Icing Conditions on Different Pavement Structures

KENT GUSTAFSON

In 1976, Test Field Linköping 1976 was constructed at the National Swedish Road and Traffic Research Institute at Linköping. The object of the investigations at 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 icing risk potential of different road constructions. The investigations included road constructions representing both conventional uninsulated road pavements and constructions insulated with plastic foam, sulfur foam, expanded clay, and pelletized slag. The field was provided with instrumentation that automatically recorded, inter alia, the temperatures on and in the various road sections and in the air, the humidity, and the radiation balance. Investigations at Test Field Linköping 1976 were carried out over the winter seasons 1976-1977 to 1979-1980. A comprehensive review of the results is given. The climatic and road conditions in conjunction with ice formation are described, as well as examples of the variation in friction, surfacing temperature, etc., on the different road pavements in the winter. On the basis of these results, the relative icing risk potential of different road pavements has been determined.

Slippery conditions on roads in cold weather occur due to the interaction of climate and road construction. Climatic parameters such as air temperature, humidity, radiation balance, and amount of precipitation are significant for the formation of ice and snow. At temperatures below 0°C and when humidity is high, there is a risk, for instance, of hoar frost, which can give rise to slippery road conditions. Under other weather conditions, ice or snow may reduce skid resistance on the road surface, thus causing problems for road users.

The construction of the road and its surfacing plays an essential role in the formation of ice. Transfer of heat at the surface of the road is affected by the construction of the road and the road materials used. A certain section of a road may, for instance, become slippery more often than others because of differences in the construction of the road. Bridge decks, which have a lesser heat-storage capacity, cool down more rapidly than adjacent conventional sections of road. Similar conditions occur on roads with thermal insulation. The insulation layer retards the flow of heat upward, which gives rise, primarily in the autumn and winter, to more rapid cooling and ice formation. Investigations of skid resistance have been carried out by the National Swedish Road and Traffic Research Institute (VTI) on insulated roads and other roads (1), and the results showed that in many cases the road construction exerts a great influence on the occurrence of slippery conditions. Different types of conventional road construction exhibit differences in icing risk potential because of the differences in materials, such as sand, gravel, and ungraded crushed rock, that are used.

In the summer of 1976, a field, referred to as Test Field Linköping 1976, was constructed at the VTI at Linköping, Sweden. The object of the investigations at the test field was to make (a) a general study of the interaction between climate and road construction that results in slippery conditions in cold weather and (b) a particular comparative study of the icing risk potential of different road constructions. The investigation included both uninsulated and insulated types of road.

Investigations of road icing on different pavements were carried out at the test field over the period 1976-1980. The results from this four-year study have been published in VTI Report 216A (2).

ASPECTS OF THERMAL PROPERTIES OF ROAD-CONSTRUCTION MATERIALS

It is the energy balance and primarily the radiation balance that govern the variation of surface temperature on a road. The temperature of the road surface is affected both by climatic action on the surface such as radiation and precipitation and by heat exchange with the underlying soil strata. Chiefly by conduction, movement of heat takes place in the road structure to or from the road surface. The temperatures prevailing in the road structure depend, among other things, on road construction and the road materials used. The thermal conductivities and heat capacities of the materials have great significance for the variation of temperature on and in a road. For mineral materials the thermal conductivity largely depends on the density and water content but also on the conductivities of the constituent minerals. Materials of low density have lower conductivity owing to the fact that there are few points of contact where thermal conduction can take place. Increase in water content results in an increase in conductivity. Ungraded crushed rock of low density contains very little water and therefore has a lower thermal conductivity than, for instance, gravel or sand.

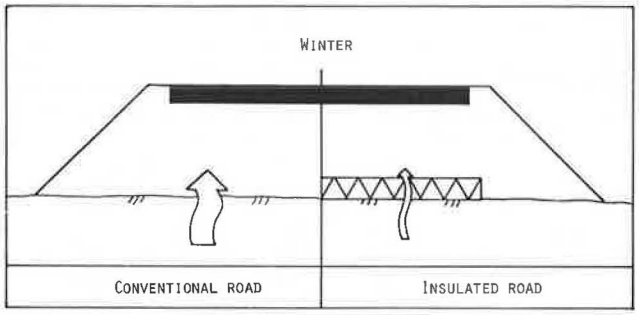
The effect on surface temperature of materials of relatively low thermal conductivity that are placed near the road surface varies somewhat depending on whether the energy balance is positive or negative. When the road is receiving energy, primarily from radiation, a low conductivity results in a smaller heat flow down into the construction, and the surface layer therefore warms up more and its surface temperature gets higher. On the other hand, when the road is emitting energy, the construction is cooled down more at the surface, owing to the fact that the upward heat flow, to compensate for the radiated energy, is retarded.

From the point of view of icing, the situation in conjunction with a negative radiation balance is of interest. For the same climatic stresses, a road pavement made up of, for instance, ungraded crushed rock will cool down more due to its lower thermal conductivity than will a pavement with gravel. A greater degree of cooling and the consequently lower surface temperature increase the risk of icing. The extreme example of the above reasoning is provided by materials of very low thermal conductivities, i.e., thermal insulation materials. Plastic foam is used for frost insulation of road pavements (3,4). Owing to the extremely low thermal conductivity of the material, $\lambda \sim 0.03$ W/mK, it cannot be placed too near the surface because of the cooling effect, which is schematically illustrated in Figure 1 (5). In winter when the energy balance is normally negative, the heat flow is directed upward. In an insulated road this flow is reduced, resulting in lower surface temperature conditions. The surface temperature also depends on the heat capacities of the pavement materials. When radiation is outward, the magnitude of cooling is dependent on the rate at which heat can be conducted up to the surface to compensate for the energy loss. The degree of cooling also depends on how much heat there is available, i.e., on the heat capacity. The available quantity of energy is mostly obtained from cooling of the material and from freezing of the

water present in the material. A moist and relatively fine-grained material, such as sand, has therefore a greater heat capacity than a coarser-grained material of lower water content, for instance, ungraded crushed rock and gravel.

For insulated road pavements, the material above the insulation layer is of the greatest significance. The greater risk of icing, generally entailed by the presence of an insulation layer, may be further accentuated if a coarse-grained and dry material such as ungraded crushed rock is placed above the insulation. A material of high heat capacity may, on the other hand, reduce the drop in temperature in cooling situations, which is beneficial from the point of view of icing.

Figure 1. Heat-flow conditions in conventional road and insulated road in winter.



STRUCTURE AND INSTRUMENTATION OF TEST FIELD

The test field was constructed in 1976 and consisted originally of 38 different road constructions. In 1978, four more sections were added to make a total of 42 sections. Each section has a surfacing area measuring 1.5x1.5 m², and the depth is 70-90 cm, depending on the construction. In order to prevent transfer of heat between the different sections, each section was insulated with 5-cm plastic foam at the sides. A conventional asphalt-concrete surfacing was laid over the test field. Figure 2 shows schematically the different road pavements. The following types of pavement were represented: (a) uninsulated conventional, (b) insulated with plastic foam at varying depths, (c) insulated with plastic foam of varying thicknesses, (d) insulated with plastic foam and including different materials in the courses above the insulation, (e) with surface dressing, (f) with rubber asphalt (Rubit), (g) insulated with sulfur foam, (h) insulated with pelletized slag, and (i) insulated with expanded clay.

The instrumentation at Test Field Linköping 1976

Figure 2. Pavement types at Test Field Linköping 1976.

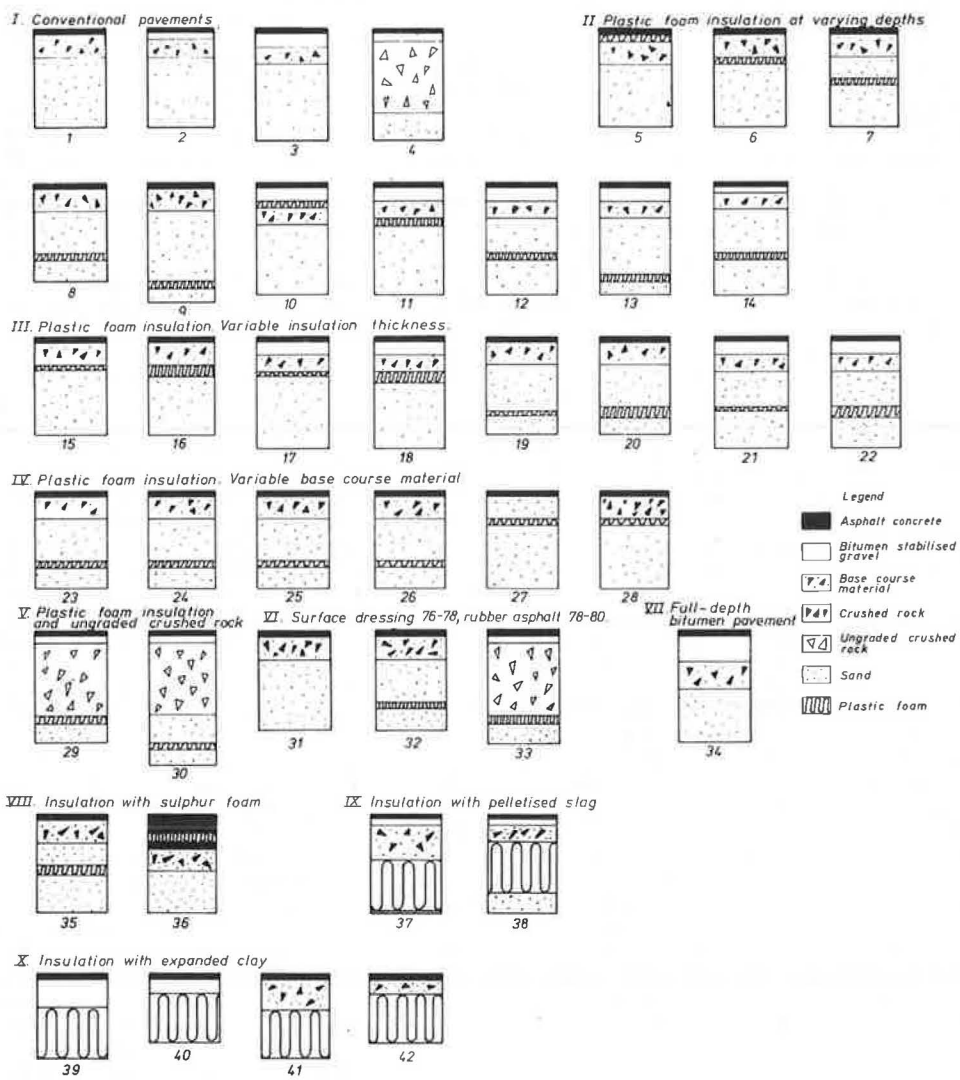
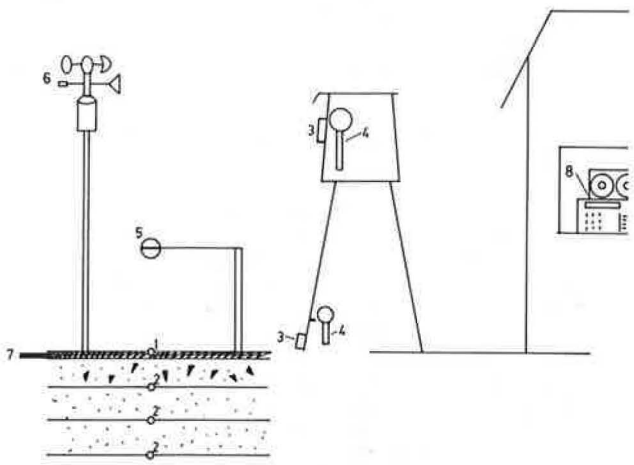


Figure 3. Instrumentation at test field.



includes sensors for the determination of temperature conditions on and in a road structure and climatic stresses on a road. The instrumentation is shown schematically in Figure 3.

The surface temperature (1, Figure 3) was measured on all sections with resistance temperature detectors of the PT100 type. The same type of temperature sensor was used for measuring the temperature at different levels in the road pavement and in the air (2 and 3, Figure 3). The air-temperature sensors were placed at two levels, 2.0 m and 0.1 m, above the surfacing and the relative humidity (4, Figure 3) was measured at the same two levels. It was therefore possible to determine the temperature and humidity gradients immediately above the surface.

The radiation balance or the net radiation (5, Figure 3) was measured with a radiation balance meter placed about 1 m above the field in order to minimize the background radiation, i.e., the thermal radiation from surfaces and objects outside the field. During parts of the four-year study, measurements of wind speed (6, Figure 3) and heat flow (7, Figure 3) in the pavement surface were also carried out. Temperatures and other measurements were recorded automatically every hour by a data-acquisition system (8, Figure 3).

During the measuring seasons the test field was kept under observation, especially when there was a risk of slippery conditions. The regional weather forecasts were used to assess this risk. On the occasions when the surface was slippery, the coefficient of friction was measured. Friction was measured during the winter seasons of 1976-1977, 1977-1978, and 1978-1979 with a portable skid-resistance tester. During the winter season of 1979-1980, however, a hand-drawn friction trolley developed at the VTI was used. In conjunction with measurements of friction, the road conditions for each section and weather conditions were recorded in a journal. During the winter any snow on the test field was removed as far as possible so that conditions would be similar to normal road conditions. No salt or other deicing chemicals were used.

ICING SITUATIONS

Slippery conditions at Test Field Linköping 1976 occurred on several occasions during the four winter seasons (1976-1980) during which the investigations were carried out. The degree of icing was usually very different among the sections of the field. The cause of this differential icing is of course the presence of the many different road pavements of variable thermal properties that are represented in the field. In certain weather situations, there is a difference in the degree of cooling of the different sections, and the surface temperatures are consequently different. It is these differences in surface temperatures that govern whether hoar frost or glaze will form or whether the road surface will remain dry. Some road pavement sections in the test field were found to be extremely prone to icing (for instance, Section 5, which has the insulation at the top), and these sections became slippery at times when roads are not usually expected to be slippery. On these sections, the surface became slippery much earlier in the autumn and was slippery more frequently during the winter season than is the case on more conventional road pavements. In Figure 4 an example of a typical cooling situation is illustrated. The net radiation, together with air, surface, and dew-point temperatures, has been plotted for November 17-18, 1977. The morning of November 18 had been preceded by clear cold weather that caused the test field to undergo considerable cooling due to radiation; i.e., there was a radiation-loss situation. Net radiation was practically constant during the night at about -90 W/m^2, which is near the maximum radiation loss that can occur in the autumn-winter period. As will be seen, there is a pronounced drop in surface temperature during the night, in some cases to below the dew point owing to the very high humidity at the time, which indicates that there is a risk of slippery conditions.

It is evident from Figure 4 that the differences in surface temperature have become very large between sections. In a radiation-loss situation of this type, the road pavement exerts a very great influence on the cooling process and thus on the surface temperatures. Different road pavements are cooled to different extents, and differential icing occurs. For instance, road conditions were different over sections 1, 5, and 28, the surface temperatures of which are plotted in Figure 4. It can be seen that the temperature of Section 5, with insulation at the top, and Section 28, with insulation near the surface and crushed rock above this layer, was below the dew point, whereas this was not the case in the uninsulated Section 1. Hoar frost is formed by direct transition, or sublimation, of water vapor in the air into ice crystals on the road surface, which has a surface temperature below 0°C and at the same time below the dew-point temperature. Hoar frost had consequently formed on Sections 5 and 28, whereas Section 1 was dry on the morning of November 18.

Another example of a situation in which the road pavement exerts a critical influence on the temperature on the surface and thus on the formation of hoar frost and ice is shown in Figure 5. The photograph shows the appearance of the test field on the morning of December 10, 1979. The radiation balance was insignificantly negative during the night prior to this icing situation, indicating that there was considerable cloud cover. During the night and morning the air temperature increased more than the surface temperature because of somewhat warmer and more moist air that came in over the area. The surface temperature was therefore in many cases lower than the dew point, and hoar frost covered several sections, as may be seen in Figure 5. In this case the construction of the road pavement had a decisive influence on the surface temperature and the formation of hoar frost. The greatest amount of hoar frost formed where cooling had been most intense. On some sections the surface temperatures were insignificantly lower or higher than the dew point, and very little or no hoar frost formed here

(judging from friction measurements and visual examination). This indicates that there is a risk of slippery conditions due to hoar frost when the surface temperature is lower than the dew point but that hoar frost is formed only when the difference between the surface temperature and the dew point is sufficiently great. The differential icing on the morning of December 10 may also be seen in Figure 6, in which the results of friction measurements are shown. (For section drawings, see Figure 2.)

Low friction was measured mainly on sections with the insulation placed high up, for instance, Sections 5, 6, 7, 10, and 11, and on sections that have coarse material near the surface, for instance, Sections 4, 29, and 30. However, the uninsulated Sections 1, 2, 3, and 34 have high values of friction, but this is also the case on the sections insulated according to Swedish specifications, namely, Sections 8, 9, 24, and 25.

It is evident from the above description and Figure 5 that the reason for the low friction on most sections is the thick deposits of hoar frost that had formed because of the low surface temperatures and the high humidity. It is also evident from the above that there is a very clear relationship between low surface temperatures and the development of slippery conditions. Road pavements that are very likely to have low temperatures in the winter--for instance, road sections containing coarse materials such as ungraded crushed rock near the surfacing or insulated road pavements in which the insulation is placed high in the structure--therefore also have the greatest icing risk potential.

EFFECT OF ROAD CONSTRUCTION ON SURFACE TEMPERATURE AND ICING RISK POTENTIAL

The surface temperatures and thus the icing risk potential of road constructions vary depending on differences in the structure of the road and the materials used. It has been shown that the surface temperature is of critical significance for the formation of ice, and, apart from the pavement construction, this is affected by the local climate, the color of the road surface, etc. Owing to the fact that the local climate and the other factors are the same for all the road sections at the test field, it has been possible to make a very thorough study of temperature variation in the different road constructions.

Uninsulated Road Constructions

In roads without insulation, it is the materials used in the road structure that govern the variation

Figure 4. Icing situation: surface, air, and dew-point temperatures and net radiation, November 17-18, 1977.

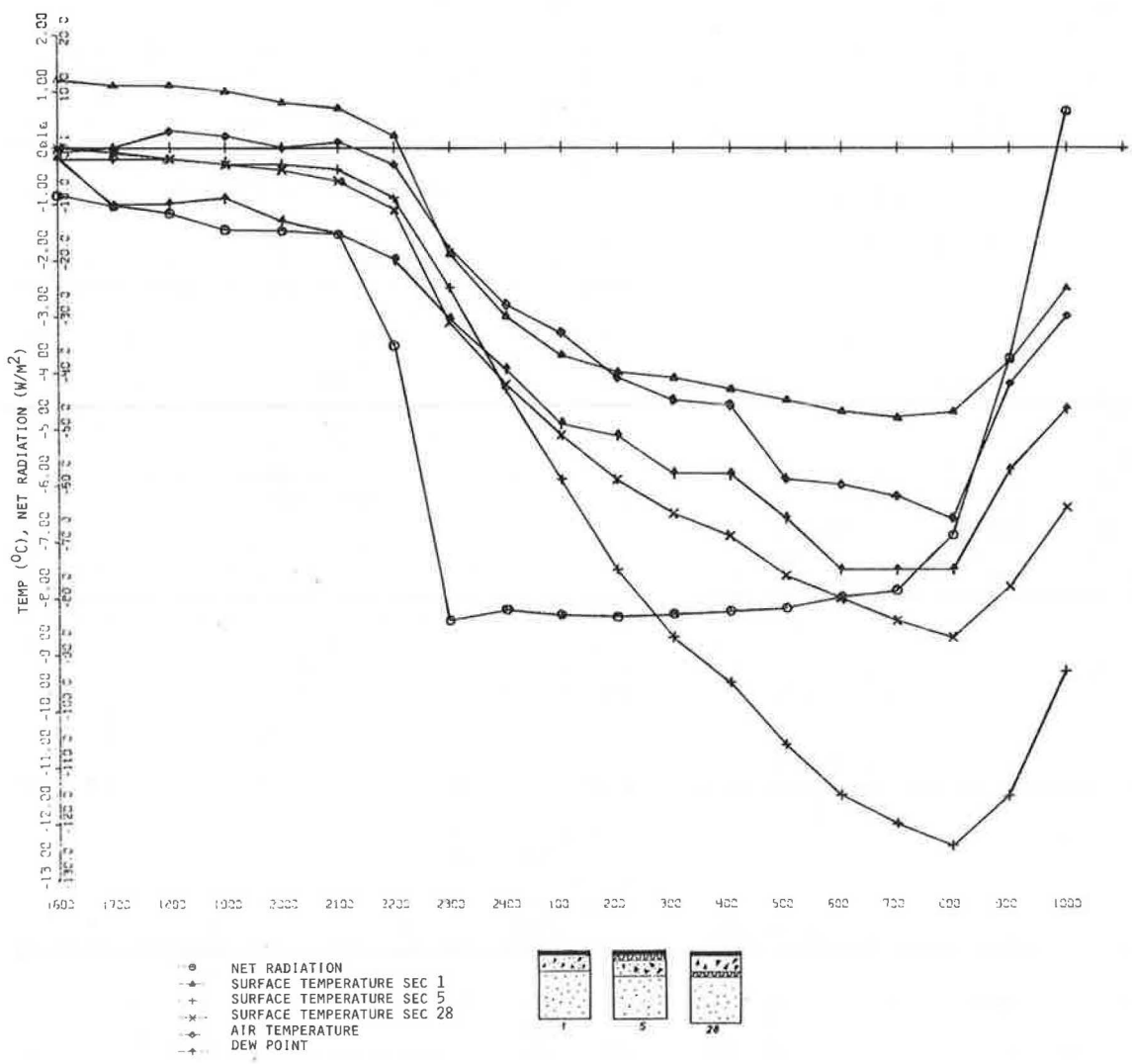


Figure 5. Test field, December 10, 1979, 10:00 a.m.

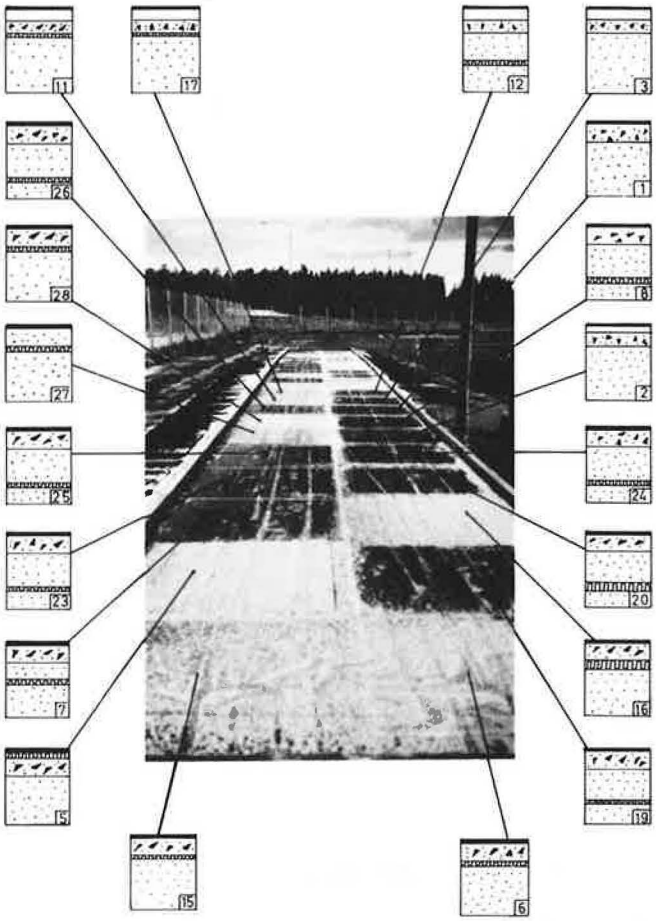
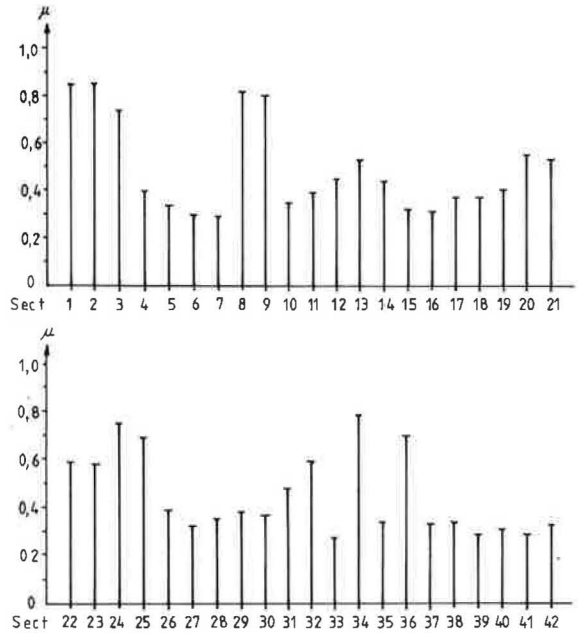


Figure 6. Friction at test field on December 10, 1979.



in temperature on and in the road and primarily in the courses nearest the surface. The thermal properties, thermal conductivities, and heat capacities of the materials are of great significance, and these properties in turn depend on factors such as density, water content, and mineral composition.

Figure 7 shows the variation in surface temperature on some uninsulated sections at the test field over the period November 17-18, 1977. The differences in surface temperature that can occur due to differences in the construction of the road can be seen extremely well. The differences between the sections are clearly marked, and agreement with the theoretical views is good.

Cooling was most intense in Section 4, which had an ungraded crushed-rock construction, as a result of which the minimum temperature during the night was much lower than that in the other sections. The cause of this greater cooling is the relatively low thermal conductivity and heat capacity of the ungraded crushed rock. In a cooling situation, the result of a low thermal conductivity is that upward flow of heat from the material courses located lower down in the pavement is retarded. The energy lost by radiation is compensated for only partially, and a temperature drop at the surface is the consequence. The low heat capacity of the ungraded crushed rock, which is due, inter alia, to its low water content, also contributes to the more extensive cooling, since, when the heat capacity is low, there is little energy available in the material to compensate for losses in energy, and this also contributes to the lower surface temperature.

When a pavement with a base course of only gravel (Section 1) is compared with one in which the base course includes bitumen-stabilized gravel (BG), it is seen that the surface temperature of the latter is a little lower overnight. Owing to the somewhat lower thermal conductivity and heat capacity of BG, the surface temperatures of Sections 2 and 34 are a little lower than that of Section 1. When the BG course is thicker, cooling is greater and the surface temperature lower. The highest temperature overnight was measured in Section 1 of gravel construction, which is due, inter alia, to the higher water content of gravel in comparison with that of ungraded crushed rock or BG.

Insulated Road Constructions

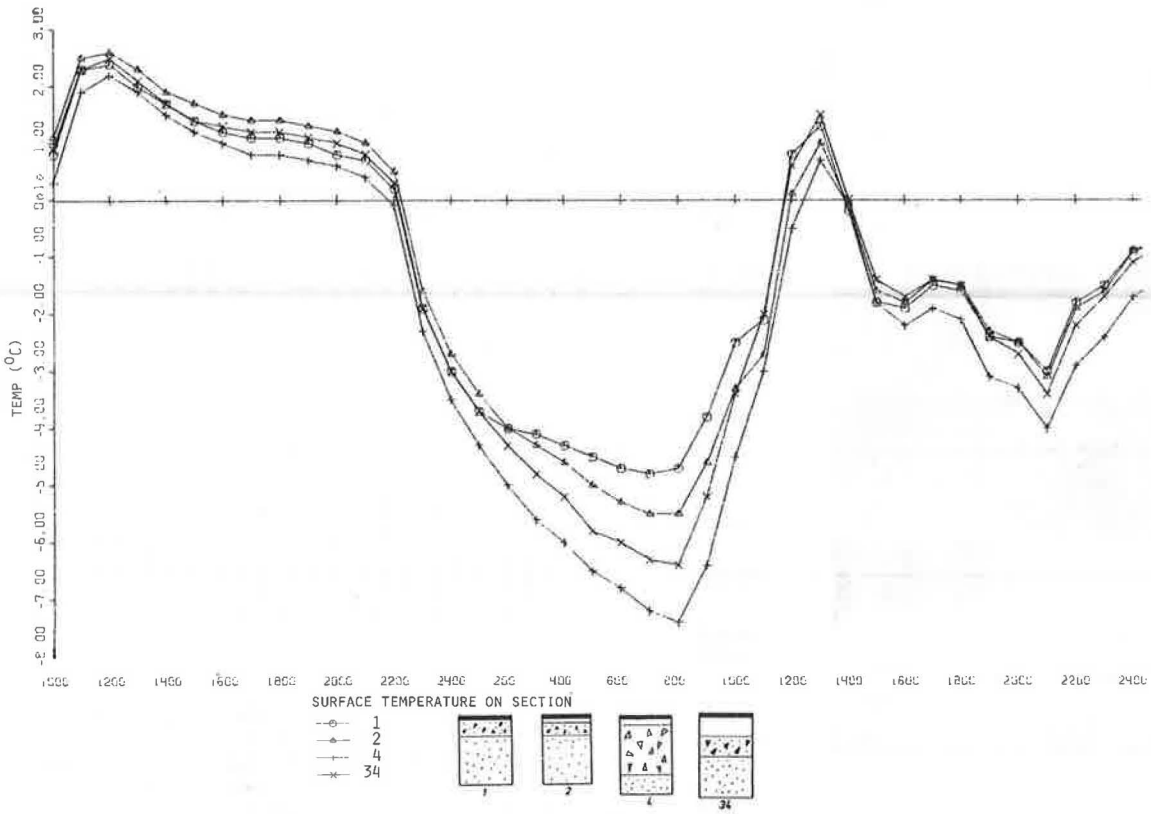
The presence of a layer of thermal insulation affects both upward and downward flow of heat in the road structure. Surface-temperature conditions in an insulated road are therefore affected by a number of factors, such as the depth at which the insulation is laid, the thickness of the insulation layer, and the material or materials in the course or courses above the insulation. The thermal conductivity λ varies for different insulating materials, and the type of material is therefore also significant with regard to temperature oscillations in the road structure.

Depth of Insulation Layer

The depth at which the insulation is placed has been shown to have a critical influence on surface temperature and therefore also on the icing risk potential. The results of the icing investigations at the test field clearly show that the icing risk potential decreases as the distance between the top of the insulation and the top of the surfacing increases. When the layer of plastic foam is laid deeper in the road pavement, the heat-storage capacity of the courses above the insulation increases, and the effect of the insulation thus decreases.

The distributions of surface temperature in some uninsulated (Sections 1 and 4) and some insulated (Sections 5, 7, and 8) road pavements during the

Figure 7. Surface temperature on uninsulated Sections 1, 2, 4, and 34, November 17-18, 1977.



winter seasons of 1977-1980 have been compared and are given in Figure 8. Sections 5, 7, and 8 are insulated with 5 cm of plastic foam at a depth of 4 cm (Section 5), 35 cm (Section 7), and 50 cm (Section 8). The left-hand bar for each section indicates the number of hours during these three winter seasons when the surface temperature was lower than -10°C. The middle bar indicates the number of hours when the temperature was lower than -5°C and the right-hand bar, when it was lower than -2°C. The distribution in Section 1 has been taken as the reference, and the amount of increase in the other sections has been shaded and indicated as a percentage. When Sections 5, 7, and 8 are compared, it is seen that the proportion of low surface temperatures drops when the insulation layer is placed lower down in the pavement structure. Extremely low surface temperatures have been measured in Section 5, where the insulation is placed at the top. Compared with the uninsulated Section 1, which has a gravel pavement, surface temperatures are lower in insulated sections, whereas Section 4, which is constructed with ungraded crushed rock, has a surface temperature distribution that is practically the same as that of Section 7, in which the insulation is placed 35 cm below the surface.

In other words, the results of surface-temperature measurements show that it is not generally true that the icing risk on insulated roads is greater than that on uninsulated roads. In comparison with uninsulated gravel pavements of the Section-1 type, insulated roads generally have a higher icing risk potential. The degree of this increase is naturally dependent on factors such as depth of insulation, insulation thickness, and base-course material. On the other hand, an uninsulated ungraded crushed-rock pavement of the Section-4 type has an icing risk that is greater than that of several insulated road pavements.

Thickness of Insulation Layer

The thickness of the insulation layer has some influence on the temperature at the top of the surfacing, and this influence is greatest when the insulation is placed high up in the pavement. In sections with thicker insulation, cooling is more rapid, and the lowest minimum temperatures overnight occur in these.

At a lower depth the effect due to thickness of insulation is less. The temperature differences between the different sections are small, and the rates of cooling are very similar. The courses above the insulation damp the temperature oscillations, and the effect of the insulation material is less pronounced.

It has been found in the course of investigation at the test field that in sections with a gravel base course in which the insulation is placed high up in the pavement, an increase in the thickness of the insulation gives rise to a slightly higher icing risk potential. The temperature distribution during the winter showed that a thicker insulation caused a slight drop in surface temperature and thus also gave rise to a greater number of hours of slippery conditions. If, for instance, an examination is made of the number of hours when the surface temperature was lower than -2°C during the winter seasons 1977-1978 to 1979-1980, it is seen that Section 16 (with 8-cm insulation at a depth of 20 cm) had about 10 percent more hours of slippery conditions than Section 6 (5 cm) and about 11 percent more than Section 15 (3 cm).

Different Materials Above Insulation Layer

It has been found that the materials nearest the surfacing have a great significance for icing risk potential in uninsulated roads but perhaps an even

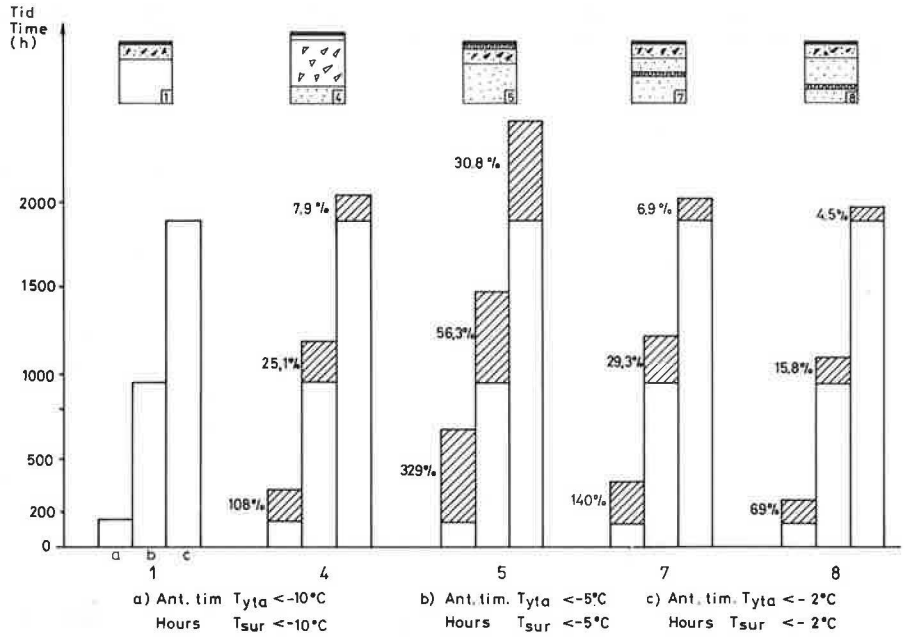


Figure 8. Surface-temperature distributions for Sections 1, 4, 5, 7, and 8 during winter seasons 1977-1978 to 1979-1980.

greater significance in insulated roads. The unfavorable effect that an insulation layer has on icing risk potential may be reduced or further accentuated depending on the choice of material in the courses above the insulation. At the test field, the effect of materials could be investigated by placing materials of such different properties as sand, gravel, and ungraded crushed rock above the insulation.

Sections 8 and 23-26 are all insulated with 5-cm plastic foam at a depth of 50 cm, but they have different base-course materials. Sections 23 and 24 have a fine-grained base-course material and Sections 25 and 26 have a coarse-grained material, whereas Section 8 could be said to have a normal base-course gravel, i.e., between the fine and coarse-grained materials.

The distributions of surface temperature during the winters 1977-1978 to 1979-1980 have been calculated for the sections at the test field, and Figure 9 gives the results for Sections 23 (fine-grained base course), 8 (normal), and 26 (coarse-grained). The explanation of the different bars is the same as that for Figure 8. In Figure 9, the increase in the number of hours in relation to Section 23 has been shaded and indicated as a percentage. As will be seen from Figure 9, Section 26 has evidently had the largest proportion of low surface temperatures. Owing to the coarse-grained base course of low water content, the icing risk potential increases and is of the same magnitude as that in a section constructed with a finer-grained base course in which the insulation is placed higher up (for instance, Section 7 with 35 cm between surfacing and insulation).

The effect of an extremely coarse material, ungraded crushed rock, above the insulation layer has also been studied. Sections 29 and 30 are insulated at 60 and 80 cm, respectively, below the surface (i.e., they satisfy the Swedish construction specifications) and have a thick course of ungraded crushed rock above the insulation. During the seasons when the icing investigations proceeded, icing occurred more often and was more extensive on these sections than on all other uninsulated road types. On an insulated ungraded crushed-rock pavement the icing risk potential is reduced somewhat if the insulation is placed at a very great depth in the pavement. However, a pavement such as Section 30 in which the insulation is at a depth of 80 cm below the surface nevertheless exhibits a greater risk than Section 4, which is the uninsulated road section of the most unfavorable icing risk properties.

CONCLUSIONS

With the aid of the road-icing investigations, and particularly the measurements of surface temperatures and friction and observations of road conditions that were carried out at Test Field Linköping 1976 over the period 1976-1980, it has been possible to estimate the relative icing risk potential of different types of pavements. The icing risk potential of the different road constructions at the field has been ranked according to a five-point scale in which 1 signifies the lowest icing risk potential and 5 the highest. The relative icing risk potential is given in Figure 10, and the following summary may be made with regard to the icing risk potential of different road pavements.

Of the uninsulated road pavements, those incorporating ungraded crushed rock obviously had the greatest icing risk potential owing to the relatively low thermal conductivity and heat capacity of the crushed-rock material. The differences among the other uninsulated pavements are relatively small. However, thicker courses of bitumen-stabilized gravel produce a somewhat elevated icing risk in relation to a pavement incorporating a gravel base course.

The depth at which the insulation is laid has a critical influence on icing risk potential. Roads with the insulation placed near the surface have a very high icing risk potential. If the insulation is laid 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 insulated in conformity with Swedish specifications, i.e., 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.

Figure 9. Surface-temperature distributions for Sections 23 (fine-grained base course), 8 (normal), and 26 (coarse-grained) during winter seasons 1977-1978 to 1979-1980.

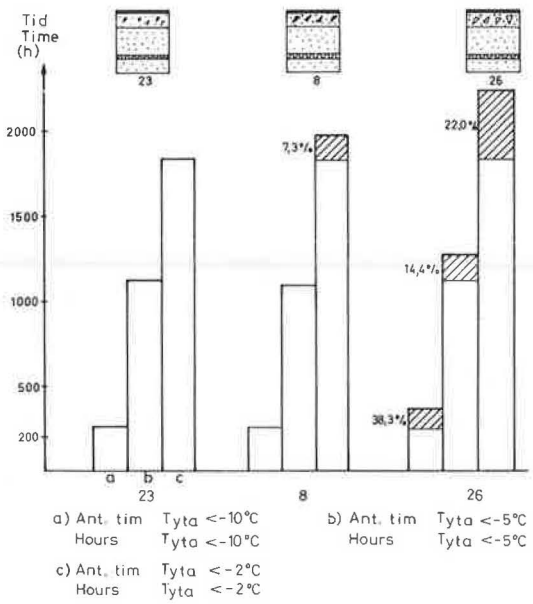
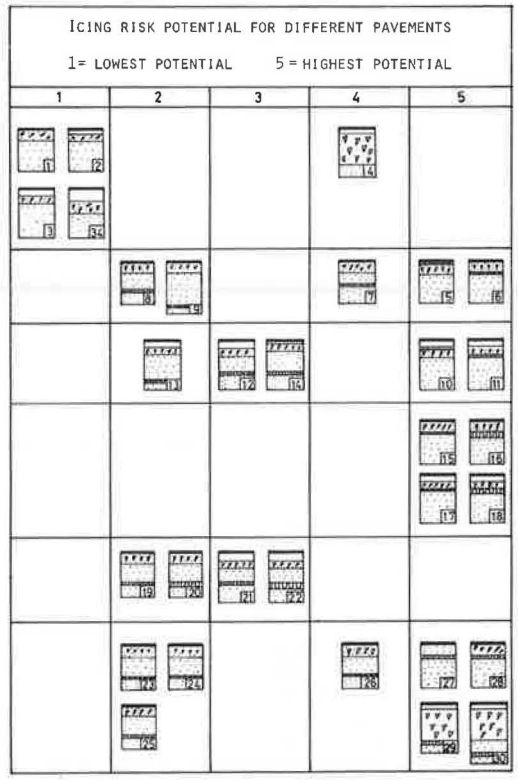


Figure 10. Icing risk potential of road pavements represented at Test Field Linköping 1976.



When insulation is laid high up in the road structure, the thickness of the insulation layer has a certain, but comparatively small, effect on icing risk potential, whereas the significance of the thickness is even smaller when the insulation is at a greater depth. Thicker insulation layers involve a somewhat higher risk of icing than thinner layers.

In the case of road types provided with thermal insulation, the materials in the course above the insulation have great significance with regard to the occurrence of slippery conditions. Pavements containing coarse and relatively dry materials such as ungraded crushed rock and coarse-grained base-course material have a higher icing risk potential than roads containing finer-grained materials of greater water content, such as fine-grained base-course material and sand.

REFERENCES

1. K. Gustafson. Halka på värmeisolerade vägar: II. Undersökningar vid provvägarna Lasele 1972 och Lasele 1973, utförda hösten 1977. (Road Icing on Thermally Insulated Roads: II. Investigations in the Autumn of 1977 at the Test Roads Lasele 1972 and Lasele 1973, in Swedish.) National Swedish Road and Traffic Research Institute, Linköping, VTI Meddelande 109, 1978.
2. K. Gustafson. Road Icing on Different Pavement Structures: Investigations at Test Field Linköping 1976, over the Period 1976-1980. National Swedish Road and Traffic Research Institute, Linköping, VTI Rept. 216A, 1981.
3. R. Gandahl. Road Insulation with Polystyrene Foam. National Swedish Road and Traffic Research Institute, Linköping, VTI Rept. 180, 1979.
4. R. Gandahl. Plastic Foam Insulation of Roads: Frost Resistance Capacity, Partial Insulation and Frost Heaving, Special Transitions, Icing, and Economy. National Swedish Road and Traffic Research Institute, Linköping, VTI Rept. 214A, 1981.
5. Frost i Jord, Vol. 17, 1976.

Publication of this paper sponsored by Committee on Winter Maintenance.

Effect of Moving Traffic on Fresh Concrete During Bridge-Deck Widening

HOWARD L. FURR AND FOUAD H. FOUAD

Traffic in lanes adjacent to a deck that is being widened or reconstructed causes deflections and vibrations in the fresh concrete deck. A study of the effects of these disturbances in concrete decks is reported here. Decks in service for years were inspected for signs of deterioration; deflections and vibrations were mea-