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R.M.HARDY & ASSOCIATES LTD.

GEOTECHNICAL INVESTIGATION

MACKENZIE HIGHWAY

MILE 544 TO MILE 635

E-2510

Prepared for

DEPARTMENT OF PUBLIC WORKS OF CANADA

VOLUME II

This report is in seven volumes. A Table of Contents is at the front of each volume.

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18. PERMAFROST

18.1.1 Muller (25) has given the following definition of Permafrost:

> Permanently frozen ground or permafrost is defined as a thickness of soil, or other superficial deposit or even of bedrock which has a variable depth beneath the surface of the earth in which a temperature below freezing has existed continually for a long time (from two to tens of thousands of years). Frozen ground is defined exclusively on the basis of temperature, irrespective of texture, degree of induration, water content or lithologic character.

18.1.2 Within the area of the present study, permafrost is discontinuous, that is permafrost is encountered at some depth beneath the soil surface almost anywhere in the area except beneath large lakes or rivers. The top surface of the permafrost is usually called the permafrost table (analogous to the water table). The layer between the ground surface and the permafrost table is known as the active layer and it is subject to freezing and thawing according to the season. The depth to the permafrost table can be found in the early fall when the depth of seasonal thaw is at its greatest. As the thawing index will vary from year to year, it follows that the depth to the permafrost table will also vary slightly.(The thawing index is the sum of the degree days of thawing for a given period and is usually evaluated from the mean daily temperature. For example, a mean daily temperature of 50 F would give a thawing index of 18 degree-days F for that day. The daily thawing indices are accumulated to find the thawing index for an entire summer.) In the Norman Wells area the slight variations in the depth to the permafrost table from year to year are not believed to be of engineering significance.

18.1.3 The thickness of the active layer is chiefly dependent on: the local climate, surface vegetation, soil type, surface drainage and degree of disturbance of the surface.

18.2 Thermal Regime

18.2.1 By definition, the maximum temperatures of the permafrost at the permafrost table cannot exceed 32°F. The temperature decreases with depth until some minimum temperature is reached beyond which depth, under the influence of the geothermal gradient, the temperature of the permafrost rises until it reaches 32°F which can be taken to be the base of the permafrost layer. As with all ground temperatures, the amplitude of the temperature variation is attenuated with depth. For practical purposes the depth of zero variation is found at about 50 feet from the ground surface.

18.3 Effects of Disturbance

18.3.1 It is now generally recognized that any disturbance to the ground surface conditions in permafrost areas will lead to changes in the ground thermal regime and the position of the permafrost table. The effects of clearing and cross country travel have been discussed by Ferrians (11), Hardy (13), Lachenbruch (21), and others. In general, removal or destruction of the natural vegetative cover and the peat layer results in degredation of the permafrost table. Conversely, where material with insulation value is placed on the ground surface, the permafrost table may rise. Where the mean annual air temperature is sufficiently low, such a rise in the permafrost table can be effected by the placement of earth fill of only a few feet in thickness.

18.4 Influence of Vegetation

18.4.1 The influence of vegetation, and particularly of the influence of moss, has been discussed by Benninghoff (2 & 3), Brown (6), Hardy (13), Hok (14).

18.4.2 Within the northern limits of the Boreal zone, the effects of vegetation on ground temperatures are greatly overshadowed by the effects of the climate. The short growing season combined with low temperatures leads to stunted trees with sparse growth. The severe climate also leads to a very shallow depth of active layer so that trees can only develop shallow root systems. Such shallow root systems cannot support large trees and the influence of the shade of trees is of only minor importance. Mosses and peat have a very great effect on heat flow into and out of the soil. Living moss reduces the surface temperature during summer when it is wet, and also acts as an insulator when dry. Additionally, dry peat has a very low thermal conductivity so that, during the summer, it makes a good insulator and retards thaw penetration. Wet peat has a thermal conductivity of approximately eight times that of dry peat so that the penetration of the thaw line in the spring is relatively rapid. However, the spring is short. Frozen peat has a thermal conductivity of 30 times that of dry peat so that withdrawal of heat from the ground is great during the winter. The presence of snow acts as an insulator during the winter. (2)

18.5 Depth of Thaw

18.5.1 The depth of thaw which can be anticipated in frozen material under a given set of conditions is extremely difficult to calculate with any degree of accuracy due to the many complex variables which influence the problem. Empirical methods based on actual field measurements appear to give the greatest promise for obtaining data of value during design. Various authors, notably Scott (28) and Sanger (27) have explored the theoretical basis for depth of thaw calculations. Compared to the references which are available on the depth of frost penetration, published data on the depth of thaw is meager. Charts showing the theoretical depth of thaw are reproduced as

Plates 2 and 3, Appendix E.

18.5.2 The influences which affect the depth of thaw at a given location can be listed as follows:

ponded surface water

thawing index (ie. air temperature and time)

wind speed

precipitation (snow and rain)

vegetation

organic cover

surface colour

topography

soil type

soil density

soil water content

It will be appreciated that the first three factors in the above list will vary from season to season although the variation will generally be within certain forecastable limits. The next three factors (vegetation, organic cover and surface colour) can be varied by man's activities and especially in permafrost regions, can be considerably altered by accident such as the making of trails and forest fires. The last four factors (topography, soil type, soil density and soil water content) will generally be fixed conditions within the lifetime of any engineering project, although the moisture content of thawed soils may vary due to man's activities. The influence of water content and soil density is illustrated in Plates 4 and 5, Appendix E. Sebastyan (29) has reported field data on depth of thaw from various potential air-field sites.

18.5.3 Thompson (31) has given values for the average and maximum thawing indices experienced at many Arctic and Sub Arctic stations over a 10 year period. Sanger (27) has shown how the wind speed can affect the surface thawing index.

18.6 Thermokarst Features

18.6.1 Thermokarst features are commonly found in permafrost areas and often take the form of small lakes or ponds scattered sporadically through areas where the ground contains large quantities of ice. It is believed that these thermokarst features are formed by the action of ice melting in the subsurface with the result that subsidence of the ground surface takes place and the depression so formed fills with water. The mechanism of thermokarst formation appears to be triggered by removal of the insulating layer of organic surface cover. The surface organic cover can be removed by fire, animal action or man's activities. In one case, a short distance from the Sans Sault Rapids, an incipient thermokarst feature was forming in an area which appeared to have been trampled by caribou or moose.

18.6.2 When a pond formed in a thermokarst depression is very shallow, the effect of warm water will only be felt during the summer months and the melting of the ground ice beneath the small pond will proceed very slowly. At some point in time the water will be deep enough so it does not freeze to the bottom during winter. The thawing action will then be carried on continuously throughout the year so that melting of the ground ice progresses at an accelerated rate. For some reason, which is not clearly understood, the thawing action takes place almost entirely in a vertical downward direction and lateral enlargement of the small ponds does not seem to occur. A possible explanation is that encroachment of vegetation and organic matter on the margins of northern lakes is taking place continuously and this action proceeds as quickly as enlargement due to thawing. The two actions counteract each other with the result that no enlargement in area appears to take place.

18.6.3 The depth of thaw and the shape of the thaw bulb are dependent on:

mean annual surface temperature

temperature of the pond water

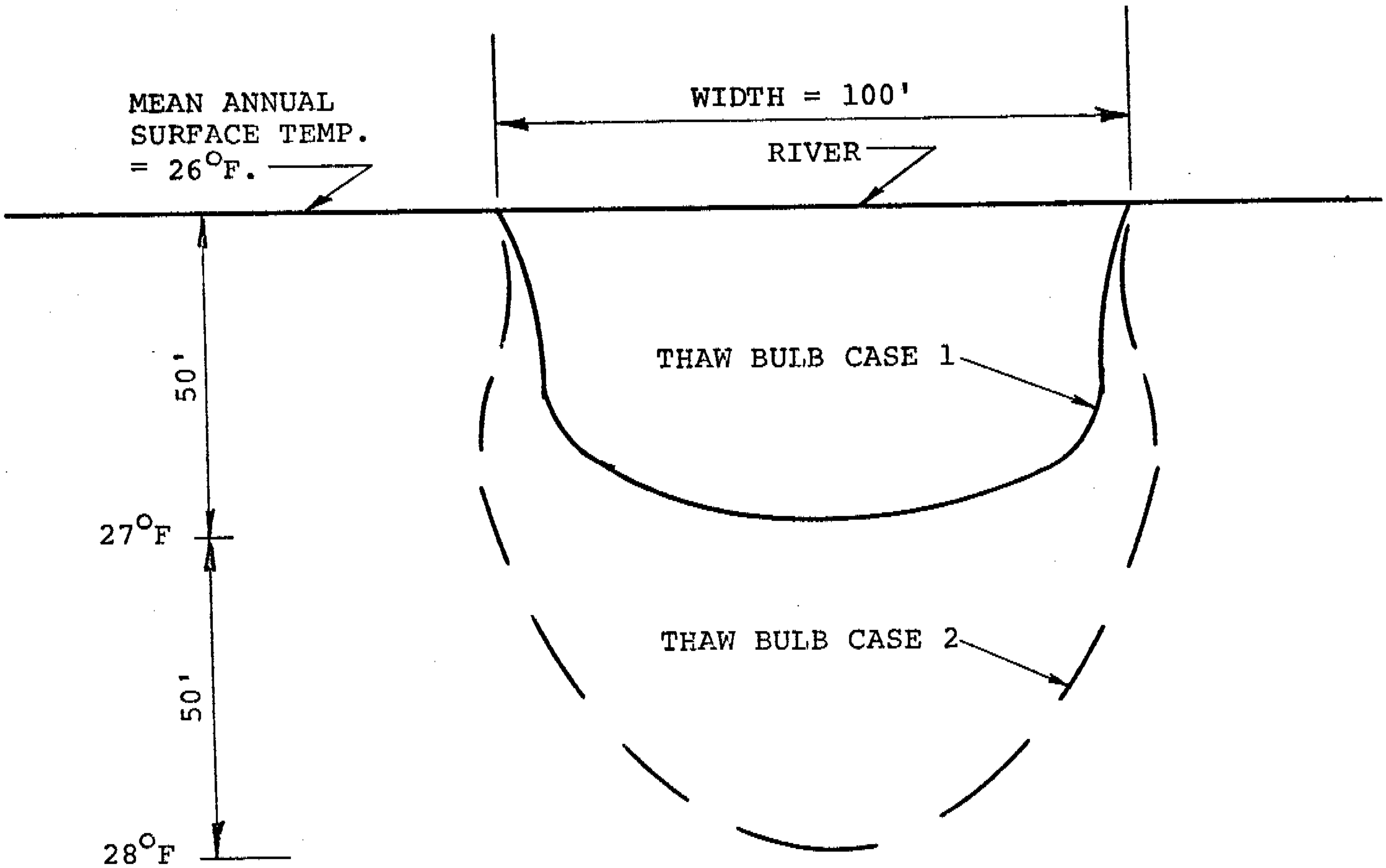
geothermal gradient

soil type and density

size and shape of the pond

18.6.4 Brown et al (9) have discussed their findings after investigating a small lake near Inuvik. They showed that the effects of a lake of only 900 feet in diameter in the Mackenzie Delta area were sufficient to completely melt the permafrost beneath the lake where the depth of the permafrost is in excess of 260 feet. The authors of this paper also note that very small changes in the mean annual temperature of the water will considerably affect the profile of the thaw bulb.

18.6.5 Brown has also prepared charts and diagrams to aid in the determination of the effects of temperature changes on the ground surface (10). These charts can be used to delineate the extent of the thaw bulb underneath different shaped areas for various conditions of surface temperature and geothermal gradient. These charts have been used in drawing the diagram shown as Figure 12. The example we have taken is a river 100 feet in width. We have assumed a mean annual surface temperature of 26 degrees Fahrenheit and a geothermal gradient of 1 degree Fahrenheit per 50 feet of depth. These last values are believed to be reasonable for the Norman Wells area. We have no data on the mean annual temperature of the water



THAW BULB BENEATH A
RIVER OF 100 FEET WIDTH

Mean Annual Soil Surface Temperature	=	26°F
Temperature Gradient	=	1°F/50'
Mean Annual Water Temperature, Case 1	=	36°F
Mean Annual Water Temperature, Case 2	=	40°F

in the rivers and streams in this area. From cases cited by Brown we have assumed that the mean annual water temperature at Norman Wells would be between 36 and 40 degrees Fahrenheit. The shape of the thaw bulb for both cases is shown on Figure 12 and it will be observed that raising the temperature of the water by 4 degrees Fahrenheit will lead to an extremely large increase in the depth of thaw. However, it will be seen that the depth of thaw in Case 1 over most of the width of the river is in excess of 40 feet and that in both cases the permafrost profile at the river's edge is almost vertical. From the point of view of constructing a bridge, or a large culvert, the actual depth of thaw beneath the river would seem to be irrelevant as the top of the permafrost table beneath the rivers will be far below the depth of excavation or embedment of piles. It will also be seen that the transition zone between frozen and thawed ground is very sharp. This has been confirmed in the field by many investigations. The shape of the thaw bulb beneath circular features will be similar to that shown on Figure 12.

18.7 Effects of Highway Embankments

18.7.1 The effects of highway embankments on the permafrost regime have been discussed by Brooker (4), Keyes (18), Knight (19) and Lachenbruch (21). Experience in the Inuvik area has shown that embankment fills of 6 feet in height or more will lead to eventual stabilization of the permafrost table at or above the level of the bottom of the embankment. When the embankment is constructed of well compacted fine grained soil, the permafrost table will stabilize at a depth of as little as 4 feet below the embankment surface. Where some insulating material is incorporated within or beneath the embankment, as when the original organic cover is left undisturbed or when rigid insulation is built within the embankment, the depth from the top of the embankment to the permafrost table may be greatly reduced.

18.7.2 In more southerly locations, the use of higher embankments or insulation will not prevent the eventual degradation of permafrost. (Degradation can refer to the lowering of the permafrost table or the ground surface. In the latter case, the term degradation infers that the lowering of the ground surface is due to melting of the permafrost and consequent degradation of the permafrost table. As the permafrost table is degraded, excess ice will thaw and there will be a consequent loss of volume in the soil mass. Where the ice content in the permafrost is extremely low, the resulting effects on the ground surface may be imperceptible.) In the latitude of Norman Wells, it has been shown (12) that the permafrost table will degrade no matter how high the embankment which is constructed upon it. Investigations along the Canol Road have shown that the degradation of the permafrost beneath a conventional highway embankment will reach a depth of 30 feet in approximately 25 years. Where there had been a considerable thickness of peat which was left relatively intact, the degradation of the permafrost took place at a much slower rate so that, in a period of 25 years the depth of degradation was only about 12 feet.

18.7.3 We are of the opinion that, for the area under consideration, it is virtually impossible to prevent the thaw of permafrost beneath a roadway embankment. The design and construction procedures should be based upon and consider whatever estimates may be made as to the rate of thaw having regard to use of the facilities and cost of maintenance. Degradation will proceed relatively rapidly at first and will then slow down. The depth to the permafrost table from the base of an embankment is roughly in proportion to the square root of time. This means that the time for degradation to reach a depth of 20 feet will be four times the length of time required for degradation to reach a depth of 10 feet.

18.7.4 It has been our experience that for the area of this study, the highest ice contents are usually found just below the permafrost table. It must therefore follow that any degradation of the ground surface due to melting of the permafrost will be extremely rapid in the first few years following construction and will then proceed less rapidly until the rate of degradation is imperceptible.

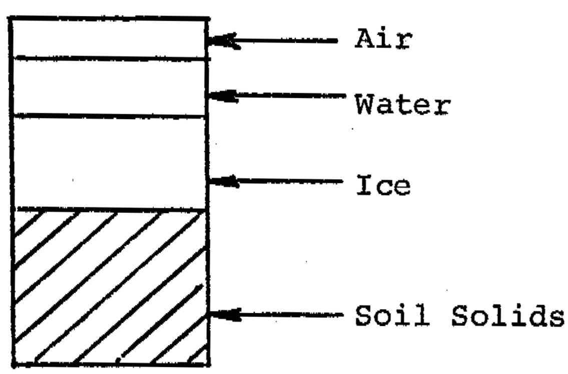
18.7.5 As leaving the surface peat layer intact will not prevent degradation but will only retard it, the only advantage in leaving such peat on the surface would be to prolong the time taken for surface subsidence to occur and may thus be of some benefit in maintenance programs. (Note that this applies only to areas south of the continuous permafrost zone.) Where high ice content soils are encountered in the subgrade, settlement of the embankment must be anticipated and must be provided for in the design and in planning of maintenance programs.

18.7.6 Where an embankment is placed over organic ground cover, the living moss layer is destroyed and the peat is compressed, thus reducing its effectiveness as an insulator. In addition, the road surface will not receive the benefit of any shade from trees and the cooling effect of evapotranspiration from vegetation will be absent. The result is that the surface of a road will be at a much higher temperature than the ground surface in undisturbed areas. The mean annual temperature of the ground surface on the embankment is therefore raised considerably and this increase in the ground surface temperature will cause temperatures beneath the road embankment to rise.

19. THAW-SETTLEMENT OF SOILS

19.1.1 When any structure is founded on, or in, frozen soil, it is important to know whether significant settlement of the soil will occur should thawing take place. If there is excess ice contained in the soil mass, significiant settlement can be expected upon thawing. (Excess ice can be defined as any ice which, upon melting taking place, cannot be accommodated as water within the voids of the soil mass.) Soils which contain excess ice are often referred to as thaw-unstable. Thaw-unstable soils have been described by Linell and Kapler (22). These authors are of the opinion that soils containing ice types Nf and Nbn are usually thaw-stable; that is, "no deterimental settlement of structures would normally be anticipated if thawing occurred. All other subgroups are potentially thaw-unstable soils and significant settlement of structures founded on them may occur".

19.1.2 In the original frozen state, frozen soils contain, besides the solid soil particles, ice, unfrozen water, and air. This relationship can be illustrated by the diagram below.



The total volume of a soil prism can be said to be made up as follows:

$$Vt = Vs + Va + Vi + Vw$$

where:

Vt = Total Volume

Vs = Volume of Soil Solids

Va = Volume of Air

Vi = Volume of Ice

Vw = Volume of Water

19.1.3 When thawing of the soil prism has been completed, there will no longer be any ice and the volume of the prism will be occupied by the soil solids, entrapped air and water. If the soil prism had originally contained excess ice, the excess water will drain away and will be expelled by the weight of the soil so that the ground surface above will be lowered. Some of the water may drain into surrounding unfrozen soil, but most of it will pond on the surface above the thawed and settled zone and eventually drain away or evaporate. Such ponded water, because of its greater ability to absorb energy from the sun's rays will increase the rate of thaw.

19.1.4 The rate at which thaw-settlement takes place will be governed by the thermal properties of the soil and its permeability (assuming that other factors such as: surface cover, aspect, surface water, thawing index and wind conditions are similar). Coarse-grained soils have higher thermal conductivity than fine-grained soils and are also more permeable. Therefore, thaw-settlement will be more rapid in such soils than in fine grained soils. (See Plates 4 and 5, Appendix E.)

19.1.5 The amount of settlement which takes place is dependent upon the in situ dry weight of the soil and the final void ratio (or porosity) after completion of thawing and consolidation. The in situ dry weight of the soil, before thawing has taken place, is very largely governed by the ratio of the ice content to the total volume. The final void ratio is dependent upon the soil type, the grain size distribution, and the overburden weight which is applied to the soil mass.

19.1.6 If the soil is a clay, the final dry density will be low and the porosity or void ratio will be high. Conversely, where the soil is a well-graded sand gravel mixture, the resulting dry density will be high and the porosity or void ratio will be low. If the soil type and the size gradation are known, the final dry density can be estimated within reasonably close limits.

19.1.7 The porosity (P) of a soil mass is defined as the ratio of the volume of the voids in a soil mass to the total volume, and is expressed as a percentage. The void ratio (e) is the ratio of the volume of the voids in a soil mass to the volume of the soil solids and is expressed as a decimal fraction. The relationship of porosity to void ratio is as follows:

$$P = \frac{e}{1 + e} \times 100\%$$

Porosity (%)	Void Ratio (e)
50	1.00
40	0.66
30	0.43
20	0.25

The volume of the soil solids per cubic foot of soil can be expressed as:

$$V_s = \frac{Dd}{G(62.4)} \text{ cu. ft.} \qquad (1)$$

where: Dd = dry density of the soil (pcf) in its original frozen condition

G = specific gravity of soil solids.

The final (thawed) volume occupied by a soil prism which was originally of one cubic foot volume in the frozen state can be expressed as follows:

$$V_f = \frac{Vs(100)}{(100-P)} \text{ cu. ft.} \qquad (2)$$

where P = final (thawed) porosity in percent.

$$V_f = \frac{Dd(100)}{G(62.4)\ (100-P)} \text{ cu. ft.} \qquad (3)$$

The difference between this volume and the original volume of one cubic foot can be expressed by the relationship

$$S = 1 - V_f \qquad (4)$$

$$= 1 - \frac{Dd(100)}{G(62.4)\ (100-P)} \quad \text{ft.} \qquad (5)$$

where S equals the settlement which has taken place in a soil prism of one foot in height. For convenience, this degree of settlement can be expressed using the term inches per foot. The relationship then becomes:

$$S = 12 - \frac{Dd(19.23)}{G(100-P)} \quad \text{in/ft.} \qquad (6)$$

19.1.8 Figure 13 shows the settlement to be expected from a prism of soil one foot in height in its frozen state versus the dry weight of soil, in its frozen state, for a specific gravity of 2.7 and for various final dry densities.

19.1.9 Linell and Kaplar have developed a chart for determining the relationships between dry unit weight of soil, ice volume and water content. This chart is reproduced as Plate 7, Appendix E. In order to use this chart, it is necessary that some estimate of the soil dry unit weight after thawing and settlement has taken place be made. If the in situ dry unit weight of the soil is known (which can be found from Shelby tube samples) and the final dry unit weight of the soil can also be found (from thaw consolidation tests on typical samples) the amount of settlement which will take place in the soil mass can be found by using the diagram in Figure 13.

19.1.10 Normally, fine-grained soils (such as clay and silt) will have high ice contents in the in situ state. These soils, after thaw-settlement has been completed, will have high void ratios which will limit the amount of settlement which can take place. Conversely, sands and gravels will have lower void ratios after thawing has been completed. The soil mass will therefore occupy a comparatively smaller volume than in the case of the fine grained soils. For example, a clay with an in situ dry weight of 60 pounds per cubic foot and a final void ratio of 1.00 will, theoretically, show a settlement of slightly more than three inches per foot due to thawing. A sand-gravel mixture which has an in situ dry weight of 100 pounds per cubic foot prior to thawing, and a void ratio of 0.25 after thawing has taken place, will show the same amount of settlement.

19.1.11 It will be appreciated, therefore, that fairly accurate estimates of the thawed dry densities of the various soils occurring under and adjacent to a highway should be made. Such estimates can be based upon minimum density tests carried out on typical soil samples. This test is fairly simple and entails mixing the soil sample with water so that the water content is equal to the in situ water content and then pouring the resulting slurry into a suitable container and allowing the soil particles to gravitate to the bottom. A small porous stone is placed on top of the sample in order to simulate the weight of the overlying soil.

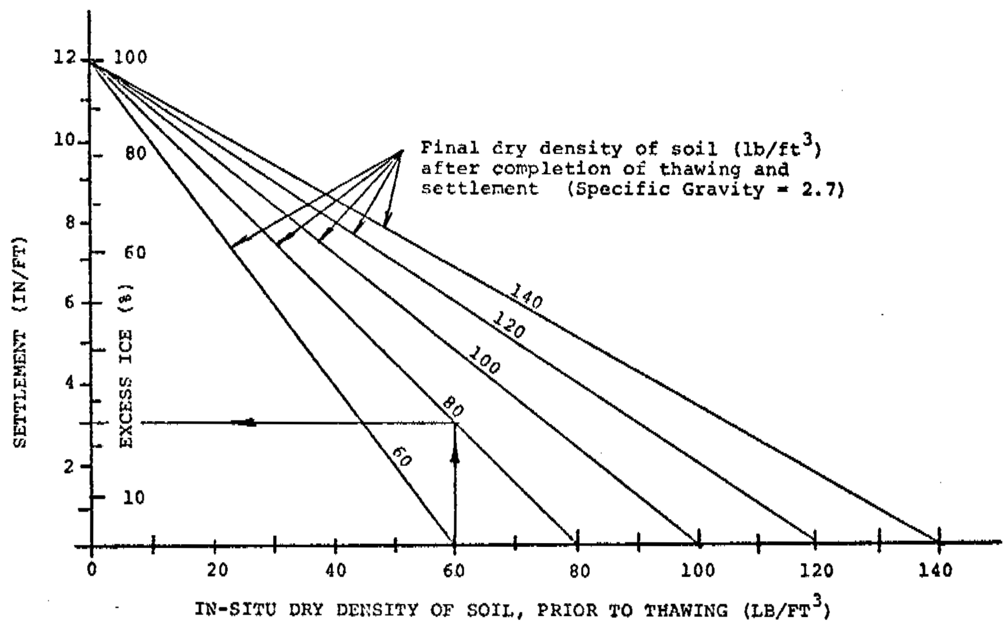


Figure 13

CALCULATED SETTLEMENT OF ICE-RICH SOILS VERSUS IN SITU (PRIOR TO THAWING) DRY DENSITY FOR VARIOUS VALUES OF FINAL (THAWED) DRY DENSITY

19.1.12 In many cases it may be difficult to obtain undisturbed samples of frozen soil by means of Shelby tubes or core drilling. In such a case, it is possible to obtain a relationship between the water content of a sample and its in situ dry density. If it is assumed that the soil sample in question is saturated or super-saturated (that is, there is no air entrapped within the ice of the soil voids) the relationship of the water content to the dry density is shown on Plate 10, Appendix E. This particular chart was drawn assuming a specific gravity of 2.7 for the soil particles and 0.88 for ice. The curve will vary with variations in these specific gravities.

20. IMPORTANCE OF DENSITY MEASUREMENTS

20.1.1 As stated in the section entitled "Thaw-Settlement of Soils" it is necessary to determine the dry density both before and after thawing has taken place in order to estimate the amount of settlement which will take place in a particular soil mass. The dry density of soils in a permafrost condition can be found by measuring undisturbed samples obtained by means of Shelby tubes or core drilling. Representative samples are measured in the laboratory, while still frozen, and weighed. The samples are then dried in an oven and weighed again and, from the data so obtained, the wet and dry densities in the in situ condition can be found. The dry density after thawing has taken place can be found in the laboratory by using a relatively simple test which we have called the "slurry test". This test has been described above. (See section "Thaw-Settlement of Soils".) For the purposes of estimating probable settlements beneath a road embankment, we believe that the slurry test will yield results which are sufficiently accurate for engineering purposes.

20.1.2 Obtaining undisturbed samples is a relatively slow process compared with drilling for disturbed or for "grab" samples. It has been our experience that, particularly during the winter, drilling production on a hole where core samples were obtained was only

1/3 and sometimes only 1/4 of the production where only grab samples were obtained. To obtain sufficient undisturbed samples for a stretch of road 100 miles in length would be extremely costly and time consuming. In addition, the necessary laboratory testing would also be far more involved and expensive than in finding water contents of disturbed samples. In this project we therefore attempted to obtain as large a proportion of undisturbed samples as would be economically acceptable to the client and at the same time obtain sufficient data to provide a basis for engineering design. We believe that the data obtained from undisturbed samples can be correlated with the data obtained from disturbed samples so as to a yield a relatively large amount of useable information. The data obtained from undisturbed samples has been analyzed with the aid of a computer program and the relationship between water content and dry density has been obtained for various types of soil.

20.2 Relationship of Water Content to Dry Density

20.2.1 Data on the dry density and water content of undisturbed samples from the Mackenzie Highway location and other projects in the Mackenzie Valley area were analyzed and the charts shown on Plates 11 and 12 were produced. The relationship between water content and dry density is:

$$Dd = 1/(A+BW)$$

where:

Dd = dry density (pcf)

W = water content (%)

A = 0.0056 (for Mackenzie Highway location)

= 0.0055 (Sans Sault area)

B = 0.0002 (Mackenzie Highway Location)

= 0.00018 (Sans Sault area)

20.2.2 By means of this relationship the existing dry density, in a frozen state, of the subgrade soils can be estimated within reasonably close limits. When the in situ dry densities are compared with the thawed dry densities the resulting difference can be used as an estimate of the probable settlement which will occur under an embankment at the location of each test hole.

20.2.3 It should be emphasized that the data we have used is from a relatively small area of the Mackenzie Valley and the relationship of water content to dry density we have found may not apply to frozen soils in other areas. This relationship should therefore be used with caution in other areas.

21. WINTER CONSTRUCTION

21.1.1 This section formed part of a report to the Department of Public Works of Canada on the subject of the Mackenzie and Dempster Highways which was submitted to the Department in January of 1973. We believe the information in it is relevant to this program and it is therefore repeated verbatim. However, it should be borne in mind that, at the time this was written, construction of the Mackenzie and Dempster Highways in the Inuvik-Fort McPherson area had just commenced.

21.1.2 There is very little experience to build on of road construction during winter in northern Canada. The Department of Highways of Alberta constructed a short section of embankment on the highway between Lac La Biche and Fort McMurray during the winter. The Manitoba Department of Highways has constructed short sections of road embankment in northern Manitoba during the winter and the Churchill Falls Corporation constructed 20 miles in Labrador during the winter of 1966-67. Some sections of the Alberta Resources Railway were constructed during the winter and some earth work at Dew-Line sites was also completed under winter conditions. At least one large dike was partially constructed during winter in northern Manitoba as part of a hydro-electric project.

21.1.3 Very few of these projects have been reported in the literature. In those few cases where such projects have been mentioned in reports, the details of the soil types and construction procedures have seldom been mentioned in detail as such details were usually incidental to the main object of each particular paper. Well documented case histories on embankment construction during the winter, mainly in the form of a published report, deal only with embankment construction either in non-permafrost areas or in areas where permafrost occurs only sporadically. It must be emphasized that there is an enormous difference between constructing an embankment in the winter with unfrozen material and constructing an embankment in the winter with frozen material. Where unfrozen material can be used, there is very little void space between the lumps of fill and most of these voids can be filled due to the compaction effort of the hauling equipment. However, where the material is placed in a frozen state there is very little possibility of any compaction effort being of any value.

21.1.4 We are not aware of any road embankments constructed on permafrost during winter in Alaska, which have been reported in the literature. Similarly, few references on such work are available from the Soviet Union. Porkhaev (26) mentioned problems caused by inclusion of silty soils in embankments constructed during the winter but also mentions that such soils have been used successfully.

21.2 Strength of Frozen Soil

21.2.1 Figure 14 shows the relationship of the unconfined compressive strength of frozen soils to temperature and water content. This chart has been taken from Thermal Soil Mechanics by Jumikis. It shows that the strength of sand is greatly dependent on the temperature and that at 0° F the compressive strength of sand is at least four times that of the strength at 30°F. Clay with silt and organic matter shows little increase in strength once the temperature drops below 20°F. Similar relationships have been noted for the shear strength of frozen soils. This chart shows that ripping frozen, coarse grained materials is almost inevitably an expensive operation.

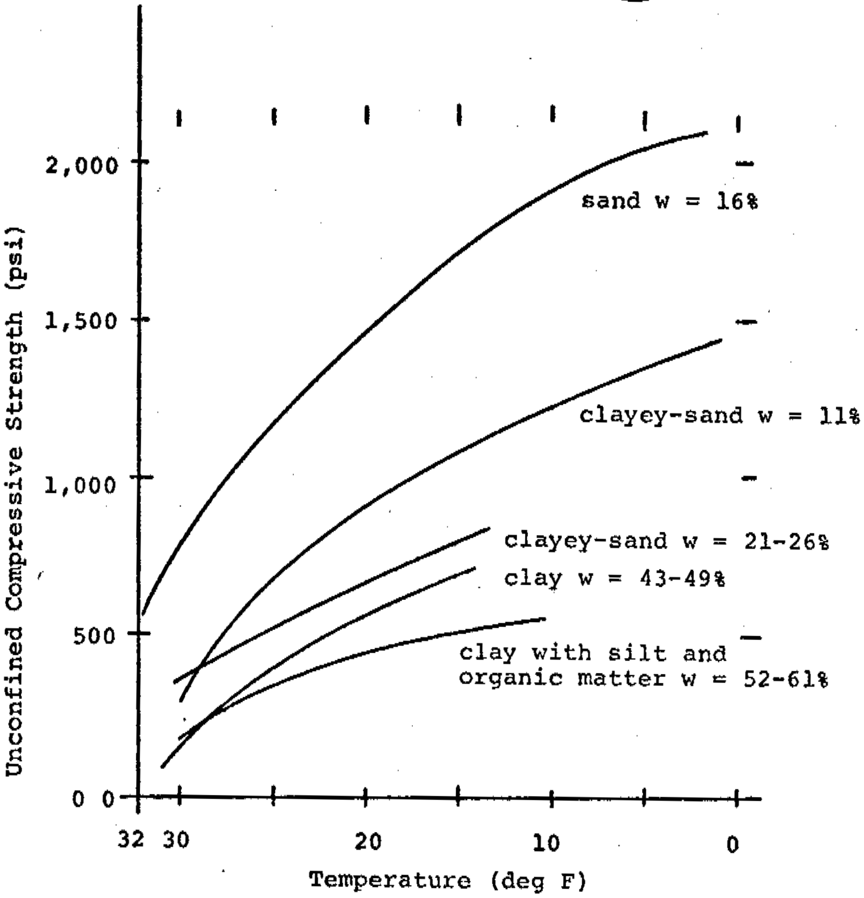


Figure 14

RELATIONSHIP OF UNCONFINED COMPRESSIVE
STRENGTH OF FROZEN SOILS TO
TEMPERATURE: (After Tsytovich)
FROM: Thermal Soil Mechanics, Junikis, p. 157
(Original Chart was in metric units)

21.2.2 Soils which have just completed thawing, invariably contain excess pore pressures which cause a drastic loss in shear strength. There is very little published information on the strength of soils during the thawing process. However, it is generally accepted that frozen soils have high shear and compressive strengths, such strength will be reduced during the thawing process and the shear and compressive strengths of the soil will be at a minimum immediately on the completion of thawing. As excess pore pressures are dissipated the shear and compressive strengths will recover. However, the strength of a thawed soil will never equal its strength in the frozen condition.

22. EROSION

22.1.1 Erosion of surface soils due to running water can be a serious problem where vegetation has been removed. Common examples include erosion of: highway ditches, cut slopes, and agricultural land where poor farming practices have been carried out. In southerly regions, most erosion is due to rainfall with erosion due to snow melt and wind being of relatively minor importance. In more northerly latitudes, rainfall is relatively light so that snow melt is a much more important factor.

21.1.2 The principle causes of erosion are:

removal of vegetation

precipitation (rain and snow)

topography (slopes and drainage areas)

soil type and density

22.1.3 Experiments in the United States have shown that erosion from land in row crops can be as much as 80 times the amount eroded from grassland. It is obvious that the amount of soil eroded from completely bare sand or silt could be enormous for a very small amount of water.

22.1.4 The slope of land will influence the velocity of running water as it runs over the ground surface. Plate 6, Appendix E, shows the relationship between the velocity of water and the gradient of the slope for a flow of 0.4 cu. ft./sec. per foot of channel width. It will be seen that the velocity of water for a gradient of 40% is only twice the velocity of the water for a gradient of 4%. The relationship between the velocity of water and the amount of sand eroded is shown on Plate 9 for a water depth of 1.2 inches.

22.1.5 The size and topography of the drainage area affects the amount and intensity of runoff as it passes any particular point. Where the topography concentrates runoff from a considerable area into a small drainage way in a short space of time, the resulting erosion can be serious. Highway embankments placed across the line of drainage often have the effect of concentrating runoff.

22.1.6 There are various factors which influence the rate at which soils will erode. Plate 8, Appendix E, shows the resistance to erosion of soil according to the grain size. Gravel has a very high resistance to erosion due to its size whereas clay has high resistance to erosion due to cohesion. Fine sand and silt have very little resistance to erosion due to small grain size and lack of cohesion.

22.1.7 In the case of cohesive soils the density of the soil has a very great influence on its shear strength and, consequently, its resistance to erosion. It is well known that thawing soils have a very low shear strength while thawing is taking place and immediately after.

22.2 Preventative Measures

22.2.1 Various measures for the prevention and control of erosion have been used. These include:

revegetation

diversions and barriers

artificial control

siltation basins

22.2.2 Vegetation is the most economical and aesthetically pleasing method of controlling erosion. In northerly areas, the short growing season and the poor quality of the soil are important factors in planning any revegetation program. A considerable amount of experiemental work is underway in an attempt to find the most suitable grass species to be used. The question of which type of plant growth to encourage and the methods to be used in reseeding are complex and are outside our field of competance.

22.2.3 It is concluded that there is insufficent data available on erosion in sub-Arctic environments to permit the development of a code of practice at this stage.

23. THAW DITCHES

23.1.1 In soil with high ice contents, it is possible to create a shallow drainage channel by deliberately disturbing the surface cover. Such disturbance can be effected by hand-cutting the vegetation and running a tracked vehicle along the cut line. The surface disturbance leads to degradation of the permafrost and consequent lowering of the ground surface. This type of ditch will avoid many of the erosion problems associated with conventional ditching procedures. We are not aware of this approach having been used and suggest some experimental work at selected locations.

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APPENDIX E

Charts and Diagrams

RAINFALL AND SNOWFALL
1940 - 1972

STATION	1940		1941		1942		1943		1944		1945		1946		1947		1948		1949		1950		1951		1952		1953		1954		1955		1956	
FORT GOOD HOPE	6	94	7	85	8	77	7	102	7	55	10	37	5	38	7	54	Ø	Ø	8	42	2	Ø	8	65	8	34	3	48	Ø	28	Ø	Ø	8	74
NORMAN WELLS	X	X	X	X	X	X	X	Ø	8	32	9	36	7	49	4	56	11	62	9	47	4	39	7	69	14	38	7	51	8	64	7	60	6	69
FORT NORMAN	X	Ø	7	69	11	31	13	43	10	34	8	36	6	64	5	36	7	Ø	4	← STATION CLOSED														
WRIGLEY	X	X	X	X	X	X	Ø	Ø	8	Ø	8	36	5	Ø	X	X	X	83	8	56	9	Ø	6	55	7	Ø	10	Ø	8	Ø	Ø	Ø	X	93

STATION	1957		1958		1959		1960		1961		1962		1963		1964		1965		1966		1967		1968		1969		1970		1971		1972		SNOWFALL MAX.	SNOWFALL MIN.	SNOWFALL MN.	RAINFALL MAX.	RAINFALL MIN.	RAINFALL MN.
FORT GOOD HOPE	4	66	4	54	5	29	5	32	6	58	5	46	5	41	4	33	8	35	5	46	7	77	2	Ø	11	39	6	Ø	8	Ø			102	28	47	11	2	6
NORMAN WELLS	5	51	7	72	6	64	9	74	10	106	9	76	7	82	6	46	6	55	7	60	10	39	4	30	9	44	10	62	10	93			106	30	56	14	4	7
FORT NORMAN																																	69	31	36	13	4	7
WRIGLEY	3	38	6	70	6	Ø	Ø	61	Ø	78	Ø	60	Ø	54	9	21	7	Ø	7	56	8	54	8	52	7	44	12	72	8	Ø			93	21	56	12	3	8

SNOWFALL (INCHES)

RAINFALL (INCHES)

MEAN ANNUAL TEMPERATURES
1940 - 1972

STATION	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956
FORT GOOD HOPE	21	17	18	21	21	20	17	18	Ø	20	Ø	Ø	18	20	18	14	16
NORMAN WELLS	X	X	X	X	Ø	21	21	Ø	20	22	21	19	20	22	21	18	18
FORT NORMAN	Ø	21	22	24	24	20	Ø	Ø	20	23	X	X	X	X	X	X	X
WRIGLEY	X	X	X	Ø	Ø	23	Ø	X	Ø	25	Ø	Ø	Ø	Ø	Ø	Ø	21

STATION	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	TEMPERATURE MAX.	TEMPERATURE MIN.	TEMPERATURE MN.
FORT GOOD HOPE	19	Ø	16	16	14	19	17	15	16	14	18	19	19	Ø	Ø	Ø	21	14	18
NORMAN WELLS	22	21	18	21	18	23	22	19	20	Ø	20	21	21	21	20		23	18	21
FORT NORMAN	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	24	20	22
WRIGLEY	23	Ø	21	23	Ø	Ø	23	21	Ø	19	22	23	23	23	Ø	Ø	25	19	23

NOTES:

X - INDICATES NO RECORD
Ø - INDICATES INCOMPLETE RECORD
VALUES ARE TO NEAREST INCH FOR RAIN AND SNOWFALL AND TO NEAREST DEGREE FAHRENHEIT FOR TEMPERATURE.

No.	REVISION	DATE	BY

REFERENCES

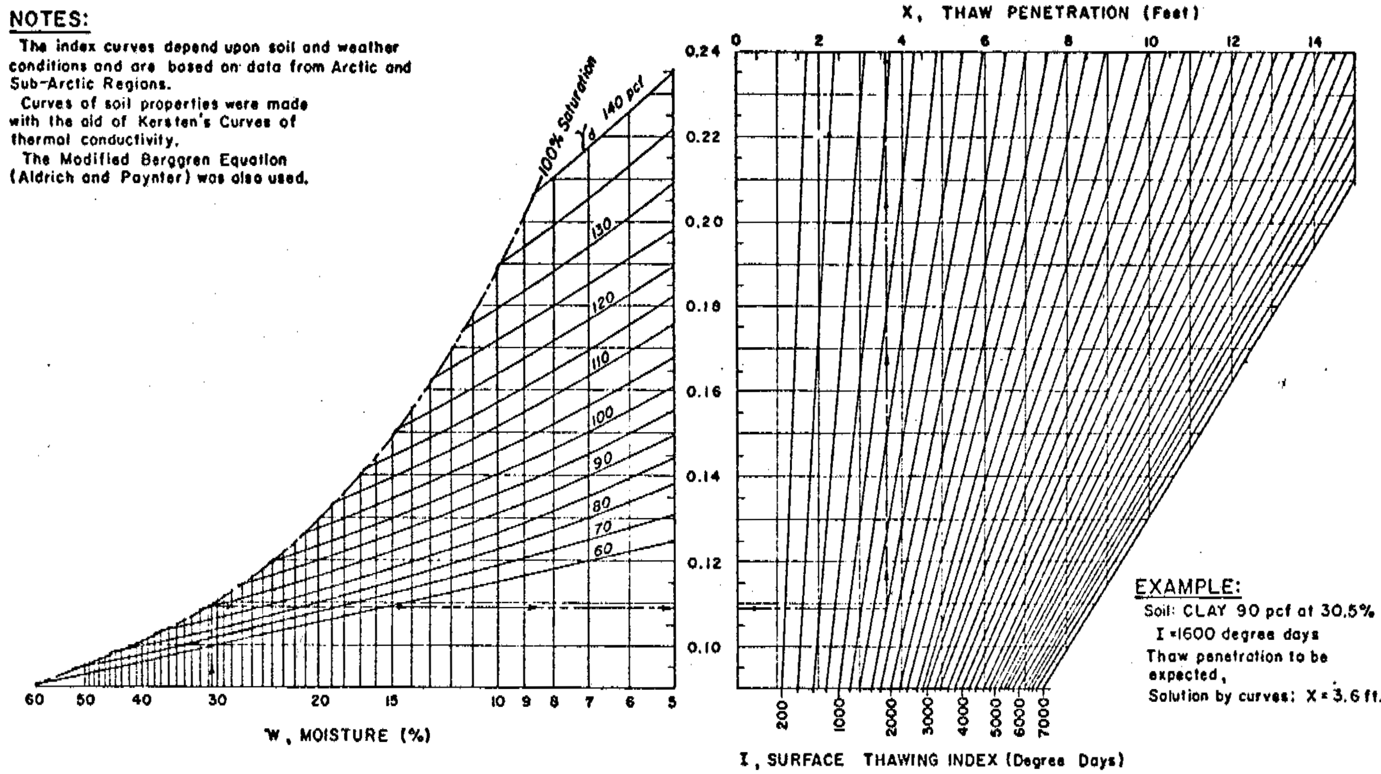
RMH R. M. HARDY & ASSOCIATES LTD.
CONSULTING CIVIL ENGINEERS
EDMONTON ALBERTA

WEATHER RECORDS
MACKENZIE HIGHWAY

SCALE ____ DATE APR. 3/73 MADE J.H. CHKD G. Mc. APPD. ____

No. E - 2510 - 101 REV.

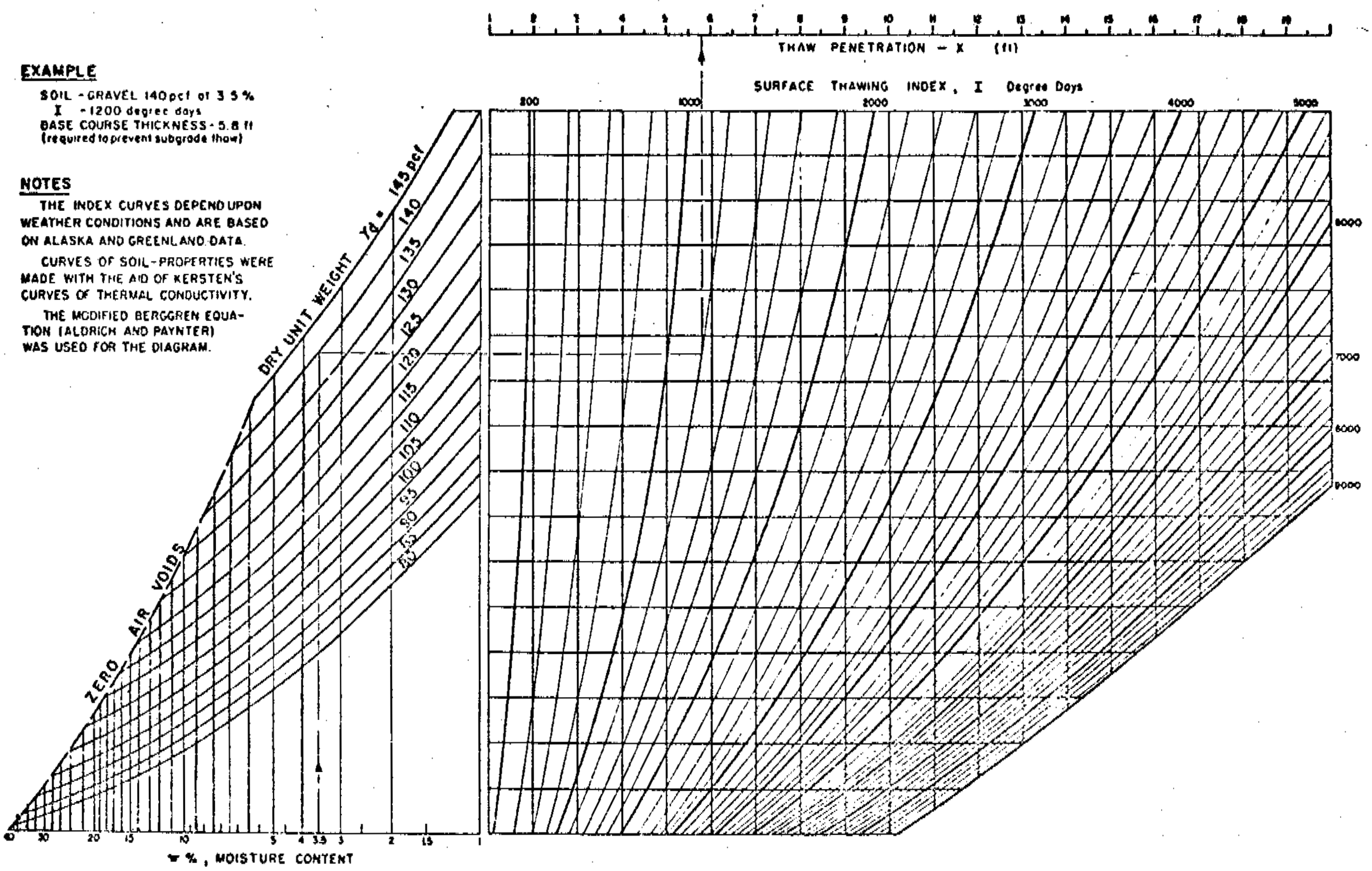
PLATE I



THEORETICAL PENETRATION OF 32°F ISOTHERM

FINE GRAINED SOILS, THAWING

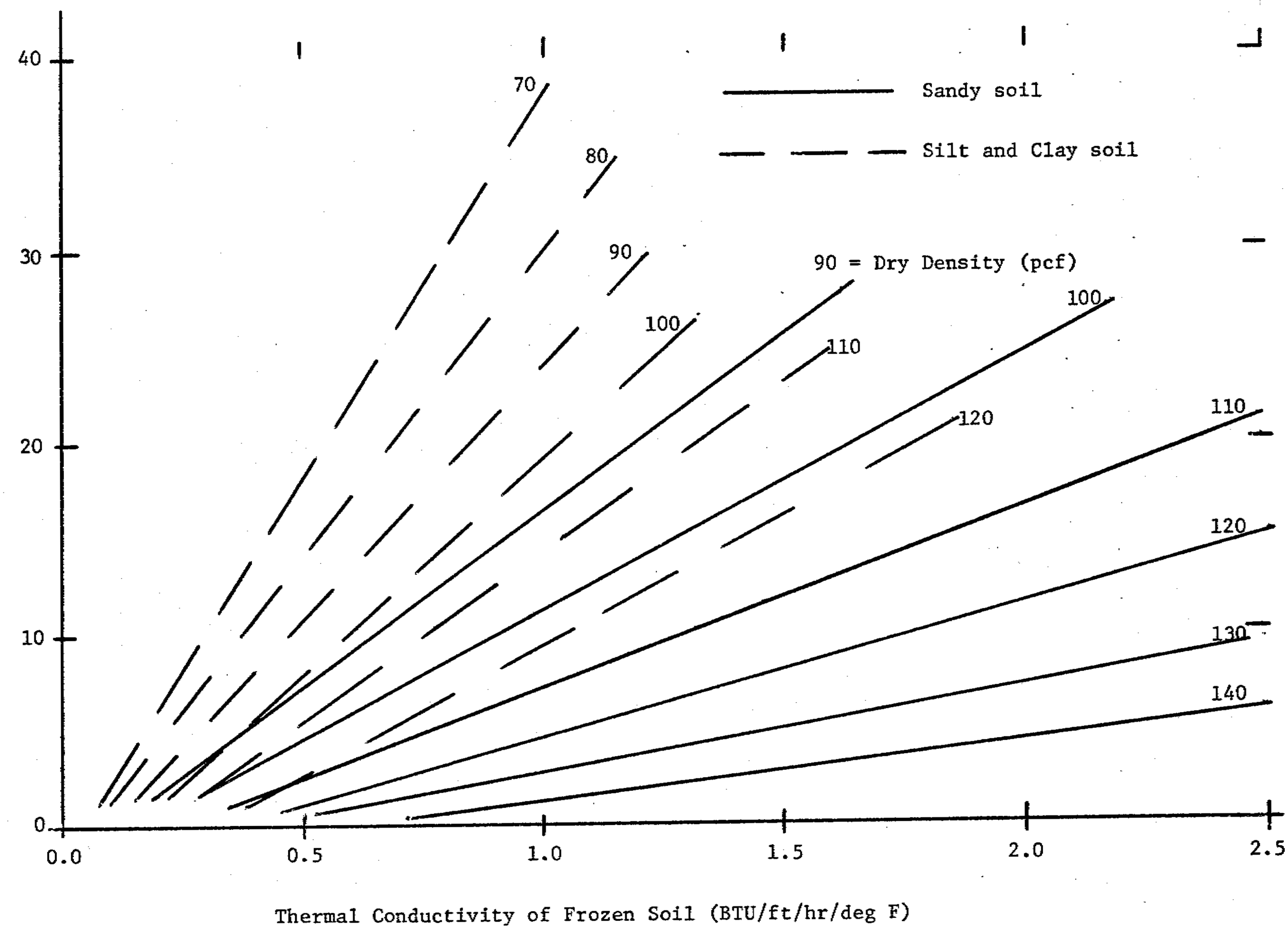
From: "Degree-days and Heat Conduction in Soils" by F.J. Sanger. International Permafrost Conference Proceedings 1963, page 258.



THEORETICAL PENETRATION OF 32°F ISOTHERM

COARSE GRAINED SOILS, THAWING

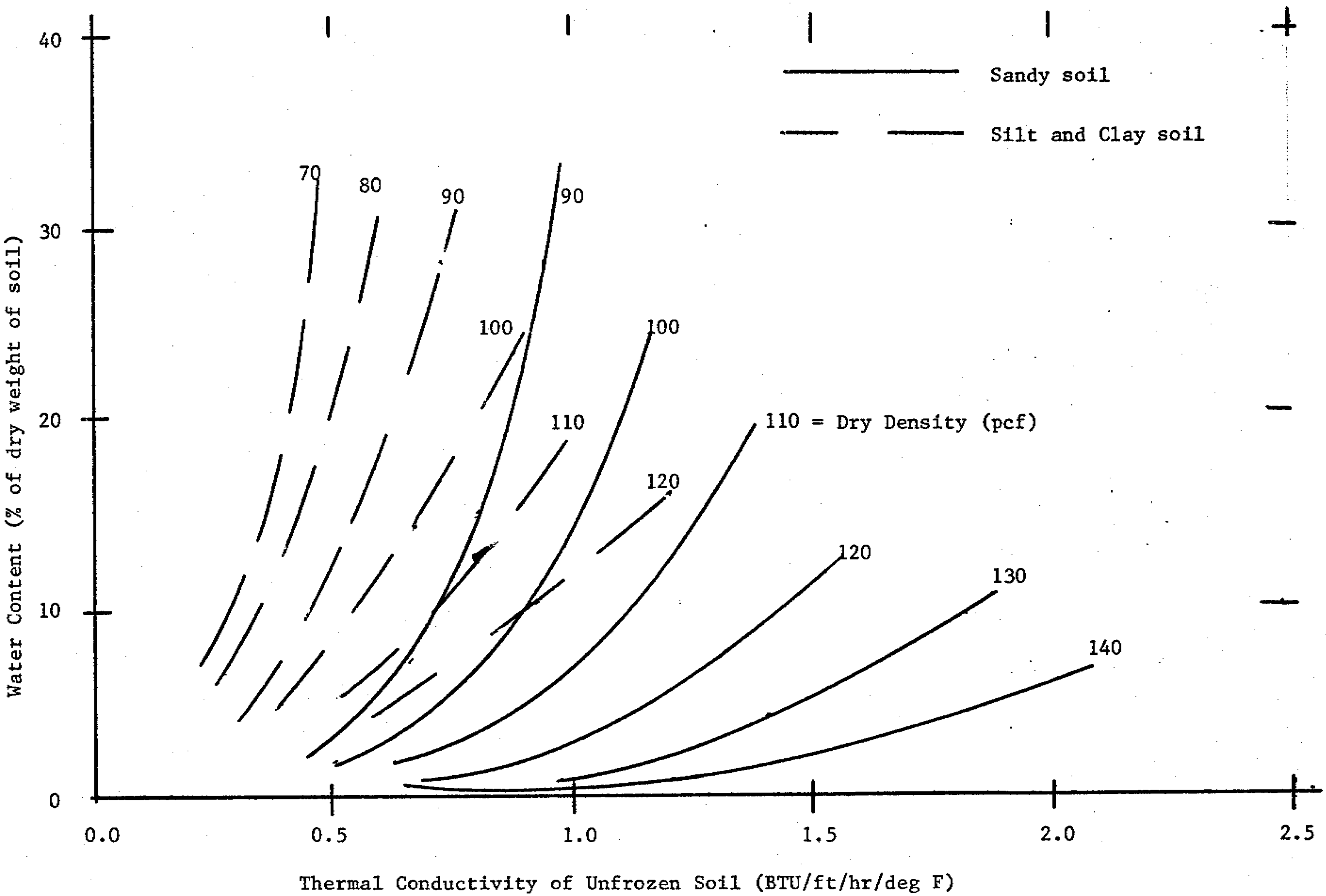
From: "Degree-days and Heat Conduction in Soils" by F.J. Sanger. International Permafrost Conference Proceedings 1963, page 257.



From: Aldrich, H.P. "Frost Penetration Below Highway and Airfield Pavements" Highway Research Board Bulletin 135 (1956) pp 124-144.

THERMAL CONDUCTIVITY OF FROZEN SOIL

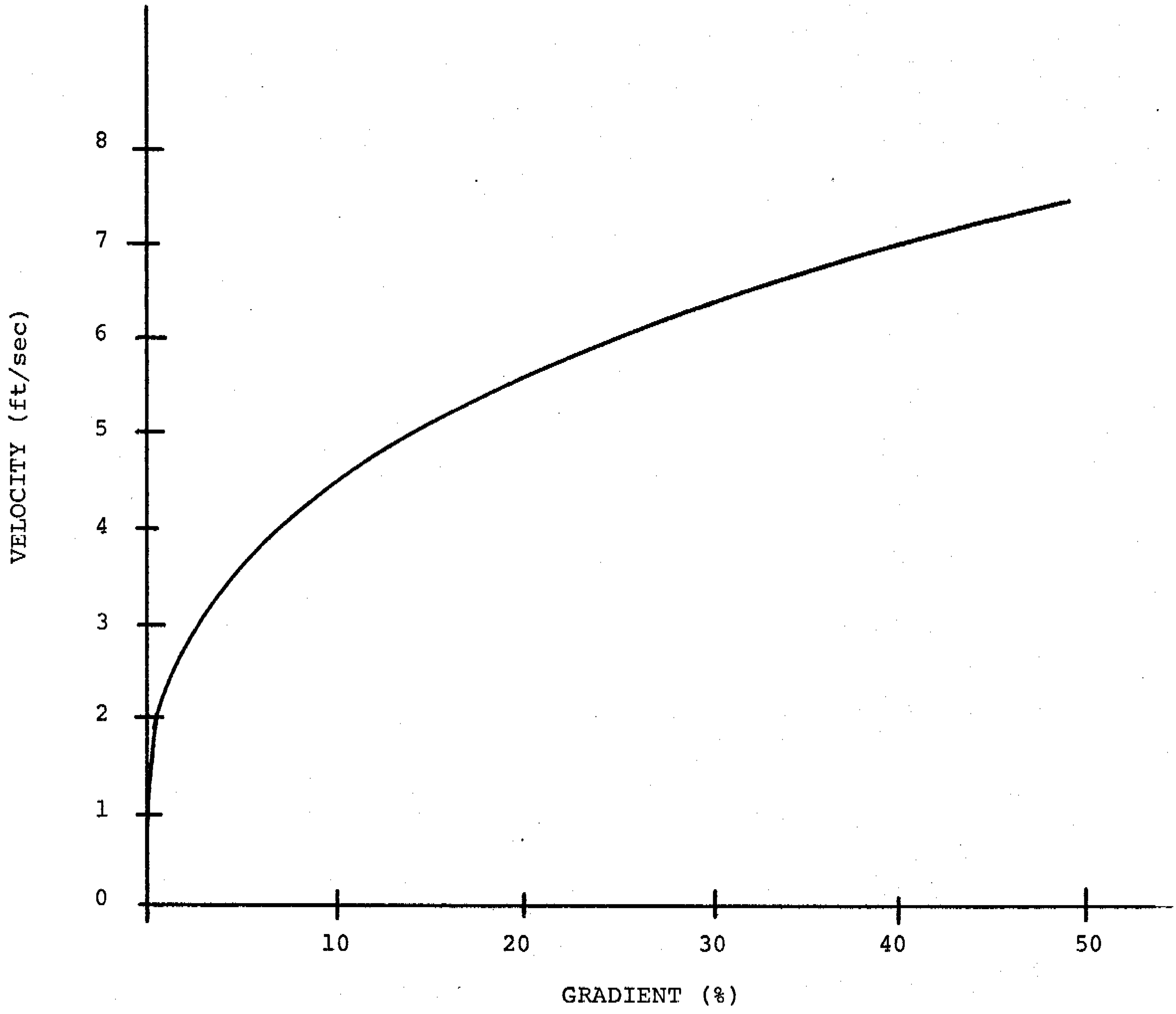
PLATE 4



From: Aldrich, H.P. "Frost Penetration Below Highway and Airfield Pavements" Highway Research Board Bulletin 135 (1956) pp 124-144.

THERMAL CONDUCTIVITY OF UNFROZEN SOIL

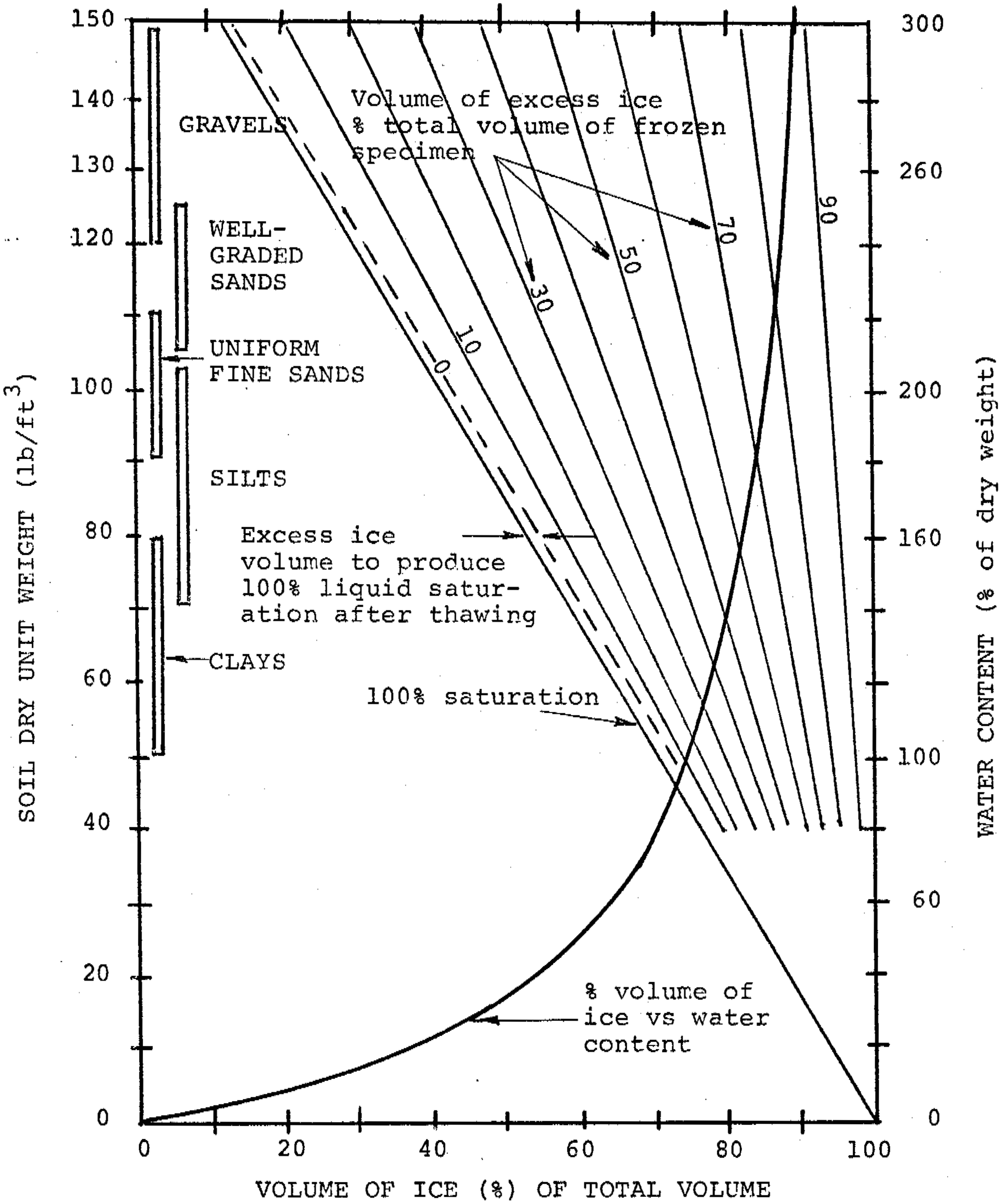
PLATE 5



RELATIONSHIP OF WATER VELOCITY TO SLOPE GRADIENT FOR A FLOW OF 0.4 cu ft/sec/ft of width USING THE MANNING FORMULA OF :

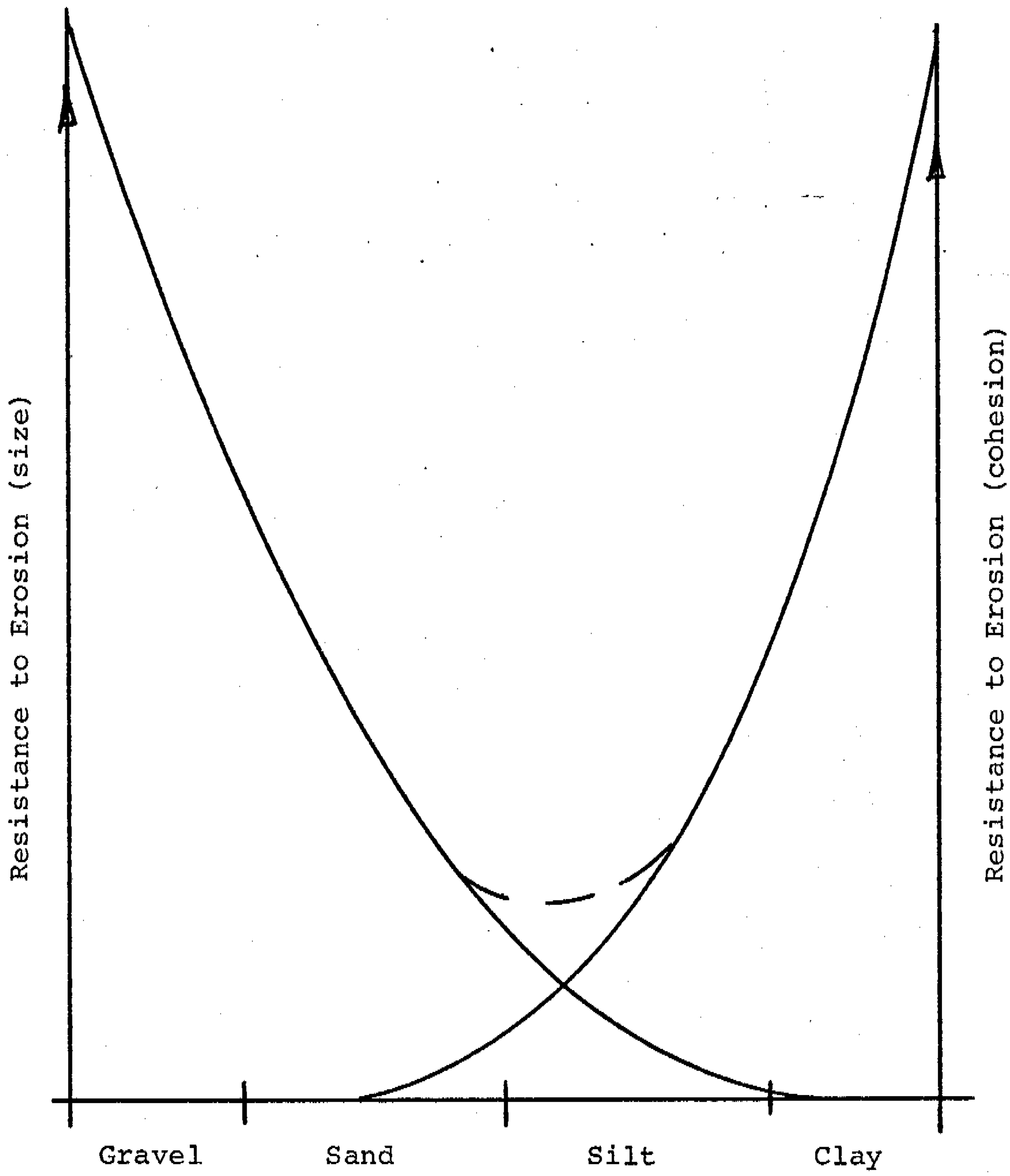
$$V = \frac{1.5}{n} R^{0.67} S^{0.5}$$

$$n = 0.02$$



DRY UNIT WEIGHT, ICE VOLUME, AND WATER CONTENT
IN FROZEN SOIL

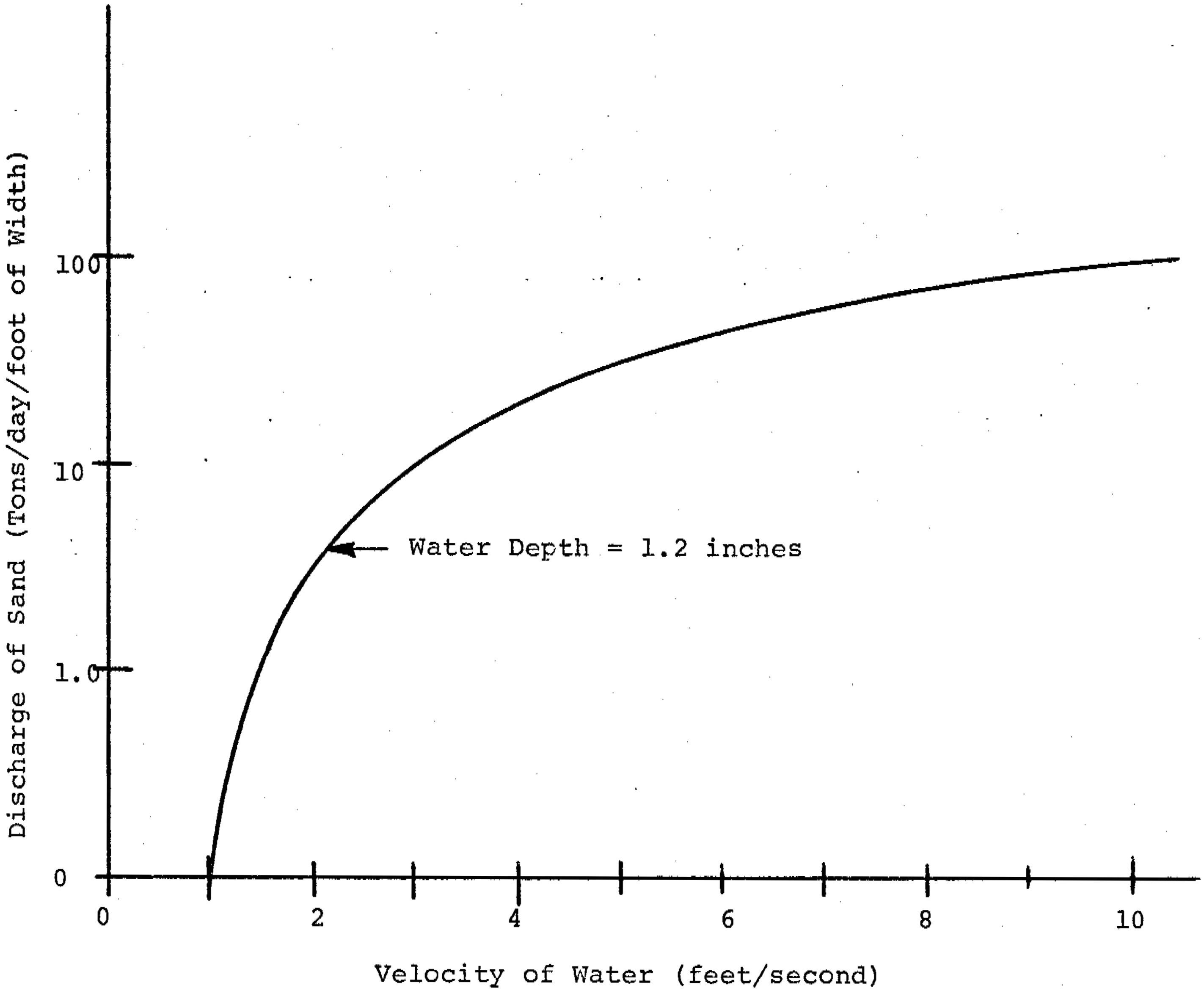
From: "Description and Classification of Frozen Soils" by K.A. Linell and C.W. Kaplar Proceedings, International Permafrost Conference, 1963, pp 481-487



<u>A QUALITATIVE PRESENTATION OF THE RELATIVE IMPORTANCE OF PARTICLE SIZE AND COHESION ON THE RESISTANCE OF SOILS TO EROSION BY WATER</u>.

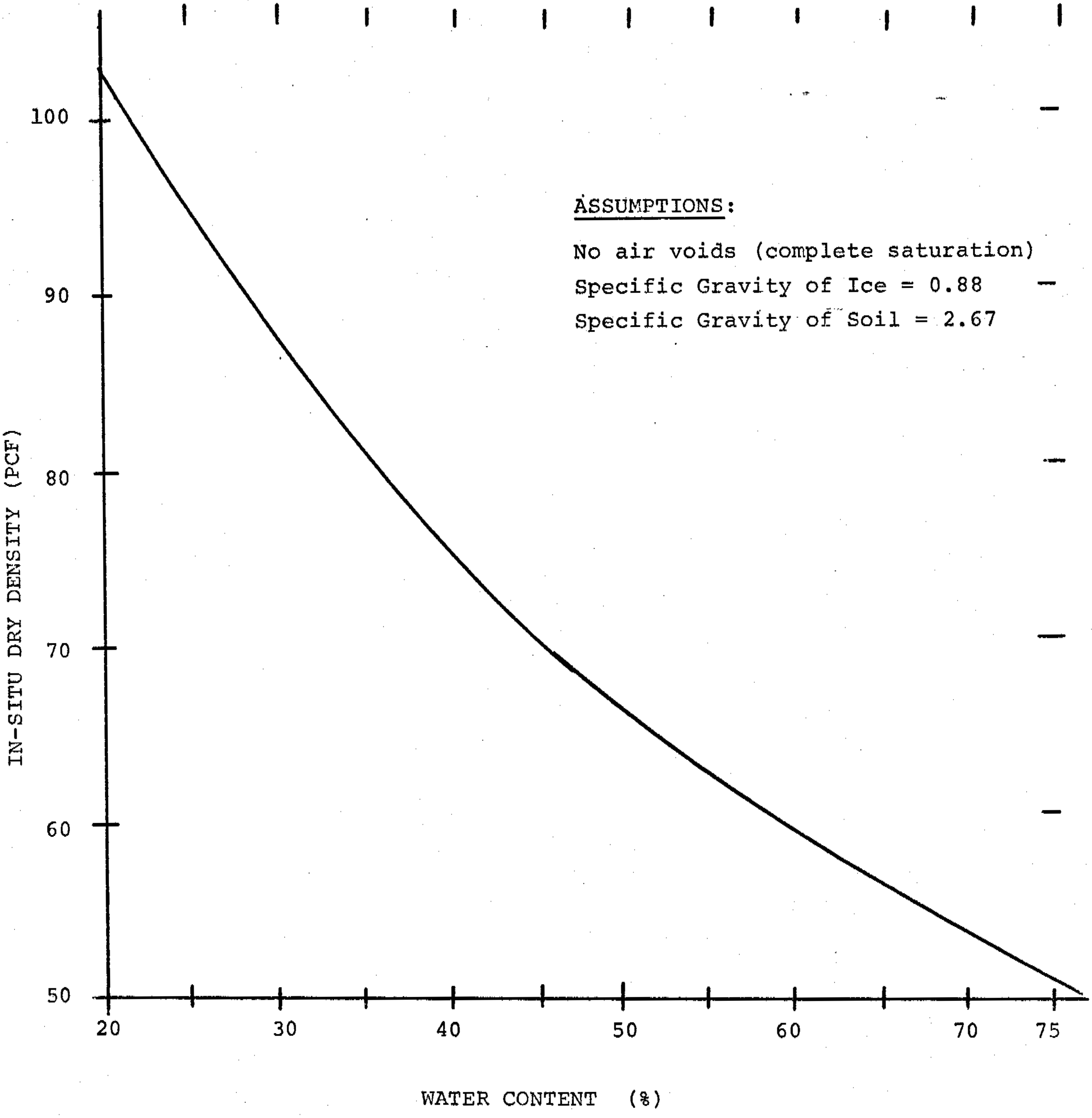
(From: <u>Aerial Photographic Interpretation</u> by D.R. Lueder page 51)

G. Mc December 8, 1972



EMPIRICAL RELATION BETWEEN TRANSPORT RATE OF SANDS AND MEAN VELOCITY OF WATER. (Water Temperature = 60 F; median diameter of sand = 0.30 mm)

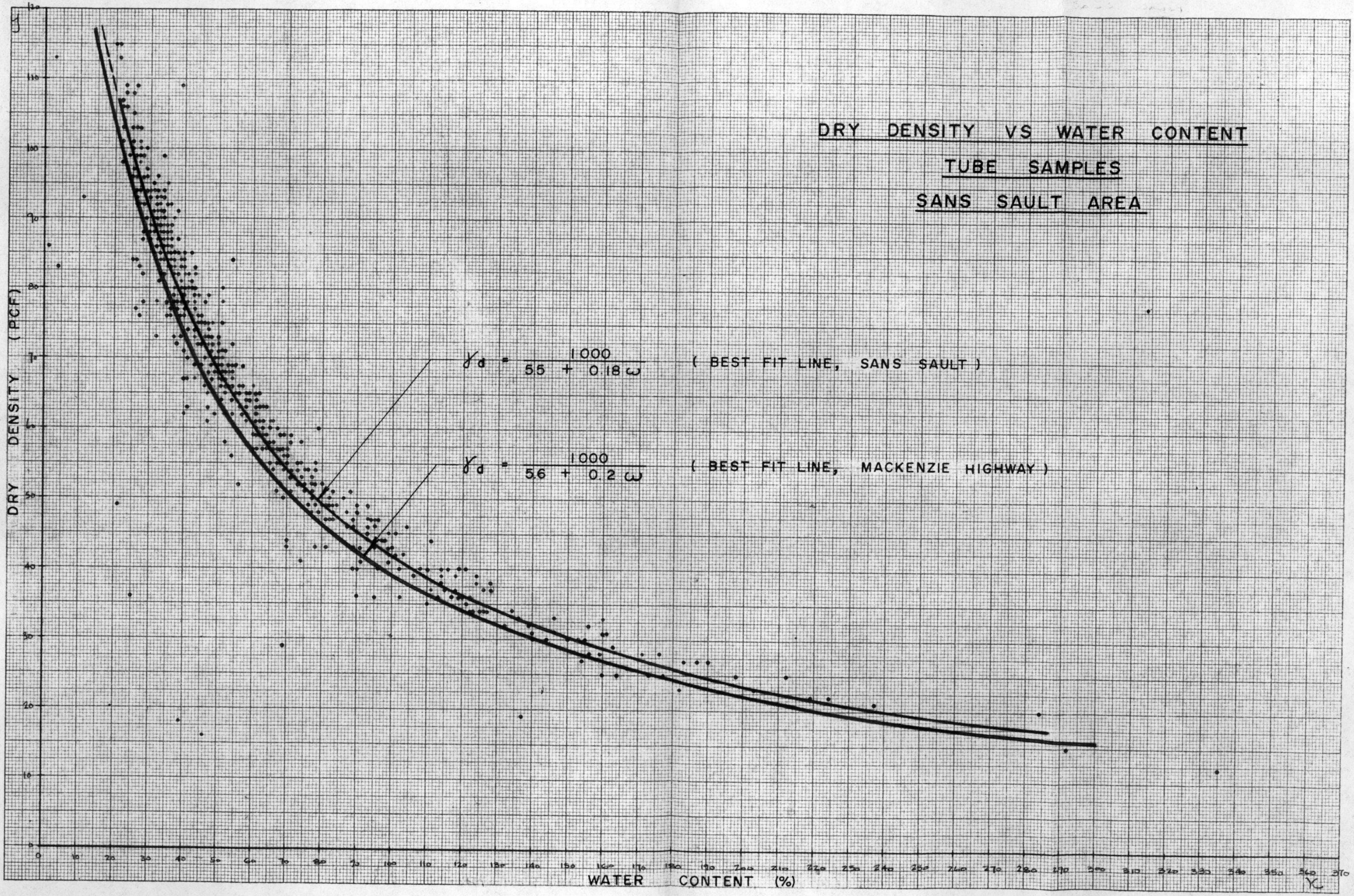
From: Fluvial Processes in Geomorphology by L.B. Leopold et al page 184.



RELATIONSHIP OF WATER CONTENT

TO IN-SITU DRY DENSITY OF FROZEN SOIL

G. Mc E-2615 March 21, 1973 PLATE 10



DRY DENSITY VS WATER CONTENT
TUBE SAMPLES
SANS SAULT AREA
$\gamma_d = \frac{1000}{5.5 + 0.18\,\omega}$ (BEST FIT LINE, SANS SAULT)
$\gamma_d = \frac{1000}{5.6 + 0.2\,\omega}$ (BEST FIT LINE, MACKENZIE HIGHWAY)
DRY DENSITY (PCF)
WATER CONTENT (%)
KEUFFEL & ESSER CO.
MADE IN U.S.A.

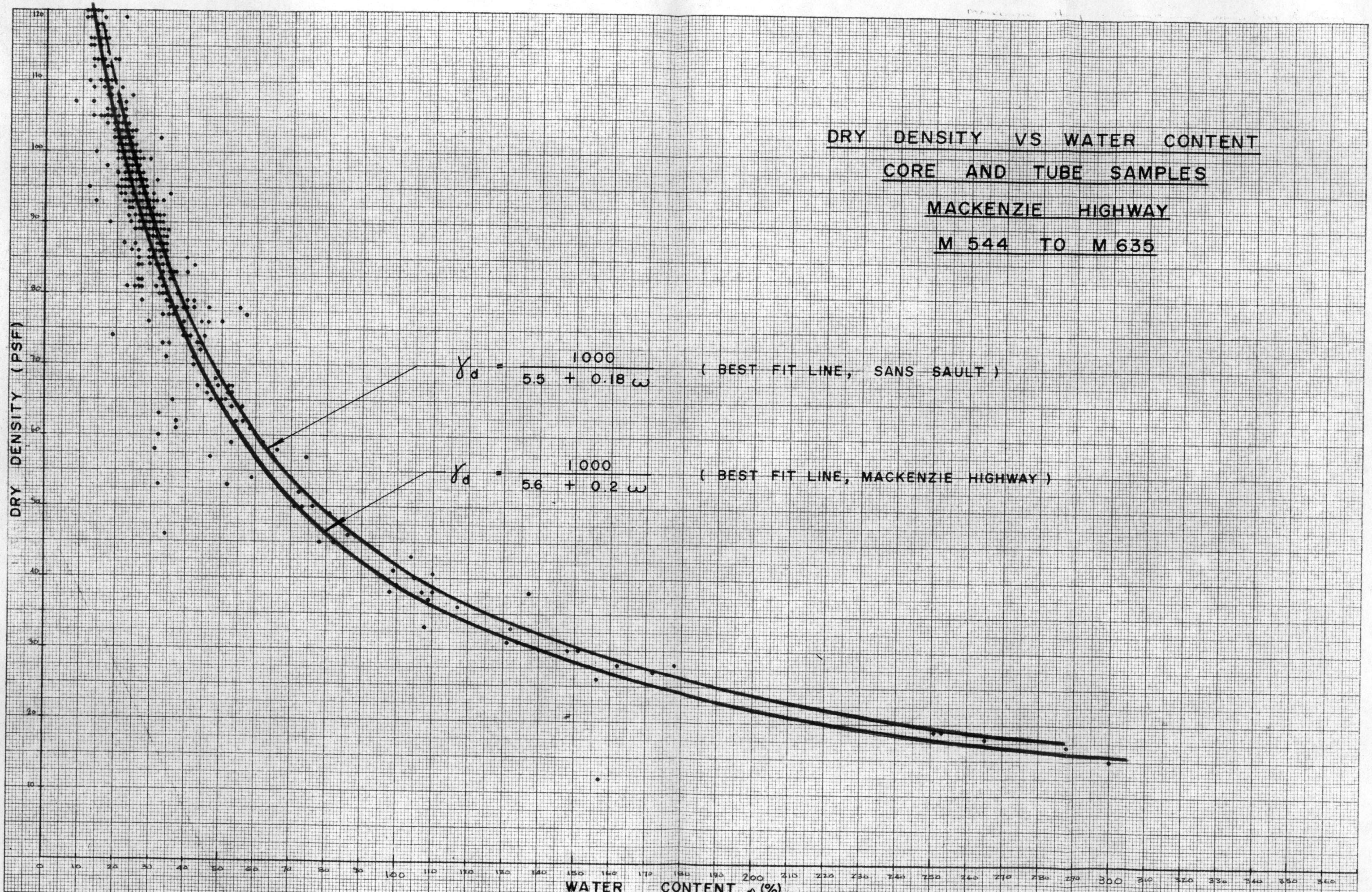

DRY DENSITY VS WATER CONTENT
CORE AND TUBE SAMPLES
MACKENZIE HIGHWAY
M 544 TO M 635
$\gamma_d = \frac{1000}{5.5 + 0.18\,\omega}$
(BEST FIT LINE, SANS SAULT)
$\gamma_d = \frac{1000}{5.6 + 0.2\,\omega}$
(BEST FIT LINE, MACKENZIE HIGHWAY)
DRY DENSITY (PSF)
WATER CONTENT ω (%)
100
200
300

PLATE 12