Icing on Pavements

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The subject, icing on pavements, is presented because of its considerable academic and practical interest to scientists, engineers and motorists. Sidewalks, streets, highways and airport runways are great potential sources of accidents when they become coated with a slippery surface of ice; vehicles skid in traversing the highways and aircraft skid in taking off and landing. To renew interest and thinking and to promote a better understanding of the icing phenomenon, the icing theory is presented. The physical conditions for the formation of icing and the temperature regime below the ground surface are described and illustrated graphically by means of tautochrones. Also presented is a discussion of variations below the surface brought about by rain droplets (at temperatures above freezing) upon their striking the frozen pavement surface.

The icing theory is demonstrated by actual conditions as they prevailed in the general metropolitan area of New York in January 1956.

●IN CERTAIN KINDS of inclement weather, snow, sleet, ice and their combinations may cause a multitude of conditions on pavement surfaces which offer special difficulties to pedestrians, motorists and/or aircraft in taking off or landing. Indeed, to keep traffic moving at all during icing periods is more difficult than might be anticipated at first glance. Upon the formation of ice, traffic first reduces speed, then moves at a crawl, and finally bogs down or stalls completely for many hours, forcing motorists to abandon their vehicles, thus further increasing the jam.

Such conditions prevailed on January 8-9, 1956, in the general metropolitan area of New York. This area, with a radius around New York of more than 75 miles, embraces New Haven, Conn.; Suffern, N.Y.; northeastern New Jersey and the Newark district; New York City; Staten Island; Long Island; and south to the vicinity of New Brunswick and Trenton, N.J., and is the most heavily traveled section of the eastern seaboard (Fig. 1). One can imagine the immense confusion which resulted on the many parkways and major highways when, on the dates mentioned, pavements and windshields were quickly covered with ice (Fig. 2), making motorists helpless. Because of the slippery pavement conditions it was particularly difficult to operate in hilly country, on curves, and on bridges and their approaches.

Particular icing conditions for the dates January 8-9, 1956, are discussed in a later section of this paper.

The purpose of this presentation is to promote understanding of the icing phenomenon.

ICING THEORY

Formation of Icing

Icing on pavements can form under several conditions. For purposes of brevity, however, this discussion is confined to that special form of icing which corresponds to the meteorological term "glaze," and which occurs under the conditions described in the following paragraph. Likewise the term "surface," as hereinafter used, refers equally to pavement surface or ground surface, since the reasoning involved applies in either case.

At the outset of this discussion it is assumed that the air adjacent to the frozen pavement or soil is cool, and that the warm droplets of rain fall through the cooled air zone. When droplets of rain at a temperature above but near freezing fall and strike a frozen surface they freeze, thereby coating the surface with a smooth, clean film of ice. After

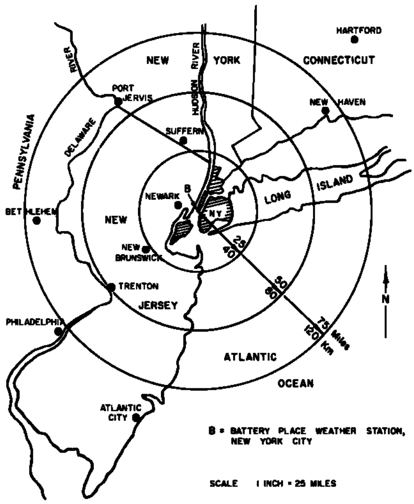

Figure 1. Sketch-map of the general metropolitan area of New York.

impact, the freezing of the droplets and the icing on the surface sometimes forms within a matter of minutes. The smooth surface of the icing affects vehicle braking distance adversely and reduces traction considerably. The coefficient of friction between the tires and pavement, according to Hewes and Oglesby (1), can reduce to about f =0.05 or less, which makes proper vehicle control almost impossible. Essentially, it is the quick process of icing on pavements which, according to some authors, poses the severity of the icing problem in traffic engineering. The crystals of the icing are extremely fine, hard, and smooth. The thickness of the icing varies from about 1 mm to about 2 mm, although this depends on the amount and duration of precipitation, evaporation, and runoff.

The size of the droplets, according to Shaw (2), is about 0.5 mm, but generally varies from 1 mm to 4.5 mm for spherical droplets, while rice-shaped droplets are about 6 mm long.

Latent Heat

On freezing, one gram of water releases 80 gram-calories of latent heat, and a certain amount of the rainwater remains liquid at about 0 C. This latent heat of fusion of rain droplets is thus more than sufficient to raise the surface temperature for a certain length of time from below freezing to 0 C, at which freezing of the rain droplets begins. Hence, during freezing the droplet itself gives off heat and at the same time the released heat raises the pavement surface temperature until both the temperature of the droplet and that of the surface become equal (that is, 0 C). Whether the aforementioned part of the unfrozen liquid freezes, depends on the coldness of the rained-on surface where freezing can be most expected. Thus, an exactly instantaneous freezing of the rain droplets does not actually occur, because latent heat is evolved with solidification, and the dissipation of heat on conversion of water to ice takes place into the surroundings, a process which takes a certain amount of time.

Latent heat of fusion can be liberated and dissipated by the following:

1. Evaporation of water.
2. Convection.
3. Conduction to the air.
4. Conduction to the pavement or to the soil.

Factors 1, 2, and 3 can be considered small as compared with the dissipation of heat by conduction to the pavement or soil. Therefore, discussion of the formation of icing on pavements is confined here to the case in which the liberated heat is dissipated principally through cooling by this kind of conduction.

According to Geiger (3), glaze forms in two ways; namely, either (a) through solidification of supercooled precipitation on warm ground or (b) through freezing of raindrops (above 0 C) on very cold ground.

In the first case, it is assumed that the temperature of 1 g of supercooled rain droplets striking the warm pavement is -5 C. Upon striking, the droplets start to freeze, and the temperature of the freezing rain droplets rises to 0 C. Thus, 5 g-cal are already consumed, and 75 more cal are to be liberated to freeze one gram of fallen rainwater. Because the value of latent heat of evaporation is 590 cal, only a small amount of the fallen 1 g of rainwater $\left(\text{that is, } \frac{75 \times 1}{590} = 0.127 \text{ g}\right)$ must evaporate to

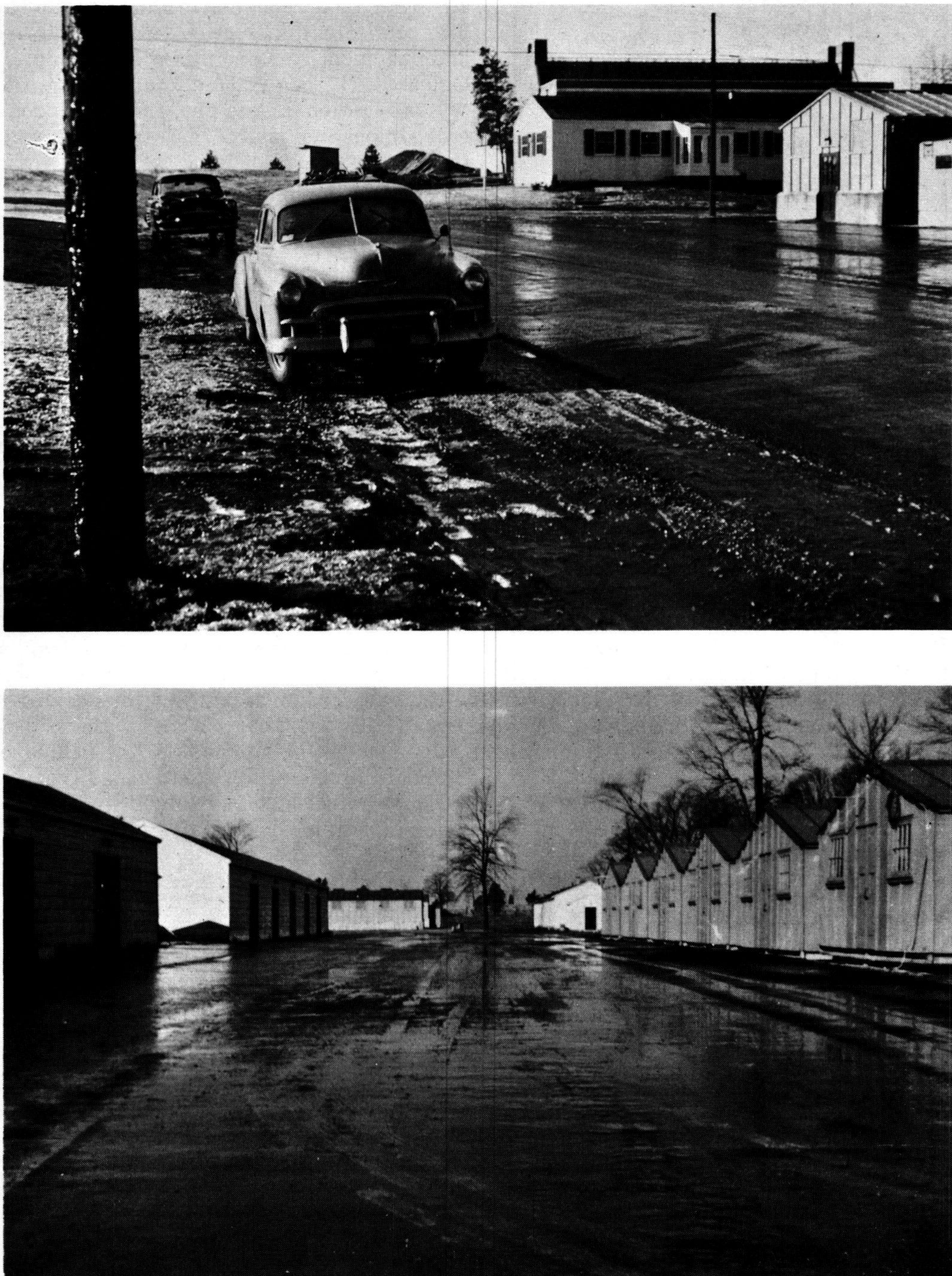

Figure 2. Examples of icing on pavements.

liberate the remaining 80-5=75 cal of heat to commence the freezing of the rainwater (that is, to form icing on pavement). This small amount of evaporation suggests that it takes place within a short period of time, and, likewise, the freezing of the rain droplets also starts within a reasonably short period of time. In this respect it must be recognized that evaporation in the freezing process is significant.

In the second case, it is assumed that the warm and falling rainwater is, for example, +4 C. Falling through the cooled air zone adjacent to the cold surface, the rain droplets cool, for instance, to 0 C. When the rain droplets at this temperature strike the cold pavement each gram of the rainwater liberates 80 g cal of latent heat. Only after this amount of heat is liberated can the water start to freeze.

From this discussion, it is apparent that the main factor in the process of icing is dissipation of latent heat into air and pavement or soil.

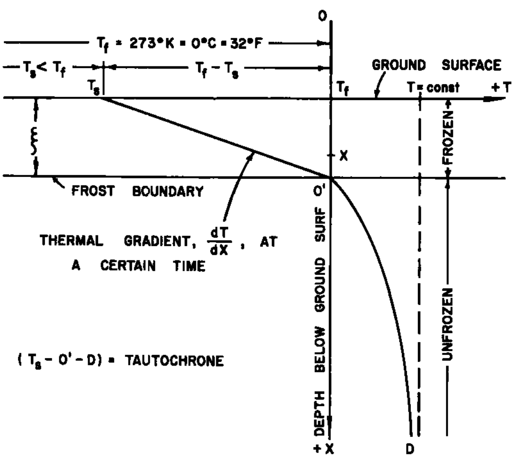

Figure 3. Tautochrone at a certain time.

Conditions Favorable for Icing

From the discussion on formation of icing, it also can be summarized that the conditions governing icing on pavements can be broadly classed into two major groups; namely, (a) meteorological conditions, and (b) thermal properties of air, water, pavement, and soil.

Meteorological Conditions.—The prime prerequisite for the formation of icing, of course, is:

1. The rapid setting in, at higher altitudes, of a warm, humid air-flow preceded by a long cold period.

Other factors are:

2. Precipitation intensity and duration, which determine the thickness of icing and its rate of formation.

3. Temperature of the rain droplets falling through the cooled air zone adjacent to the cold surface.

4. Temperature of the pavement (usually below freezing).

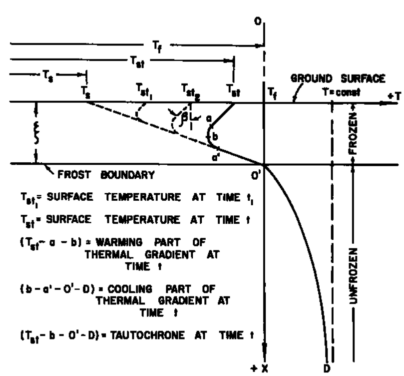

Figure 4. Tautochrone during liberation of latent heat.

Thermal Properties.—The processes of heat absorption by radiation and heat transmission by conduction of soil and pavement depend on the surface properties, heat capacities, thermal conductivities, and densities, of the materials. These influence (a) the storage of heat in water, soil, and pavement; (b) the dissipation into the surroundings of the latent heat liberated upon cooling and freezing of the rain droplets; (c) the temperature regime in pavement and/or soil; and (d) the heat absorption by radiation.

Analytical Treatment

Let it be assumed that the cold temperature distribution at a certain time below the pavement or ground surface within the frozen zone is linear—that is, dT/dx (Fig. 3), where $dT = T_f - T_s$ is the temperature difference between the freezing (273 K = 0 C) and surface temperatures, respectively, and x is the depth below the ground or pavement surface (Fig. 3). (The Kelvin temperature system is used in the figures.) Also, it is assumed that there is no lateral heat flow or horizontal tem-

perature difference. Upon freezing, the liberated q_L (=80 cal) of latent heat are transmitted by conduction into the soil.

Amount of Latent Heat

The amount of latent heat liberated during the time of rainfall, dt, at an intensity of h_r cm/sec through 1 sq cm of surface area is $q_L \ \gamma_w \ h_r$ dt cal per sq cm, where q_L is the latent heat (=80 cal per g), and γ_w is the unit weight of water, in g per cc. It is understood that part of the liberated heat is dissipated into air. It is difficult, however, to ascertain in what proportion heat dissipates into the air and into the ground. However, for reasons of simplicity, it is assumed, as previously mentioned, that all of the liberated heat is conducted into the pavement or soil. Because the thermal conductivity of air is approximately 1,000 times smaller than that of a certain frozen soil (that is, K_s/K_{fs} = 0.000055/0.055 = 1/1000), the assumption that practically all of the liberated heat can be assumed to be conducted to the ground seems to be reasonably correct.

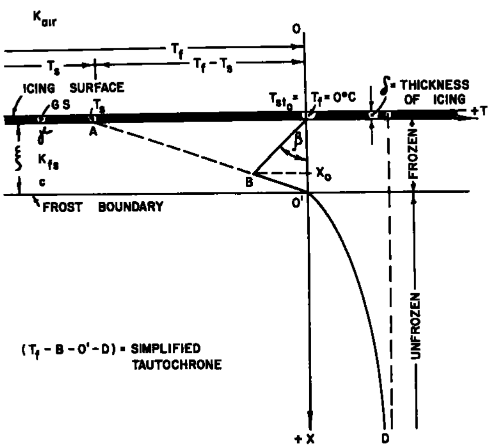

Figure 5. Simplified tautochrone at time t_0 when the surface temperature is 0 C.

The amount of heat conducted into the ground or pavement is

$$K \frac{\partial T}{\partial x} \, dt = q_L \ \gamma_w \ h_r \ dt \qquad (1)$$

in which

K = coefficient of thermal conductivity of the frozen ground or pavement, in cal per cm per sec per deg C;
x = depth coordinate;
dt = time differential; and
$\frac{\partial T}{\partial x}$ = temperature gradient at any point at time t = const. Here the partial derivative $\partial T/\partial x$ is chosen instead of dT/dx to indicate that the temperature T varies not only with depth x below the surface but also with time.

Warming Gradient

During the period when the pavement is being warmed up by the liberated latent heat the temperature gradient within the frozen zone below the surface bends around and moves towards the freezing point of temperature, T_f = 273 K (= 0 C) at the surface (Fig. 4). Ruckli (4) suggests replacing the curved part (a-b-a') of the bend of the temperature gradient in the frozen zone by a straight line (Fig. 5). Then from Fig. 5 and Eq. 1, for a uniform rate of warming of the frozen zone from the surface downwards, the thermal gradient is

$$\frac{\partial T}{\partial x} = \tan \beta = \frac{q_L \ \gamma_w \, h_r}{K} \qquad (2)$$

Time to Freeze the Fallen Rain

The time t_0 to freeze the rain can be calculated from the heat balance:

$$\left\{ \begin{array}{l} \text{Latent heat liberated during time} \\ t_0 \text{ of the fallen rain droplets} \end{array} \right\} = \left\{ \begin{array}{l} \text{Heat received by the warmed zone} \\ \text{during same time } t_0 \end{array} \right\}$$

or

$$q_L \ \gamma_w \ h_r \, t_0 = c \ \gamma \, x_0 \, \frac{(T_f - T_s)}{2} \qquad (3)$$

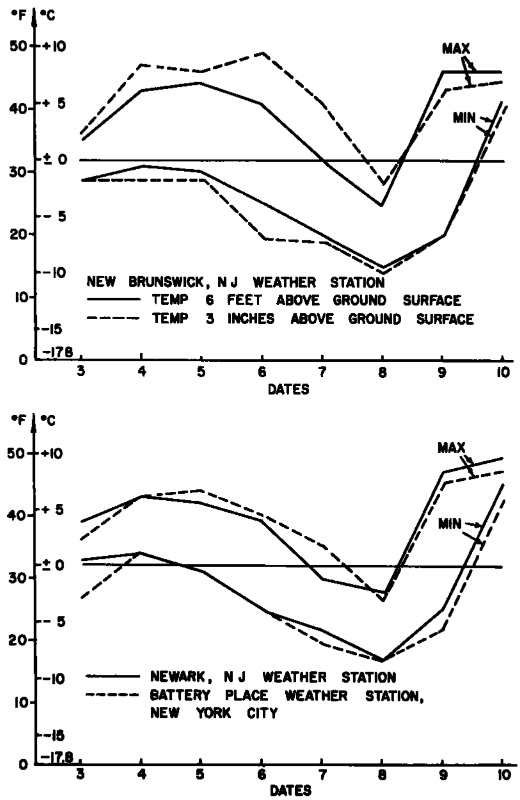

Figure 6. Maximum and minimum air temperatures, metropolitan New York area, January 3-10, 1956.

With

$$x_0 = \frac{\xi}{1 + \xi \dfrac{\tan \beta}{(T_f - T_s)}} \qquad (4)$$

(refer to Fig. 5 and (4))

$$t_0 = \frac{c\ \gamma\ (T_f - T_s)}{2\ \gamma_w\ q_L\ h_r}\ x_0 \qquad (5)$$

in which

c = specific heat;
ξ = frost penetration depth in cm;
γ = unit weight of the soil or pavement material in g per cc; and
x_0 = depth coordinate when the warming tautochrone at its upper end passes through the 0 C-point.

Thickness of Icing

During such time t_0 all of the rainwater is frozen, and the icing has grown to a

$$\delta = 1.09\ h_r\ t_0 \text{ cm} \qquad (6)$$

thickness of hard and slippery ice. Because, from observation, icing forms rapidly, it can be assumed that the runoff coefficient is unity. The coefficient 1.09 takes care of the expansion of ice by 9 percent.

After all of the rain droplets have frozen on the surface the warmed zone gradually cools again and under still-prevailing freezing air temperatures the surface temperature drops. The frozen condition and icing remain until the meteorological conditions change for the warmer.

ICING IN THE METROPOLITAN NEW YORK AREA, JANUARY 8-9, 1956

Temperature Records

Records (5) for the area and time indicated show that after a period with temperatures above freezing on January 5, the air temperatures during January 6, 7 and 8 dropped to below freezing, reaching their low in the forenoon of January 8 when the temperature readings at several weather record stations were 15 F to 18 F. The course of the air temperature regime can be followed from Tables 1 and 2 and Figures 6, 7 and 8.

On January 8, glaze began at 8:20 p.m. and ended at 6:15 p.m. on the 9th.

The variations of air temperatures and soil temperatures are shown in Figures 6, 7, and 8. Soil temperatures (6) are given in Table 2.

Soil Properties

Some of the properties of the Nixon loam soil used for this study are as follows:

Depth Below Surface (in.)	Composition (%)			Void Ratio, e	Unit Weight	
	Sand	Silt	Clay		(pcf)	(g/cc)
0.8	38	40	22	-	-	-
8-12	30	44	26	-	-	-
12-32	28	44	28	-	-	-
	-	-	-	0.71	96.14	1.54

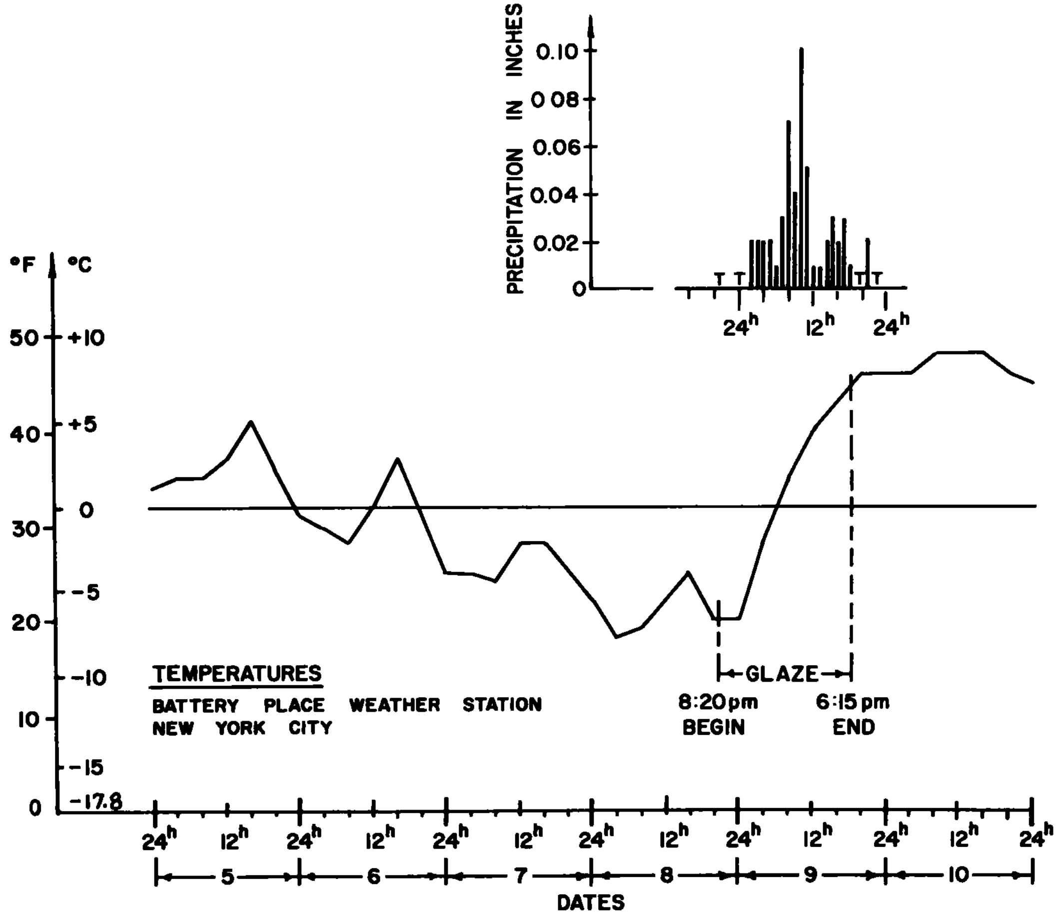

Figure 7. Hourly air temperatures, metropolitan New York area, January 5-10, 1956.

Tautochrone Movement

From Figure 8 it can be seen that on January 8, during freezing of the rainwater on the surface, the soil tautochrone had moved to the warm side of the vertical line 0 - 0'; that is, from position No. 1 to position No. 2. Then, about midnight, the tautochrone moved back to the cold side (position No. 3), and during the next day (January 9) moved into position No. 4; that is, because of the rise in air temperature, icing was over.

Hitherto not many serious attempts have been made to obtain the pertinent data on

TABLE 1

HOURLY AIR TEMPERATURES[1] AND PRECIPITATION[2] IN THE GENERAL NEW YORK METROPOLITAN AREA
JANUARY 5-10, 1956

REPORTING WEATHER STATION	Date, Jan. 1956	2	4	6	8	10	12	2	4	6	8	10	12
			a.m.				noon		p.m.				
U.S. Dept of Commerce													
(5)	5	36	36	34	35	39	42	44	42	37	35	33	31
NEWARK, N.J.	6	30	29	29	30	34	38	39	36	32	29	27	25
(Newark Airport)	7	24	25	25	26	27	31	32	30	27	26	23	20
Ground Elevation: 11 ft	8	18	18	18	18	21	24	27	26	20	19	19	23
Freezing drizzle and rain fell during the evening of												T 0.01/T	
Jan. 8, continued over night,	9	28	31	35	39	41	43	44	44	44	44	45	45
ended following morning, causing slippery roads in	Prec.	T	T	T/0.01	0.01/0.01	T/0.01	0.01/0.01	T	0.01/—	T/T	0.01/T	T/—	
New York area	10	46	46	45	46	46	46	46	47	45	44	43	43
Rutgers University	5	35	35	34.5	33	32	41.5	43.5	41	35	33.5	32	31
College of Agriculture	6	29	28.5	28	29	37	38	40	36	31	28	26	24
Dept. of Meteorology	7	23	24	25.5	25	33	24	32	30	28	26	23.5	20
NEW BRUSNWICK, N.J.	8	17	15	16	16	19	22.5	24	22.5	18.5	18	18	20
(College Farm)	9	25.5	29	33.5	36	39	41	43	43	44	43	46	45.5
Ground Elevation 80 ft	10	46	46	45.5	45	46	45	46	45	45	44	43	42
Height of measured temperatures. 4' 6"		Total precipitation on Jan. 8 =0 in. Total precipitation on Jan. 9 =0.08 in.											
U.S. Dept. of Commerce	5	35	35	34	34	36	37	39	41	39	36	33	31
NEW YORK, N.Y.	6	31	30	29	28	29	32	36	37	33	31	29	25
CITY OFFICE	7	25	26	25	24	25	28	28	28	25	25	23	22
(Battery Place)	8	19	18	18	19	19	22	25	25	22	20	17	20
Ground Elevation: 10 ft	Prec.											T/T	T/T
	9	24	28	31	35	37	40	42	43	45	46	46	46
	Prec.	0.02/0.02	0.02/0.02	0.02/0.01	0.03/0.07	0.04/0.10	0.05/0.01	0.01/0.02	0.03/0.02	0.03/0.01	T/T	0.02/T	
	10	46	46	46	48	48	48	48	48	47	46	46	45

[1] In degrees F.
[2] In inches (T =trace). Numerator in precipitation line indicates amount during odd hours; denominator, during even hours.

exact temperatures of surface, air, and rain, and thickness and continuity or discontinuity of the icing process, necessary for a fully scientific approach to this problem.

TABLE 2

MAXIMUM AND MINIMUM SOIL TEMPERATURES AT THE COLLEGE FARM,[1] RUTGERS UNIVERSITY COLLEGE OF AGRICULTURE (6)
JANUARY 5-10, 1956

	Soil Temperature (°F) at Depth Below Ground Surface											
	1 in.		2 in.		4 in.		8 in.		16 in.		32 in.	
Date	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
5	33	32	32	32	32	31	33	32	35	34	38	38
6	33	31	32	31	32	31	33	32	35	34	38	38
7	32	30	32	31	32	31	33	32	35	34	38	38
8	31	28	31	30	31	30	33	32	35	34	38	38
9[2]	33	29	32	30	32	30	33	32	35	34	38	38
10	34	33	32	32	32	32	33	32	35	34	38	38

[1] Soil covered with blue-green turf.
[2] Ground covered with ice, freezing rain.

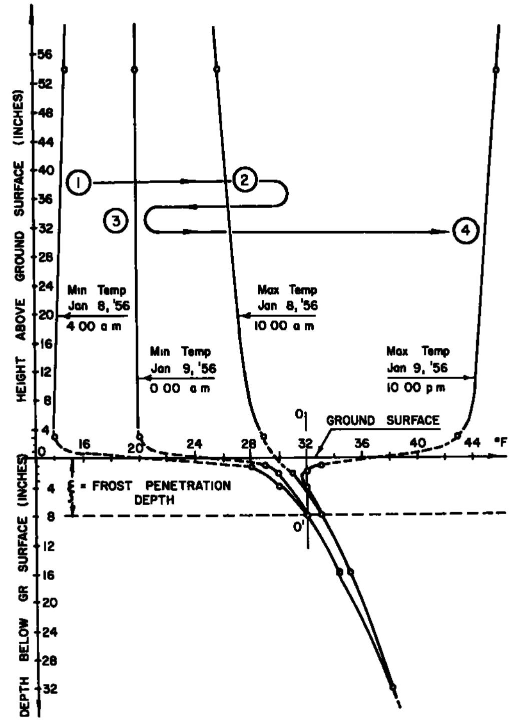

Figure 8. Maximum and minimum tautochrones, January 8-9, 1956.

CALCULATED FREEZING TIME AND THICKNESS OF ICING DURING GLAZE, JANUARY 8-9, 1956

From Figure 8, the surface temperatures on January 8, at 4:00 a.m. were: T_s = 21 F = -6.11 C ≈ 267 K, and T_f = 32 F = 0 C = 273 K. The frost penetration depth at that time, just before or about the time of raining, was 8 in., or 20 cm. The average precipitation at Newark Airport can be assumed to be h_r = 0.01 in. per hr = 0.000007 cm per sec, and at Battery Place (New York City) $h_r \approx$ 0.03 in. per hr = 0.000021 cm per sec.

With a coefficient of thermal conductivity of a frozen soil of K = 0.0075 cal per cm per sec per C, and specific heat of c = 0.20 cal per g per C, the warming thermal gradient, by Eq. 2, is:

$$\frac{\partial T}{\partial x} = \tan\beta = (80)\ (1.0)\ (0.000007)/0.0075 = 0.0746 \text{ C per cm}$$

for h_r = 0.01 in. per hr, and $\tan\beta$ = 0.224 for h_r = 0.03 in. per hr. By Eq. 4 the depth coordinate x_o at time t_o when the surface temperature reaches 0 C is

$$x_o = \frac{20}{1 + 20 \cdot \frac{0.0746}{6}} = 16 \text{ cm} = 6.3 \text{ in.}$$

for h_r = 0.01 in. per hr, and x_o = 11.6 cm. = 4.56 in. for h_r = 0.03 in. per hr.

The time t_o during which the fallen rain freezes is, by Eq. 5,

$$t_o = \frac{(0.20)\ (1.54)\ (6)}{(2)\ (1)\ (80)\ (0.000007)} = 26,400 \text{ sec} = 7 \text{ hr } 20 \text{ min for}$$

h_r = 0.01 in. per hr, and t_o = 6,439.5 sec = 1 hr 47 min for h_r = 0.03 in. per hr, respectively.

By Eq. 6, the thickness of icing is δ = 0.201 cm ≈ 2mm, and δ = 0.147 cm ≈ 1.5mm.

CONCLUSIONS

1. The thermal and meteorological conditions, soil properties, amount of latent heat, and time t_o to warm up the cold pavement to 0 C to freeze the fallen rain, are very significant. The greater the rain intensity, the less is the time t_o, and the thinner the icing.
2. For the purpose of studying the icing problem, surface temperatures should be observed and published, along with air temperatures, by the meteorological stations.
3. More data on thermal and physical properties of pavements and soil are desirable.
4. Official weather records should contain exact data on the beginning and end of icing periods, and rainwater temperature.
5. This study indicates that the rainwater does not freeze almost instantaneously, as indicated at the beginning of this paper, but, depending on the rainfall intensity, takes several hours to freeze.

6. Although highway and airport maintenance crews do everything possible to remedy the treacherous conditions on icy pavements, in many parts of the world icing on pavements still remains a physical-technical problem to be solved in pavement technology and traffic engineering in order to combat icing conditions effectively.

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