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# On the increasing danger of frost damage to our highways

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**Publisher's version / Version de l'éditeur:**
https://doi.org/10.4224/20331473
*Technical Translation (National Research Council Canada); no. NRC-TT-568, 1955*

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# PREFACE

Due to the extremely cold climate experienced in many areas of Canada coupled with the vast network of highways, the problem of frost damage is of prime importance. The study of ground temperatures and frost action was therefore one of the first to be initiated by the Soil Mechanics Section of the Division of Building Research.

Since the ratio of highway mileage to population served is so great in Canada it is impossible, except for main arteries, to entirely eliminate the use of frost-susceptible soils. A means of evaluating the degree of frost danger, as outlined in this paper, is therefore particularly important.

This translation will make a valuable contribution to the information available in English on this subject. Our thanks to Mr. D. Sinclair are here recorded for the translation.

Ottawa
October, 1955

N.B. Hutcheon,
Assistant Director.

NATIONAL RESEARCH COUNCIL OF CANADA

Technical Translation TT-568

Title: On the increasing danger of frost damage to our highways.

(Über die zunehmende Gefahr der Frostschäden für unsere Verkehrswege).

Author: Lothar Schaible.

Reference: Die Bautechnik, 31 (9): 287-292, 1954.

Translator: D.A. Sinclair, Translations Section, N.R.C. Library.

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# ON THE INCREASING DANGER OF FROST DAMAGE TO OUR HIGHWAYS

## 1. Frost-Susceptible Soils

The extent of frost heave occurring for a given frost penetration in a given soil is frequently regarded as the criterion of danger from frost. This, in turn, depends on the thickness of the ice lenses. Since ice lens formation normally increases with increasing fineness of the soil, we would expect greater frost danger from clay soils or soils containing a large proportion of clay than from silty soils. However, in view of the low water-permeability of the clays, soils with a high proportion of silt are especially dangerous. Despite less tendency towards ice lens formation, these soils absorb water rather quickly, and in doing so easily reach and exceed the liquid limit. However, in contrast to most frost criteria, whereby only clays and silts (0.002 to 0.02 mm.) are described as dangerous, the investigations of Beskow in Sweden and Dücker in Germany have shown that ice lenses can also form in cohesionless soils. According to Beskow's investigations, the upper grain size limit for uniformly-graded soils is about 0.1 mm. Dücker obtains only 0.05 mm. as the maximum grain size for ice lens formation in uniformly-graded quartz sand. In this connection Ruckli of Switzerland has already pointed out that a period of four hours' freezing is too brief for such tests.

As confirmed satisfactorily by the present research, a great many cases of frost damage can be attributed largely to very fine sand. Therefore it is doubtless necessary to include this grain classification (0.02 to 0.1 mm.) among the soil types which are dangerously susceptible to frost.

Calcareous soils appear to be very susceptible to frost, as indicated by the numerous cases of frost damage occurring in Jurassic and fossiliferous limestone regions. According to Ruckli, a large lime content appears to render clay somewhat more water permeable and less plastic. Similarly, the presence of humus in the soil increases its susceptibility to frost owing to its rapid absorption of large quantities of water accompanied by a sharp decrease in bearing capacity.

If soils are considered according to their frost susceptibility it is apparent from the varying degree of frost damage that no hard and fast line exists between soils that are safe and those that are dangerous, but on the contrary there is a large intermediate group of frost-sensitive soils in which moderate damage is apt to occur.

The vast majority of frost damage cases, and almost all serious ones, however, occur not during frost heave and ice lens formation, but rather during the thaw, i.e., they are really thaw damage. Whereas frost heave is a comparatively slow process, taking weeks and proceeding with relative safety and full bearing capacity, settlements due to thawing are much quicker, requiring only a few days and sometimes only hours. Rapid thawing of the ice lenses liberates the excess water in one layer of soil after another causing them to become plastic or even liquid, so that their bearing capacity is greatly impaired. It is in just this period of minimum bearing capacity that heavy traffic becomes destructive. Beneath the traffic lane a highly porous packed-base or crushed-rock reinforcement is pressed down into the softened subgrade, so that simultaneously with decreasing roadbed strength we get increasing frost damage in the form of cracks, depressions and finally cave-ins (Fig. 1a). Closed constructions, such as concrete pavements, at this time show their great superiority, since no permeation of the base course with soft soil with consequent weakening of the roadbed, is possible. However, even more important than the flexibility of the concrete pavement is its bending strength, which should be great enough to bridge the soft subgrade to a large extent. When the bending strength of a concrete surface no longer suffices, single cracks or groups of cracks may occur in concrete slabs, but depression or collapses will be totally absent (Fig. 1b). From these considerations it may confidently be said that frost danger depends less on the extent of the frost heave than on the bearing capacity of the subgrade during the period of thaw. The traffic requires roads whose bearing strength will change little under varying weather and load conditions. Therefore, all efforts must be concentrated on the maintenance of this bearing strength.

## 2. Secondary Frost Damage

Most cases of frost damage are obviously due to influences of the subgrade. These will therefore be termed primary frost damage. However, a second small group exists which can be attributed to inferior building materials or poor workmanship. Inferior building materials include stones which weather rapidly or which have insufficient bonding agents and thus crumble under traffic. However, the term may also refer to the popular but dangerous puddling method, where artificial wear of the broken stone matrix in addition to a softened subgrade, may result from too heavy a roller and overabundant sprinkling. In both cases frost-susceptible fines may be produced from the broken rock. Also, dirt can be washed into the roadway through open joints and cracks. Such damage must be termed secondary frost damage. From 23 samples taken from old roadbeds consisting of fossiliferous limestone, Jurassic limestone and moraine gravel and the like, the following fine-grain components were found:

Summary of frost-susceptible components in old, much-travelled broken stone surfaces

Proportions in % referred to

| | (a) entire soil: coarse silt + fine silt + clay over 20% | 10-20% | below 10% | | (b) fine soil: coarse silt + fine silt + clay over 20% | 10-20% | below 10% | |
|---|---|---|---|---|---|---|---|---|
| No. | 14 | 7 | 2 | (total 23) | 22 | 1 | - | (total 23) |
| in percent | 61% | 30% | 9% | = 100% | 96% | 4% | - | = 100% |

The high proportion of fines in these much-travelled gravel surfaces appears even greater when this is referred to the fine soil only. On this basis 22 out of 23 = 96% frost-safe crushed limestone surfaces have acquired frost-susceptible fines and the twenty-third has become frost-sensitive as well, simply in the course of time.

One need only see these softened and yielding crushed stone surfaces, full of cracks and depressions during the disappearance of the frost in spring, to recognize the preponderant effect of the fine soil compared with the inert rock structure.

In five new silty-sand road constructions investigated (fossiliferous and Upper Jurassic limestones), four of them, immediately after rolling, showed a fines content sufficient to make them susceptible to severe frost damage, and in the fifth case the fines were sufficient to cause moderate frost damage. It is not surprising, therefore, that frost cracks sometimes appear in new surfaces on comparatively frost-safe soils even in the first years.

For example, the grain composition of two such broken Jurassic limestone surfaces on the heavily travelled Federal Route No. 10 at Ulm is as follows: (Table on next page).

Since all the samples were taken from places which had suffered obvious frost damage and which during the breakup period show low bearing capacity and severe deformation, this prominent role played by the fines or soft soil **despite the presence of a large proportion** of broken stone and gravel in the structure should be particularly emphasized.

In the case of ungrouted stone pavements the pure subgrade sand has been darkened by the seepage of dirty water, and this has resulted in light to moderate frost damage. Bituminous surface coatings with numerous cracks, depressions

Grain composition of a frost-susceptible Upper Jurassic limestone surface

| Federal Route 10 Distance from Stuttgart km. | F-R=P | Coarse stone 50/30 in mm. | Medium stone 30/15 in mm. | Fine stone 15/2 in mm. | Sand 2/0.1 in mm. | Fine sand | Silt | Clay | Percentage of fine grain referred to total sample | Percentage of fine grain referred to soil under 2 mm. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | in % | | | | | | | | |
| 10.850 | 12-9=3 | 16 | 11 | 26 | 26 | 8 | 10 | 3 | 21 | 43* |
| 10.851 | 13-9=4 | 14 | 15 | 23 | 25 | 8 | 11 | 4 | 23 | 48* |

*Heavy frost damage

or porous places show similar results due to the retention of dirt in the cracks, since these dirt-filled cracks cannot close up again during thermal expansion in the summer, which may even lead to scaling.

## 3. Summary of Results

3.1 Frost damage related to location in the terrain. From the point of view of frost damage the location of the road in the terrain plays an important part. From a large series of completed investigations the following results are given:

Frost damage related to grade conditions

| Kind of road | No. | Longitudinal grade | | No. of pronounced hilltops | No. of pronounced depressions |
|---|---|---|---|---|---|
| | | 0-3% | over 3% | | |
| Highways | 167 | 136 | 31 | 25 | 18 |
| Autobahns | 26 | 16 | 10 | 5 | 2 |
| Total | 193 | 152 | 41 | 34 + | 20 = 54 |
| Percent | 100% | 79% | 21% | 28% | |

This table shows that most severe frost damage (152 = 79%) occurs on stretches of road where the grades are slight. 54 = 28% occurred at comparatively prominent elevations or depressions, thus accounting for a greater proportion than the stretches with longitudinal grade greater than 3%. In the latter case ground water plays an essential part. However the location of the particular road cross-section is even more important.

Frost damage related to the road cross-section

| Kind of road | No. | Level with terrain | Slopes | Cuts | Embankments |
|---|---|---|---|---|---|
| Highways | 167 | 62 | 51 | 31 | 23 |
| Autobahns | 26 | 7 | 6 | 14 | 2 |
| Total | 193 | 69 | 54 | 45 | 25 |
| Percent | 100% | 36% | 28% | 23% | 13% |

This comparison shows that the greatest number of cases, 36%, occur on stretches which are level with the terrain. Next come the slopes with 28%, the two together accounting for 64% of the damage. The number of slopes, 54, at first appears rather high, but this is due to the hilly nature of the region investigated in southern and central Germany. In flat country the number of slopes would be reduced in favour of the terrain-level stretches, but this would not affect the overall relationship. On the other hand, the cuts, with 23%, show comparatively few cases of damage, while the proportion accounted for by the embankments, with 13%, is again considerable - often showing troughs like those illustrated in Figs. 4 and 7.

3.2 Frost damage in relation to drainage. The decisive part played by water in the production of frost damage has already been described. Drainage of the road surface, for road preservation and traffic safety, is carried out mainly by creating flat lateral slopes (crowning) of 1.5 to 2.5%. As a result, when the longitudinal grade is rather steep (3 to 6%), water from precipitation is apt to run too far along the roadway or along the edge. Hence, where precipitation is heavy much damage occurs along the side and central strips. Furthermore, a considerable amount seeps into the joints of stone and concrete pavements or the cracks and depressions of bituminous surfaces, resulting in dangerous soft spots or internal erosion of the subgrade, and also in silting from the top down. It has also been found that the wide, flat autobahn side ditches only 20 cm. deep are inadequate because they fill up with soil too rapidly. They should have a minimum overall depth of 40 cm. This would also take care of lateral drainage of the base course (Fig. 2).

Underground drainage is still less satisfactory, especially in new construction where the builder almost always tries to adapt the lateral slope of the subgrade to that of the road surface. However, when the longitudinal grade is comparatively steep this is a very dubious practice, since seepage water will follow the direction of greatest slope. In such cases, therefore, the lateral slopes of the subgrade should be made larger, in order to get the seepage water as rapidly as possible away from the roadway. In the case of bases endangered by frost and without frost protection, underground drainage soon becomes impossible owing to compression of the subgrade (Fig. 3) and this further increases the frost damage. The following lateral slopes have been found necessary in the subgrade.

| Necessary minimum lateral slope in the subgrade | For a longitudinal road grade of |
|---|---|
| 2.5% | 0 to 3% |
| 3% | 3 to 5% |
| 4% | 5 to 8% |

For a very wide subgrade this minimum lateral slope must be increased still further.

3.3 <u>Frost damage in relation to water conditions.</u> The following table showing the water conditions encountered at individual places of damage, is highly instructive:

| Kind of road | Number of damaged places | Surface water table | Ground water table | Perched water table | Precipitation |
|---|---|---|---|---|---|
| Highways | 167 | 9 | 27 | 72 | 59 |
| Autobahns | 26 | - | 2 | 15 | 9 |
| Total | 193 | 9 | 29 | 87 | 68 |
| Percent | 100% | 5% | 15% | 45% | 35% |

At first glance the high proportion of perched water tables, 45%, is surprising, but this is due to the fact that the region investigated was predominantly hilly and mountainous. During the last few years, which had abundant precipitation, many cases of perched water tables have recurred after the preceding dry years. They are particularly visible and effective during the time of thaw, whereas in summer for the most part they recede sharply and in dry years they vanish altogether. Fundamentally, however, perched water is simply precipitation which reappears at the surface after flowing underground for a short distance. At high locations, in regions which have abundant precipitation or which are highly permeable (limestone or sandy region), the precipitation generally plays the decisive role.

In contrast to earlier ideas, it is clear that the precipitation from above, as well as water seeping in from the surface and from the side, has a great deal more to do with the water content of the soil than the water sucked up from below by capillary action. Where there was a distance of more than 1.50 metres between the water table and the roadbed no danger due to capillary water could be discovered (Fig. 4). As the investigations have shown, most cases of severe frost damage can be attributed to water seeping in from the surface or from the side. At a number of damaged places the rapid seepage of rain and thaw water, through cracks, seams and depressions on the surface of the road, was observed in considerable amounts per day (Fig. 5), and the same was true of water entering from the ditch on the uphill side in slope sections and from wet side and middle strips (Fig. 6).

Another perfect example of the effect of water from above is shown by the overpass of Federal Route No. 10 at Dornstadt above the Stuttgart-Ulm autobahn built in 1936. In the high terrain with no underground water, the autobahn engineers had built up the 150 to 200 metre-long bridge approaches out of tertiary marl which is highly susceptible to frost, and over this, without any frost protection, they laid a roadbed 25 cm. thick with a treated surface (Fig. 7). Since the year 1948 there has been increasing frost damage about half way up each ramp, primarily along the edges. All the moisture penetrating the bridge approaches comes from the surface water running down the ramps and from the bridge itself, flowing along the top shoulder where the change of slope occurs. Although the precipitation has been comparatively light, nevertheless, over a period of fifteen years this, together with the heavy traffic, has caused the softening of the subgrade to spread throughout the entire roadbed and considerable frost damage has resulted.

3.4 <u>Frost damage related to the width of the roadway and the thickness of roadbed.</u> Our modern roads suffer from two main defects: their inadequate width and depth. These inadequacies become particularly noticeable in places which are exposed to frost damage. A narrow roadway is endangered, of course, by an excessive traffic load. However, too shallow a roadbed is even more detrimental. From investigations of frost-susceptible highways the following picture has emerged:

Roadbed thicknesses and their properties

| Damaged locations | Roadbed depth | | | | Roadbed quality | | |
|---|---|---|---|---|---|---|---|
| | less than 20 cm. completely inadequate | 20-30 cm. inadequate | 30-45 cm. adequate | Above 45 cm. good | Inadequate | Adequate | Good |
| Number 167 | 26 | 50 | 76 | 15 | 152 | 15 | - |
| Percent 100% | 16% | 30% | 45% | 9% | 91% | 9% | - |
| | 46% | | | | | | |

Thus half of all the places where damage occurred (46%) are eliminated just because of their inadequate depth, but practically speaking this includes all of them when we take into account the state of the roadbed encountered. Nothing but greatly weathered and pulverized stone base and gravel courses were found and some which were largely penetrated by the frost-susceptible subgrade. It is only a question of time before the remaining 9% will attain this unsatisfactory state.

3.5 Frost damage related to roadway surfaces. Ordinary crushed rock surfaces and unsealed stone pavement surfaces may be regarded as intrinsically water permeable. Considerable seepage occurs here even under normal precipitation conditions, and after frost heaving, which always opens the seams of such surfaces to a certain extent, the seepage becomes greater. The proportion of the area taken up by the seams in pavement surfaces, related to the total area, is shown by the following figures:

| Road surface | Joint area per square metre | |
|---|---|---|
| | (a) New surface | (b) Old surface |
| Large paving blocks (15 × 15 cm.) | 14% | 28% |
| Small paving blocks (8 × 10 cm.) | 13.2% | 33% |

With such considerable receptivity to water from the surface it is not surprising if unsealed stone pavement surfaces with humps and depressions showed themselves particulalry susceptible to frost damage. However, most of our modern roadways are furnished with bituminous coatings from simple surface treatment up to the heaviest asphalt-tar concrete. In a good state of repair these flexible surfaces remain impermeable to water from above, but not from the shoulders and ditches (Fig. 6). If the frost-heaved roadways are rapidly and unevenly depressed again by the traffic during the thaw, cracks, depressions and displacements occur through which considerable water can penetrate. On the other hand, a considerable quantity of water liberated by thawing rises to the surface under the traffic (Fig. 8). Light surface treatments are particularly susceptible in this respect, and if they are not properly maintained show considerable spreading and porosity associated with a reduced grain size of the soft gravel. Of course, heavier surfaces are just as poorly protected against frost damage, although very flexible thick pavements can overcome these effects for a time (Fig. 9). Unlike the elephant-skin formation which occurs in treated surfaces, heavy surfaces show frost damage in the form of a random mosaic with wide zones of cracking (Fig. 10). With the occurrence of large depressions and displacements severe damage progresses rapidly and soon leads to fundamental disturbances. Concrete surfaces, distributing their pressures over wide areas of the subgrade, possess great advantages in this respect especially as their closed structure permits no penetration by a softened subgrade (Fig. 1b). Only crack formation and step formation acts detrimentally here allowing water to get into the subgrade and soften it in the vicinity of the seams.

3.6 <u>Frost damage in relation to side strips.</u> Side strips are dangerous collectors of water, since in addition to the water running into them they have to accommodate the run-off water from the impermeable surface. From there the water can get under the edges of the roadway, so that the latter are depressed by the traffic to produce longitudinal cracks and an increased lateral slope. This is the reason for the widespread damage to the edges of roads. The side strips themselves may suffer so much damage that they may be forced down completely into the ditches along with the ordinary roadway gutters (Fig. 11). Such dangerous wetting of the subgrade must therefore be prevented by means of a deep edge skirting of the surface in the interests both of maintenance of the surface and of traffic safety.

3.7 Frost damage in relation to geological formations. Contrary to many opinions, it is here emphasized that no formation in itself is particularly safe or dangerous from the point of view of frost. This applies equally to such geological formations as sandstone, oapalinuston, sand, etc. Fundamentally, all derived soils have a certain proportion of fine grain components, depending on how near they are to an advanced weathering at the surface. In the completed research assignment the following rock content of frost-endangered soil was established.

| Kind of road | No. | Rock content (grain sizes 2 to 100 mm.) of the soil in % | | | | |
|---|---|---|---|---|---|---|
| | | 0 | 0-10 | 10-30 | 30-50 | over 50 |
| Autobahn | 44 | 1 | 10 | 18 | 7 | 8 |
| Highways | 210 | 68 | 34 | 36 | 29 | 43 |
| Total No. | 254 | 69 | 44 | 54 | 36 | 51 |
| Percent | 100% | 28% | 17% | 21% | 14% | 20% |

According to this, only a few soils are comprised of fine soil only, a fact which is frequently overlooked. In the laboratory, of course, only fine soils are used for the determination of a number of soil coefficients.

3.8 <u>Frost damage in relation to the subgrade.</u> Of the important factors underlying the occurrence of frost damage the grain composition in the subgrade is the one which shows the smallest variation from one damage point to the next compared with the much greater variation of the other three main factors. Although variations do occur depending on the area and the depth, this condition remains valid except for a number of rapidly weathered types of soil such as marl and schist. Therefore, in our present state of knowledge the grain composition remains a good criterion for assessing frost damage and is used by a number of investigators as a basis of frost criteria. Observations have shown that it is not the whole soil which is involved in frost danger, but rather the soil matrix alone, which acquires the same importance as concrete mortar in concrete construction work. The bearing strength of a soil depends principally on this soil matrix, not only with respect to frost damage, but above all during the dangerous thawing period.

3.9 <u>Frost damage in relation to frost criteria.</u> Since the prevention of frost and thaw damage is at present one of the most important problems of highway research, attempts have been made for some time to determine the frost susceptibility of the subgrade with the aid of frost criteria. These are based almost entirely on the grain composition of the soil and essentially they distinguish between soils which are safe and those which are dangerous. However they do not reveal the degree of danger from frost, a factor which becomes more and more important as the extent of frost damage increases along the traffic routes. In practice a distinction has long been made between light, moderate and severe frost damage, thus expressing the need for characterization according to severity as well as to the nature and urgency of the conditions. An assessment based on appearances is subject not only to the subjective interpretation of the observer but also to the conditions of weather, traffic and the like, and may therefore vary widely. For the assessment of frost danger, pure research workers are conducting laborious but restricted laboratory experiments with a view to determining the extent of frost heave, but have so far failed to provide economical solutions which can easily be applied in practice.

The much used frost criterion of the eminent research worker A. Casagrande goes back to the year 1934 and is very simple in its construction. Based on the theory of ice lens formation and the frost heave caused thereby, the frost danger, according to this criterion, exists to the full degree at 3% by weight of soil fractions of less than 0.02 mm. for non-uniform soils, or 10% less than 0.02 mm. in the case of very uniform soils (which are very rare). In the present work, for 254 soil samples, despite 90% severe frost damage, a degree of non-uniformity "U" of less than 5 occurred only three times, so that this very rare exception can be disregarded in practice. In reality non-uniform soils prevail with "U" greater than 15 and hence this criterion establishes the fact that practically all soils with silt and clay content are to be regarded as dangerous. This criterion (originating from the early studies of frost damage) is still overcautious, and is therefore uneconomical. Again, it provides no information about the degree of danger from the frost. Another disadvantage is the relating of the criterion to a single grain diameter, although later investigations have shown that non-cohesive grain sizes possess frost-endangering properties as well (Beskow, Dücker). Therefore, since the proponents of this criterion, have for years been citing the existence of thousands of experiments, it would now appear to be time, in view of contradictory results, that they presented their proofs. Already in a report on the frost damage of the winter of 1939-40 Dr. L. Casagrande shows that severe damage is to be expected only when the 3% minimum is exceeded by a considerable amount.

In the present work, the problem of the degree of frost danger has been investigated very thoroughly on the basis of many separate surveys for each instance of frost damage and the especially important question of severe and moderate frost damage has been attacked. After 20 years of thorough observation of many cases of damage in Central Europe, the author has also come to the conclusion that the grain composition of a soil plays a decisive part in any assessment. Further observations, however, have shown that not the whole of the soil is involved in an assessment of the frost danger, but rather just the fine soil or soil matrix (grain size components below 2 mm.). The extensive survey of regularly occurring frost damage - 90% of places severely damaged, 10% of places moderately damaged - therefore resulted in the classification of dangerous grain sizes in percent of fine soil. This is done

(a) for the clay and silt series

(b) for the clay, silt and very fine sand series.

Accordingly the following table was drawn up for the assessment of the frost danger from soils:

| Kind of road | No. of investigations | Frost-susceptible fractions in % of fine soil | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (a) According to appearance | | | | (b) Clay and silt | | | (c) Clay, silt and very fine sand | | |
| | | Fo | Fl | Fm | Fs | 0-10 Fo/Fl | 10-20 Fm | >20 Fs | 0-20 Fo/Fl | 20-40 Fm | >40 Fs |
| Highways | 167 | 1 | 7 | 87 | 72 | 7 | 30 | 130 | 2 | 16 | 149 |
| Autobahns | 26 | - | 1 | 24 | 1 | 2 | 5 | 19 | - | 5 | 21 |
| Total | 193 | 1 | 8 | 111 | 73 | 9 | 35 | 149 | 2 | 21 | 170 |
| Percent | 100% | - | 4% | 58% | 38% | 5% | 18% | 77% | 1% | 11% | 88% |

This classification affords a possibility of determining the degree of frost danger of soils on the basis of the grain composition.

| Fractions in % of fine soil (< 2mm.) | | Theoretical Classification | Practical Classification |
|---|---|---|---|
| (b) | (c) | | |
| 0 to 5 | 0 to 10 | No frost damage = Fo | Safe |
| 5 to 10 | 10 to 20 | Light frost damage = Fl | |
| 10 to 15 | 20 to 30 | Med. frost damage = Fm | Sensitive to frost |
| 15 to 20 | 30 to 40 | Med. to strong frost damage = Fm/Fs | Near upper limit; use caution and carry out comprehensive investigation |
| over 20 | over 40 | Strong frost damage = Fs | Dangerous |

With this new frost criterion (Fig. 12), therefore, it is immediately possible to decide from the grain composition at each place what maximum possible degree of frost damage can occur when all the important factors coincide unfavourably. This is the most important question of all in practice, so that protective measures of a more permanent nature can be taken.

## 4. Summary

In recent years, with the particularly heavy increase in traffic and the greater demands being made by those using the roads, the extreme danger of frost damage in our network of highways built on shallow foundations has become apparent. Millions have already had to be spent annually for the repair of such damage, which far exceeds all other subgrade effects, and the winter of 1952-1953 brought us to the brink of a traffic catastrophe. With damages amounting to about two hundred million

marks (50 million dollars) in West Germany (including cities, etc.) a very definite warning has been sounded.

In 1953 the author concluded a three-year research assignment on behalf of the Federal Ministry of Transport for the investigation of frost damage throughout the road network of West Germany. Along with a newly-developed frost criterion, the important problem of economical remedies was also studied. The causes of frost damage, as well as this new frost criterion, are briefly discussed in the present paper. The many effects of weather, climate and location are mentioned, along with the influences of seepage water and heavy commercial traffic, and finally, the important question of grain composition of the soil, which constitutes the basic principle of the new criterion, is considered. Although the frost-susceptible grain sizes are extended to include those of very fine sand, on the other hand their admissible minimum components have been considerably raised, thereby opening the way to considerably more economical solutions. By distinguishing several grain sizes, the degree of frost danger could also be established. In addition, it has been found that not the whole of the soil, but only the fine-grain component or soil matrix, determines both its bearing capacity and its susceptibility to frost.

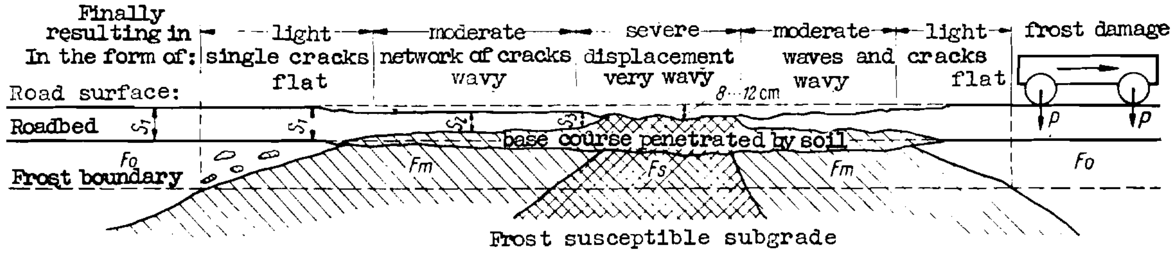


Fig. 1a. Thaw damage in pavement above a softened subgrade of varying bearing strength. Original roadbed $S_1$ gradually decreases in thickness at Fm to $S_2$ and at Fs to $S_3$. At $S_3 = 0$ severe frost damage is inevitable (collapse of surface).

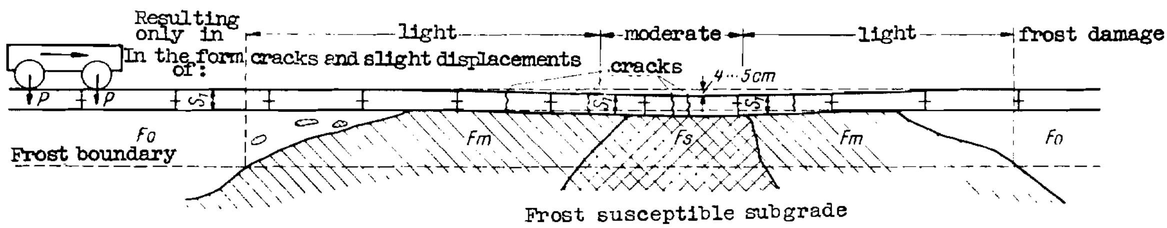


Fig. 1b. Thaw damage in a concrete pavement (dowelled and reinforced) over a softened subgrade of varying bearing strength. Full slab thickness $S_1$ is maintained throughout. Owing to their high bending strength the concrete slabs settle fairly uniformly in the softened subgrade. Only individual cracks and slight tiltings occur. Dowelling diminishes settlement (elastic chain of slabs).

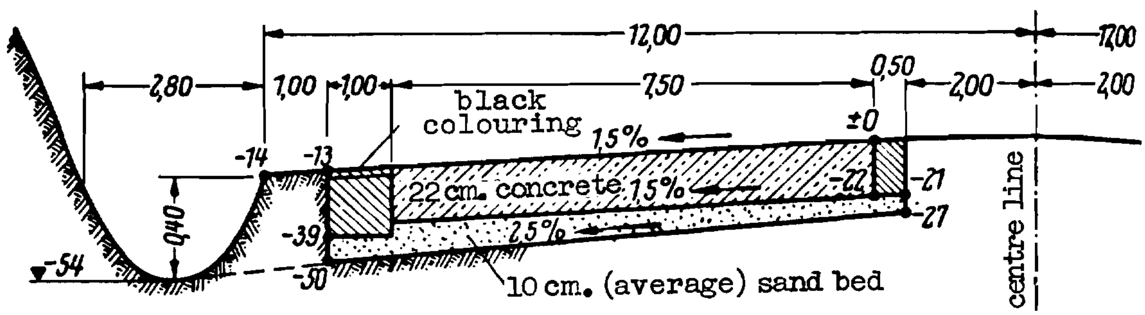


Fig. 2. Design of concrete surfaces for the autobahn requires a minimum ditch depth of 40 cm. for drainage of base course. Representation of a design with a 10 cm. sand bed on a frost susceptible subgrade and with a longitudinal grade up to 3%.

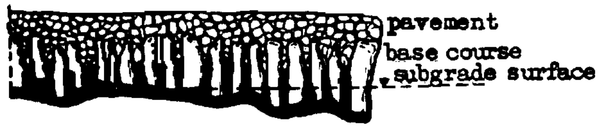


Fig. 3. Actual appearance of pavement and subgrade surface after rolling and under traffic, with a frost-susceptible subgrade. Non-uniform subgrade surface and hightly compressed subgrade hamper drainage.

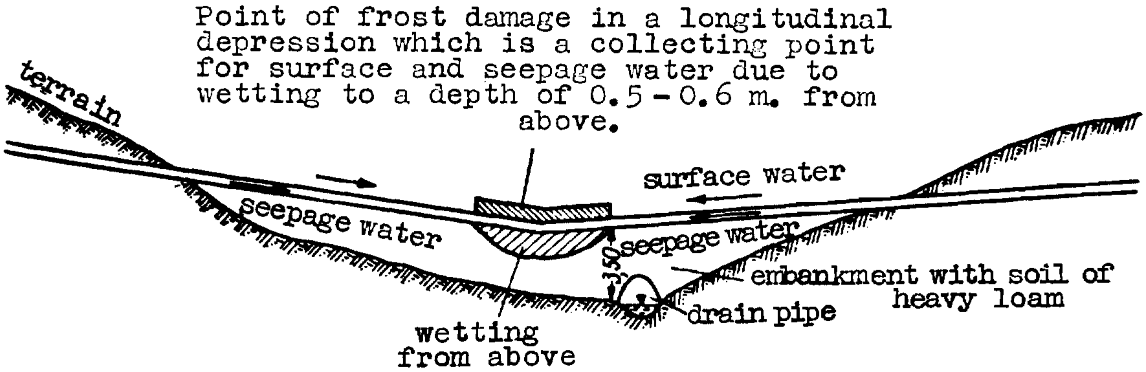


Fig. 4. Frost damage in a longitudinal depression of an embankment 3.5 m. high due solely to wetting by surface and seepage water, where water from the sides plays a decisive role. Capillary wetting was clearly shown to a height of 1 m. above the water table in a trench that was open for six weeks and by the appearance of a marshy spot.

Fig. 5. On digging up a superficially dry, damaged place, seepage water is found emerging from a roadbed.

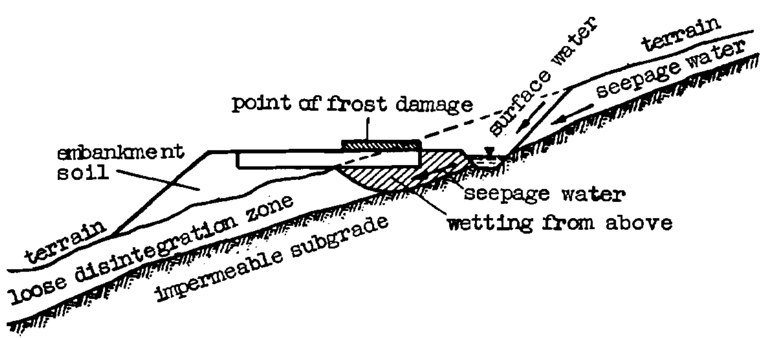


Fig. 6. Frost damage on a slope construction at the side nearest the hill.

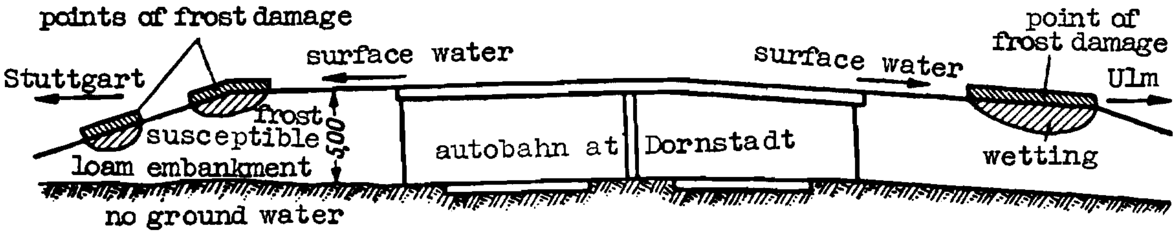


Fig. 7. Frost damage on a high bridge ramp.

Fig. 8. Water liberated in the soil during the thawing period re-emerges through a cracked, treated surface. The thaw water is forced out by the traffic.

Fig. 9. Frost damage. Appearance of cracks in a 15-year old, medium-heavy pavement as a result of heavy truck traffic.

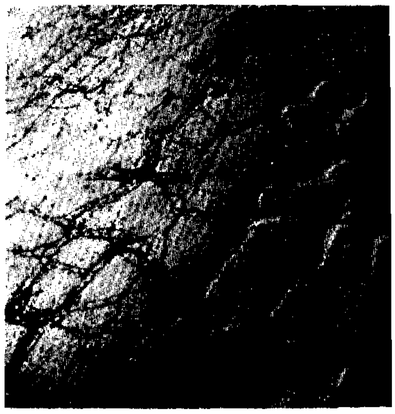

Fig. 10. Frost damage on a heavy old surface in the form of a random pavement mosaic occurring under heavy truck traffic. Broad crack zones in a pavement which has become brittle.

Fig. 11. On a stretch of road badly broken up by frost, the softened side strips of loess loam are forced down into the road ditches by passing trucks.

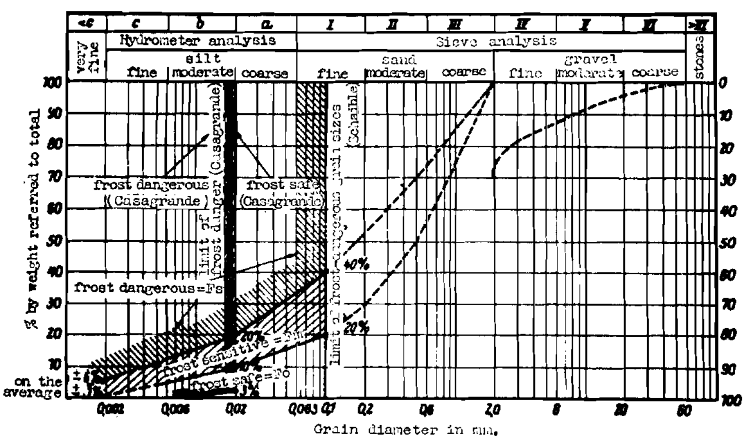


Fig. 12. Grain distribution curves for assessing frost damage.