a function of road construction, a special test field was organized at Linköping *(2)*. The object of the investigations in the test field was to make a general study of the interaction between climate and road construction that results in slippery conditions in cold weather, and to make a particular study of the risk potential of different road constructions, most of them insulated with plastic foam. A total of

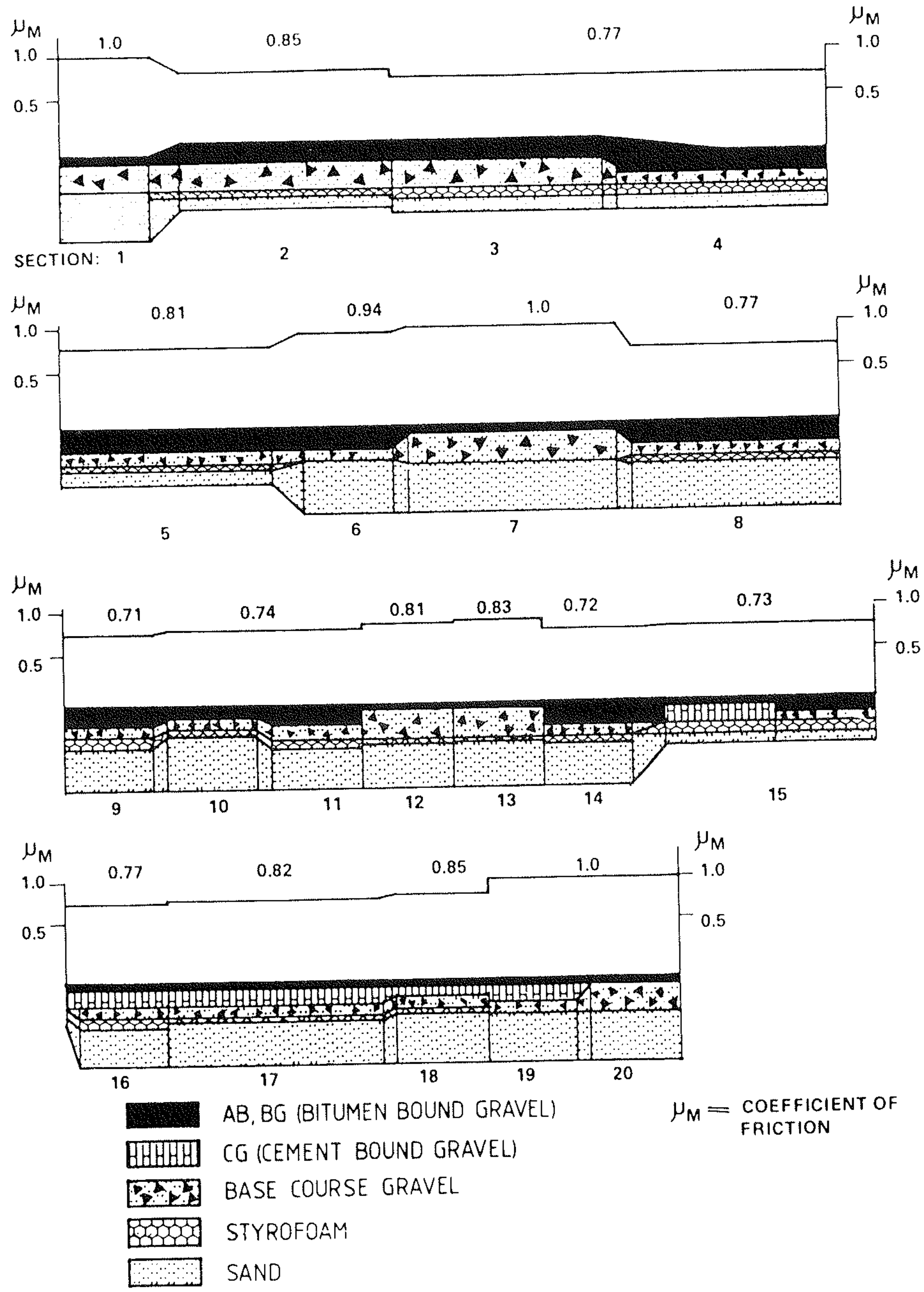

FIGURE 3 Test sections on test road Edsvalla 1967.

42 different pavement types were studied in the test field, see Figure 6.

According to K. Gustafson of VTI, the background for the icing process can be expressed as follows:

> The presence of an insulating layer in the road pavement affects the flow of heat upwards and downwards. In a heating situation, the insulation layer retards the downward flow of heat in the road, while in a cooling situation upward flow of heat from material courses underneath the insulation is retarded, and outward radiation of energy from the road surface is therefore compensated to a lesser extent than in a road without insulation. The consequence is that the insulated road generally has a somewhat lower surface temperature than most types of road without insulation. Surface temperature conditions in an insulated road are affected by (a) the depth at which insulation is laid, (b) its thickness, and (c) the materials in the courses above the insulation. The temperatures are also influenced by the thermal conductivity of the insulating material.

The results of the observations from the test field over the period of 1976 to 1980 are summarized and concentrated in a table, see Figure 7. In this table the different pavements are arranged according to the potential risk of icing. It can be seen that the highest risk, predictably, is found where the plastic foam layer is near the road surface or even far from the surface when the base is built up of crushed rock. It is also interesting to find that a base without plastic foam but with crushed rock near the road surface has a fairly high risk of icing. The lowest icing risk potential is shown by the uninsulated bases with natural ungraded gravel and sand. If the foam insulation is laid

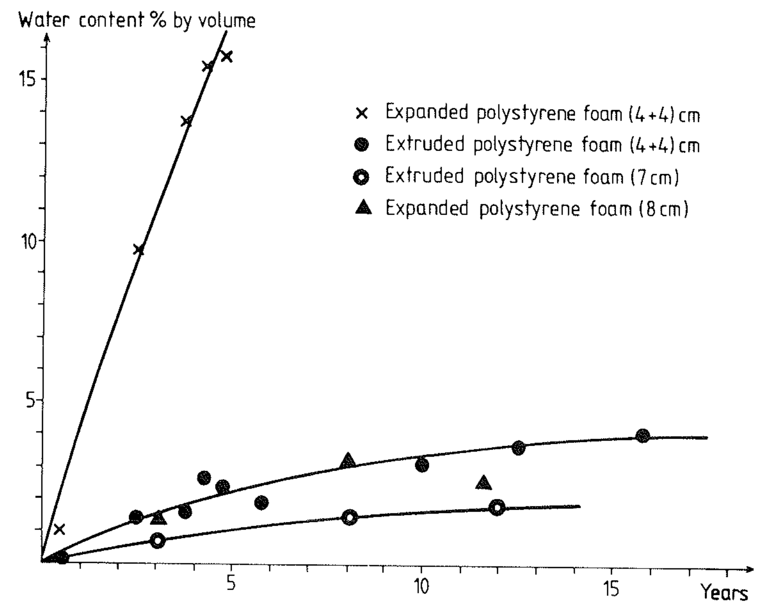

FIGURE 4 Moisture absorption in polystyrene foam, test roads Edsvalla 1966 and 1967 and Lasele 1972.

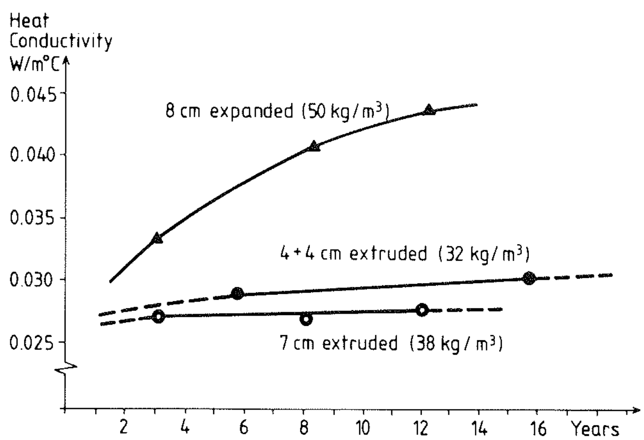

FIGURE 5 Change in heat conductivity of polystyrene foam with time on test roads Edsvalla 1966 and Lasele 1972.

at a depth of about 35 cm, the icing risk potential is high in relation to most uninsulated road structures, but is about the same as that of a pavement incorporating ungraded crushed rock below the asphalt concrete wearing course. For roads with the insulation laid at a depth of 50 cm or more, the risk of icing is relatively small, but is still somewhat higher than that of most uninsulated roads. Many roads in Sweden have been constructed with the insulation layer at a depth of 40 and 50 cm beneath the road surface without any serious icing problems. In the 1984 specifications for public roads, the lower depth of 40 cm is consequently allowed.

DESIGN AND DIMENSIONING OF A ROAD BASE INSULATED WITH POLYSTYRENE FOAM

Three layers contribute to the frost-resistance capacity (in degree-days) of a roadbase insulated with plastic foam. The greatest contribution comes from the plastic foam layer itself and only a smaller amount comes from the overlying bearing course. What is sometimes not considered, however, is the fact that the soil layers of non-frost-susceptible material immediately beneath the plastic foam layer contribute to a degree that cannot be ignored.

The frost-resistance capacity is defined as the frost quantity (freezing index) that is required for freezing the road base totally. The frost-resistance capacity is calculated by the formula of Sv. Skaven-Haug, of Norway, which is described as follows:

The calculation is based upon the model

$$F = \Sigma\Omega + E, \text{h°C}$$

where F is the frost-resistance capacity and h°C is hr/°C.

The resistance to freezing from latent heat for a single soil layer is

$$\Omega = \frac{q \cdot s^2}{2\lambda} + q \cdot s\,\Sigma\left(\frac{s_0}{\lambda_0}\right), \text{h°C}$$

where

s = thickness of soil layer (m),
q = frost-accumulating ability of material (kcal/m^3)
λ = heat conductivity (kcal/mh°C), and
s_0/λ_0 = resistance to heat flow of frozen layers (m^{2}h°C/kcal).

The freezing resistance due to heat flow is the earth to the frost line (stored heat in unfrozen soil), which can be expressed as

$$E = kGT\lambda\Sigma\left(\frac{s_0}{\lambda_0}\right), \text{h°C}$$

where

- k = a constant (usually 0.7),
- G = temperature gradient below frozen zone of February 1 (°C/m), and
- T = actual reference time (h) for stored heat.

In Figure 8 the frost-resistance capacity calculated (as already described) of a road base built up of layers of sand and gravel and of a roadbase insulated with polystyrene foam, is plotted as a function of the thickness of the gravel-sand base and of the thickness of the polystyrene foam layer *(3)*. However, these capacity values are not to be generally used. When calculating the frost-resistance capacity for any single base, appropriate input values have to be chosen *(3)*. The

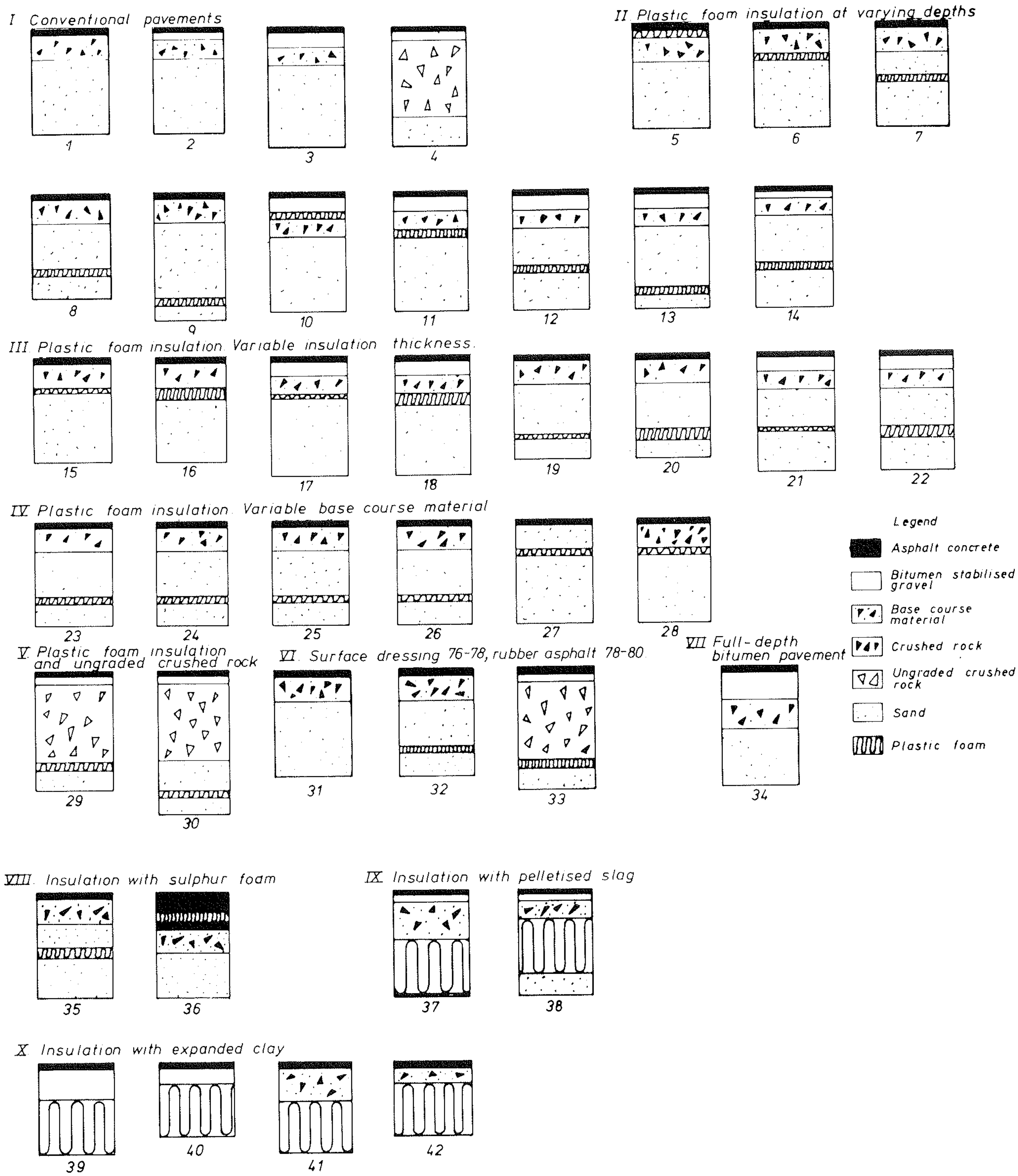

FIGURE 6 Pavement types in test field at Linköping 1976 *(2)*.

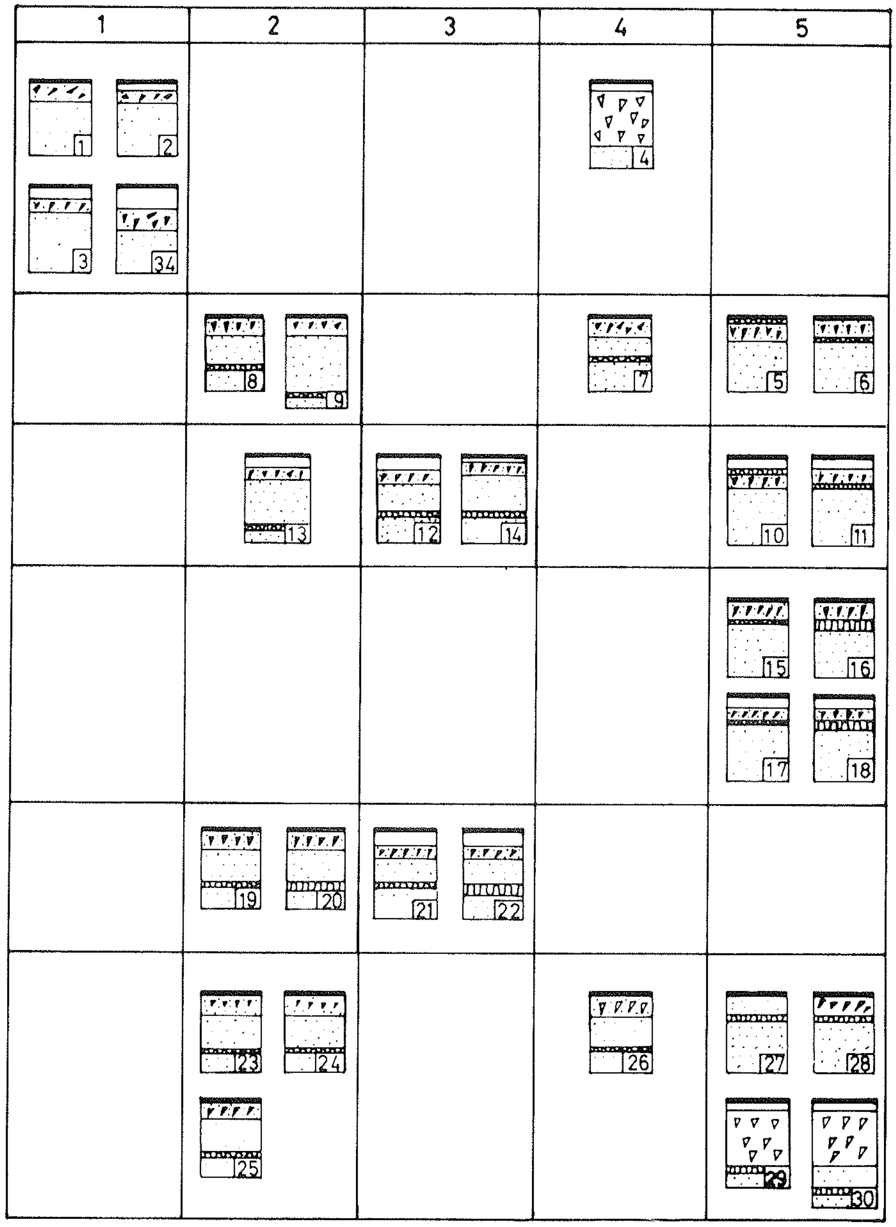

FIGURE 7 Icing risk potential of road pavements represented in the test field at Linköping 1976. Summary of measurements made over period 1976–1980 *(2)*.

design freezing index is assumed to be 1,000 degree-days for the particular part of the country. Thus, if during one winter the freezing index reaches the value of 1,000 degree-days, the bases will freeze but the subgrade will not. That means that by choosing either a 200-cm-thick roadbase of gravel and sand or a base insulated with 4.5 cm of polystyrene foam with a total base thickness of around 85 cm, 100 percent frost protection can be obtained for either base during that winter.

The frost-resistance capacity of the polystyrene foam insulated base is dependent mostly on the insulation properties of the polystyrene foam (thermal conductivity) and also on the water content of the layer of sand below. Figure 9 is a diagram describing frost-resistance capacity related to the thickness of the polystyrene foam for different thermal conductivity values of the foam.

Figure 10 shows the importance of the water content of the layers beneath the plastic foam. This acts as a freezing resistance layer and is consequently more efficient the more water it contains. As old roadbases are often built up of fine-grained and moist material, it may be an advantage to insulate them with plastic foam by merely placing the foam boards directly on the old road surface and constructing a new base upon the plastic foam layer.

The philosophy of this related art is the basis for the determination of the thicknesses needed for the polystyrene layer in the design table, Table 1. The thicknesses of the polystyrene layer including the non-frost-susceptible layer beneath it correspond to a frost protection degree of some 90 percent, allowing the frost to penetrate and act in the subbase or subgrade every tenth winter. During these winters there will consequently be some frost heave. The magnitude of the heave depends on the insulation properties of the roadbase.

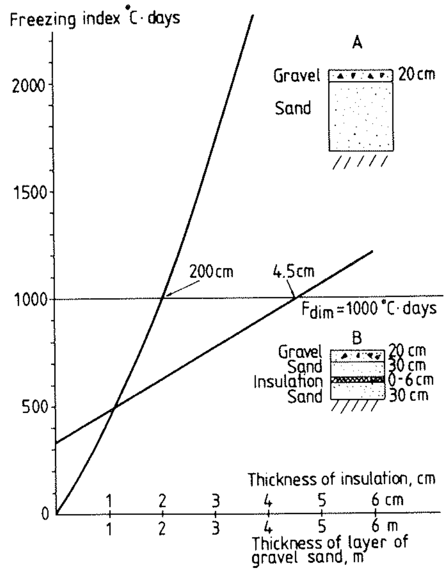

FIGURE 8 Example showing calculated frost-resistance capacity of sand-gravel roadbase and base protected against frost with polystyrene foam.

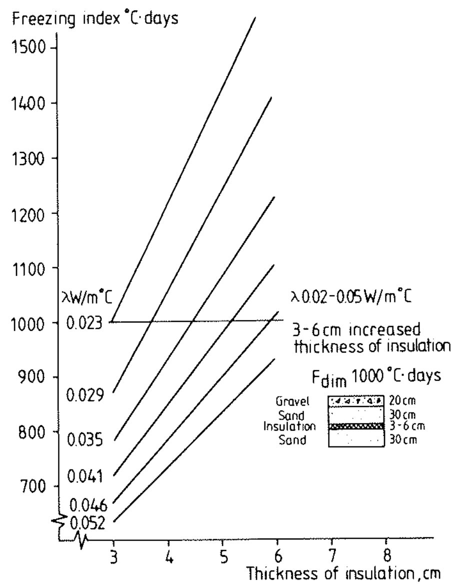

FIGURE 9 Frost-resistance capacity of roadbase with polystyrene foam for different values of thermal conductivity as a function of thickness of foam layer *(3)*.

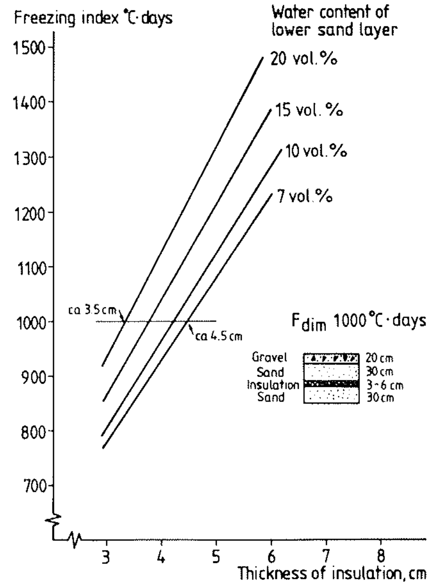

FIGURE 10 Frost-resistance capacity of roadbase with polystyrene foam for different values of water content of material in layers just beneath foam layer as a function of thickness of foam layer *(3)*.

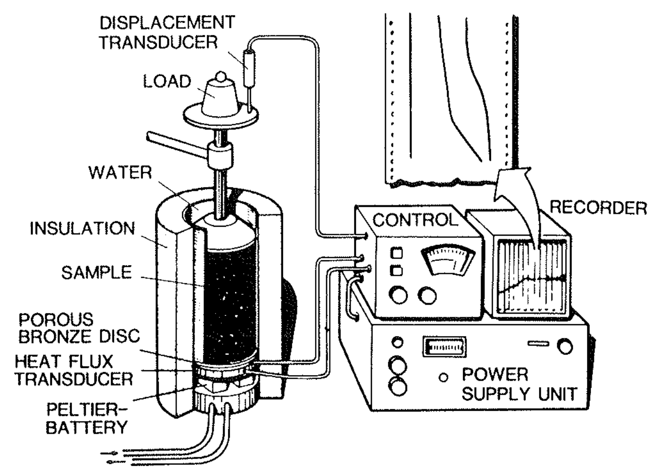

FIGURE 11 Swedish Road and Traffic Research Institute (VTI) equipment for freezing tests *(4)*.

A procedure has been developed that makes it possible to calculate the frost heave when the frost penetrates deeper than the base and the base is underlain by frost-susceptible soils. The frost heave depends on the thermal (road surface temperature) and moisture (water content and groundwater level conditions) road and subgrade structure, but most important are the heave properties of the soil in the subgrade. The latter are determined by an apparatus invented and accurately adjusted at the VTI *(4, 5)* (see Figure 11). The values describing the frost heave properties (ice segregation potential and sensitivity to load pressure) determined with the apparatus are directly usable in calculation of the frost heave. The calculations, which are computerized, run in steps from the natural autumn conditions through the winter.

The importance of heat conductivity with regard to frost heave is easily recognized from a calculation performed by L. Stenberg at VTI, see Figure 12. The thickness of a polystyrene foam layer is calculated for two values of the conductivity, both giving the insulated roadbase a specific degree of frost protection. From the curves it can be read off that when 4 cm of frost heave is allowed, the thickness of the foam needed is 3.5 cm when $\lambda = 0.045$ *W*/m°C, and 2.55 cm when $\lambda = 0.033$

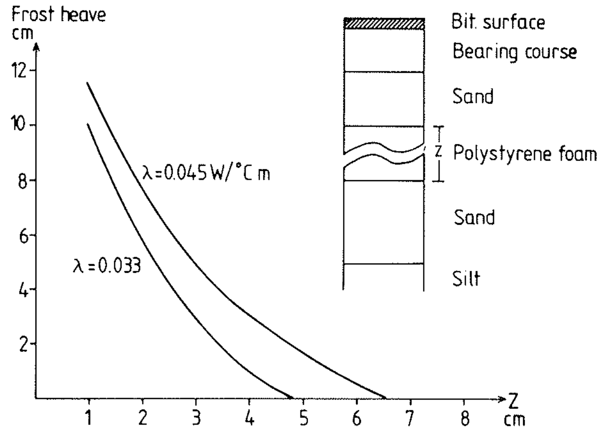

FIGURE 12 Frost heave as a function of thickness and heat conductivity in roadbase insulated with polystyrene foam. (Calculation by L. Stenberg.)

W/m°C. In this way, the thickness of the polystyrene foam layer can be appreciated for different values of the thermal conductivity.

DESIGN THERMAL PROPERTIES OF POLYSTYRENE FOAM

Polystyrene foam, which is an organic material, is relatively new and is available in several varieties and qualities. The main types of polystyrene foam are the expanded and the extruded. The extruded type has proved to have the best frost-insulating properties in the long run.

In order to discriminate between the different types of frost insulation material, it must be possible to determine the development of the heat conductivity during a proposed sequence of years.

In polystyrene foams the conductivity increases with time due to the water takeup. This applies both to expanded and extruded polystyrene foams. For extruded polystyrene foam, it must also be added that the heat conductivity increases because of the cell-gas exchange, which continues for a long time. The heat conductivity of the extruded polystyrene foams of the qualities known so far is, however, always lower than the heat conductivity of the expanded polystyrene foams.

To determine a heat conductivity value of polystyrene foam for dimensioning, it is necessary to perform accelerated tests in the laboratory and long-term tests in the field. To achieve this, a procedure has been worked out that is now undergoing final adjustment in cooperation with the National Testing Institute in Sweden. In this procedure, the water takeup is studied when the vapour gradient is increased in comparison with the natural conditions. An extra splitting of the boards forces the cell-gas exchange to accelerate. Values from the laboratory and the field are compared. Through extrapolation it is now possible to determine the development of the heat conductivity over a longer time with the help of known theories of water takeup and cell-gas exchange. From the curves describing the changes in heat conductivity with time it is possible to evaluate a heat conductivity value for dimensioning, see Figure 13.

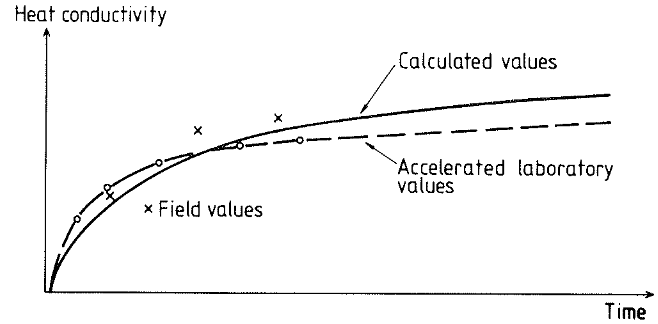

FIGURE 13 Variation of heat conductivity of polystyrene foam as a function of time due to moisture absorption and change in cell-gas content.

To assess the frost-insulating properties of a new and little-known material, a method of analysis is proposed by testing the materials in the laboratory on small test surfaces and eventually at natural field-test areas.

THE USE OF POLYSTYRENE FOAM ON ROADS IN SWEDEN

The main purpose of using polystyrene foam on Swedish roads is to counteract frost heave. As the frost heave in the north of Sweden can exceed 30 cm during an average winter, much more in an extremely cold winter, it is understandable that the frost protection measures must be of an efficient type. Insulation with polystyrene foam is one of them. According to the design table in Table 1, a standard insulation consists of a bearing course of 40 to 50 cm and a polystyrene layer of a thickness that depends on the thickness of the non-frost-susceptible layer underlying it. The thickness can be read off from the design table by starting with the average freezing index at the particular site, for example, 900 to 1,000 degree-days (°Cd). If the thickness of the non-frost-susceptible material under the foam layer is only 100 mm, the thickness of the foam should be 80 mm. But if the foam layer is to be placed on an old road surface and the road base thickness is 500 mm, the foam thickness can be reduced to 40 mm, with a saving in cost of the insulation material of 50 percent.

The thickness of the plastic foam layer in Table 1 is applicable for conditions where a uniform thickness of the insulation layer is appropriate. The most usual case is a road along which the frost-heave properties of the subgrade or the roadbase itself change irregularly. By dimensioning the foam insulation so that no detrimental frost heave arises even on those parts of the road where the heave potential is highest, longitudinal evenness of the road surface is achieved.

Difficulties caused by frost on Swedish roads become worse farther north because of cold winters and the high degree of frost susceptibility of the soils in the subgrade (see map and table on frost heave, Figure 2). The terrain that gives the most severe problem is that where the subgrade is made up of mixed layers with frost and non-frost-susceptible materials and where at the same time groundwater level is high. In this type of terrain, which is common in Sweden, insulation with polystyrene foam is used as an efficient frost protection measure.

Another field where insulation by polystyrene foam is used with success and is especially economically feasible is at culverts. Figure 14 illustrates how uneven frost heave can be counteracted. The figure gives the longitudinal section through a culvert in an ordinary road. The frost heave before and after the provision of the insulation is plotted. It is clearly demonstrated that insulation with plastic foam results in a smoother road surface.

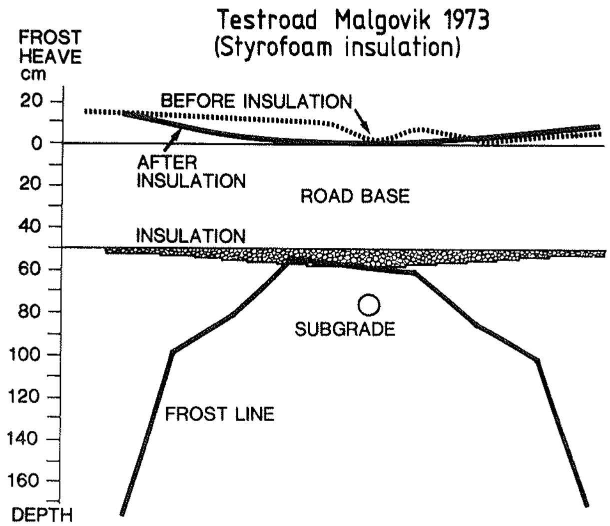

FIGURE 14 Insulation of culvert with polystyrene foam by double transitions.

Insulation with plastic foam at a culvert is achieved constructionally by tapering the foam layer. The same technique is also used as a transition when a conventional foam insulation along the road is to be terminated.

In the Swedish national road network every year, an area of about 150,000 m^2, which corresponds to a road length of 10 to 15 km, is insulated with polystyrene foam. This figure will certainly increase in the future, when the technique of designing and dimensioning has been further improved and the application of the insulation concept has been even better adapted in practice.

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