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ENGINEERING METEOROLOGY:
THE EFFECTS OF WEATHER AND CLIMATE ON CONCRETE PAVEMENT*

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ABSTRACT

Concrete pavement may be adversely affected by weather and climate through the freezing process either within or under the pavement. The common results of freezing action that are detrimental to the durability and usefulness of the pavement are: differential frost heave, loss of subsoil bearing strength, migration of subsoil, loss of strength of the concrete itself, and scaling of the pavement surface. Temperature and moisture are the dominant factors in each of these effects.

1. Introduction

Concrete shows some peculiar weathering effects that have no direct counterparts in other types of pavements. On the other hand, influences on the pavement due to frost action in its soil base could not be ignored. The part of this paper devoted to "sub-pavement" effects will apply directly to other types of pavement within limits, and to non-paved roads.

At one time, direct weathering of concrete was a very severe problem, but it is now much less severe. This weathering is quite interesting and, in some areas, still a thing to be reckoned with. The major destructive actions have been greatly alleviated by the introduction of air-entraining concrete. Air-entraining concrete has not eliminated, although it has diminished, deterioration due to "salt scaling" of the concrete surface. This interesting phenomenon takes place in regions of frequent, heavy snows. The snow is often removed by the application of salts to the road. It has been shown that the salt caused, or at least seemed to cause, flaking or scaling of the concrete.

The "sub-pavement" actions that influence pavement durability are those processes which take place in the soil region from the bottom of the pavement to a depth of several feet. The general term usually employed for these processes is "frost action", which is the freezing and thawing of moisture in materials, and the resultant effects on these materials and on structures of which they are a part or with which they are in contact.(1) The undesirable effects of frost action are a heaving of the soil which tends to displace the pavement in the vertical direction, a wetting or lubrication action which causes the soil to lose its ability to support pavements subjected to heavy loading, and a slipping or lateral movement of the soil, also due to the lubricating action.

Engineering techniques have reduced the more direct effects of frost action, but again they have not been eliminated. This is probably the major weathering problem in highway engineering today and is the object of a great deal of study. In a paper of this scope, only some of the more salient aspects of frost heave can be presented, and the discussion will be entirely qualitative.

A few examples of the scope and severity of frost action will serve to place the problem in its proper perspective. In Nebraska the loss of bearing capacity of the sub-pavement soil during the spring break-up period was determined by a series of tests to be 29.4 percent of normal strength on the average. In Minnesota the loss in 126 tests over the state was 40 to 46 percent.[2,3] New Hampshire estimated that the cost of repairs to concrete roads for one year was $73 per mile.[4] The loss of bearing strength for Nebraska and Minnesota occurred during the spring break-up period, therefore the roads recovered most of that loss during the summer. This means that the road sub-soils lose bearing strength only gradually over the years, but that in the spring the loads transported over roads may have to be considerably reduced in order to avoid severe damage. Alternatively, the highway could be overdesigned for most of the year to reduce damage during spring break-up.

2. Frost Action Within the Concrete

Fresh Concrete. - The freezing action in fresh concrete, i.e., before significant hardening has taken place, is markedly different from the action in hardened concrete and will be discussed separately. The period from the time of pouring until the hardening process is well along is the most critical in the life of concrete with respect to frost action.

The water-cement ratio of the fresh paring concrete mix is usually about 0.5 by weight or less. In this state it is a thick, plastic, semi-fluid containing a conglomeration of aggregate particle sizes from about $1\frac{1}{2}$ inch down to extremely fine cement particles. There is an abundance of moisture available for freezing and freezing will usually commence at about -6 degrees contigrade. The fresh concrete is medium-gray in color and provides much surface water for evaporation. It is normally poured at temperatures well above freezing, and is protected by its own heat of hydration and sometimes by artificial heat. The rate of hydration is temperature dependent, and thus its own internal heat supply will be diminished, if the concrete is cooled. Thus the cooling process will tend to increase with lower temperatures, especially on a cold, clear, windy night.

Ice crystals tend to form on the surface of the aggregate particles and to extract water from the contiguous mortar as they grow.[5] This is not a reversible process since it forms a pocket of water which separates the aggregate particle from the surrounding mortar as the crystal melts. The mix proportions and type of cement employed do not influence this process significantly. Thus the air-entraining cements, which do help after the concrete has hardened, are not more frost-resistant than other cements during this period.

Concrete frozen only a few hours after it has been poured may lose up to 50 percent of the normal strength (the strength of similar concrete not frozen).[6] The degree of loss sustained diminishes greatly with the length of the curing period prior to freezing. If the curing period is at least 24 hours, the strength loss for a single freezing will be negligible. The temperature at which the concrete in initially frozen affects loss of strength, but once the concrete is frozen through, neither the temperature to which it may be further reduced nor the length of the freezing period seem to affect the loss greatly. Any strength lost in this way cannot be regained, the concrete is permanently damaged.

Some protection against freezing damage is probably attained through the use of a white curing membrane. This is a water impervious membrane that is sprayed on fresh concrete to increase the curing time. It accomplishes this by preventing evaporative water losses and by reflecting solar radiation. Since it retards evaporative heat losses, fresh concrete covered with the white membrane would not cool as fast as uncovered concrete on cold, windy nights.

Hardened Concrete. - When the concrete has hardened, it cannot be readily damaged by frost action. After hardening, a process which proceeds rapidly at first and then with diminishing speed, the structure of the concrete is markedly different, and thus the freezing action is also quite different. To understand this, it will be necessary to examine the nature of hardened concrete.

Hardened concrete appears to be a solid mass as hard as rock. In a general way it is usually thought of as a homogeneous mortar interspersed with aggregate particles. This is indeed general, because the mortar itself and, to a lesser degree, the aggregates are porous and non-homogeneous.

The coarse aggregate particles, usually gravel or limestone, have dimensions of the order of 1/4 to 1-1/2 inch in diameter in paving concrete. They are nearly always obtained locally, i.e., close to the mixing site, and vary widely in composition. There are many particles that are objectionable from the standpoint of resistance to freezing action, and the elimination of these is very important in the development of frost-resistant concrete. There are three classes of deleterious particles: (1) soft particles including shale, soft sandstone, ochre, coal, iron bearing clay, weathered schist, shells, floaters, and partially disentegrated particles, and cemented gravel, (2) "chert", and (3) hard absorbent particles.[7] Even the best aggregates are capable of absorbing some water, but this is usually a small amount which gives little if any trouble.

The cement is composed of extremely fine grains before being mixed with water. After mixing, hydration (the hardening process) produces particles whose dimensions are of the order of magnitude of 100 Angstroms.[8] This mater, in a colloidal state, forms a continuous, porous, solid mass called the "cement gel". Water and air are present in the gel-pore spaces and in the capillary spaces. The capillaries within the gel are so fine as to be beyond the limit of resolution of light microscope.[9]

Volume changes of the cement gel may be caused by thermal expansion and contraction, or by freezing and thawing of the capillary water. Freezing can cause distress in concrete by expansion of ice in the pore spaces of the aggregate, the cement paste, or both. The capillary water in the cement gel begins to freeze in the temperature range from -6 to -15 degrees centigrade. Water in the much smaller gel-pore spaces does not freeze, even at temperatures down to -78 degrees centigrade.

If the paste is saturated, the gel-pores and the capillary pores are full of water. Freezing will begin in the largest capillary pores and they will expand as the water freezes. This freezing will cause dilation of the pore or the expulsion of water from it. Since the permeability of the paste is extremely low, the growing body of ice exerts a hydraulic pressure on the system. The hydraulic pressure in the paste and the direct expansion in the aggregate are the damaging features of the freezing process.

If air is artificially entrained in the paste in the form of small, well distributed voids, the stresses and strains will be greatly reduced. The hydraulic pressure is relieved by the passage of water from the capillary pores via the gel pores to the boundary of the air void. Each air void can absorb pressure from many adjacent capillaries since it is gigantic in size compared to the capillaries. About 9 percent of air by volume should be entrained in the mortar fraction of the concrete to give adequate resistance to frost action.[10]

A certain critical amount of water must be present in the concrete before any of these actions can become important. This critical amount is about 90 percent of saturation. Even a non-air-entraining concrete can be made frost resistant in some cases. The proportions of the mix (cement, sand and gravel) have no effect on frost resistance, but the initial water to cement ratio does. A water-cement ratio of about 0.4 (which is less than the normal ratio) by weight seems to have good frost durability.[9] Such concrete will hold little freezeable water. The latter method is not as popular, and probably not as dependable or effective, as the use of air-entraining cement since concrete of such a low water-cement ratio presents considerable control problems during its manufacture.

Scaling of Concrete Surfaces. - On concrete pavements in the winter season, the removal of ice and snow is usually accomplished by the application of various chloride salts. In addition to being effective in removing ice and in corroding automobiles, the salts cause surface deterioration of the concrete called "scaling". In some cases, where severe winters have demanded frequent applications of salts, scaling has been extensive as to cause complete disintegration of the concrete.

In the search for ways of preventing the scaling effect, various additives and surface treatments were tried. The additives used were air-entrainment, Table I, varying from 1.5 to 7.2 percent, used crankcase oil, paraffin oil, and asphalt oil, Table II. Various combinations of SAE No. 10 oil and gasoline were used as a surface treatment for the concrete, Table III.[11] Table IV gives the rating scale used.

TABLE I

RATING OF RESISTANCE TO SURFACE SCALING OF CONCRETE SLABS CONTAINING VARIOUS PERCENTAGES OF AIR

Cement Sk/cu.yd.	Air[1] Percent	Rating after cycles of freezing and thawing indicated[2]				
		30	36	42	50	60
6.0	1.5	8	10			
6.0	2.7	6	8	10		
6.1	6.0	2	3	5	6	8
5.9	13.0	0	0	0	2	2
7.0	1.5	3	7	10		
7.2	2.7	2	5	8	10	
7.2	4.9	0	2	5	10	
7.1	7.2	0	1	2	4	6

Each value is average of 3 tests.
Slabs cured in moist air for 21 days followed by 14 days storage in in laboratory air.

[1] Air content determined by ASTM tentative method C 231-49T

[2] Freezing and thawing tests were discontinued when surface scaling rating was 10, or at 60 cycles.

TABLE II

RATING OF RESISTANCE TO SURFACE SCALING OF CONCRETE SLABS CONTAINING OIL AS ADMIXTURE

Admixture	Air[1] Percent	Rating after cycles of freezing and thawing indicated 20	30	50	65	75
None	2.0	1	2	3		10
Used Crankcase Oil	5.7	1	1	1	2	4
Paraffin Oil	2.0	3	4	4	10	10
Asphalt Oil	2.4	3	5	5	10	10

Each value is average of 5 tests. Other notes same as Table I.

TABLE III

EFFECT OF OIL SURFACE COATING ON THE RESISTANCE OF CONCRETE TO SCALING

Number of Appli-cations	Surface Treatment	$CaCl_2$ thawing	Rating after cycles of freezing and thawing 15	40
-	None	No	2	4
-	None	Yes	4	8
1	50% SAE 10, 50% gasoline	Yes	2	4
1	75% SAE 10, 25% gasoline	Yes	2	3
1	100% SAE 10 oil	Yes	2	2
-	None	No	2	4
-	None	Yes	4	8
3	50% SAE 10, 50% gasoline	Yes	2	2
3	75% SAE 10, 25% gasoline	Yes	2	3
2	100% SAE 10 oil	Yes	2	3

Each value is average of three tests.
Surface treatment applied at the rate of 1 gallon per 20.
Square yards at age of 28 days.
Cured same as Table I.

TABLE IV

RATING SCALE FOR EVALUATING SURFACE SCALING OF CONCRETE

0	No scale
1	Scattered spots of very light scale
2	Scattered spots of light scale
3	Light scale over about 1/2 the surface
4	Light scale over most of the surface
5	Light scale over most of the surface, a few moderately deep spots
6	Scattered spots, moderately deep scale
7	Moderately deep scale over 1/2 the surface
8	Moderately deep scale over entire surface
9	Scattered spots of deep scale otherwise moderate scale
10	Deep scale over entire surface

Most of these seemed to retard scaling to some degree, but none of them eliminated it. Air-entrainment was found to be the beneficial agent in each of the additives, but no percentage of air was completely satisfactory, nor was it understood at the time why air-entrainment helped.

The thawing agents calcium chloride, calcium chloride with rust inhibitor, sodium chloride, ethyl alcohol, and urea were tried.[11,12] Urea was known to be a non-corrosive thawing agent to metals, and it did retard scaling but was also slower in its de-icing action. The other agents were no better. On the basis of all this evidence, it was concluded that the problem was physical rather than chemical.

Brunauer[8] has offered an explanation that seems to fit the observed evidence. He suggested that the hydraulic pressure incurred in the freezing of concrete is the important agent in scaling. The salts used in de-icing were found to significantly decrease the already low coefficient of permeability of the hardened paste. The hydraulic pressure generated in the capillary pores in freezing could not be as readily relieved by the air voids in the surface layer. This would result in increased hydraulic pressures and greater deterioration. Due to the thawing effect, the salts would also provide a water supply for the saturation of the concrete.

3. Sub-Pavement Frost Action.

The frost action which occurs under highway pavements is well known, and there have been many comprehensive papers on the subject. e.g., (1,13,14,15). Because of the importance of this topic to highway engineering, it is appropriate to offer a brief discussion of the measures taken to combat subgrade frost action. This topic does not lie within the domain of meteorology but is germane to it. The two primary factors in frost action, soil moisture and soil temperature, are considered to be climatic elements[13] because of the many meteorological parameters that influence them such as: air temperature, precipitation, insolation, cloudiness, humidity, air pollution, atmospheric pressure, wind speed, length and severity of the winter, and the number of warm-cold spells in the spring.

The specific detrimental effects of soil frost action on pavements are the heaving of the ground surface due to formation of ice lenses, lubrication of soils due to melting with the consequent loss of bearing strength, and solifluction or lateral movement of soils under pressure or vibration.

The fact that soil moisture is vital to frost action has led to the conclusion that adequate drainage will eliminate or reduce frost to a safe level. It is certainly true that a dry soil does not heave or lose its bearing strength, but drainage alone will not maintain a dry soil. Moisture can defy drainage by capillary action, vapor migration, ice suction, and by ice-blocked drainage. Good drainage, although necessary and well understood, is not always easy to attain. The ground water table must be lowered many feet from the pavement. Lateral drainage from slopes must be diverted. Ideally, the drains should penetrate the lowest layer of wintertime frost to absorbent soils. These improvements are being incorporated into modern highway construction, but these improvements alone are not sufficient.

If the highway subgrade could be sealed off from vapor migration the problem would be well in hand. To this end, various types of oils and films have been tried.[16] However, oil, concrete, and even asphalt films of considerable thickness were found to be pervious to water in the vapor phase.

It has been found, through experience, that some soils are fairly resistant to frost action. The exclusive use of these soils is a satisfactory solution, when they are available. Turner and Jumikis[17] tested 34 New Jersey soils and subbase materials, and graded them according to their loss of bearing capacity. The soils tested are listed in Table V and the results in Table VI.

TABLE V

DESCRIPTION OF SOILS TESTED

F-1	A well-graded mixture of freezable shale fragments from gravel to clay sizes.
F-2	A sandy silt-clay mixture with considerable gravel.
F-3	A silty sand with traces of gravel.
F-4	A clay-silt-sand mixture with considerable gravel.
F-5	A sandy silt-clay mixture.
F-6	A silty, clayey sand with some gravel.
F-7	A gravelly sand with small amounts of silt and clay.
F-8	A fine sand with traces of silt and clay.
F-9	A clayey silt containing much sand.
F-10	A mixture of coarse, medium and fine sands, containing considerable gravel and some silt and clay.
F-11	A well-graded mixture of gravel, sand, silt and clay.
F-12	A silt and clay mixture containing considerable sand with traces of gravel.
F-13	A sandy gravel with considerable silt and clay.
F-14	A well-graded mixture of gravel, sand, silt and clay.
F-15	A well-graded sand-silt-clay mixture containing considerable gravel.
F-16	A mixture of sands.
F-17	A mixture of coarse, medium and fine sands with traces of gravel, silt, and clay.
F-18	Medium fine sand containing considerable clay and silt.
F-19	A gravelly, silty, clayey sand.
F-20	Sand containing considerable sand and some silt and clay. Also very high organic content.
F-21	A sand, silt, clay mixture with traces of gravel.
F-22	A sandy silt-clay mixture containing considerable gravel.
F-23	A well-graded gravel-sand-silt-clay mixture.
F-24	A well-graded mixture of gravel, sands, silt and clay.
F-25	Coarse and medium sands containing considerable fine gravel and some silt and clay. Subbase.
F-26	A medium sand with considerable gravel and some silt and clay. Subbase.
F-27	Gravel containing considerable sand and some silt and clay. Subbase.
F-28	A gravelly sand. Subbase.

TABLE V (CONT'D)

DESCRIPTION OF SOILS TESTED

F-29	A sandy gravel. Subbase.
F-30	A gravel and sand mixture containing numerous rounded shale particles. Subbase.
F-31	A sandy gravel, essentially shale and sandstone. Subbase.
F-32	Traprock screenings.
F-33	A sandy gravel. Subbase.
F-34	A sandy gravel. Subbase.

The increasing size of the annual road construction program has made the search for acceptable soils imperative. Some localities do not have such soils and others are rapidly using them up. Transport over long distance is uneconomical, so the next best thing is to treat available soils in some way to render them frost resistant. Lambe[18] tested about 40 additives with 15 soil types. The additives were divided into four groups: (1) void pluggers and cements, (2) aggregants, (3) dispersants, and (4) "waterproofers" - according to their action in soils. The void pluggers and cements fill the soil pores to prevent movement of water and cement the particles together to provide resistance to expansion. In order for soils to be frost susceptible they must contain a minimum of 3 percent by weight of particles finer than 0.02 mm. This is not a very stringent requirement because there are some soils which meet it, but are still frost susceptible. However, it is a convenient specification. A soil can be rendered non-frost-susceptible by removing these fines. The action of the aggregant is to cause the fine particles to aggregate into larger units. This is done with cements or chemicals. An example of such a chemical is the polyvalent cation (Fe^{+++} or Al^{+++}) whose action is to shrink the diffuse double layers around the soil colloids enough to permit the interparticle attractive forces to make the particles cohere. Some chemicals, the dispersants, such as the polyvalent anions, disperse the natural soil fines. They expand the diffuse double layers around the colloid which increases the interparticle repulsion and makes it easier to manipulate the soil into a more orderly and denser structure. This results in higher density, lower permeability, higher stability to water, and, by decreasing the sizes of the soil voids, lowers the freezing temperature of soil moisture. The "waterproofers" alter the soil surface so as to render it hydrophobic. Such a soil will not "wet" and has little or no adsorbed moisture.

TABLE VI

RELATIVE BEHAVIOR OF SUBBASE AND SOIL MATERIALS BASED ON MAXIMUM HEAVE AND CUMULATIVE HEAVE

Relative Position In Order	Maximum Heave During 1 Freezing Cycle Soil No.	Maximum Heave During 1 Freezing Cycle Heave ft.	Cumulative Heave During Entire Winter Soil No.	Cumulative Heave During Entire Winter Heave ft.
	Subbase materials in 12 in. deep pits.			
1	F-29	.011	F-29	.064
2	F-34	.015	F-28	.068
3	F-28	.021	F-34	.079
4	F-31	.025	F-30	.087
5	F-30	.029	F-27	.113
6	F-27	.035	F-31	.115
7	F-32	.044	F-32	.126
8	F-33	.046	F-33	.135
	Soil materials in 24 in. deep pits.			
1	F-17	.004	F-17	.043
2	F-25	.008	F-25	.053
3	F-10	.017	F-10	.055
4	F-26	.018	F-26	.076
5	F-2	.019	F-2	.084
6	F-20	.021	F-20	.089
7	F-14	.022	F-14	.091
8	F-5	.026	F-13	.097
9	F-13	.027	F-12	.098
10	F-21	.030	F-5	.104
11	F-12	.032	F-21	.113
12	F-6	.032	F-9	.113
13	F-15	.032	F-15	.114
14	F-9	.033	F-6	.120
15	F-19	.045	F-4	.127
16	F-4	.064	F-1	.143
17	F-1	.065	F-19	.151
18	F-11	.069	F-11	.155
19	F-22	.091	F-22	.162
20	F-23	.103	F-23	.165
21	F-3	.127	F-3	.178
22	F-24	.145	F-24	.178

Another treatment that is temporarily effective is to alter the characteristics of the pore water. This is done by the addition of salts which lower the freezing temperature. Road tests have shown this procedure to be effective for about three years. By this time the soil moisture movement had diluted the salt solution and carried it away.

The final results of Lambe are shown in Table VII.[18]

TABLE VII

OVERALL EVALUATION OF ADDITIVES AS FROST MODIFIERS

Additive	Required Concentration Percent	Cost per lb.	Field Use	Evaluation
Void Pluggers				
a. Calcium acrylate	5+	50¢+	Difficult to control	Poor
b. Resins	1+	1 to 15¢	No problem	Promising
c. Portland cement	4+	1 to 2¢	No problem	Int. to Poor
d. Natural fines	6+	0 to 2¢	Unusual mixing	Interesting
Aggregants				
a. Polymers	1-	12¢ to $1	Moderate mixing	Int. to poor
b. Cations	0.5-	2¢ and up	No problem	Very promising
Dispersants	1-	5¢ to $1	No problem	Very promising
"Waterproofers"	0.5+	25¢ to $2	Need for high degree of drying	Promising

Adjective scale: poor, interesting, promising, very promising, excellent.
+ = greater than, - = less than.

In existing highways where frost action weakens the pavement, the remedy is usually to install more frains and/or excavate the offending materials and replace them with gravel. This is obviously a very expensive procedure and is the justification for prior treatment of soils.

4. Conclusion.

The problems that continue to be of interest to both highway engineers and to meteorologists are the freezing of fresh concrete, scaling of hardened concrete, and frost action in the soils beneath the pavement surface.

The first problem, freezing of fresh concrete, is largely a matter of pouring the concrete in suitable weather, and taking precautions to insure that it does not cool off too quickly. The use of the white membrane probably is very good in this respect although it is used to prevent rapid curing by reflecting solar radiation and eliminating evaporation. One question still current about the white membrane is its characteristics in the infra-red. This is quite important since nearly 50% of the incoming radiation is in the infra-red. It is also important in its effect on nighttime cooling.

Scaling of hardened concrete is largely a question of snow and ice removal. Some way must be found to affect the removal without damaging the pavement, although the use of air-entrained concrete has gone a long ways toward alleviating this problem. In this connection, it is worthy of note that the highway engineers are not unaware of the effects of the de-icer on cars. If the hypothesis of Brunauer is correct, one would conclude that the concrete must be saturated or the surface rendered more impervious and then frozen for scaling to occur. Elimination of any one of these should help to prevent scaling.

Frost action in the underlying soil is still a problem although the chemical additives mentioned before may prove to yield a satisfactory solution. They have not been extensively tested in the field as yet. It takes many years after a road has been laid to determine whether or not it is susceptible to frost action. If the immediate and more spectacular effects have been alleviated, there are still the long-term, cumulative effects to allow for. Weakening of highway sub-soil is a process than continues for years and may not be detected until a heavy load finally causes the pavement to crack and fail.

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