conditions and the seeming necessity of building roads of lesser importance but of huge mileage makes it desirable that more effort be devoted to the improvement of suitable, but less expensive designs But the more costly types still have as high importance as ever and this fact is not overlooked in your committee's program of work.

It would be a dreary and boresome performance were I to go into detail regarding our research program which now is being completed. I shall content myself with a bare outline of its contents. There are five main divisions including:

I. Subgrades and Drainage
II. Traffic
III. Climate
IV. Road Types.
V Special Problems

Under each of these there appear a multitude of research projects, some of which have already been worked upon and partially solved, but a majority of which have not been completed or even investigated Upward of a thousand topics have been listed and no doubt some of them may be subdivided into many more.

So the field of research in the structural design of roads is extensive and there is abundant opportunity for the Highway Research Board to bring about a coordinated and cooperative system of highway research which should net results of tremendous value and importance There is need for just such an agency as the Highway Research Board for marshalling the increasing investigative efforts of the country and a well-laid out program now seems quite essential to the accomplishment of that end.

THE INFLUENCE OF CLIMATE ON THE BUILDING, MAINTENANCE AND USE OF ROADS IN THE UNITED STATES

F H Eno

Research Professor of Highway Engineering, Ohio State University

It is the province of Sub-Committee No. III of the Committee on Structural Design of Roads, of the Highway Research Board, to prepare an outline of the information regarding the various phases of climate that affect the building, the maintenance, and the use of highways

Much of this information is available through the published works of the U S Weather Bureau Many do not know, however, in what an acceptable form it has been prepared and presented by that Bureau.

This committee will attempt therefore, from time to time, to present the salient features of the Weather Bureau reports that affect in any manner the building and use of highways, and to outline further lines of research that will be necessary to complete our knowledge of the effects of climate upon roads

Your committee has tentatively outlined the work to be considered and will present it under the following general heads, viz:

1. Temperature.
2. Frost
3. Sunshine
4. Wind
5. Humidity
6. Precipitation
7. Run-off
8. Evaporation
9. Application of the data to highway activities
10. Further lines for research.

U S WEATHER BUREAU PUBLICATIONS

Of the many publications issued by the U S Weather Bureau, the committee will confine its present report to two sets, namely, the three volumes of Bulletin W, entitled "Summaries of Climatological Data by Sections," and "Part II—Climate" of "The Atlas of American Agriculture"

From Part II, "Section A—Precipitation and Humidity" and "Section B—Temperature, Sunshine and Wind," with a few loose pages upon Frost will be briefly described

Bulletin W summarizes the climatological data into tables The United States is divided into 106 sections The sections are small, many of the states being divided into three or four sections

Within these sections the climatological data for each town of any consequence, which has a weather bureau observation station, are given in tables.

The summaries contain full tables of monthly and annual precipitation, tables of snowfall, averages and extremes of temperature, relative humidity, sunshine, wind, dates of first and last killing frosts for each year, the elevation of the observation station, and other special data

The charts in the Atlas picture these tabulated figures in diagrammatic and map form.

As your committee has had no opportunity to search widely for climatological data it will present a preliminary report illustrating what may be found in the U S. Weather Bureau publications. These publications may be found in all of the state libraries and most of the university and large city libraries.

TEMPERATURE

Temperature, either as heat or cold, affects practically every phase of road building, road maintenance or road use Heat causes blow-ups of concrete and monolithic brick roads It softens tar and asphalt treated surfaces It seriously affects the integrity of green concrete that has not been perfectly protected Extreme heat materially decreases the amount of work performed by labor and seriously affects its character

Extreme cold is as adverse in its affects upon road building, or more so, than extreme heat

Therefore, any definite information, easily available to the engineer and contractor, about any climatic factor enables them to more surely build good roads

There are three distinct or major types of physical climate—marine, continental, and mountain There are minor types such as coastal climate, desert climate, and the like

Marine climate is marked by more even, uniform temperatures throughout the year.

Continental climate shows greater temperature extremes and more rapid changes

Mountain climate has lower temperatures than the adjacent lowland areas, and greater variation between the daily maximum and minimum temperatures

Figure 1 illustrates the annual march of temperature from January to December for selected stations in four distinctly different regions of the United States, viz:—The Atlantic Coast, the Pacific Coast, the Mississippi Valley and the Rocky Mountain area

The engineer is deeply interested in the risks which low temperatures bring to his work Figure 2 presents a map of the United States upon which are located lines showing the lowest observed temperatures throughout the country, based upon the records of about 600 stations These lowest observed temperatures range from — 65° F. in eastern Montana to + 41° F. at Key West, Florida

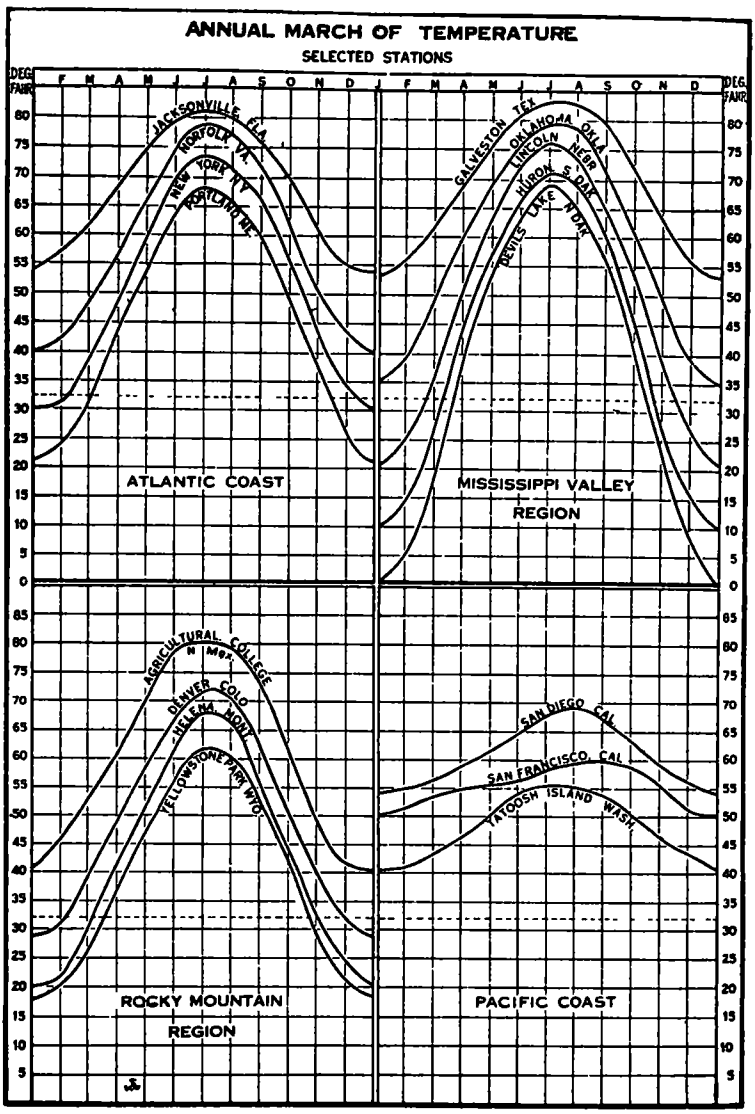

Figure 1. Annual March of Temperature

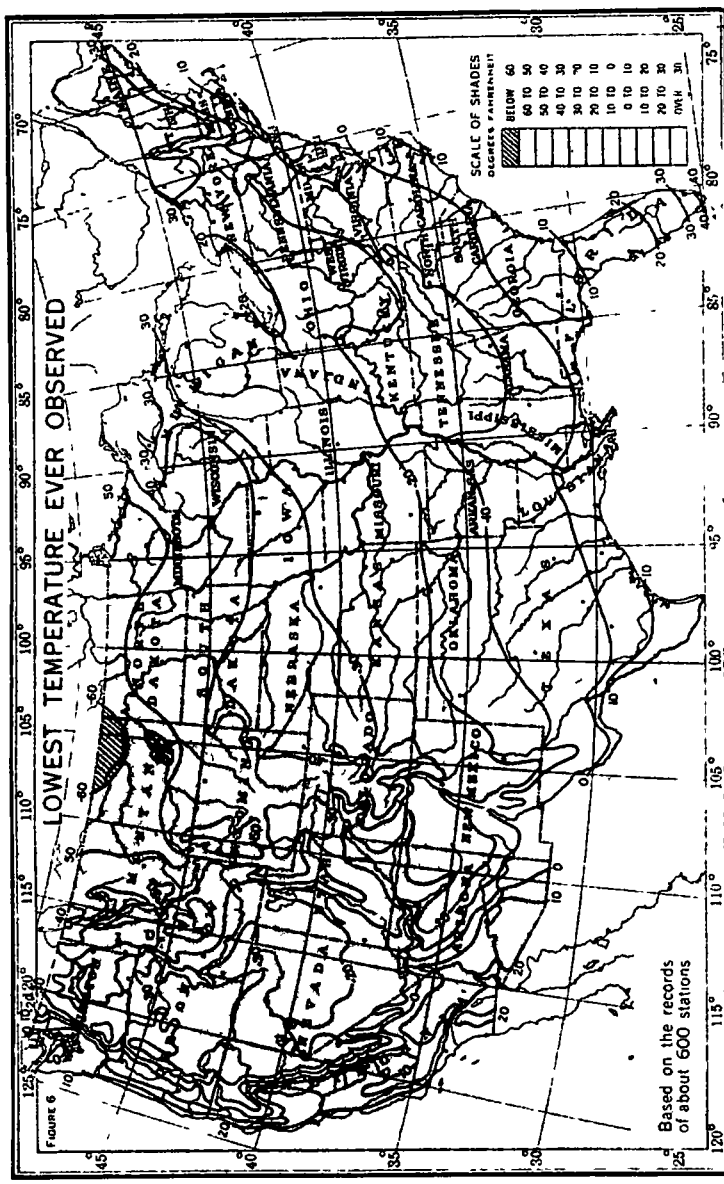

Figure 2. This Map Shows the Lowest Temperatures Ever Observed up to and Including the Year 1922, Based on the Records of the Regular Reporting and of Selected Cooperative Stations. These Absolute Minimum Temperatures Range from —65° F. in Eastern Montana to 41° at Key West, Fla. Temperatures of —40° have been Recorded in Northern New England and Northern New York, and as Low as —20° as Far South as Tennessee, Arkansas, and Oklahoma, and Zero Temperatures Have Occurred in the Central Gulf Coast Districts. Along the Central and Southern California Coast the Lowest Temperatures of Record are from 24° to 28°

For the concrete and highway engineers and contractors, northeastern Montana is a very undesirable anti-paradise

The Weater Bureau Atlases show mean high, low and average temperature maps of the United States for each month of the year.

Figure 3 shows the lowest monthly mean isotherms for the month of April, while Figure 4 shows the same lines for November.

By selecting a number of stations scattered over the United States and spotting them upon a U S Map, a valuable graph of the annual march of temperature across the country from south to north is presented.

The average daily maximum and minimum temperatures, the average monthly, the absolute minimum and maximum temperatures are all thus shown on one sheet, on Figure 72, in Section B of Part II, Climate, in the Atlas of American Agriculture

FROST

Frost affects the work of the engineer in two ways, one in the actual depth to which freezing occurs in the ground and the other in the chill of the air that affects the rate of setting of concrete and may actually seriously damage its strength

In the first case, the freezing of the ground delays and even totally interrupts the grading and drainage work of construction It also causes heaving of the finished pavement from slight amounts to such an extent as to totally destroy the pavement.

In the second case, beginning at a temperature of about 45° to 40° F , temperature first retards setting concrete and later as the temperature falls it begins to damage the green concrete by freezing crystals of water throughout the mass, segregating the mortar and causing material weakness

The committee upon its first visit to the Weather Bureau found that little had been done in the way of collecting material as to the depth of freezing in soil over the United States area

At a second visit, however, the committee found that the Bureau had been very actively collecting such data and would have information available probably early in the summer of 1930.

Such data may be collected from Telephone and Telegraph Companies, from contractors who construct sewers, water supply mains and other subsurface construction, from Public Utility Companies and cities

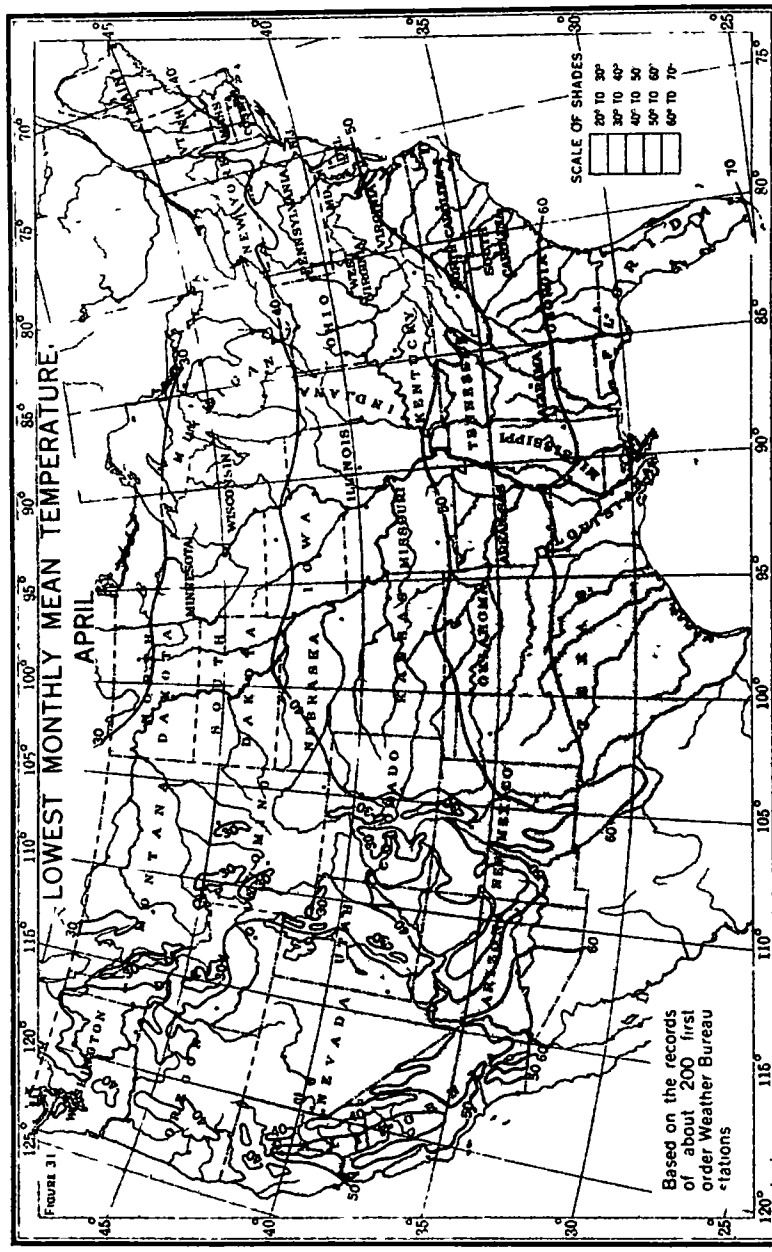

Figure 3 Lowest Monthly Mean Temperature, April

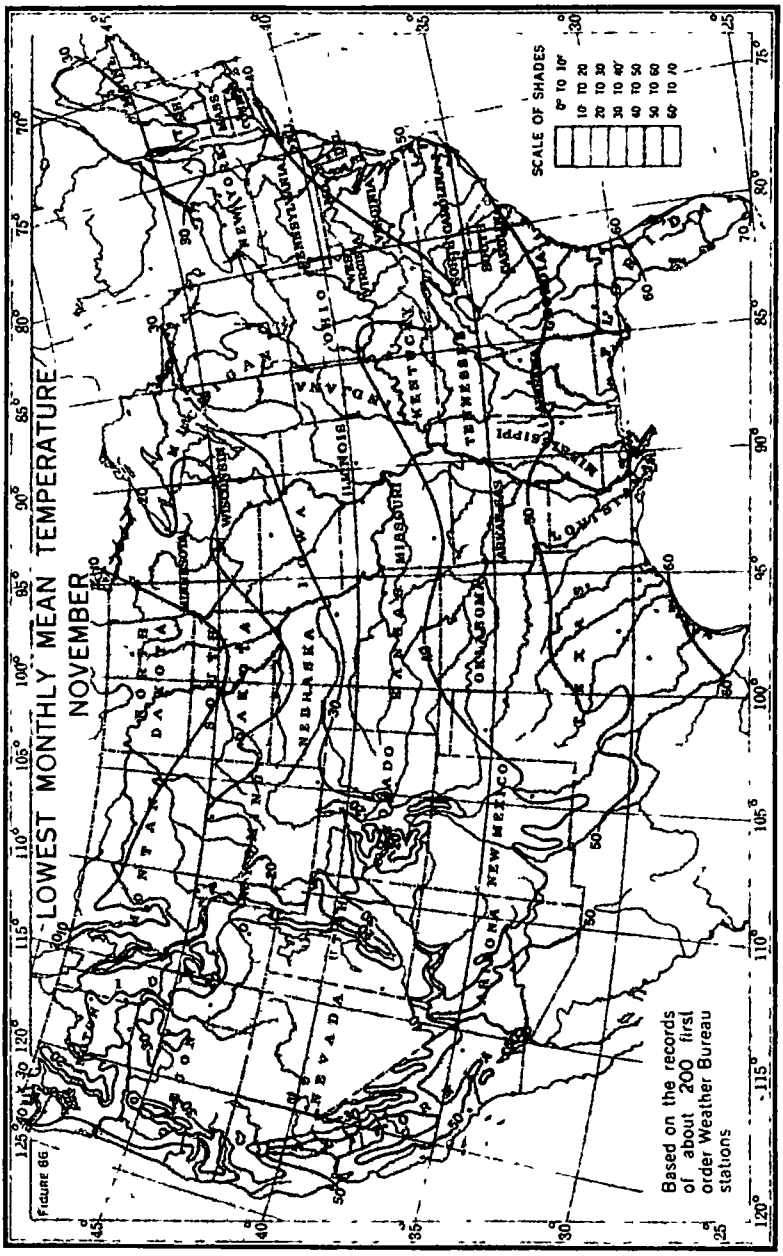

Figure 4 Lowest Monthly Mean Temperature, November

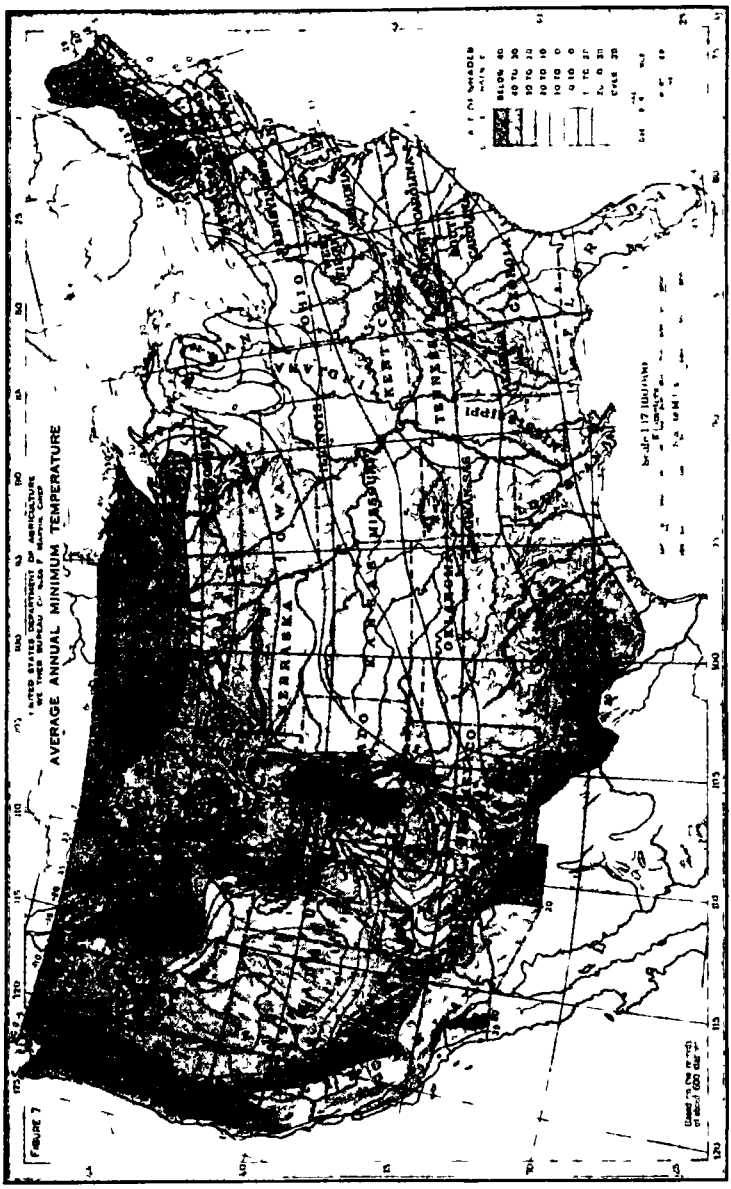

Figure 5 This Map Shows the Average of the Lowest Temperatures Recorded Each Winter As a Rule, the Lowest Temperatures in the United States Occur in the Northern Portions of North Dakota and Minnesota, Usually About —40° or Slightly Lower The Other Extreme is Found at Key West, Fla, Where the Lowest Temperature for the Year Ordinarily Does Not Go Below 50° Along the Immediate Gulf Coast the Average Annual Minimum is 22° to 25°, Whereas Along the Immediate Pacific Coast it Ranges from About 25° at the North to 36° at the South The Marine Influence is Markedly Shown by the North and South Trend of the Isotherms Along the Pacific Coast, and is Noticeable Along the Atlantic Coast, Where the Isothermal Lines Trend in a Northeasterly Direction as They Approach the Ocean and Terminate at the Coast Several Hundred Miles Farther North Than the Latitude at Which They Cross the Mississippi Valley The Tempering Effect of the Great Lakes is Shown by the Trend of the Isotherms Along Their Leeward Shores in Michigan, Ohio, and New York

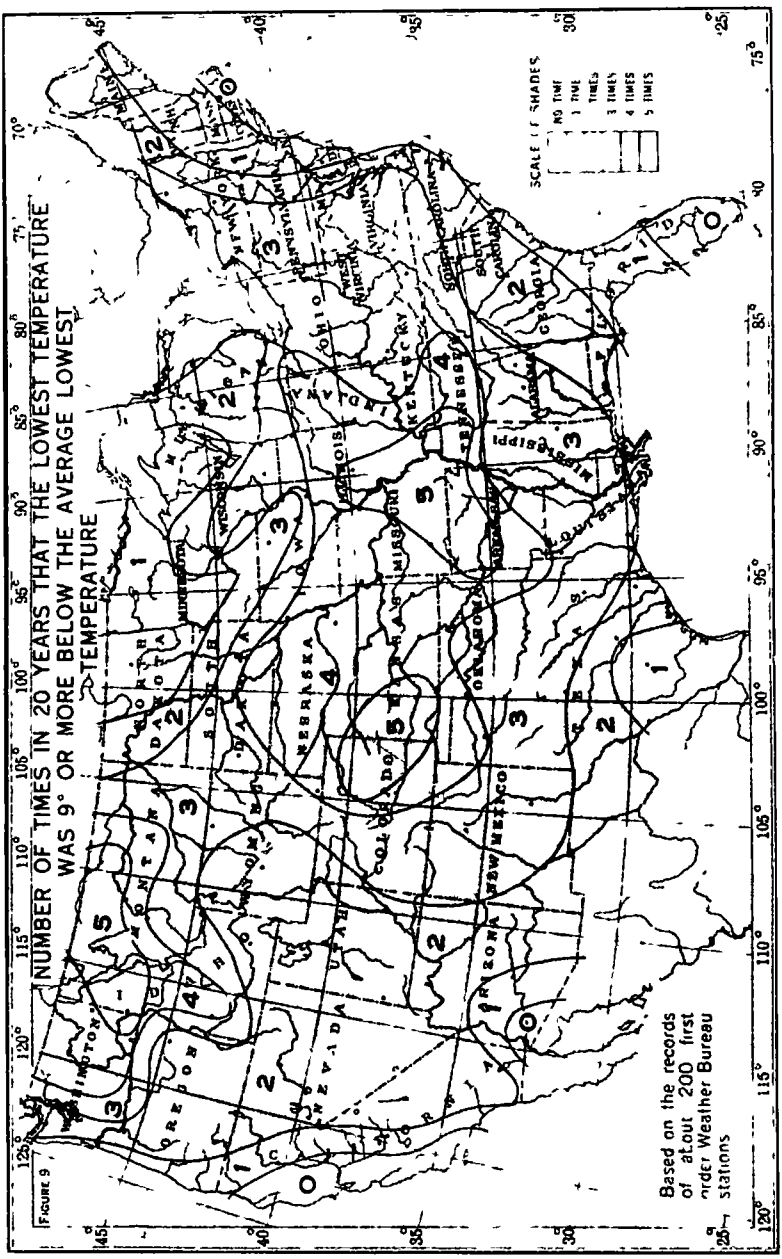

Figure 6. Number of Times in 20 Years that the Lowest Temperature was 9 Degrees or More Below the Average Lowest Temperature

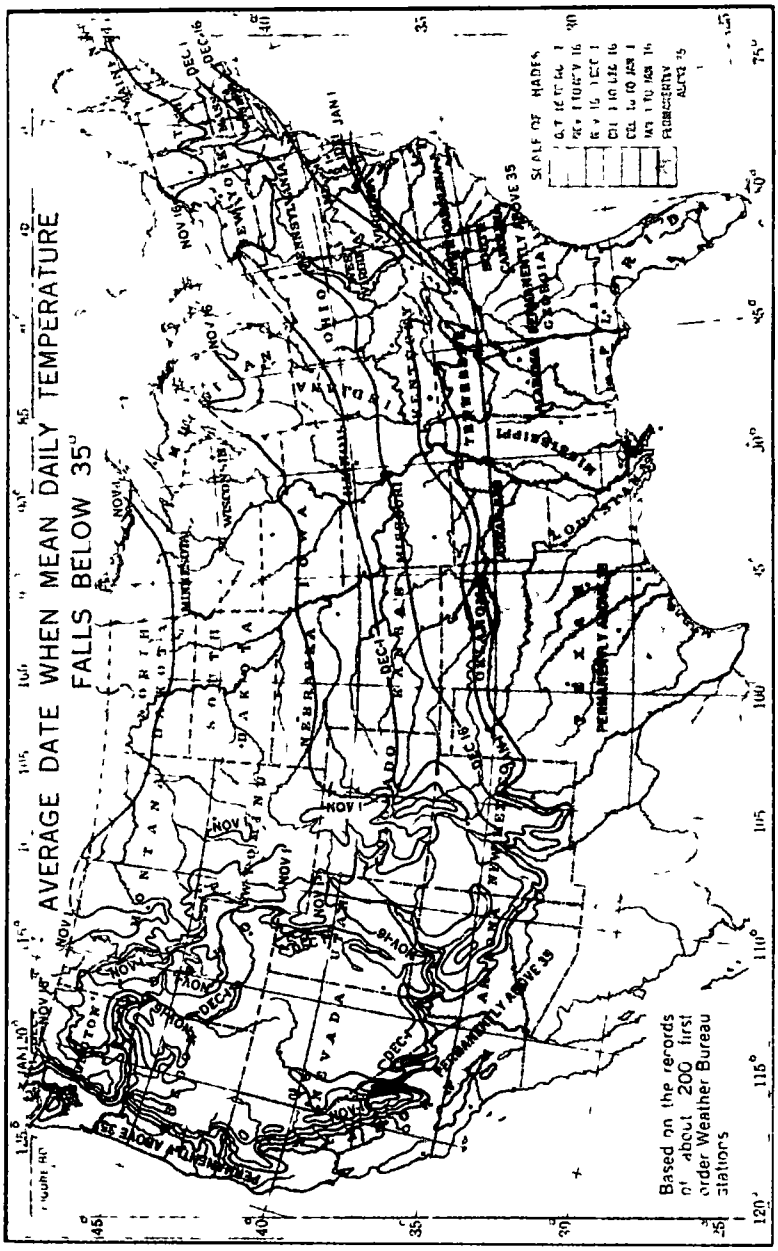

Figure 7. Average Date When Mean Daily Temperature Falls Below 35°

The State Highway Departments ought to be able to aid in collecting such information and possibly much valuable information might be obtained through the help of farmers.

Figure 5 shows the average annual minimum temperature throughout the United States.

In Figure 6, the average annual number of days in which the temperature is continuously below freezing is shown.

A study should be made of various frost phenomena, effect of the water content of the soil at the time of first freezing, the change in water content at varying intervals during the frozen period, the determination of alleviating agents such as snow covering, sod covering, black surfaces, cinder covers, black earth cover, depth of frost beneath the road, on the shoulder and in the field opposite, etc

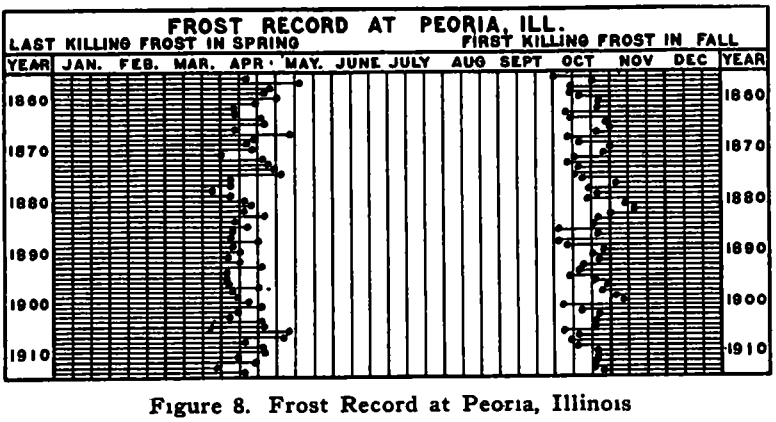

Figure 8. Frost Record at Peoria, Illinois

Figure 7 presents the data lines for the average date when the mean daily temperature falls below 35° F. This is a time when engineer and contractor must begin to take account of the placing of concrete in cold weather Discussion in the committee brought out the fact that a temperature map for 40 or 42° F would be better

A similar map is shown in the folios for the time when the temperature rises above 35° F. in the spring

To illustrate the fickleness of fall and spring, Figure 8 is presented showing the first date of killing frost in the fall and the last date of its appearance in the spring for a period of 60 years at Peoria, Illinois

The average space between these events is the period of working time given to the concrete contractor, within which period he may quite safely operate. This was also attacked in the committee discussion as being too low a temperature for safety in laying concrete and that consequently, the working period should be much reduced.

Figure 9 gives the average date lines across the United States of the last killing frost in the spring as an average for a period of 20 years, from 1895 to 1914. A similar map is given of the first frost in the fall. Figure 10.

SUNSHINE AND WIND

The length of days for the June and December solstices are graphed for 5 degree intervals of latitude across the United States from Florida to Minnesota

The length of day on December 22 varies from 8 hours and 26 minutes for northern Minnesota and Maine to 10 hours and 24 minutes for southern Texas and Florida.

The length of day from sunrise to sunset on June 21 ranges from 13 hours and 53 minutes for lower Texas and Florida to 16 hours for northern Maine and Minnesota

Figure 11 shows the percentage lines of *actual* summer sunshine to the total possible sunshine at various points throughout the United States.

Figure 12 gives the lines of wind velocity throughout the U. S. at 3 p m. when the wind velocity is normally at its greatest.

Abnormal winds such as Chinooks, blizzards, hot winds, low and high barometric-caused winds are also discussed in the text. It is the normal winds, that have the greatest effect upon climate because they carry the great amount of moisture laden air across the country

Other graphs of sunshine and wind are given.

HUMIDITY

The humidity of the air affects road work in several ways. The setting and curing of concrete, the drying out of the subgrade, the curing of oil and tar treated surfaces The amount of work done by the workmen, the efficiency of the work they do, all are affected by the amount of humidity in the atmosphere.

Humidity records are of two types, absolute humidity and relative humidity.

Absolute humidity is the actual amount of moisture held in the atmosphere, and is usually expressed in inches of barometric pressure, usually termed "vapor pressure." Absolute humidity depends upon the temperature and the proximity to large bodies of water.

Relative humidity is more important climatologically than absolute humidity It is the ratio that the amount of moisture present in the

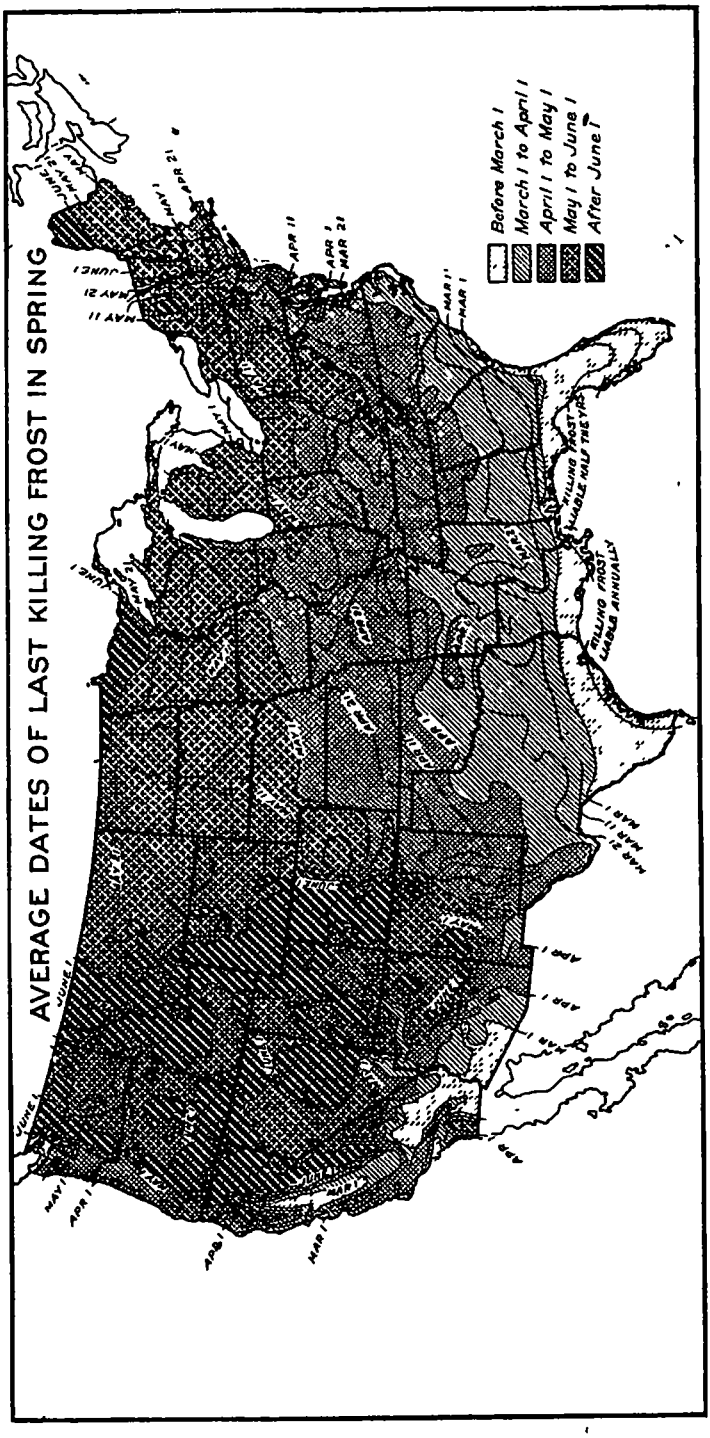

Figure 9. Average Date of Last Killing Frost in Spring In Half the Years it Will Occur Earlier Than the Dates Shown and in Half the Years Later Than These Dates It Follows That Spring Crops Which are Advanced Sufficiently to be Harmed by Frost on the Average Date of its Last Occurrence Will be Killed in 50 Per Cent of the Years. Killing Frost Usually Occurs Each Year to the Gulf Coast and to the Central Portion of the Florida Peninsula, but in Extreme Southern Florida it Occurs, as a Rule, in Less Than Half the Years In Some Extreme Northern Districts and in the Higher Elevations of the Western States the Average Date of Last Killing Frost is Later Than June 1, but in the Gulf Coast Sections it is Infrequent After March 1

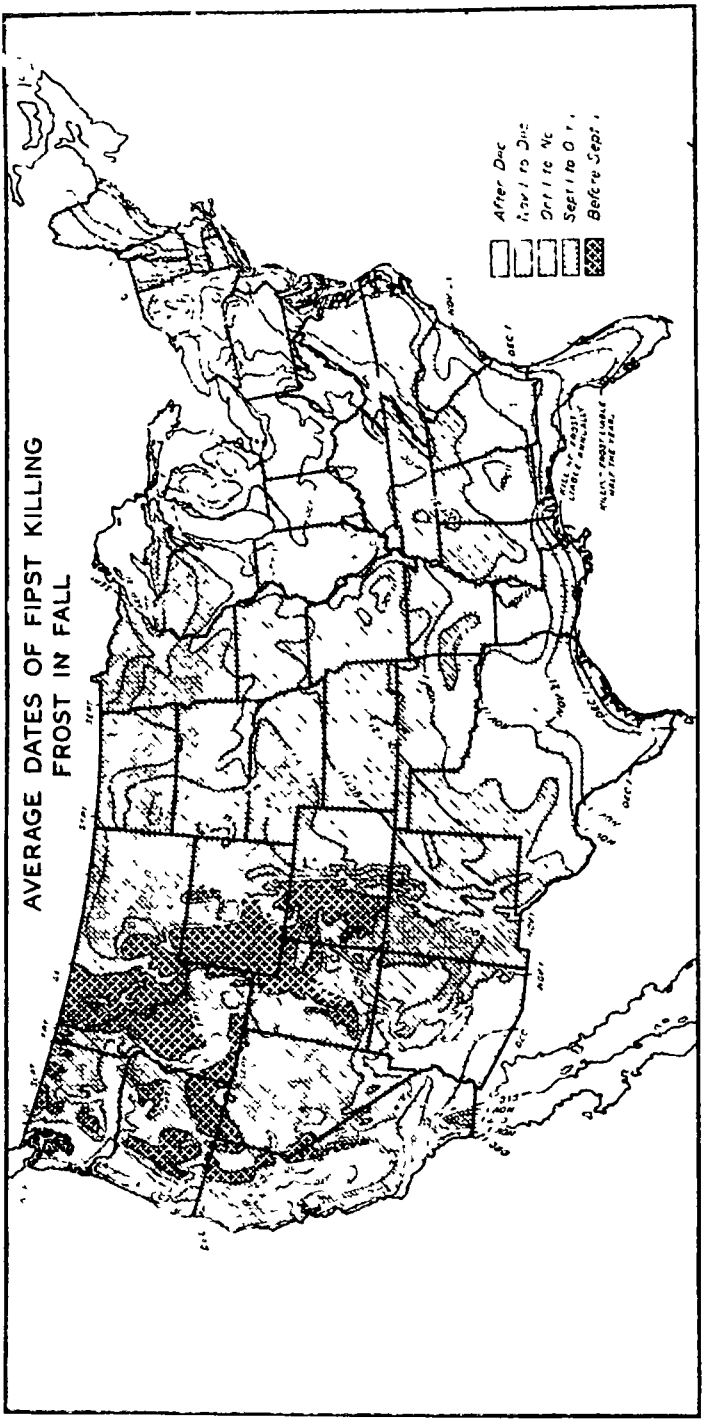

Figure 10 Average Date of First Killing Frost in Fall, by Which Time it May be Expected to Occur in Half the Years. Many Summer Crops are Subjected to Frost Damage Before Maturity in Fall, Especially When Growing Conditions During the Summer are Such as to Retard Developments The Average First Fall Frost Dates Range from Before September 1 in Some of the Colder Sections of the Country to December 1 on the East Gulf Coast In Much of the Northern Portion of the Corn Belt the Growing Season Usually is Terminated by Killing Frost During the First 10 Days of October, Whereas in the Northern Cotton Belt the Average Time of First Killing Frost is Near the End of That Month Killing Frost has Occurred at Every Point on the Mainland of the United States Where Records Have Been Kept Key West, Fla, Being the Only Station with no Record of Killing Frost

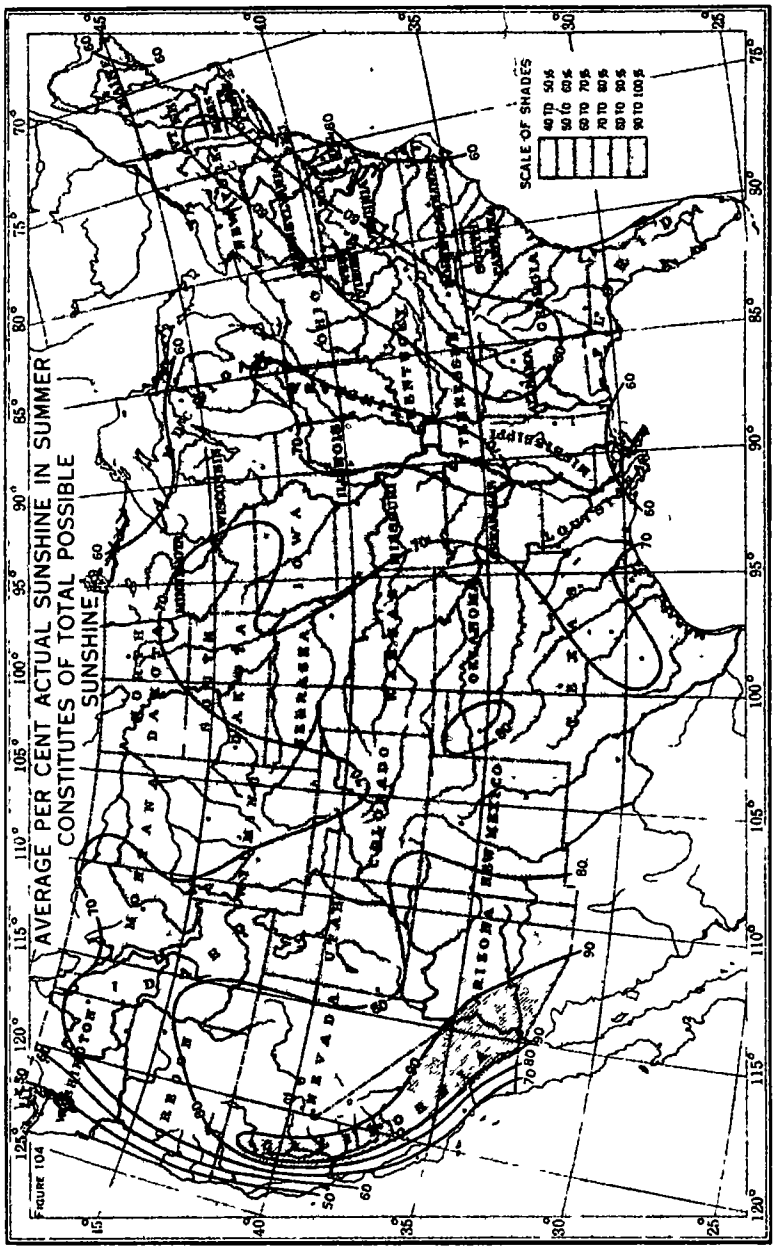

Figure 11 Average Per Cent Actual Sunshine in Summer

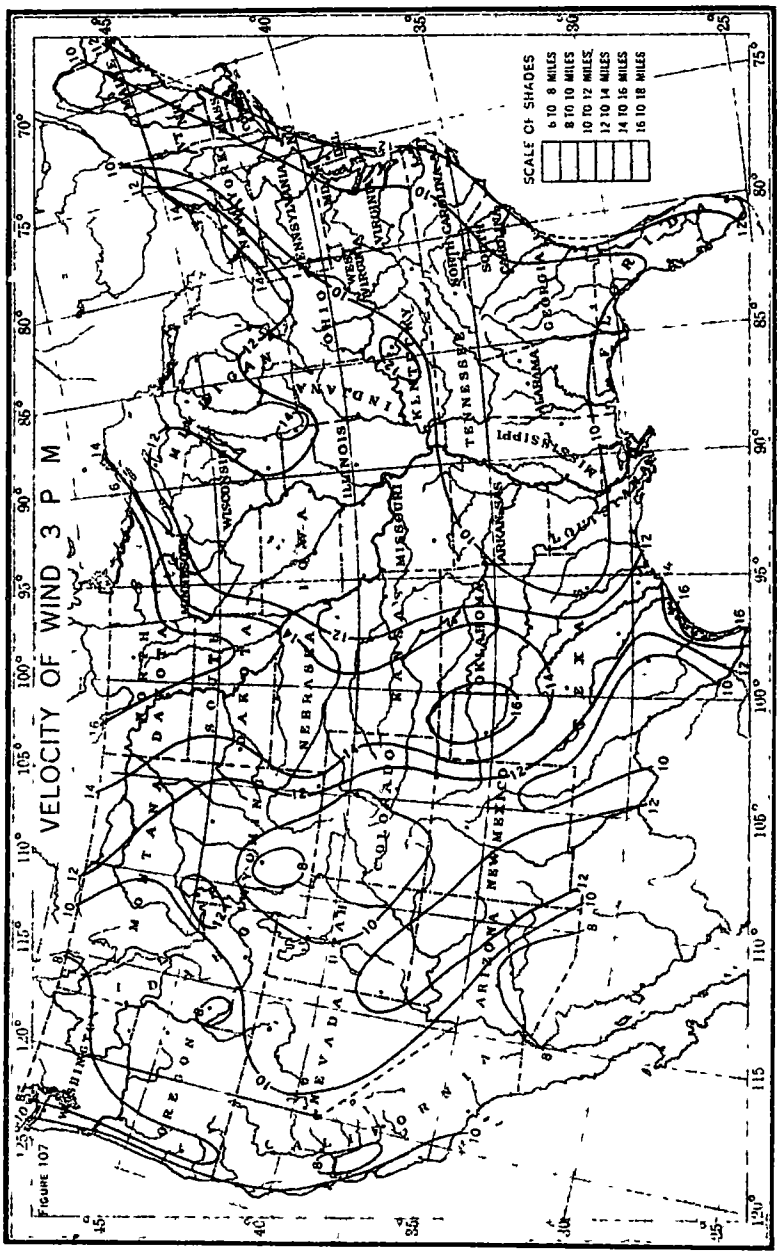

Figure 12 Average Velocity of Wind During the Year M. P H. Figs. 106 and 107

air at any time bears to the amount that could exist there without condensation under the same conditions of temperature and atmospheric pressure

Lower relative humidity means a higher evaporation rate and a higher humidity means a smaller rate of evaporation

The dew point is the temperature at which saturation of the air occurs and the condensation of the invisible vapor in the air begins

Figure 13 shows the humido bars for the average minimum relative humidity throughout the United States for October

EVAPORATION

Evaporation is closely tied up with humidity and wind movement as well as with the temperature conditions It varies largely during the year and throughout the United States It occurs in the dead of winter from ice surfaces

Some work has been done in obtaining data upon this subject but much needs yet to be done

Figure 14 shows some of the data collected by various agencies The evaporation is given in inches of water evaporated from water surfaces from April 1 to September 30 The figures enclosed in circles were observed by the office of the U S Biophysical Investigations, Bureau of Plant Industry, and cover periods of observation from 5 to 11 years in length

The figures in the squares are data taken by the U. S Weather Bureau during 1916-17

The figures in the upright triangles are measurements made by the U S Weather Bureau, The U S Reclamation Service, and the U. S Geological Survey during 1909

These figures range from 25 inches along the Atlantic sea coast and the great lakes, to 88 inches in southern California and 93 inches in north central New Mexico

Note that the greatest evaporation from water surfaces takes place at points where the least annual rainfall occurs

PRECIPITATION

One of the very important if not the most important phases of climate relative to its effects upon the highway is the amount, distribution, intensity, character, and disposition of precipitation

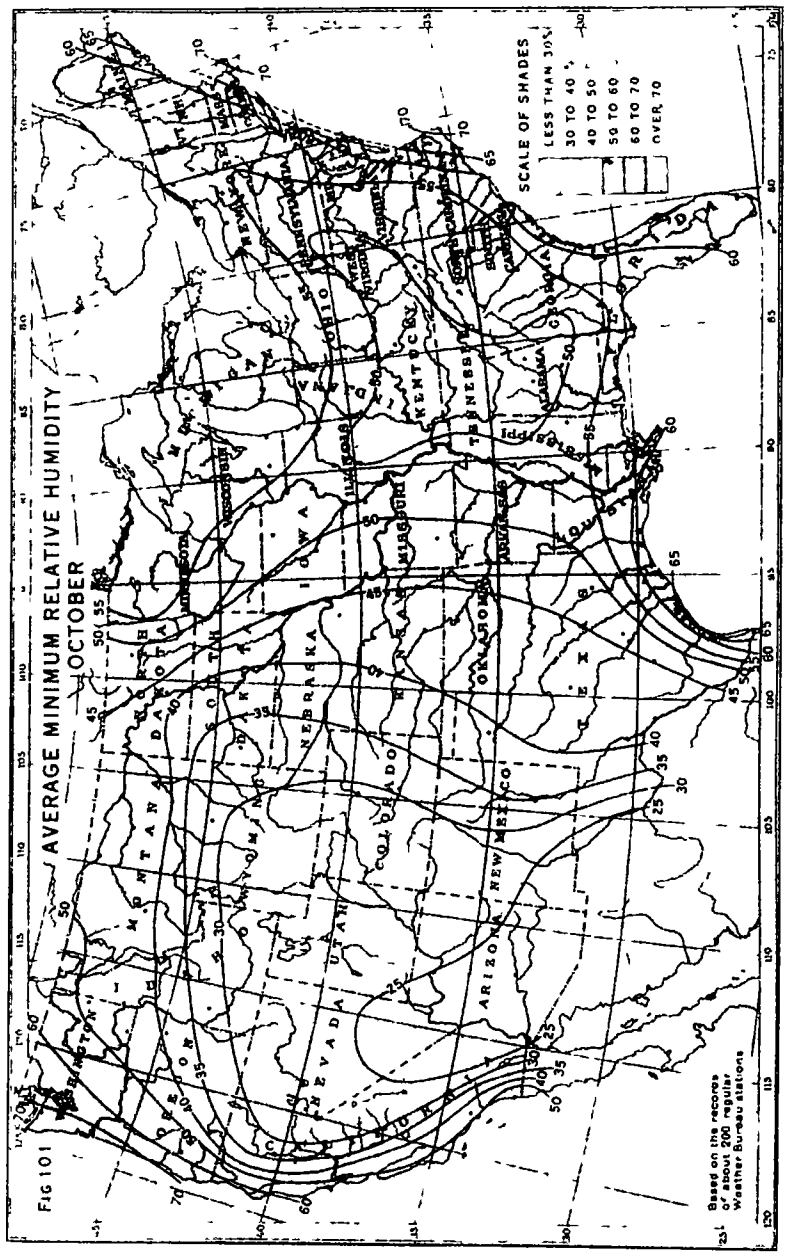

Figure 13 Average Minimum Relative Humidity, October

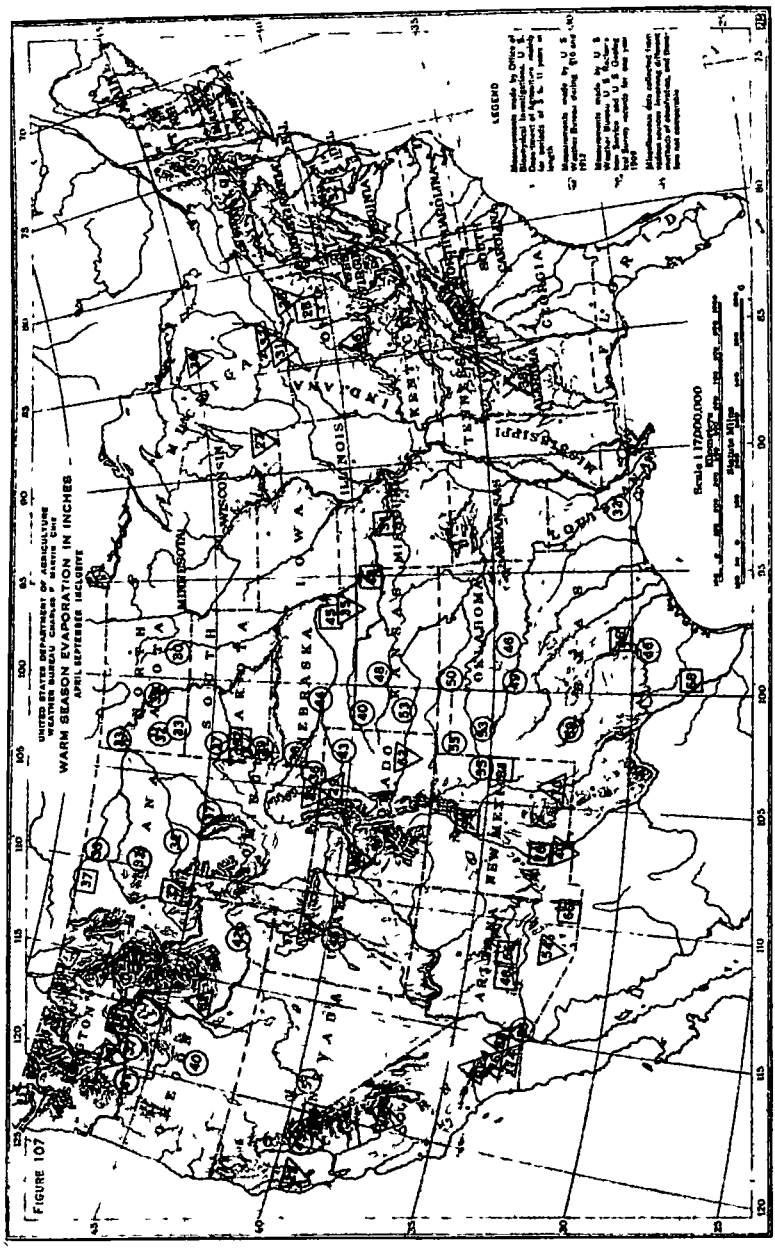

Figure 14. Warm Season Evaporation, Fig. 107

It occurs in five forms, rain, snow, fog, hail, and dew At least four of these produce problems that the engineer and contractor must meet and solve as economically as possible. All four affect the safety of the use of the road

The U S Weather Bureau classifies rain, hail, and snow under the one head of precipitation

Figure 15 shows the average annual precipitation in inches for the United States for a period of 20 years from 1895 to 1914, inclusive

It varies from 5 inches in southern California and western Arizona to 60 or 70 inches in limited areas in the southeastern part of the United States and up to 120 inches in a limited area in western Washington.

The great Mississippi Valley ranges between 20 and 40 inches except for a small part in the southeastern section of the valley that rises to 50 and 55 inches per year

In much of the great American desert precipitation falls below 10 inches annually

This map is based upon the records of about 1600 stations for the entire 20-year period and upon about 2000 other stations running for shorter periods but adjusted to relate their data with the 20-year period

Figure 16 indicates the variation in annual precipitation at selected stations over the United States, and it also illustrates the great difference in records between stations in different parts of the country

Note especially the difference in precipitation between Winnemucca, Nevada, and Tullahoma, Tenn

Figure 17 illustrates the fact that we have no records covering a sufficient period of time in this country to indicate any noticeable tendency toward permanent change in the rainfall statistics

This figure shows the records from six long-record stations from different parts of the country

The distribution of precipitation throughout the year is as marked a phase of climatic differences as is the difference of rainfall from different sections of the country

Figure 18 shows this marked difference of rainfall types. It shows the percentage of annual rainfall which occurs each month at a number of selected stations throughout the country. The averages are again for the same 20-year period from 1895 to 1914

Figure 19 shows a comparison of the average monthly precipitation for three 20-year periods taken in three cities Here again no marked trend of change in amount can be noted.

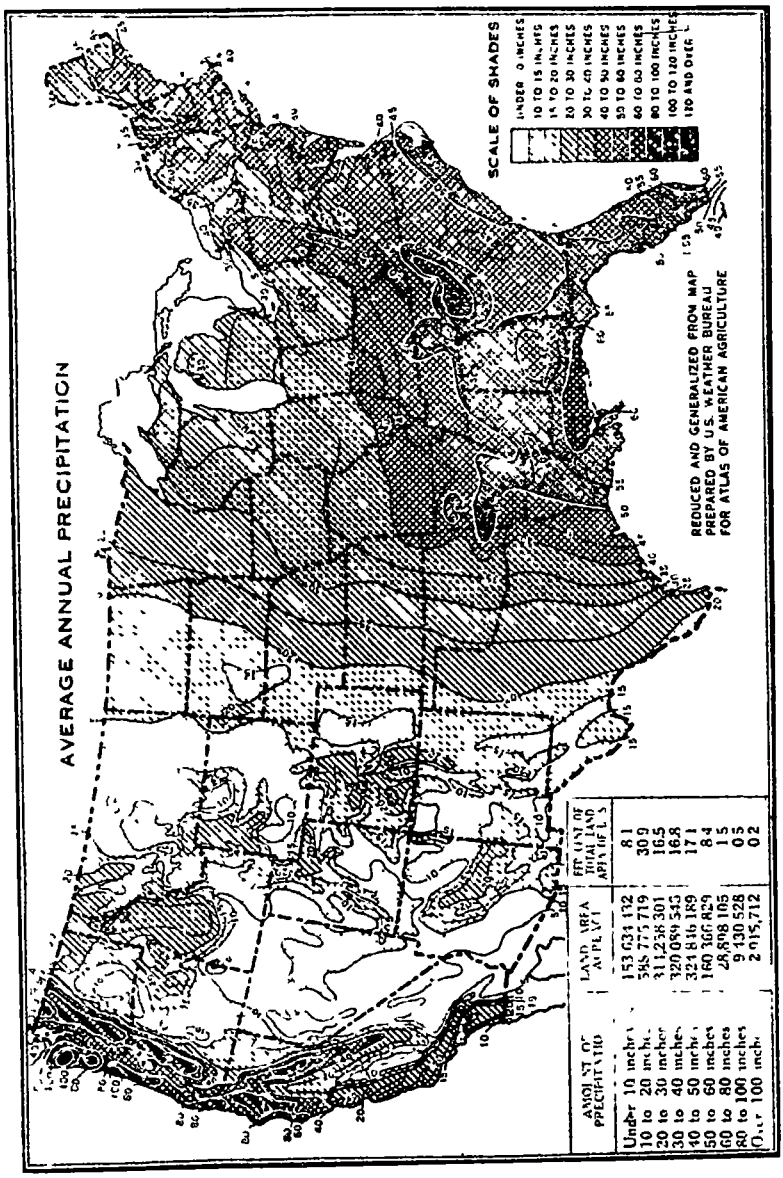

Figure 15 Average Annual Precipitation

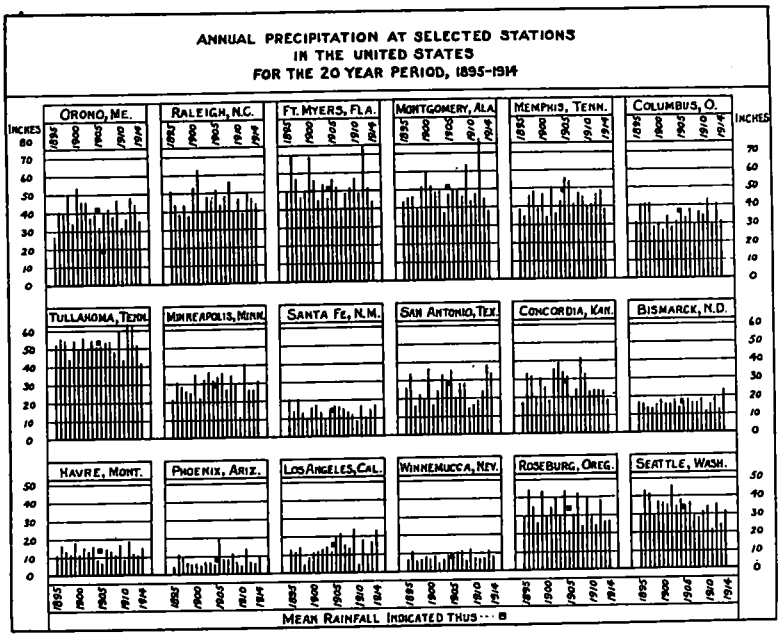

Figure 16. Annual Precipitation at Selected Stations for the 20-Year Period, 1895-1914, Arranged by Geographic Districts

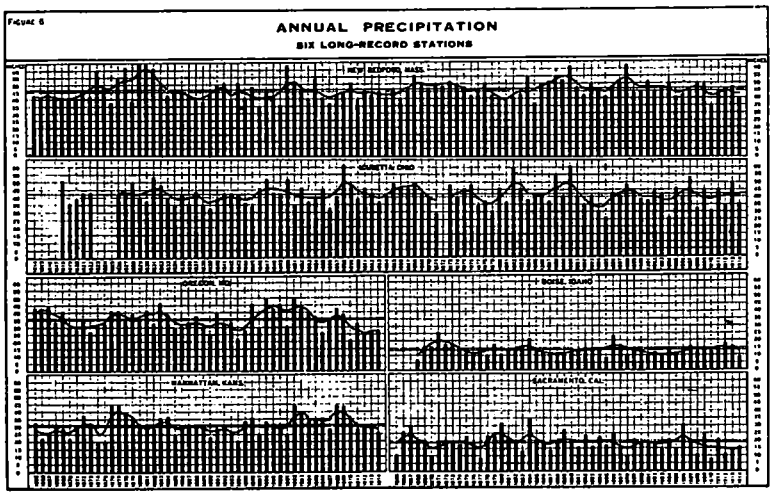

Figure 17. Annual Precipitation. Six Long-Record Stations

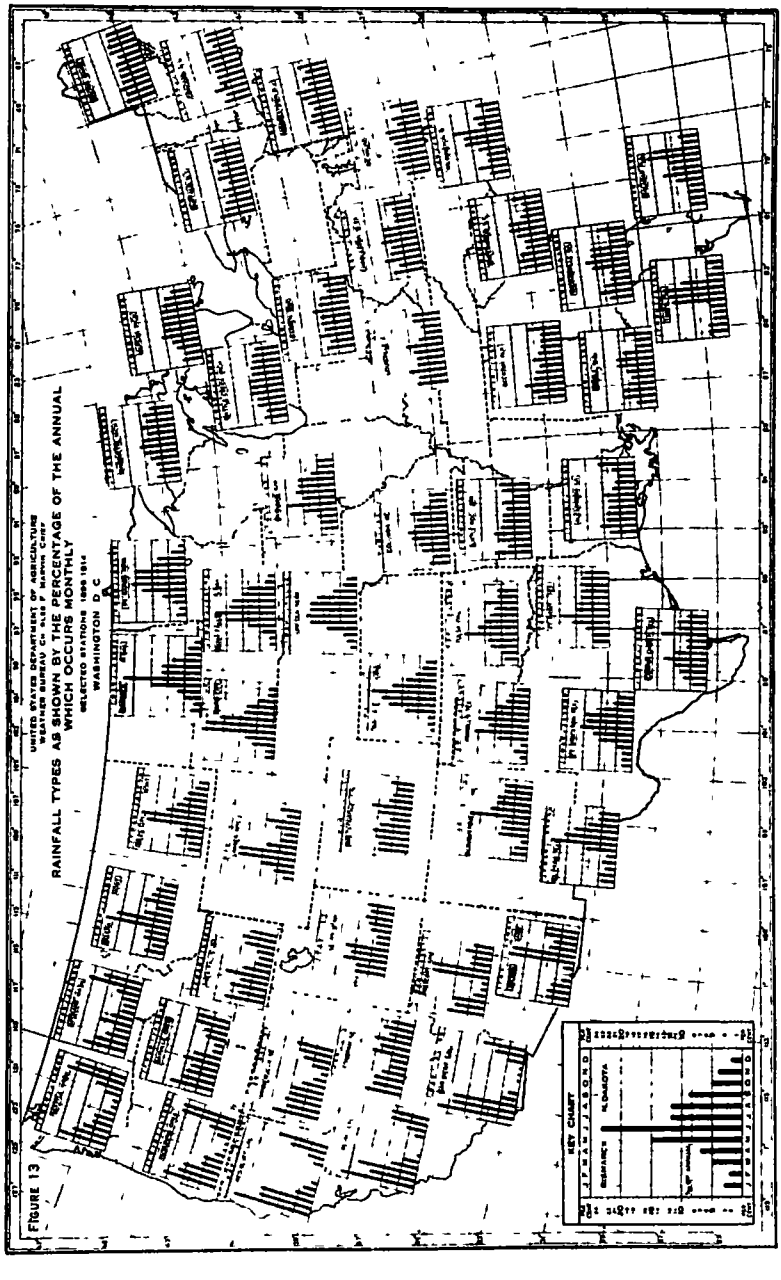

Figure 18. Rainfall Types

Figure 20 shows the total number of periods of 20 consecutive days or more without 0 25 inch of rainfall occurring in 24 hours during the season from March 1 to September 30, for the 20-year period above used. This map only includes that portion of the United States east of the great plains.

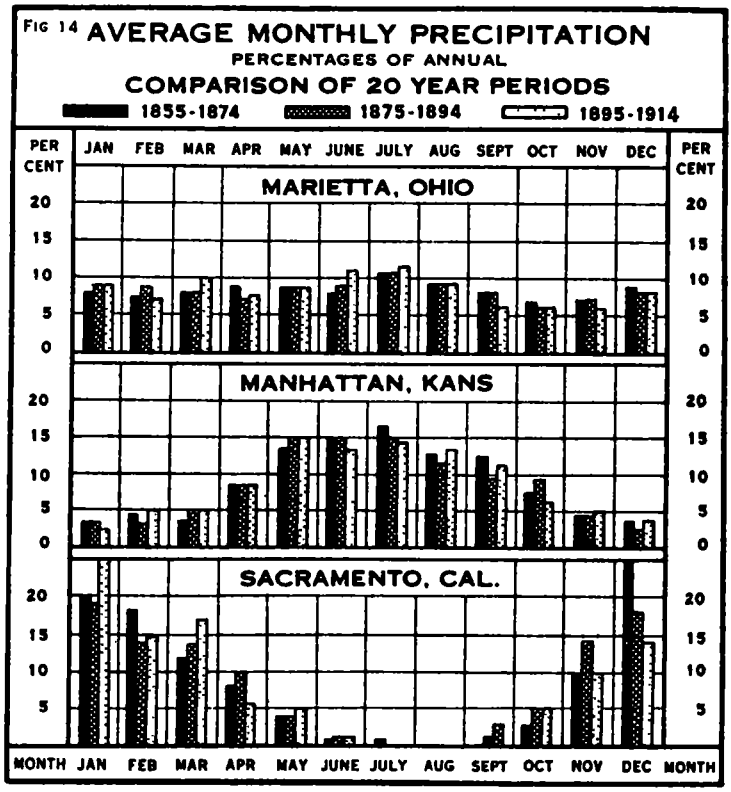

Figure 19 Average Percentages of the Annual Precipitation That Occurred in Each Month During Three Successive 20-Year Periods at Marietta, Ohio, Manhattan, Kans., and Sacramento, Cal, Representing the Three Principal Rainfall Types in the United States Solid Bars Represent the Period, 1855-1874; Closely Shaded Center Bars, 1875-1894; and Lightly Shaded Bars at the Right, 1895-1914

Snowfall. The precipitation in the form of snowfall introduces another set of problems for the engineer and highway executive. It increases the dangers to travel and may totally prevent travel for considerable periods It increases the cost of maintenance; may reduce the ill effect from frost; may increase the instability of the subbase by holding on and supplying to it a surplus amount of water to saturate and soften not only the subbase but the road shoulders and surrounding areas; and in general it becomes an expensive form of precipitation to handle.

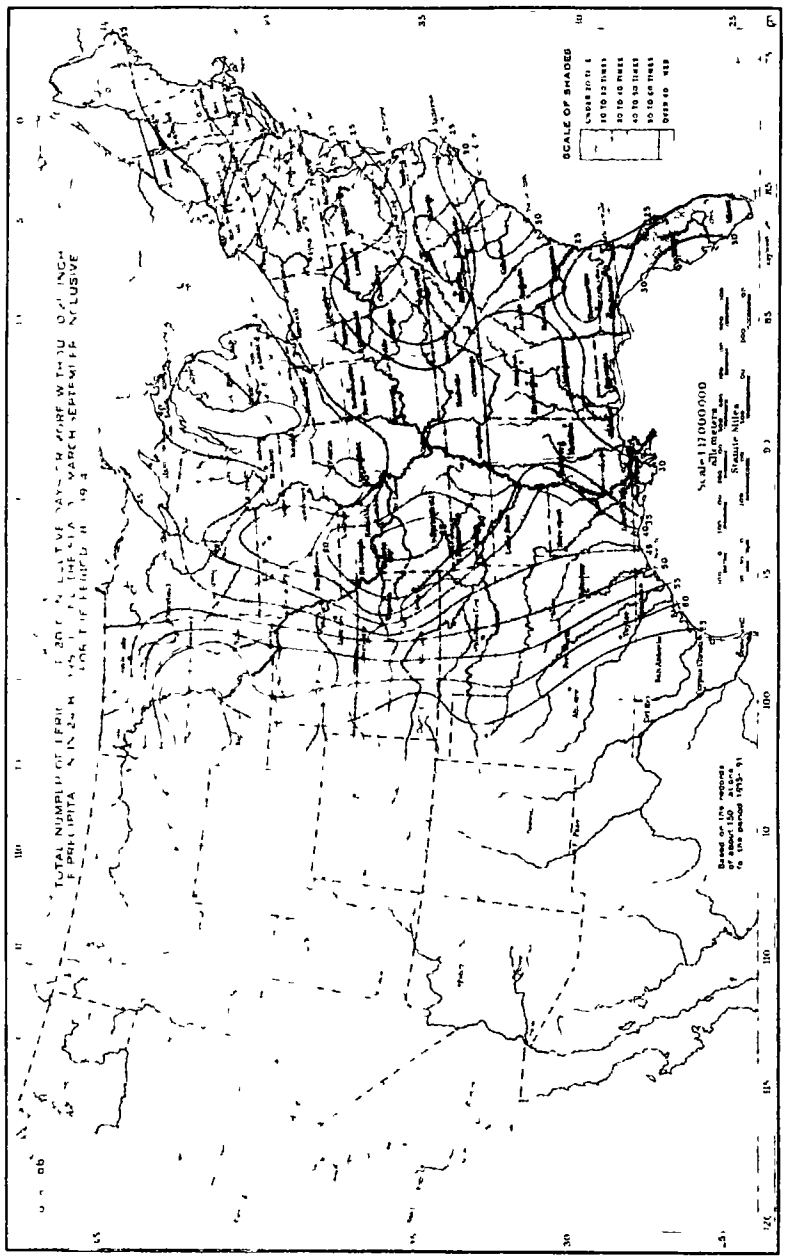

Figure 20 Total Number of Periods of 20 Consecutive Days or More Without 0.25 Inch of Precipitation in 24 Hours

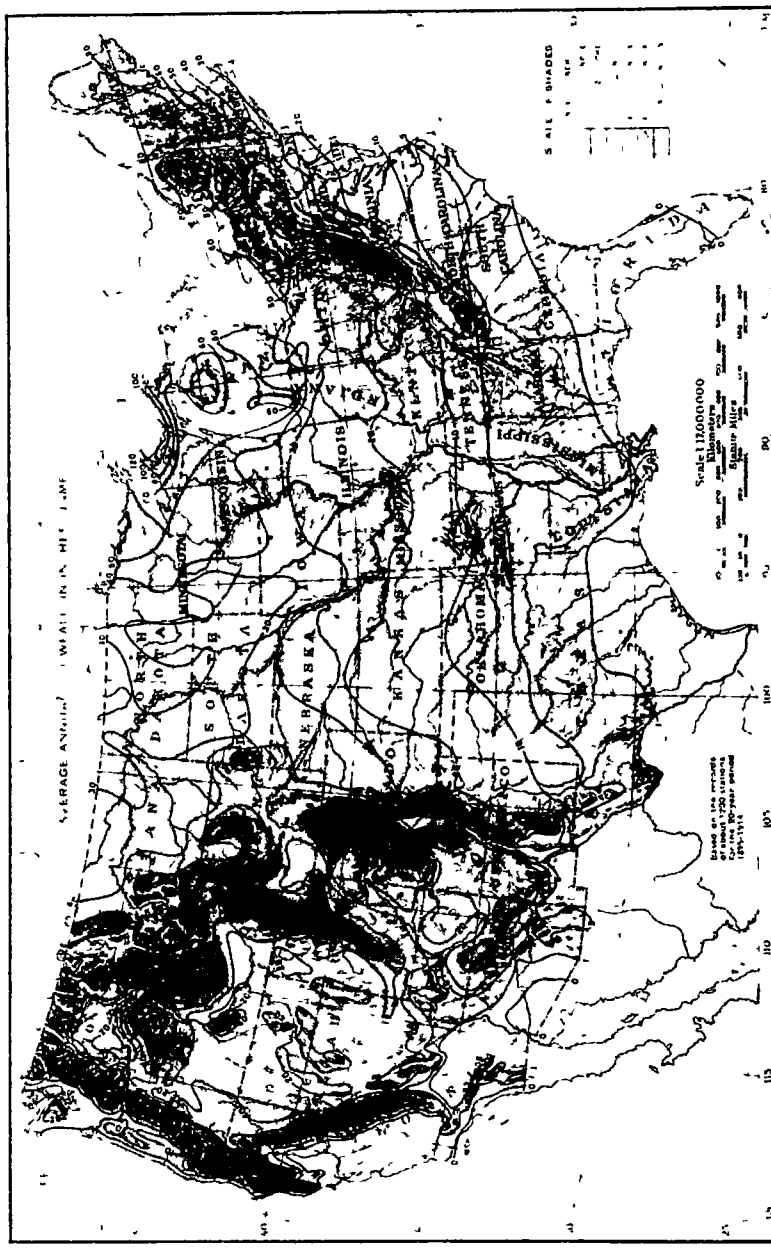

Figure 21 Average Annual Snowfall in Inches Unmelted

Figure 21 shows the lines of average annual snowfall in inches of unmelted snow, throughout the country

The greatest annual snowfall occurs on the western slopes of the Sierra Nevada and Cascade mountain ranges where in some places it averages from 400 to 500 inches per year.

East of the Rocky Mountains the greatest snowfall is in a small area along the southern shore of Lake Superior where 120 inches per year is recorded.

Figure 22 shows the average annual number of days with snow cover on the ground in the United States.

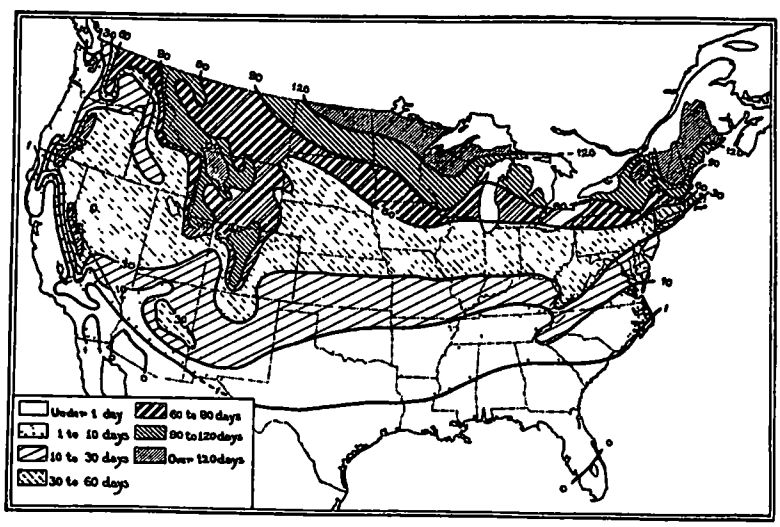

Figure 22. Average Annual Number of Days With Snow Cover

Hail occurs on an average of but two days per year over the greater portion of the United States. Over a small area in the Rocky Mountains it averages 4 days per year for the frostless season

The U. S. Weather Bureau recognizes two degrees of fog—dense and light. If objects are obscured to the sight at 1000 feet it is classed as a dense fog.

The Pacific Coast is the most afflicted area in the country. A strip along the sea coast running back to the Sierra Nevada mountains is affected from 40 days per year near the coast to 10 days per year back on the mountain ridges

The great American plains have 5 days or less of dense fog per year. The eastern half of the United States seldom exceeds 10 days of dense fog per year except for small areas in northeastern New England states and along the tops of the Allegheny Mountains

The danger from fogs are twofold—first, slippery roads, and second, occluded vision

Figure 23 shows the annual number of clear days for the 20-year period from 1895 to 1914.

The range is from 80 days in western Washington, 100 days in northern Michigan, Ohio, Pennsylvania and New York, to 300 days in southeastern California and western Arizona.

RUNOFF

Runoff of rainfall is not usually considered when alluding to climate. It is so intimately connected, however, with every factor in climate that it is here included.

The relations existing between precipitation, percolation, evaporation, surface retention and runoff are so varied and so largely affected by the distribution, intensity, duration, amount, and character of precipitation as well as by temperature, wind and humidity, that formulas and theories can but imperfectly apply

The best that formulas can do to express the probable amount of run-off for any given area is to approach some approximation Long continued measurements give what has occurred and point approximately to what may occur under similar conditions in the future

The comparison of the runoff from one area with what may occur on another area apparently similarly located may be quite distinctly in error, depending largely upon the question as to how many of the variables that enter into each result are of similar value

The United States Geological Survey has been measuring the runoff in streams in the United States since 1888. For many years this was done at only a few points upon a few of the streams. At present there are 2002 active stations maintained in the United States and Hawaii, while 2562 have been discontinued It is estimated that about 4500 stations would be required for a complete inventory of stream flow.

The records from the 2002 active stations represent a total of 17,569 years of observation.

The results of stream-flow measurements are now published annually in 12 parts, each part covering an area whose boundaries coincide with the natural water shed lines of some great drainage basin.

Complete sets of the publications of the U. S G S. may be consulted at 29 widely distributed points in the United States and at Honolulu, Hawaii.

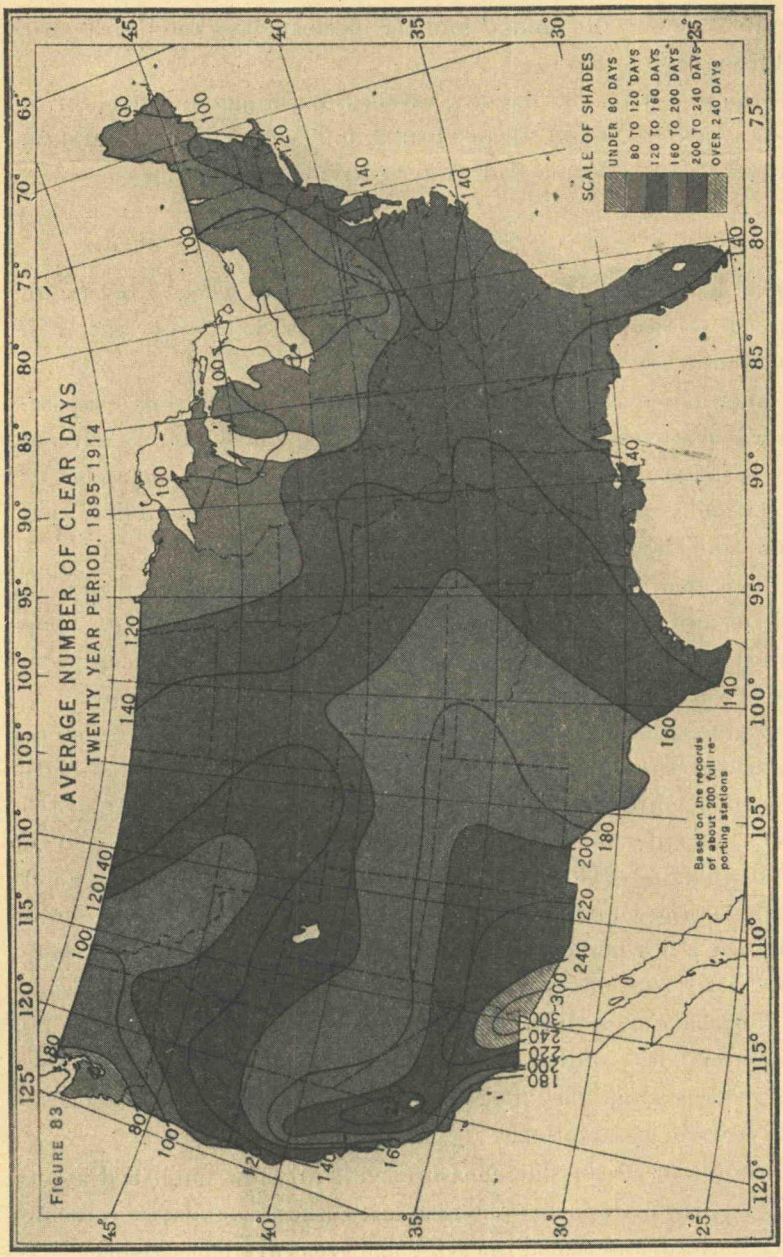

Figure 23. The Annual Number of Clear Days in the Twenty-Year Period from 1895 to 1914. Cloudy Weather Occurs With Greatest Frequency Along the North Pacific Coast in the Region of the Great Lakes Where There Are on an Average, Fewer Than One Hundred Clear Days a Year. In Portions of the Southwest, Three Hundred or More Days are Clear

The papers themselves may be secured at a nominal cost from the Superintendent of Documents at the Government Printing Office, Washington, D. C.

Another source of valuable information is contained in the large number of papers published in the Transactions of the American Society of Civil Engineers from 1900 on to the present time

Some eighteen or twenty papers not including nearly as many more published in connection with the Mississippi flood Symposium, discuss every angle of rainfall, runoff, and stream flow.

In this preliminary report there is not sufficient time to enter further into the question of runoff.

An editorial in Engineering News-Record of October 17, 1929, calls attention to the comparison of bridge losses in two southern states caused by the heavy storm of September 30 to October 3, 1929, which was about equally severe in each state. In one state not a bridge built by the State Highway Department was lost. In the other, 13 wooden and 5 concrete structures suffered Quoting, the editorial says, " The comparison between the flood experiences of the two states serves to show the value of an intensive engineering study of bridge hydraulics, and the adequate public support for enduring bridges "

THE APPLICATION OF CLIMATOLOGICAL DATA

The question arises, Is there sufficient need for information along the lines just presented to warrant the time of a committee spent upon the work? Of what practical value will such information be to the road builder and road user?

The committee has attempted to indicate briefly the value as each item has been presented.

It will be well, however, to summarize some of the more practical uses for this information, and for further information that should be collected.

The engineer must know how large to make his bridge and culvert openings The losses sustained in South Carolina contrasted with the insignificant losses sustained by North Carolina from the early October storm emphasize this need

In order to be prepared for every phase of drainage that arises for the highway engineer, he must be able to put his fingers on the best data available regarding precipitation in all forms, runoff, percolation, stream flow and stream velocity, surface retention of water,

evaporation, the effects of humidity, wind, temperature, sunshine and frost as they unite in affecting the runoff and his subdrainage problems.

The stability of the subgrade soil is dependent upon its freedom from saturation which is affected by rainfall, snow, frost, evaporation, temperature, wind, sunshine and the humidity of the air above it.

The action of frost in the soil and cold weather above the soil upon capillary water, the freezing of free water in clear layers of ice in the soil beneath the pavement, due, as Professor Taber says, to the molecular cohesion, form problems that the engineer must be prepared to meet.

The contractor knows only too well the effect of both extreme heat and extreme cold upon the *amount* of work performed by his forces and the greater frequency with which he discovers defects in their work. For these reasons he must make allowance in his estimates and bids.

The other elements of climate also act in a similar manner but possibly with less effect.

The maintenance of the road shoulders and ditches are largely affected by various elements of climate. The maintenance engineer must organize his forces for different classes of work as the various elements of climate alternate in their attacks.

Tar and asphalt surfaces may be softened by heat and become badly deformed under traffic, or under excessive cold become brittle and crack, admitting water beneath the surface to injure and destroy the foundation and subgrade.

Pavements may be heaved up or displaced by the swelling or shrinking soil or by frost so that they become shattered or totally destroyed.

Snow brings up the organization of the maintenance forces for the setting of snow fences, snow plowing, cinder covering of hill slopes, and the opening of ditches and drainage channels in the early spring

The engineer may consider or neglect certain construction and maintenance features if he knows the average, maximum, and minimum limits of these various climatic factors.

The user of highways is met at some definite period in the spring with a sign: "Loads limited to (5 or) 7½ tons until further notice." The slipperiness of many roads is caused by fog, rain, ice, snow, and mud from side roads The length of vision and the safety in use of road is affected by sun, fog, rain, snow, and wind

NEEDED RESEARCH

1. The depth to which frost penetrates the soil in various localities over the country should be determined
2. The relation of frost depth to the length and the severity of the cold weather season or spell should be sought.
3. The influence of various covers to prevent deep freezing should be tried out. (Especially covers of adjacent road shoulders.)
4. Runoff data has been widely taken, but a condensed volume of the best data should be compiled and a concise statement regarding the various formulas made
5. Further research into the field of evaporation and of percolation should be made.
6. The actual effect in reduced labor efficiency, and number of defects caused by the influence of these various factors upon labor, should be studied.
7. Determination of the best means of determining the field percolation value of any given soil, etc.

DISCUSSION

ON

THE INFLUENCE OF CLIMATE ON THE BUILDING, MAINTENANCE AND USE OF ROADS IN THE UNITED STATES

MR. J A SOURWINE, *U S Bureau of Public Roads* Mr. Eno's paper presents a phase of research, which as a general study is not new, but which as applied to highway design and construction opens new and interesting fields of study.

I wish to discuss two items of the paper:

(1) Ground freezing
(2) Precipitation and runoff.

Perhaps in any phase of study it is worth while to get a general picture of the relative value, and dollars and cents importance, of the general project. A study of the damage to State Highways during the winter before last (1927-8), was made by the Engineering News-Record, and approximate estimates of frost damage were submitted by various state highway organizations. Minnesota reported 2000

miles of highway affected by ground freezing, and stated that the loss by reason of interrupted traffic and delayed business would be still greater than the direct damage Michigan reported an average frost damage of $50 per mile on gravel, $100 per mile on macadam and $150 per mile on concrete pavements Ohio estimated frost damage at one-quarter million dollars Maine reported an estimated cost of one-half million for required repairs Lacking complete reports from all states, but taking the reports available, and supplying an approximate estimate where state highway reports are not available, the amount of state highway repairs required, covering frost damage during the winter season 1927-8, is approximately three million dollars This estimate covers state highways only If we apply an arbitrary estimated additional percentage in the ratio of two-thirds of the state highway repair cost, to cover allowance for frost damage to municipal and county roads, we obtain an estimated total highway frost damage in the United States, for the winter of 1927-8, of five million dollars Such general inquiry as I have been able to make, indicates that the frost in the winter 1928-9, was not widely different, on the whole, from the winter 1927-8 Capitalizing this damage at five per cent, we have an approximate estimated value of the highway ground-freezing problem in the United States Twenty-nine states are directly affected and over two-thirds the population of the United States This gives us a general picture of the relative magnitude of our problem

When we turn to consider in detail the ground-freezing problem, we encounter: First, the problem of freezing weather during construction, Second, the problem of low temperature occurrence, duration and frequency, over a longer period, being the estimated life period of the highway under consideration I will limit my discussion to the latter, being the phase of study affecting highway design

The first question we face is—can existing records of past climatic conditions be used as a guide, to assist us in determining what is relatively dangerous area, and what is relatively safe area, for highway ground-freezing? Certainly the records of absolute minimum temperatures may not be so used An illustration is the case of Washington, D C The absolute minimum temperature which has ever occurred here is — 15° F A large number of those present are reasonably familiar with Washington It is probably safe to say that common opinion would not concur in accepting the extreme low minimum of — 15° F , as in any way typical, or as giving any basis which may be used, for comparative study, as representative of Washington,

D C Because this low temperature has occurred once, during an available period of record of 48 years, does not make this value a basis for design

After some study of United States weather data, the lowest monthly average of daily minimum temperatures—during winter months—was selected as offering a basis for comparative study and for serving as a guide, in determining approximate relatively dangerous and relatively safe areas, from the low temperature standpoint, as affecting highway ground-freezing The detail study leading to the determination of a tentative critical value, for lowest average of daily minimum, will be presented later in written form through report to the U S Bureau of Public Roads This much of general discussion may be given Using the lowest monthly average of daily minimum temperatures, an isothermal chart has been prepared—first, one chart for each state through which the tentative critical isothermal passes, and then one combined chart, to a smaller scale, for the entire United States Some data as to low winter rainfall, indicating arid regions, where the relative danger of highway ground-freezing seems more or less doubtful, at moderate extremes of cold temperature, is shown also on the same chart This chart is not calculated for use as an arbitrary determinator of areas dangerous for ground-freezing—but it is submitted as a guide chart, which, supplemented by other local data and special studies as available, will possibly form a tentative framework, on which may be built up, following several years of further study, and modification as required—an accurate reference chart, indicating climatic territory relatively safe, and relatively dangerous, for highway ground-freezing

Let us go one step further We have considered only low temperatures How about the "duration of cold period," and how serious a modifying element is this item of duration? The best reply is to cite some actual field tests made by Mr George J Bouyoucos—at the Michigan Agricultural College Experiment Station. Throughout the month of January, 1915, Mr. Bouyoucos ran a series of comparative temperature measurements in air and in soil His air temperatures were taken in air four feet above ground surface, and his soil temperatures at a depth of three inches below the surface of the ground His records show daily minimum, daily mean, and daily maximum temperatures, in ground and in air. A cold period began on January 20, when the minimum air temperature dropped to 8° F. There followed a continuous cold period, for the remainder of the month. On the

eighth day of this cold period the minimum air temperature dropped to — 6° F On the ninth day the minimum air temperature was — 13° F. On the tenth day the minimum air temperature was — 13° F, or exactly the same as on the ninth day. The mean daily air temperatures for the three days, 28th to 30th inclusive, were 2° F, 0° F, and 2° F In a word, the mean air temperature for the tenth day of the cold period was 2 degrees warmer than on the ninth day, and the minimum air temperature was the same Yet the minimum soil temperature, at a depth of three inches below the surface, was, on the ninth day, 14 5° F, and on the tenth day 7.5° F. In a word, the minimum air temperature was unchanged, but the additional duration of extreme cold period caused the minimum soil temperature, at three-inch depth, to drop 7° F The answer to our question is plain The record answers for us. Duration of cold period is a factor we must consider, as affecting relative danger of ground-freezing, in any locality.

Duration, being a factor, we have seen three variables· (1) Minimum temperature, (2) duration of cold period, and (3) frequency of cold period The question comes, can we in any way combine or relate two or more of these variables, in order that we may obtain a closer determination of territory relatively dangerous and relatively non-dangerous for highway ground-freezing, from the standpoint of climatic conditions? After some puzzling, the answer comes. We have combined variables through a simple method, in other engineering studies It is only necessary to apply a similar principle here We are all familiar with the term "ton-miles" Why should we not use with equal accuracy, and with similar degree of effectiveness, the term "degree-hours"? In such a combining of the "minimum temperature-cold period duration" factors, we have to determine first our critical temperature, at or below which ground-freezing begins, in average soil. The "degrees of cold" are then measured downwards in degrees below the critical temperature The "duration" is measured in hours of cold period below critical temperature One-half the product of "degrees of cold" and "duration," as above measured, gives "degree-hours," measuring the approximate actual value of "quantity of cold," in any given cold period.

Using the method just outlined, for any point where a continuous thermograph record is available, over a period of years, we may tabulate the total number of cold periods below critical temperature, with the duration and minimum temperature of each cold period. If

from these tabulated data, we plot two curves, (1) a minimum temperature-frequency curve, and (2) a cold period duration-frequency curve; we can then, from these two plotted curves, determine and plot a third curve, a "degree-hour-frequency curve," which takes into account all three variables, of minimum temperature, cold period duration, and cold period frequency. It rests then with the executive body planning new highway improvement, to determine on what basis of allowable frequency they desire to base their highway design. For the allowable frequency fixed upon, the climatic records of actual previous occurrence determine a definite "degree-hour" value.

Following up the "degree-hour-frequency" method, or "quantity of cold" method, the thought is suggested that if we may agree upon a tentative value of "allowable frequency," for cold period occurrence, as a basis for design, we may determine and plot a series of "degree-hour" contours, in any state, or across the United States, which degree-hour contour chart may be used as a supplementary chart, to the temperature—rainfall chart already determined and plotted, and by the use of these two charts, we may have available a useful guide, for the determination of climatic territory relatively safe, and relatively dangerous, for highway ground-freezing Such a "degree-hour contour chart" is now being determined and prepared, and will be made available in a report to be issued shortly by the U S. Bureau of Public Roads.

Now if I may touch very briefly on the second item of Mr Eno's paper, which I wish to discuss—"Precipitation and Runoff." Or possibly we may elaborate slightly Mr Eno's heading, and say "Precipitation, Runoff, and Stream Control, as affecting public highways" The question I wish to call to your attention is—"What relative importance has this phase of study—and may it properly and directly be incorporated as a part of highway research, to form a portion of future basis for highway design?

I visited Vermont in November, 1927, a few days after the severe flood of that year, making—together with Mr C V. Jarvis and with Mr G. H Miller, District Engineer of the U. S. Bureau of Public Roads, a study of flood conditions. The direct highway damage in the small state of Vermont caused by three days flood, for the large part on non-navigable streams was approximately eight million dollars I made a study of the indirect damage, through interruption to, and delay in business, due to highways not operative—and this indirect damage ran into several millions of additional loss.

I was in Southern California in the winter of 1915-16, as county engineer for San Bernardino County, California, when the excessive precipitation and runoff of that year occurred The estimated highway damage, direct and indirect, caused by this four day's flood in Southern California, was approximately fifteen million dollars

These are two typical instances, twelve years apart in time, and three thousand miles apart in geographic distance, the locations varying from the extreme northeast to the extreme southwest portion of the United States Other instances are multiplied, occurring at intervals in nearly all parts of the country. The instances I refer to do not have to do with navigable streams throughout the United States. And they affect directly the cost of construction, maintenance and operation of public highways in the United States

Mr. Eno touched on this problem of " precipitation and runoff " as one possibly not entirely to be included under the heading of " climate," but as a problem so closely allied and of such magnitude of importance as affecting highway construction, that he felt it should have further study.

I would point out, as Professor Eno has done, and I would like to place added emphasis, if it be possible, on the importance and on the practical value, of further study and cooperative constructive research, on these two general projects, (1) ground freezing, and (2) precipitation, runoff and stream control—both as affecting highway design and construction, in the United States

PROF D P. KRYNINE, *Moscow Superior Technical School* Professor F H Eno and the Committee on Structural Design of Roads are to be congratulated for having given start to a new branch of highway science, namely to the study of climatic conditions Similar ideas have been formed in the Russian Highway Research Bureau, too, they may also be found in my Russian text book on Highway Engineering, edition 1929

At the present time the science and practice of highway engineering have become international A similar thing occurs for instance in North and South America, as I have learned from the brilliant talk of Mr. Pyke Johnson about the Pan American Conference of 1929 However, this circumstance obliges us to pay great attention to the difference of climatic conditions, and to the elaboration of new specifications accordingly. In the opposite case, a danger may arise either of producing an unsafe structure or of wasting a certain quantity of money in unnecessary work.

The effects of temperature, frost, sunshine, wind, humidity, precipitation, run-off and evaporation upon various phases of highway activities are interestingly discussed by Professor Eno. To this long list of climatic factors one more should be added namely, the influence of atmospheric pressure

IMPORTANT DEVELOPMENTS WITH RESPECT TO SUBGRADE INVESTIGATIONS

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AND
Henry Aaron
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Among the important developments disclosed by subgrade investigations during the past year are the following.

1. A conception of the physical laws controlling the stability of subgrades
2. A conception of the detrimental effects produced by elasticity in subgrades
3. A conception of the physical laws controlling the occurrence of frost heave
4. An understanding of the benefits which may be furnished by treating subgrades
5. Suggested tentative grouping of subgrades based upon their performance
6. The use of relatively few and comparatively simple laboratory tests which serve (a) to identify the dominating constituents of subgrade soils, (b) to disclose the important characteristics possessed by subgrade soils, and (c) to suggest the proper corrective measures to be used in pavement construction

STABILITY OF SUBGRADES DEPENDS UPON BOTH INTERNAL FRICTION AND COHESION

(a) Internal friction or that portion of the resistance to shear which is dependent upon the external force applied, and

(b) Cohesion or that portion of the resistance to shear which is independent of the external force applied