Climate in Relation to Frost Action

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This paper attempts to illustrate the great need of correlating the main climatic factors with frost action damage. This has already been done, on a modest scale, with evidence of some success. Although adequate climatic data is available in most populated regions, much-more-concise information on actual road damage is required for a complete analysis of the effect of climate. Two specific cases of climatic influence on spring breakup are discussed.

● IN practically all of Canada and most of the United States frost action is a problem of major importance in highway and airport engineering. The term "frost action" is used here in its broad sense to include any detrimental effect on engineering works resulting from the penetration of frost below the surface of the ground.

For more than a century scientists and engineers have been concerned with the destructive effects of frost action. The advent of modern land and air transportation has added urgency to the necessary solution of the problem. This has resulted in many investigations and a voluminous literature on the subject. Fortunately this was studied, abstracted, and correlated in the admirable review of the literature on frost action by Johnson (1952).

DEVELOPMENT OF THEORIES ON FROST HEAVING

The most-significant developments in the understanding of the frost action phenomenon occurred about 25 years ago. Much good work had been done earlier but it was the publishing of Taber's treatise on "Frost Heaving" in 1929 that introduced the elements of the theories on frost action which are now widely held. Coincident with Taber's work was the equally important work of Beskow in Sweden. Although Beskow had visited America during the First International Conference on Soil Mechanics and Foundation Engineering in 1936, his work was not widely known in this country until Osterberg translated his original papers into English in 1947.

Taber postulated that a steady penetration of frost into certain types of soil would result in the formation of ice lenses which would produce heaving of the surface. In 1930 Benkelman and Olmstead, on the basis of laboratory studies and many field observations, proposed that freeze-thaw cycling of air temperature was necessary for the formation of lenses. Although Taber's theory appears to be more-widely accepted, the significance of freeze-thaw cycling has not yet been satisfactorily resolved. Heat-flow theory indicates that there is no limit to the thickness to which an ice lens may form under a slow steady extraction of heat from the ground. There is, however, some reason to believe that cycling of air temperatures, a common feature of the weather, contributes significantly to frost damage to roads (see Johnson, 1952, p. 133).

EMPIRICAL RELATIONSHIPS

There are many variables that affect the penetration of frost into the soil (Crawford 1952). There are many additional factors that will affect the frost damage to subgrades (Johnson 1952). In the solution of the problem, there are two methods of approach in which these variables have vastly different significance. In fundamental investigations into the mechanics of frost action, the investigators must attempt to consider all variables. In practical investigations or in the application of fundamental results, however, the engineer must exclude minor variables and apply averages or statistical factors to the variables of major importance.

Consider, for example, the role of the soil moisture content, a factor which is obviously important and which, to a large degree, determines the severity of frost action. In a fundamental analysis the investigator must understand the physical state of the soil water, its chemical content, its rate of movement and whether it moves as liquid or vapor under temperature gradient. In addition to its direct effects, the soil moisture will greatly influence such variables as the coefficients of thermal conductivity, specific heat, radiation, and evaporation. On the other hand, in attempts to explain frost damage in the field, average values only can be cited. Because of variability in the soil and sampling difficulties, further refinement is not possible.

This same limitation will apply to any attempt to relate climatic effects to frost action. It will be necessary to neglect completely many important factors in order to obtain workable relationships. The design of the roadway and the volume of traffic, in addition to climate and soil type, will have a considerable influence on the amount of damage which can be attributed to frost action, but these two factors are superimposed conditions and must therefore be neglected.

Casagrande, in 1931, illustrated an empirical relationship between the cumulative degree-days of below freezing air temperatures and the penetration of frost into the ground. The idea of this simple relationship had been mentioned 2 years earlier (Sourwine 1929). It is based on the premise that a reasonable measure of the magnitude and duration of cold for any one day is given by the number of degrees that the mean temperature is below freezing; the sum of these daily values for the winter season is now called the "freezing index." Approximate values of the freezing index can be calculated by using only the monthly mean temperatures or by plotting the monthly mean temperatures and finding the area between the resulting curve and the freezing line. If accurate values are needed, however, it is necessary to use daily mean temperatures for the computations.

Many subsequent investigators have noted a similar correlation. A definite empirical relationship has been established for a particular soil type under snow-free conditions (Shannon 1945).

Although it will be readily admitted that this empirical relationship is an oversimplification of complex phenomena, no improvement of the original curve has yet been possible. It is now generally referred to as the U.S. Corps of Engineers "Design Curve" (Corps of Engineers 1947). It has been suggested (Belcher, 1940; Legget and Crawford, 1952) that the rate of accumulation of degree-days of freezing air temperatures will have a significant effect on frost penetration but sufficient data are not available to establish this effect.

CLIMATIC STUDIES

In 1929 F.H. Eno presented a paper to the Ninth Annual Meeting of the Highway Research Board outlining the available climatic data which are of most importance to highway engineers (Eno 1929). Twenty-three figures were used to illustrate various features of air temperature and freezing, sunshine, wind velocity, relative humidity, evaporation, and precipitation. He emphasized the application of climatological data to drainage, subgrade and surface stability, construction operations, maintenance, snow problems, load restrictions and safety. This paper was an introduction to the importance of climate in highway engineering, but 25 years have passed since its presentation, and relatively little effort has been devoted to the promotion of its implications.

Certain features of the paper were elaborated in the discussion by J.A. Sourwine, Senior Highway Engineer, U.S. Bureau of Public Roads, who in the following year (Sourwine 1930) published results of an extensive climatic study of frost occurrence for use in highway design. His purpose was to establish a method of using recorded weather data to determine the probability of ground freezing. His method included the effects of the intensity, duration, and frequency of low air-temperature occurrences based on past records.

From the work of Bouyoucos and Petit on the required duration and lowering of air temperature to produce freezing in soil and a study of low temperature durations from meteorological records, Sourwine established 23 F. as the "critical initial air temperature" for freezing of the ground surface. He then assumed a depth of 3 inches as the "depth below which ground freezing becomes a problem for consideration in highway design." Again referring to the work of Bouyoucos and Petit, he established 26.4 F. as the "absolute minimum soil temperature coincident with the inception of ground freezing," based on the required super cooling of the soil and corrected for duration of cold period as shown by meteorological records.

From the field observations of Bouyoucos, 16 F. was found to be the "average minimum air temperature equivalent to a soil temperature of 26.4 F. at a depth of 3 inches. From the records of several stations of the U.S. Weather Bureau, Sourwine analyzed all periods during which the air temperature fell below 23 F. (the critical initial air temperature for ground freezing) and found that the absolute minimum temperature during any period was on the average 13 F. colder than the minimum temperature occurring with 5 percent frequency.[1] From this he reasoned that, since 16 F. is the air temperature at which ground freezing begins at a 3-inch depth, 3 F. represents a "critical absolute minimum air temperature" coincident with 5 percent frequency of ground freezing at a 3-inch depth.

He then compared values of monthly average daily minimum temperature and absolute monthly minimum temperature for four stations and found, by coincidence, a critical value of 23 F. for the "lowest monthly average of daily minimum temperature" which he assumed to be a critical design value for highway ground freezing.

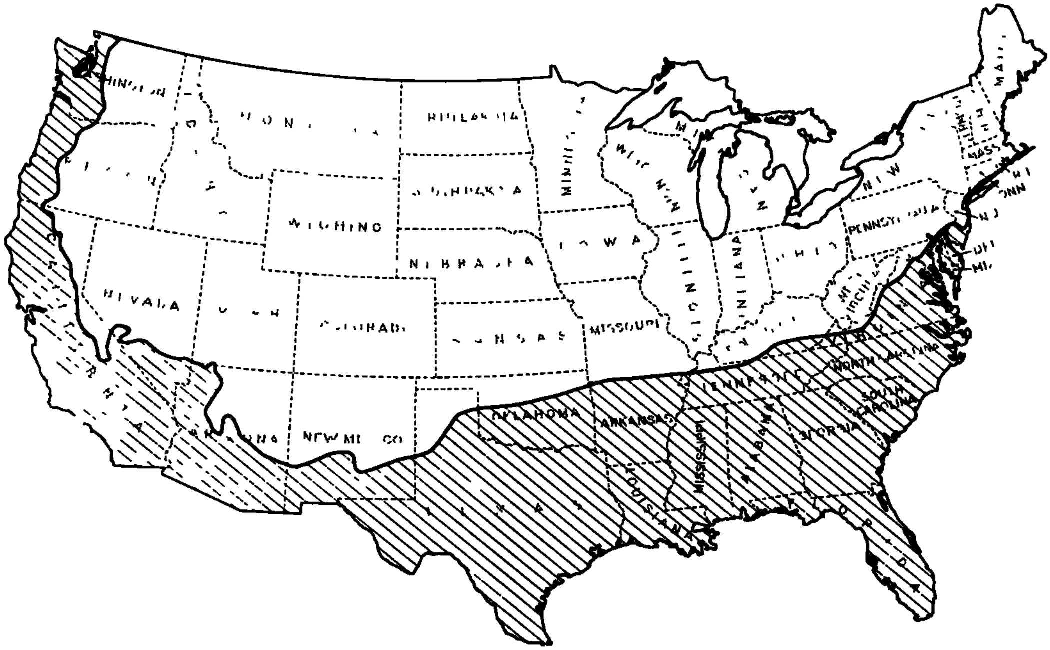

Figure 1. Critical index line for highway ground freezing (Sourwine, 1930).

Sourwine extended his initial work to a study of the effect of duration of cold periods. He studied records over a 15-year period for 35 stations near the 23 F.-minimum-air-temperature isotherm and determined in each case the cold period duration in degree-hours which occurred in 5 percent of all cold periods. After considerable study, a "degree-hour-index" of 900 for 5 percent frequency occurrence was chosen to represent the danger line for highway ground freezing.

Combining these two studies, Sourwine plotted a "critical index line for highway ground freezing" on a map of the United States, Figure 1, which, on the basis of weather records alone, separates territory relatively safe from highway ground freezing from territory in serious danger of Highway ground freezing. A portion of the territory in serious danger,

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[1] This "5 percent allowable frequency" is arbitrarily defined to mean that when we consider for any locality all cold periods sufficient to cause freezing of average surface soil, ground freezing below 3 inches in depth may occur one time in 20. A frequency of more than 5 percent, or more than 1 period in 20, we designate as "objectional frequency."

according to temperature data, was modified to be a region of doubtful danger due to the nature of its winter (December to February) rainfall. This region, mainly in the south central United States, has less than 2 inches of average winter precipitation, with a lowest monthly average of daily minimum temperature between 10 F. and 23 F.

This review of Sourwine's work is presented because it is the most-extensive analysis of weather records in relation to frost action known to the authors. The purpose of the study was to determine, on the basis of meteorological data only, the approximate southe boundary of probable highway frost damage. It does not include important intrinsic variables, such as soil type, soil moisture content, density or surface cover; but, to a degree, the objective was accomplished and the approach encourages further study for relat purposes.

RECENT CLIMATIC STUDIES

In recent years many studies have been made relating climate and soil temperatures. From these studies there resulted some general relationships between climate and frost action, but few specific correlations have been evolved. It was encouraging to the authors, therefore, to review the work of Dolch (1952) who, working at Purdue University, attempted to combine temperature and precipitation data to explain variations in the sever ity of spring breakup of roads.

Using average values for about seventy stations in Indiana, he plotted monthly mean temperature, monthly total precipitation and normal precipitation in relation to time, for 16 winter seasons. Using smooth curves through these monthly average points he computed the "freezing index" (area between actual air temperature and 32 F.) and a "pre-

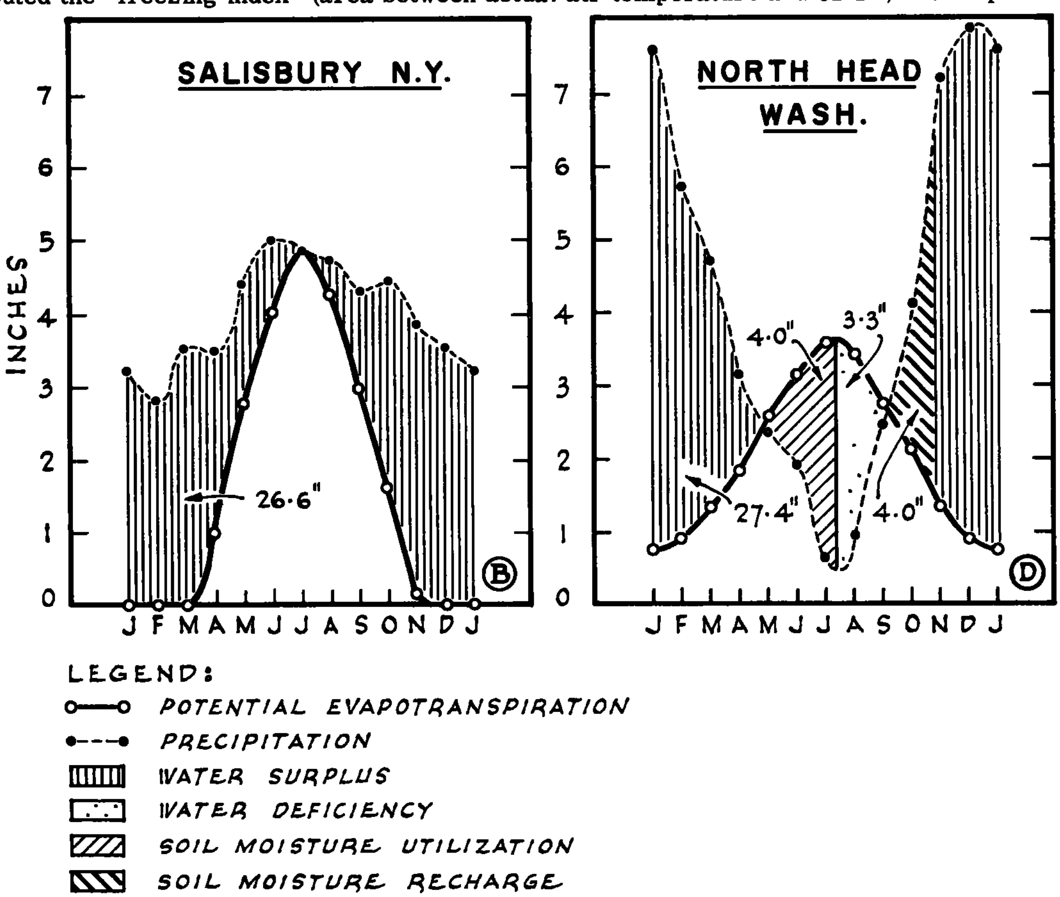

Figure 2. Extreme climatic variation (Thornthwaite, 1948).

cipitation index" (area between normal and actual precipitation during the 30-day period before freeze-up) for each winter season.

Figure 3 shows similar curves for Calgary, Alberta, during the winter of 1951-52.

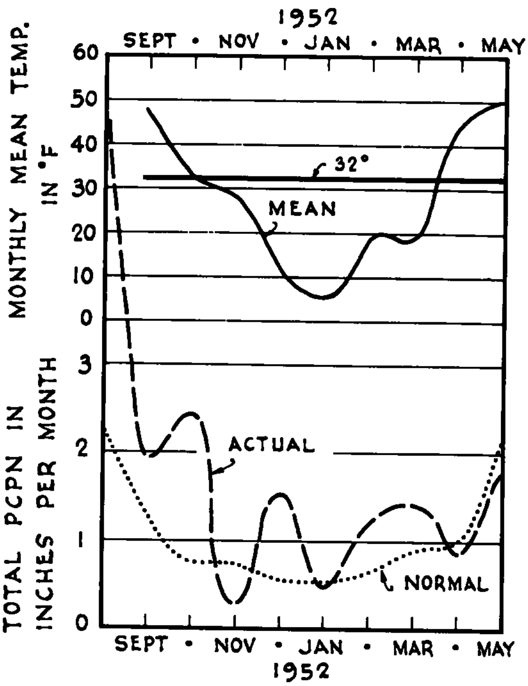

Figure 3. Calgary temperature and precipitation.

Though various combinations of temperature and precipitation were tried, the best correlation between actual spring breakup of roads and weather was found using the product of freezing-index and the 30-day precipitation index as a measure of the severity of road breakup.

Dolch recognized that freezing characteristics alone would not indicate the potential severity of spring breakup and his data certainly support this view. (One of the most-severe breakups followed a winter during which the approximate freezing index for the state was only 8 degree-days.) He also concluded, from his weather data, that snowfall and freeze-thaw cycles had no bearing on the severity of spring breakup.

There are certain disadvantages in using a precipitation index such as that used by Dolch. For example: the use of departure from normal precipitation restricts a broad application of the data, and further, the precipitation during a particular period may not be proportional to the amount of moisture in the soil at the end of the period. The amount of soil moisture depends not only on precipitation and soil type but also on other weather elements.

In a general analysis of the problem, the engineer can turn to climatology and to agricultural soil science for further assistance. Thornthwaite (1948) has pointed out that precipitation alone does not indicate whether a climate is moist or dry. It must also be known whether precipitation is greater or less than the water needed for evaporation and transpiration. Where precipitation exceeds water need, the climate is moist; and where it is less than water need, the climate is dry.

The combined evaporation from the soil surface and transpiration from plants is termed "evapotranspiration." The amount of water that would evaporate and transpire if it were available is called "potential evapotranspiration." Thornthwaite points out that evapotranspiration and precipitation, representing flow of moisture to and from the atmosphere respectively, are equally important climatic factors. Evapotranspiration can be measured only with considerable difficulty, and potential evapotranspiration must be determined experimentally.

Since the determination of potential evapotranspiration is so difficult, it was necessary to establish a relationship between potential evapotranspiration and other weather elements. This was done by Thornthwaite, and although the relationship is entirely empirical, it has been found to be satisfactory. Computed values can be obtained from temperature records and latitude.

The annual potential evapotranspiration ranges from more than 60 inches in the southern part of the United States to less than 18 inches in the western mountains; it varies greatly from summer to winter. Along most of the Canadian border it is less than 21 inches. In southern Ontario it ranges from 20 to 26 inches. (Sanderson 1950).

Monthly or daily values of potential evapotranspiration and precipitation can be used to keep an account of the amount of moisture stored in the soil, and of any surplus or deficit.

It is assumed that a certain amount of rainfall can be stored in the soil near the surface and any amount in excess of this quantity will run off or be used in recharging the ground-water table. On the other hand, when the storage has been exhausted, a deficit will occur due to the potential evapotranspiration.

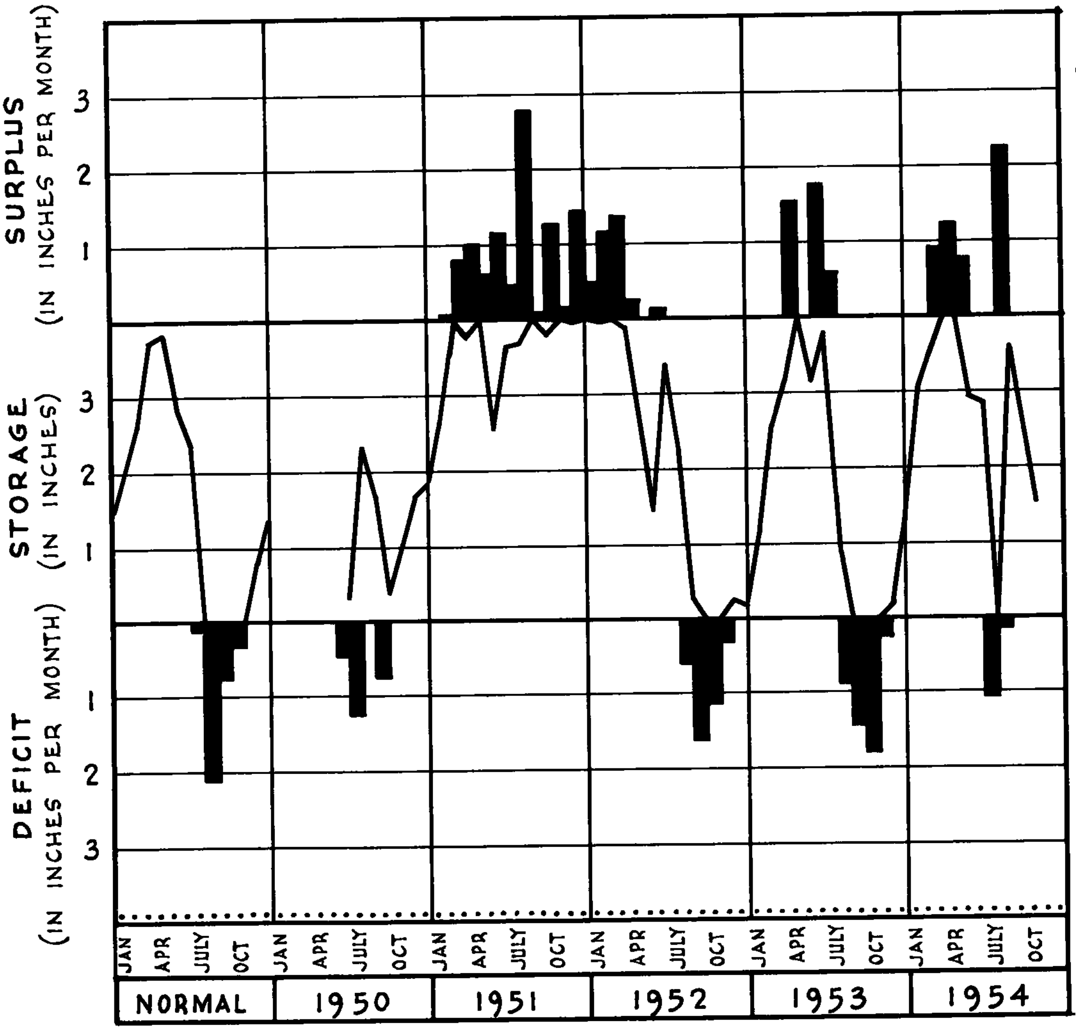

Figure 4. Soil moisture at Calgary.

TABLE 1
WEATHER DATA, CALGARY, ALBERTA

Winter	Freeze Thaw Cycles	Date of Freeze-up	Freezing Index (degree-days)	30-day Precip (Inches)	Dolch Breakup Index	Soil Moist Storage (Inches)	Modified Breakup Index	Conditio of Road During Spring
1948-49	13	Nov 16	2421	0 37	896	0 30	726	
1949-50	17	Dec 2	2889	0 01	20	0	0	
1950-51	14	Nov 5	2493	1 22	3041	0 94	2343	Worse than normal
1951-52	15	Oct 15	2313	2.16	4996	3 50	8789	Worst on record
1952-53	18	Nov. 14	1143	Tr	6	0	0	Worse than normal
1953-54	15	Nov 17	1824	0 31	565	0.24	438	Better than normal
6-Year Av	15	Nov. 11	2180	0 68	1589	0 88	2049	

It is recognized that the storage capacity will vary with soil type and distribution of root systems. Thornthwaite states the "except in areas of shallow soil the water storage capacity available to mature plants with fully developed root systems varies around a mean that is the equivalent of about 10 centimeters, or 4 inches, of rainfall."

For purposes of illustration two extreme climatic cases are shown in Figure 2 (from Thornthwaite 1948). It is seen that at Salisbury, New York, no water deficiencies occur during the average year. At North Head, Washington, on the other hand, where annual rainfall is slightly greater, a serious deficiency lasting more than 4 months may be expected during the average year. It seems obvious that groundwater and soil moisture conditions at these two locations will be entirely different. Furthermore, it is probable that there exists a relationship between the combination of precipitation and potential evapotranspiration and the soil moisture conditions at any location.

a) April 2, 1953.

b) April 1, 1954.

c) April 2, 1953.

d) April 1, 1954.

Figure 5. Contrast in spring breakup during 1953 and 1954.

The importance of climate to practical aspects of building research led, in 1949, to a useful arrangement between the Division of Building Research of the National Research Council and the Meteorological Division of the Department of Transport. By this special agreement the full time services of a trained meteorologist are seconded to the Division of Building Research for cooperative work on building problems while he retains the associations and facilities of the Meteorological Service. One of the first joint studies was to analyze the weather conditions which accompanied an unusual spring breakup of roads in the Province of Alberta.

EXAMPLES OF SPRING BREAKUP OF ROADS

Calgary, Alberta

During the spring season of 1952, roads in the Calgary district of Alberta suffered unusual deterioration, while roads in the Edmonton area, to the north, experienced a normal breakup. It is known that frost action in the Calgary area, a region of silty soil mantle, is always more severe than in the predominantly clay soils around Edmonton, but in this particular year the breakup was so severe in the southern part of the province that a special investigation of the weather was thought to be warranted.

TABLE 2

WEATHER DATA, OTTAWA, ONTARIO

Winter	Freeze Thaw Cycles	Date of Freeze-up	Freezing Index (degree-days)	30-day Precip (Inches)	Dolch Breakup Index	Soil Moist Storage (Inches)	Modified Breakup Index	Condition of Roads During Spring
1948-49	11	Nov 28	1269	4 17	5292	4 00	5076	
1949-50	18	Nov 17	1719	2 04	3507	2 76	4744	
1950-51	13	Nov 21	1491	3 76	5606	4.00	5964	Very Bad
1951-52	13	Nov 1	1557	1 50	2336	0 51	794	Very Good
1952-53	12	Nov 28	933	2 13	1987	4 00	3732	Bad
1953-54	14	Dec. 15	1449	2 56	3709	3.41	4941	Good
6-Year Av	13	Nov 23	1403	2 69	3740	3 11	4208	

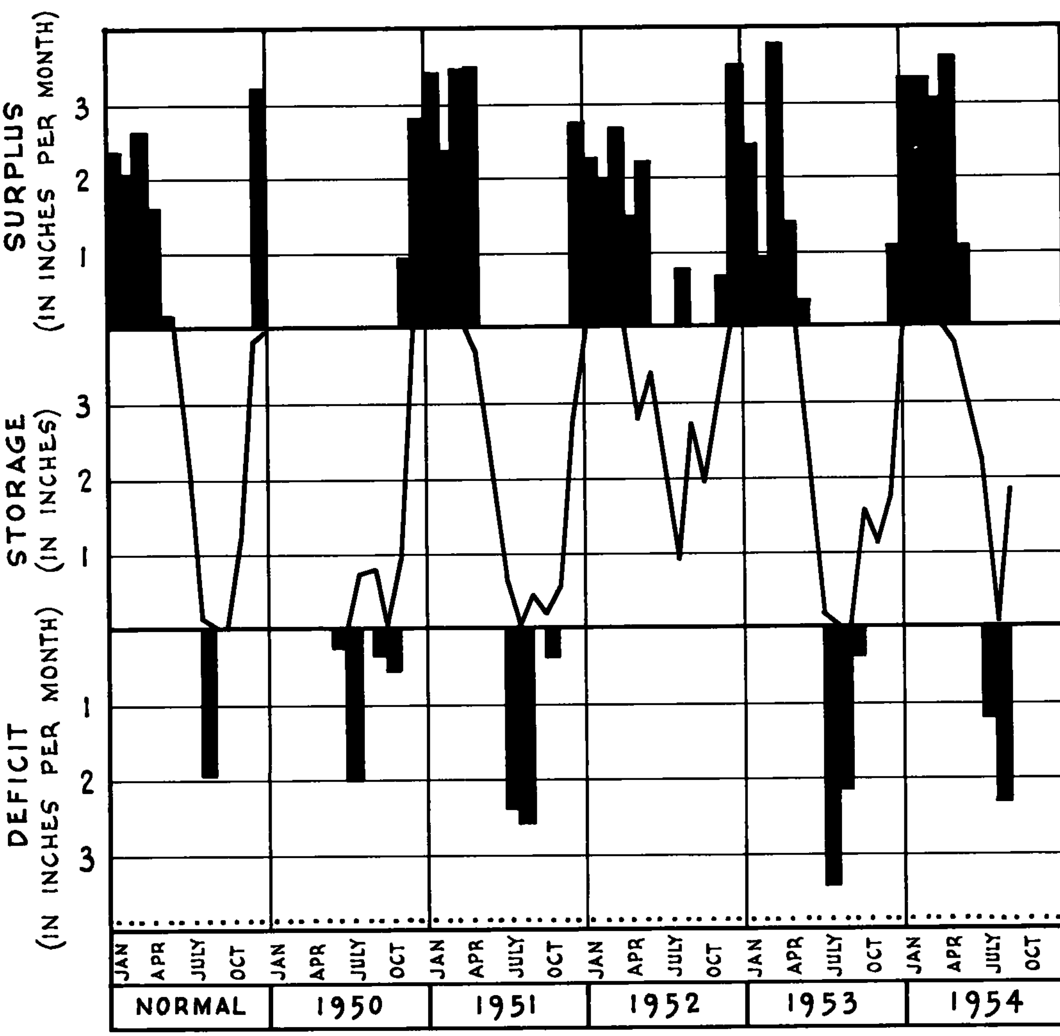

Figure 6. Soil moisture at Ottawa.

The most-difficult problem encountered in an investigation of this type is the evaluation of relative road damage, both in its variation over a wide area and in disparity from year to year. It was possible to obtain only descriptive terms, based on experience, in order to differentiate the degree of damage from year to year. Significantly, the road breakup near Calgary during the spring of 1952 is termed "the worst on record." This was attributed, in a general way, to a comparatively wet cycle in the weather which caused a general rise in ground-water levels. Study of the records does, in fact, show that this was probably the case.

In the climatic investigations, a large volume of data was assembled and analyzed in an attempt to establish a relationship between road damage and the weather. Weather records for 6 years at Calgary were studied; the results are shown in Table 1. Freeze-thaw cycles were based on daily mean air temperatures; each figure indicates the number of times during the winter that the mean temperature fell below and rose above the freezeing point. The freezing index was computed using monthly mean temperatures. This procedure is an approximation, adequate for comparative purposes but resulting in an index which is usually low.

In the correlation of road damage to weather it was considered desirable to refine the index which was originated by Dolch. Accordingly the "30-day Precipitation" is the actual total precipitation which occurred during the 30-day period before freeze-up, rather than the "departure from normal" based on graphical analysis. The Dolch breakup index, reported in this paper, is the product of the freezing index and the 30-day precipitation as outlined above. Values of soil-moisture storage were computed using Thornthwaite's theories; the value represents storage in inches at the time of freeze-up. The modified index is the product of freezing index and soil moisture storage. In the opinion of the authors this index provides a more accurate evaluation of soil moisture conditions than is possible using precipitation data alone.

For a comparison of the winter of 1951-52 with that of other years, reference may be made to Table 1. During this particular winter, the occurrence of freeze-thaw cycles was equal to the 6-year average. The freezing index was about 6 percent greater than average, but the freeze-up occurred much earlier than usual. The most-significant variations occurred in the precipitation which preceded freeze-up and in the soil moisture storage. Precipitation during the 30-day period before freeze-up was more than three times the 6-year average and soil moisture storage was more than four times the average.

Reference to Figure 4, showing soil moisture conditions at Calgary from 1950 to 1954, supports the general opinion that the Calgary area was experiencing a wet cycle. This diagram illustrates the variation of soil moisture storage on a monthly basis. The bar graphs indicate the total amounts of surplus and deficiency which occurred during each month.

Unforturately, it was possible to obtain comparative opinions of the severity of road breakup for the last four seasons only. The breakup indices for three of these years are in the appropriate order. The indices for the winter of 1952-53, however, indicate a light breakup when in fact it was worse than normal. Significantly, the freezing index for this year was only about half of the 6-year average; it was one of the mildest winters on record. Further comments on this feature will be made later.

A study of weather records for Edmonton during the period from 1948 to 1954 showed much less variation in the Dolch index (535 to 1,944) than at Calgary (6 to 4,996) during the same period. This climatic feature, together with the great difference in soil type, previously mentioned, results in greatly different average breakup conditions.

It is noted in a private communication from R.M. Hardy of the University of Alberta: "The effect of frost action is usually much slower in becoming apparent as damage to pavements than is the case in the Calgary area. In the Edmonton area, damage to pavements may still be developing as late as July by subbase failure while in contrast, in the Calgary area, pavement failure occurs almost within hours after the breakup."

An extensive survey of thirty blocks of newly paved streets (Hardy, 1950) showed that pavement damage occurred only where ice segregation took place within a depth of 18 or 20 inches of the surface. Redesign of these streets using a mechanically stabilized pit-run gravel base with minimum thickness of 24 inches has proved adequate, even during the spring of 1952.

Ottawa, Ontario

Observations of road breakup at Carleton County, near Ottawa, Ontario, during the past two spring seasons have shown the remarkable effect of weather variation on frost damage. During the spring of 1952-53, the county experienced a severe deterioration of its road system. The following year damage was confined to a few isolated frost boils.

Figure 5 shows typical road conditions at two locations during the two spring seasons. Figure 5 (a) shows a section of road that was barely passable on April 2, 1953. A few days earlier it had been completely closed to traffic. The same road is shown in Figure

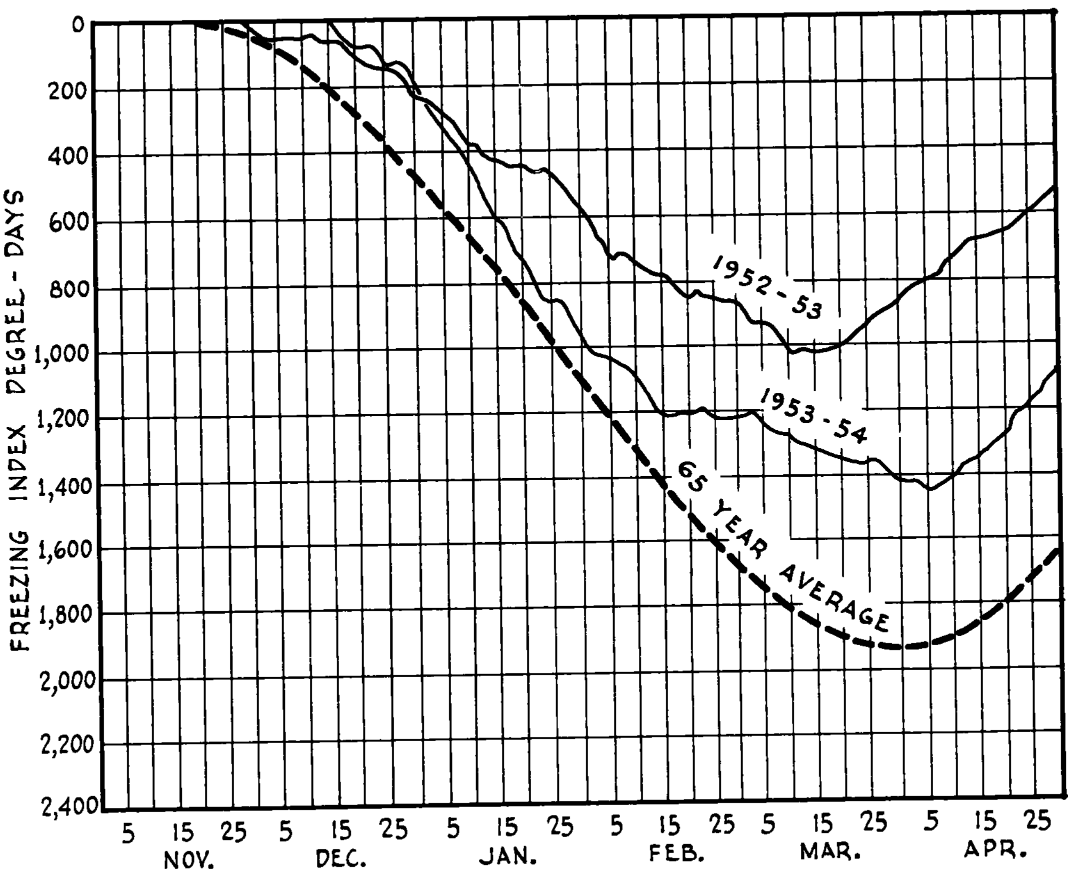

Figure 7. Freezing index at Ottawa, 1952-54.

5 (b) a year later. Although no change had been made in the road structure during the previous year, it remained in good condition. Figure 5 (c) shows a similar piece of roa that was impassable on April 2, 1953, but quite satisfactory during the spring of 1954, Figure 5 (d). This road had been treated with about a foot of pit-run gravel following th spring breakup of 1953 but is shown as a typical contrast between the two seasons.

Table 2 shows weather data for Ottawa similar to those shown previously for Calgary It was again possible to obtain an assessment of road breakup during only the last four years. During this period freeze-thaw cycles did not differ significantly. Freezing indexes were near normal, except during 1952-53, which was the mildest winter on recor Both breakup indices indicate a bad road breakup during the spring of 1951, and the mod ified index indicates a negligible breakup during the spring of 1952 and a bad breakup in 1953. To this extent the index is a satisfactory guide. But the indices intimated a bad road breakup during the spring of 1954, when in fact breakup was light. A more-detaile analysis of weather data illustrates at least part of the reason for the varying usefulness of the indices.

Figure 6 shows soil-moisture conditions at Ottawa (according to the Thornthwaite criterion) from 1950 to 1954. Reference to Figure 6 and Table 2 will show that the soil was saturated at the time of freeze-up in 1950 and 1952, the years followed by bad breakup. During 1951-52 there was no surplus and only about ½ inch of storage during freeze-up. Although the freezing index was about 10 percent above the average, no road breakup occurred.

During 1953 a water deficiency existed early in September and storage remained less than 2 inches until early December and was still not saturated at the time of freeze-up in mid-December. These observations show substantial differences in the amount of water in the soil during the fall seasons which appear to be related to the degree of breakup during the following spring.

The seasonal variation in water content of soil is not well understood. There is no question but that in most regions it is dependent on the weather, but much correlation is necessary to establish the relationship between weather and the ground-water table. Measurements of ground-water levels near the Building Research Centre in Ottawa show values which are probably typical of the region. At the time of freeze-up in 1952, the ground-water table was less than a foot below the surface; in 1953 it was about 6 feet below the surface. Although no other actual records are available, the Water Resources Division of the Geological Survey of Canada confirms this trend throughout the Ottawa area.

The accumulation and decrease of degree-days below freezing during the 1952-53 and 1953-54 winters are compared with the normal in Figure 7. Several anomalous features are evident from these curves. During the first month of the 1952-53 winter season, degree-day accumulation was extremely slow; a situation thought to favor ice lensing. Later, two significant periods of slow freezing occurred and the winter ended about 2 weeks earlier than usual.

The winter of 1953-54 began quite late but the air temperatures during January and the first two weeks of February were exceptionally cold, causing rapid accumulation of degree-days of freezing. This was followed by about 3 weeks of very mild weather, with mean daily temperatures near freezing. Ground temperatures, during this mild period, were very near the freezing point in the upper few feet indicating a softening of ice formations and possibly some redistribution of the soil water. It is thought that the rapid accumulation of degree-days of freezing early in the winter and the sustained mild weather which followed were responsible for the absence of road damage and for the failure of the break-up indices to assess the situation adequately.

COMMENTS

In considering the general problem of frost action as it affects the performance and maintenance of highways, two problems are paramount: pavement heaving and loss of strength during spring thaw. Obviously freezing air temperatures, a frost-susceptible soil, and water are prerequisites for road damage. The soil can be eliminated from this discussion of the effect of climate; since, in general, it is affected by climate only in the pedological sense and so can be assumed to remain in the same physical and mechanical state from year to year. Air temperature, however, needs close attention.

In regions of doubtful freezing danger, climatic studies, such as those of Sourwine, are helpful in predicting the possible frequency and degree of damage. In colder regions, the rate of accumulation of freezing temperatures probably has great effect on the depth of frost penetration and on the degree of ice lensing in the soil. Consequently, it affects the amount of heave and the potential loss of strength during break-up.

The rate at which the frost "leaves the ground" must also be of prime importance, insofar as loss of strength is concerned. A rapid thaw is usually followed by severe breakup, due to the quick release of excess water within the upper part of the soil which cannot escape quickly, due to the frozen layers below. The quantity of water released during breakup is, of course, dependent on the amount of heaving.

Although in this study the freezing index is incorporated in the indices of road breakup, it is evident that factors other than cold weather are extremely important in causing road failures during spring thaw, except in regions where the freezing index is occasionally equal to zero. It is submitted that two features in particular greatly influenced this notable difference in breakup. These two features are the amount of water available and rate of

accumulation and decrease of degree-days of freezing. The data quoted support this vie
Dolch cited cases of severe breakup following very mild winters. At both Calgary an
Ottawa following the exceptionally mild winter of 1952-53, a "worse-than-normal" road
breakup occurred. Therefore, a wide collection of case histories must be made if the fu
effect of air temperature is to be understood.

The last, and probably most-important, variable is water. It is a much-more-compl
variable than temperature, since it occures in three phases and comes in variable amou
the utilization of which depends largely on temperature, drainage, vegetation, and soil t
Since the amount of water available affects the degree of frost lensing, the position of th
ground-water table is important. The ground-water table, in turn, depends on the above
variables.

Although Thornthwaite's method of dealing with water utilization was developed for cl
mate classification, it can probably be used, in a general way, to assess soil moisture
and ground-water levels for engineering purposes. The quantitative method of separatin
from precipitation the amount of water used by evaporation and transpiration is an impo
tant development.

As previously mentioned, the problem of assessing road breakup is difficult. Adjec-
tives, as used in this report, are not adequate. Perhaps a breakup classification can be
developed which would allow more-direct comparisons with weather. Other possible me
ods of evaluation include plate-bearing tests, the cost of repairs, or a combination of m
and duration of road breakup. Plate-bearing tests are expensive and, therefore, not ma
extensively. But it has been suggested by N. W. McLeod that this type of evaluation may
best be carried out using the Benkelman Beam Pavement-Deflection Indicator. Recent
tests with this instrument (Carey 1954) have shown much promise in this regard. An ex
ample of road breakup evaluation based on pavement maintenance costs has been given b
Otis (1952), but in the case of the Carleton County study this method was quite unreliable

CONCLUSIONS

This paper is an attempt to draw attention to the necessity of studying climate to gain
more-complete understanding of frost action in soils. Owing to the fact that an entire ye
is necessary for the collection of each piece of evidence, relatively little field data have
been presented. The following tentative conclusions may, however, be stated:

1. The partial success of Dolch's index in assessing spring breakup at Calgary and
Ottawa indicates that a combination of air temperature and precipitation can be used as a
index of spring breakup of roads.

2. The somewhat-greater success of the modified index indicates that Thornthwaite's
formulas lead to a better evaluation of the moisture available for frost action than does p
cipitation alone.

3. There is no evidence that very cold winters result in severe breakup. In fact, in
northern regions where annual freezing always occurs, the slope of the freezing index cu
probably has more effect than the absolute value of the index on frost damage to roads.

4. This investigation has revealed no evidence that the number of freeze-thaw cycles
air temperature affect the degree of frost damage to roads.

In the general approach to understanding frost action, the phenomena must be studied
in the laboratory as well as by studies in the field. Problems such as the role of moistu
movement and the criteria for frost-susceptible soils require fundamental studies. But
even if these phenomena were completely understood, highway engineers would still be
baffled by the weather. To understand the phenomenon of frost action in the field consid-
eration of the effect of climate is essential. With such an understanding, it can be hoped
that accurate forecasting of the amount of heave, the duration and the degree of spring
breakup and thus improved roadway design will follow.

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