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to the cohesion of the water films surrounding the soil grains; the hydrodynamic subpressure, or suction-force, can be calculated by the frost-heaving of freezing tests or by direct manometric measuring.

If there is no extended groundwater-level, the water needed to supply the ice-lenses is drawn from the free water, accumulated in the pores of the soil beside and under the lens.

The resulting plane and the spatial groundwater flow towards an ice-lens has been calculated. The rate of flowing and therefore the frost-heaving in the centre of the lens is inverse proportional to the diameter of the lens.

Therefore on flexible pavements small lenses cause greater frost-heavings than lenses with large surfaces.

On rigid pavements, frost-heavings on small surfaces cannot occur, because of the high specific pressure which has to be compensated, in consequence of the dowelling of the slabs.

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This report represents an extract of the writer's book "Der Frost im Baugrund" (The Frost in the Sub-soil), which will be published probably in Autumn 1948, by the firm "Springer, Vienna".

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## VIII e 4

### FROST-DAMAGE TO ROADS IN DENMARK

AXEL RIIS, Chief Engineer  
Danish State Road Laboratory

#### INTRODUCTION.

During the severe winters of 1939/40, 1940/41, 1941/42, and the long but no less severe winter of 1946/47, Danish roads were damaged by frost to an unprecedented extent.

For this reason the Danish Road Laboratory x) began in March 1940 a systematic examination of frost damage. A questionnaire was sent to all county surveyors, and city and municipal engineers, together with the offer of assistance in the elucidation of the underlying conditions, with a view to providing against future damage.

In March and April 1940 a considerable number of soil samples were received. The work then begun has since continued, and, particularly in connection with the motorway construction initiated during the war, has attained considerable extent. To date the Laboratory has examined some 1500 samples of soil and has indicated in many cases how frost-heaving in the sub-grade may be counteracted. Information has also been collected from the county surveyors upon the methods generally employed to make good frost damage and the cost thereof.

The above work is briefly described in the following.

#### METHODS EMPLOYED TO DETERMINE THE FROST HAZARD OF A SOIL.

In the examination of a soil for its potentiality to cause heaving during frost the Laboratory employs in general the method of Dr. Gunnar Beskow, Departmental Head, State Road Institution, Stockholm, by which the frost hazard is determined partly by grain size analysis and partly by determination of the capillarity.

Grain size analysis. Beskow differentiates between homogeneous soils (sediments) and heterogeneous soils (moraine-soils).

x) An advisory institution established in 1928 under the Ministry of Public Works, to afford information to all municipal authorities on technical road questions, to examine road materials and pavings etc. and develop proposals for standards for same, and for the execution of road works.

His rule for the former is that they are with certainty not frost-hazardous when not more than 50% of the fines (i.e. < 2 mm) is under 125  $\mu$  (A.S.T.M. sieve No.120) and not more than 35% is < 75  $\mu$  (A.S.T.M. sieve No.200). On the accompanying diagram (Fig.1) these two points are marked with two small concentric circles. Soils for which curves lie to the right of these points should, therefore, represent frost-safe sediments, and those lying to the left frost-hazardous.

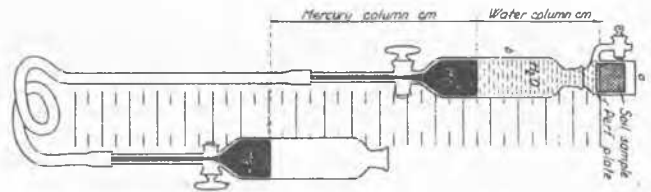
For heterogeneous soils two limit curves are given (drawn in thin firm lines on the diagram) between which will lie the more doubtful cases, while here again curves to the right of the doubtful area represent safety and those to the left hazard, unless the curve lies so much to the left and so high that it depicts a fine-grained soil that is so impervious to water that it is practically safe.

It is seldom there is any doubt as to which soils are to be regarded as homogeneous and which heterogeneous, but for doubtful cases there is a rule "x").

Capillarity.

Dr. Beskow's rule states that samples of soil with a capillarity < 1 m water column are not frost-hazardous under any circumstances. If the capillarity lies between 1 to 2 m and 10 to 20 m the soil is very hazardous while when over 20 m the hazard is slight.

Capillarity is measured by Beskow's capillarimeter (fig. 2) the design of which, however, does not permit the measurement of greater capillarity than 10 m. Greater capillarities



Dr. Beskow's Capillarimeter.

FIG. 2

If the particles are so uniform that the heterogeneous number is < 5 this requirement is less strict and fines under 20  $\mu$  may reach 10% by weight before the soil is to be regarded as frost-hazardous. By "heterogeneous number" U is understood the relation  $d_{60} : d_{10}$  where  $d_{60}$  denotes the grain size (mesh size) under which 60% of the material lies, and  $d_{10}$  that under which 10% lies.

As a rule evaluations carried out by the two methods give similar results. In borderline cases, experience has shown that for moraine-soils the Casagrande method is more severe than the Beskow. A soil passing the Beskow test as frost-safe both in grain range and capillarity, may be classed doubtful by the Casagrande method. The contrary can also happen, albeit very seldom. Such a case is that of a sediment consisting of fine sand (Mo) with a heterogeneous number < 5 which can well have a grain curve lying to the left of Beskow's 2 limit points, capillarity > 1 m and with less than 10% by weight of particles < 20  $\mu$ .

Beskow also gives some practical tests to enable the potential danger of a sample of soil to be estimated, but these are seldom used. In many cases the capillarity rule alone will be sufficient to decide whether a given soil is frost-hazardous or not.

EXAMINATION OF SAMPLES OF FROST-HEAVING SOILS AND THE CONCLUSIONS EVOLVED.

When the Laboratory's frost damage investigation began in March 1940, 54 soil samples were received. About a third of these arrived in an undisturbed coherent condition without loss of ice of water.

In its circular to county surveyors and municipal engineers, the Laboratory had requested samples both from frost heaved areas and those immediately adjacent thereto. A number of the latter samples were received.

As an instance of the information to be gathered by observation alone of the undisturbed frozen samples, a photograph is given in Fig. 3 of 3 chalk samples as received at the

x) Cf. Gunnar Ekström Klassifikation af svenska åkarjordar" (Classification of Swedish arable soils) Stockholm 1927 p.39, cf. also "Meddelelser fra Vejlaboratoriet (Publications of the Road Laboratory) No.23 p. 73 et seq., regarding the method used for grain analysis by the Road Laboratory.

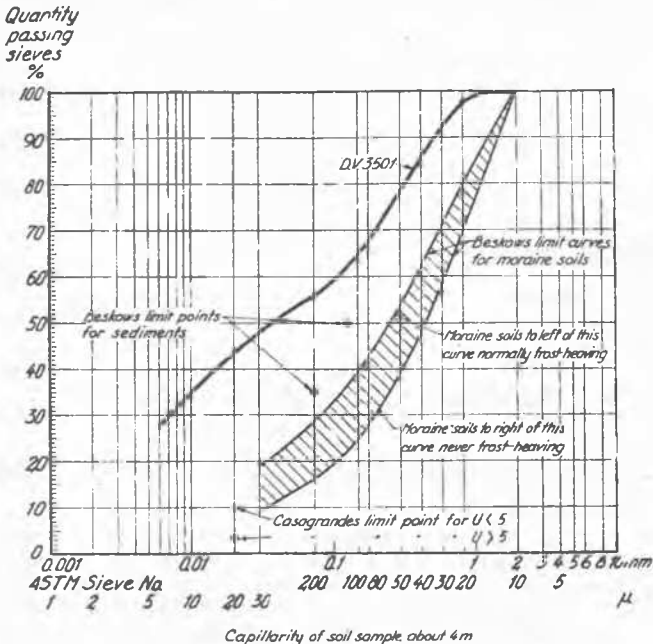
xa) Beskow's formula for capillarity (k) in cm watercolumn is  $k = c/d$ , where c is a constant (which for homogeneous sediments is 0.7 - 0.8 and for heterogeneous moraines 0.4-1.0, usually approx. 0.9) and where d is the grain centre of gravity in cm calculated from the equation

$$\log d = 1/100 \sum \frac{1}{2} (\log d_1 + \log d_2) \times p$$

where p is the percent weight of material between grain size (mesh size)  $d_1$  and  $d_2$ ; cf.

Meddelande 25 from Statens Väginstytut p. 33-35

Danish Road Laboratory

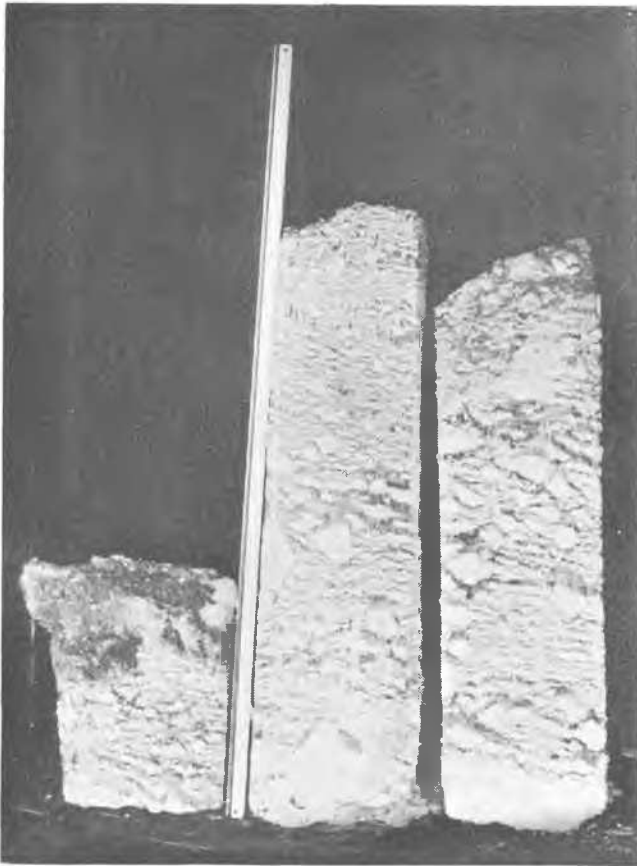


Grain-size diagram of a soil sample D.V. 3501.

FIG.1

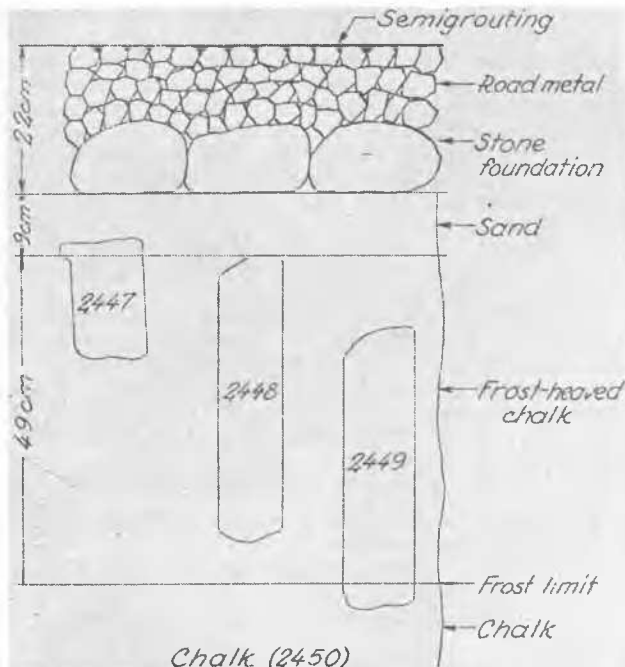
than this are calculated on the basis of grain sizes xa).

In addition to the above rules, the Laboratory also employs the Criterion formulated by Dr. Arthur Casagrande, which was used in the evaluation of the sub-grades of the German Reichsautobahns. Casagrande's rule is, that soils having a "heterogeneous number" > 5 must not contain more than 3% by weight finer than 20  $\mu$  if it is to be characterised as frost-safe.



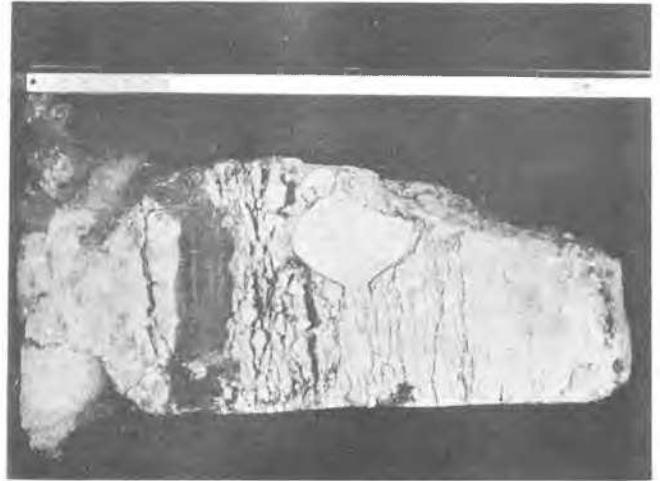
Photograph of chalk sample No. 2447-2449, taken from frost heave. Ice layers are seen as dark streaks between layers of chalk. The boundary between sand and chalk is seen in the upper part of the sample at the left (No. 2447) and the frost limit in the lower part of the sample at the right (No. 2449). Cf. Fig. 4

FIG.3



Sketch of position of samples Nos. 2447-2450.

FIG.4



Photograph of chalk sample No. 2454 taken from frost heave. Ice forms dark horizontal streaks, the lowest of which (3 cm thick) is situated some 2 cm above the frost limit. In the centre of the picture a piece of closer texture chalk is seen which is not disintegrated by frost.

FIG.5



Photograph of clay soil sample No. 2470 from frost heave. Heavy icelenses in centre and below

FIG.6

Laboratory, and in Fig. 4 a sketch of the positions under the road from which these samples were taken. The frost heave at the site concerned varied between 20 and 27 cm and extended in length for about 35 m. The frost had penetrated through the 22 cm metalling, the 9 cm sand layer and 49 cm deep into the underlying chalk, in all to 80 cm under the road surface. In Fig. 3 the ice layers are seen as dark streaks in the fragmented chalk. At the lower part of the sample on the right the frost limit is observable.

The water content in the frozen chalk (average of 5 determinations at various depths) was found to be about 92% of the dry weight of the samples, while in the lower unfrozen chalk the water content was about 25%.

Fig. 5 shows another chalk sample, taken in undisturbed condition from a road bed that had not yet been metallated but was covered by a thick layer of snow, the frost penetration was consequently only 40 cm. The picture shows an ice layer some 30 mm thick, whose lower ed-

ge was only a cm or two above the frost limit.

Regarding water content in the samples received, it can be mentioned that in two clay soils taken respectively from a frostlifted area and a non-lifted area immediately adjacent thereto, the quantity was found to be 47% and 13% of the dry weights. Both samples were frost-hazardous and similar. Worthy of note is that although both sampling points were about 5 m from a 3 m deep excavation, the sub-surface water conditions were not equalised at the two points (which lay in a  $\frac{1}{2}$  m deep cutting). In another case for similar adjacent clay samples the water content was found to be 115% and 15%, the former being the greatest amount found in a sample of frozen soil. Fig. 6 shows the sample concerned; thick ice layers are seen in the centre and below.

The greatest frost heave determined amounted to 35 cm, with a frost penetration of about 80 cm. The greatest penetration measured was approx. 100 cm with a frost-heave in this case up to about 20 cm.

The chief results of the investigations carried out in the spring of 1940 can be stated as:

- 1) The most frost-hazardous are chalk and clay soils. The very considerable frost-heaving caused by chalk must be due to the fine cracks which facilitate the passage of water. The frost-heaved clay samples consisted for the most part of lean clay with a capillarity of from 2-6 m water column.
- 2) By far the greater number of frost-heaves occur in cuttings.
- 3) It would seem that it has frequently been the more or less ease with which water has access to the soil, and not so often the frost-hazard characteristics of the soil itself, that has been the determining factor in the extent of the frost-heaving taking place.
- 4) Drains along the road cannot be relied upon to insure uniform conditions with regard to access of water.
- 5) The greatest frost effect is not concomitant with deep penetration. Lens-ice-formation hinders frost penetration. With very moist earth the frost penetration is comparatively slight.

In connection with later investigations of frost damage, a case may be quoted illustrating how rapidly frost-hazardous conditions in a soil can alter. A frost-heave of 20 cm in a shallow cutting levelled out in a distance of less than 1 m. Samples were taken every 25 cm to a total depth of 1.5 m in two excavations, respectively 2.5 m south and 2.5 m north of the heave. Excavation in the frost-heaved portion showed the presence of ice-lenses from 25 cm down to 10 cm under the road. Examination in the Laboratory placed all the frost-lifted samples, except the uppermost, in the frost-hazardous class, while all the 6 samples from the non-lifted area were frost-safe. Soil can thus change from the one to the other in a length of less than 5 m. The 7 frost-safe samples consisted of fine diluvial sand with a capillarity of 45-85 cm, while the 5 frost-heaved portions consisted of fine silt (mjala) in that the major portion of these samples was made up of particles between 2 and 20  $\mu$  in size; the capillarity ranged from about 6 to 9 m.

In February 1942 the Laboratory issued a similar circular to that of March 1940, requesting information on the frost damage, occurring during the winter of 1941/42 and the measures taken, or contemplated, to prevent future damage.

Damage consisted mainly of 1) heave, with and without destruction of the paving and 2)



FIG. 7

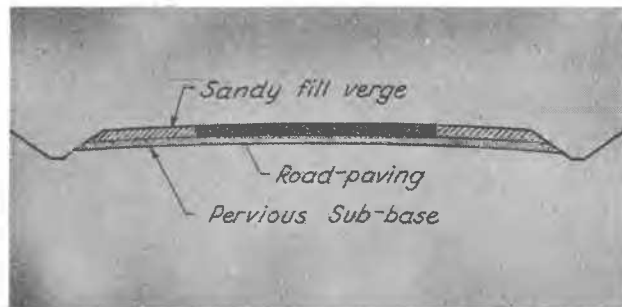


FIG. 8

thaw damage, traffic having broken through the paving due to the inability of the over-saturated sub-grade to support it.

In many cases of heave the paving had apparently returned to its original position without having suffered observable damage - concrete paving, however, excepted. Heave had amounted to 25-30 cm in height and in extent had varied from 1 m<sup>2</sup> to a 30 m stretch the full width of the road. With concrete pavings, the heave most frequently caused vertical displacement of the slabs in relation to each other; dowels counteracted this but had sometimes given rise to breakage at the slab ends. Heave-cracks occurred in many places. Heave was often greatest in the centre of the road, due to the sides having usually been covered with snow. Longitudinal centre joints will, for this reason, often gape.

Where damage occurred during thaw, it was, almost without exception, macadam roads that suffered, and often severely.

The replies to the second questionnaire confirmed that damage is found much more frequently in cuttings than on embankments.

The measures taken to counteract frost damage consist, as a rule, of 1) a pervious subbase and 2) drainage, and will be further referred to later.

In the circular to county surveyors x)

x) Public roads and streets in Denmark on 1.1.1947 amounted to:-	
Main roads (county roads)	8138 km
By-roads	44740 "
Town roads and streets	3042 "
	<hr/>
	55920 km

County roads are administered by the county council with a county surveyor in technical charge.

an attempt was made to obtain data for an estimate of the extent of frost damage and the cost of making it good on main roads (county roads) for the severe winters. With regard to cost the following figures were arrived at:

for 1939/40	Kr. 300.000,00
" 1940/41	" 200.000,00
" 1941/42	" 500.000,00
" 1946/47	" 2.300.000,00

Even taking into consideration the altered price levels in 1946/47 it will be seen that damage in this winter was very much more extensive than that of the previous winters and indicates that it can recur and to an even greater degree.

In comparison with the above sums it may be mentioned that in a prewar normal winter the amount expended on all county roads for repairing damage arising from frost in the sub-grade would only be Kr. 40-50.000,00.

It can also be mentioned that the direct effect of wintry weather on pavings is less in severe winters with long continued frost than in mild and damp winters with frequent alternation of frost and thaw.

As an instance of the manner in which ice lenses, formed in a slanting plane by the conditions of exposure, can bring about a horizontal movement, a picture of an underpass viaduct is shown in Fig. 7. The carriageway is sunk up to 2 m below the foot- and cycle paths. Both retaining walls were cracked in an approximately horizontal plane, probably at a concreting joint. Displacement of the one wall was  $2\frac{1}{2}$  cm and of the other  $4\frac{1}{2}$  cm.

#### MEASURES TO COUNTERACT FROST DAMAGE.

Even when frost-heaves do not occasion the destruction of the paving, they will, especially if repeated, generally cause the paving to become more and more uneven, due to its not returning exactly to its original level.

It has become increasingly important, therefore, on account of the fast traffic, to prevent or reduce frost-heaving, or at least

to endeavour to ensure as far as possible a uniform heave.

These desiderata are, in the opinion and according to the experience of the Laboratory, best attained by a pervious subbase, i.e. a layer of frost-safe material (sand, gravel or clinker) under the paving, and of a thickness corresponding to the depths of the frost-hazardous sub-grade. If the pervious layer is not carried down to a frost-free depth it must be drained. In the case of a main road this is best done, as shown in Fig. 8, by carrying the subbase out to the ditches on either side; this also ensures that falling on the road is prevented from percolating into the sub grade.

Drains will only be useful in preventing capillary absorption of water from a high groundwater level up and into the sub grade immediately beneath the paving. While drains, therefore (under Danish conditions), only very seldom will counteract frost heave, it is possible that by drawing off the excess water formed by the melting of the ice-lenses, they may reduce thaw damage. Drains, however, should never be placed under the carriageway, as they will create non-uniform heaving and draining conditions.

Regarding the thickness of the pervious sub-base, the motorways under construction in Denmark, which will be paved with concrete, are being built with a 60 cm pervious sub-base in cuttings and 45 cm on embankments. For roads of lesser importance, however, it can generally be assumed that normally frost-hazardous soil is harmless at a depth 50-60 cm under the road surface, cf. an article by O. Godskesen, Permanent-Way Engineer, in the Danish "Ingeniøren" No. 30, 1945 - "Frost-safe depth is often very much less than frostfree depth".

Finally, it may be stated that a pervious sub-base often is effective in strengthening the paving, and the thicker and more stable this sub-base is the thinner the paving may be. The stabilising of the sub-grade, however, is at matter outside the scope of the present report.