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Publisher's version / Version de l'éditeur:

RILEM Symposium on Winter Concreting [Proceedings], 1957-02-01

NATIONAL RESEARCH COUNCIL
CANADA

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BY

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TECHNICAL PAPER NO. 46

OF THE

DIVISION OF BUILDING RESEARCH

REPRINTED FROM RILEM SYMPOSIUM:
WINTER CONCRETING, COPENHAGEN, FEBRUARY 1956.

NRC 3830 OTTAWA PRICE 75 CENTS

FEBRUARY 1957

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RILEM SYMPOSIUM: Winter Concreting

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NATIONAL RESEARCH COUNCIL

Canada.

Session A

General Report

No.8575

WEATHER IN RELATION TO WINTER CONCRETING

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S U M M A R Y

This report deals with the various factors which influence the cooling of concrete exposed to winter weather and with the quantitative methods by which weather data may be applied in practical cases. The overall situation is examined on the basis of the two general problems: the prediction of the environmental conditions to which a concrete mass will be subjected, and the prediction of the resulting conditions throughout that mass.

Cases are cited and the components of the basic heat exchange between the concrete mass and its environment are identified. The elements and factors of climate are considered on the basis of their role in cooling, and winter weather data are assessed. The effects of various local factors on the pertinent weather elements are considered in relation to the cooling of concrete. The use that can be made of statistical weather-data, of forecast information, and of a knowledge of the influence of microclimatic factors is discussed in terms of the size and duration of a job.

The problem of predicting temperatures within the concrete is recognised basically as a heat exchange situation. Heat transmission phenomena are reviewed briefly, and it is noted that convection and radiation can be dealt with by modifications to simple conduction theory, thus greatly simplifying the equations and calculations. A review is given of quantitative methods already developed for purposes of prediction of concrete temperatures.

It is suggested that laboratory investigations are useful primarily in the determination of quantities and coefficients required in calculations, to the study of phenomena, and to assessing the approximations that may be employed.

RÉSUMÉ

Le rapport préparé par l'auteur précité a trait aux divers facteurs qui influencent le refroidissement du béton exposé aux intempéries de l'hiver, ainsi qu'aux méthodes quantitatives servant à appliquer à des cas pratiques les données sur la température. L'auteur axamine l'ensemble de la situation en se basant sur les deux problèmes généraux suivants: a) la prédiction des conditions du milieu auxquelles une masse de béton sera soumise et b) la prédiction des conditions qui en résulteront dans toute la masse.

Monsieur Swenson cite certains cas et identifie des éléments de l'échange calorifique de base qui se produit entre la masse de béton et son ambiance. Il condidère les éléments et les facteurs du climat en se basant sur leur role lors du refroidissement; il évalue aussi les données sur la température d'hiver. L'effet exercé par divers facteurs locaux sur les éléments pertinents de température sont aussi l'objet d'une étude par rapport au refroidissement du béton. L'auteur discute, en outre, en termes de l'étendue et de la durée d'un projet, l'emploi qu'on peut faire des statistiques sur la température, des prédictions et de la connaissance de l'influence des facteurs microclimatériques.

Le problème de la prédiction des températures à l'intérieur du béton est reconnu fondamentalement comme un cas d'échange calorifique. L'auteur examine rapidement les phénomènes de transmission calorifique et note qu'on peut considérer la convection et la radiation comme des modifications de la théorie de conduction simple, ce qui simplifie grandement les équations et les calculs. L'auteur fait une revue des méthodes quantitatives qui ont déjà été mises au point pour prédire les températures du béton.

Il indique que les recherches le laboratoire servent surtout à la détermination des quantités et des coefficients requis pour le calcul, ainsi qu'à l'étude des phénomènes et à l'évaluation des approximations qu'on peut utiliser.

WEATHER IN RELATION TO WINTER CONCRETING

In order to achieve the proper curing environment for fresh concrete it is necessary to employ means of modifying or controlling the effects of weather, regardless of season. Winter concreting poses the special problem of protecting the concrete from the effects of below-freezing temperatures until it has attained the necessary "freezing resistance".

Despite the difficulties involved in winter construction due to low temperatures, snow, short daylight periods and general inconvenience and discomfort, building technology makes year-around construction practical and modern needs make it necessary. The added costs are often balanced by such advantages as the greater availability of materials and labour and the ease of transportation over frozen ground (1). Proper protection of concrete in cold weather can also provide more uniform curing conditions than are often obtained in summer work (2).

The protection required during winter concreting has thus far been selected almost entirely on the basis of rule-of-thumb methods derived from field experience. Weather influence has been considered primarily in terms of atmospheric temperature with little or no regard for other environmental factors. It has only recently been recognized that concrete can harden satisfactorily at relatively low temperatures. It is now realized that protection has often been excessive. The minimum conditions under which acceptable curing is achieved are now being defined, and it is possible to develop quantitative methods for the rational design of protection for fresh concrete placed under winter conditions.

It is the purpose of this paper to examine winter weather conditions and the relationships between them and the thermal and moisture environment of fresh concrete.

II THE BASIC PROBLEM

An excellent example of concreting under extremely severe winter conditions was the construction of a concrete bridge at Saskatoon, Canada, twenty-four years ago. Continuous temperature records in this case illustrate the remarkable retention of heat in mass concrete with relatively little protection, and the positive moderating influence of a water body (3). The concrete in this bridge is in excellent condition today.

This bridge, shown in figure 1, was built under conditions which called for the provision of a maximum of winter employment. The use of machinery was restricted and the concrete had to be wheeled by labourers from the mixers to the piers as far as 1000 feet away, regardless of weather conditions.

Figure 2 shows the temperature recordings in one of the piers, the concrete for which was placed in an excavation when the daily minimum air temperature was as low as -30°F. Only the formwork served as protection up to the ice level of the river. The 25-foot section above ice level was housed and heated. Despite wind speeds of up to 20 m.p.h., the thermometers against the forms never read below 50°F.

The roadway and sidewalk slabs were placed under similar extreme conditions. The sidewalk concrete was protected by hot sand, sawdust, and tarpaper. The roadway concrete was kept above freezing for more than three days by running hot water over it continuously day and night.

Figure 3 shows the temperatures recorded in another pier, in the springing arch section attached to it, and in the roadway slab. The river water, at 32°F, had a remarkable moderating effect on the temperatures in the pier. This effect extended through the arch ring and even to the crown, a hundred feet from the pier and at an elevation of 75 feet above the water line. The temperatures in the road-deck followed the air temperature quite closely, but the "thermally attached" arch ring showed a much lower response to ambient temperatures. A similar but opposite effect was recorded during the hot summer. Although the data shown in figure 3 were obtained in hardened concrete, they serve as a good illustration of the influence which contact with large masses can have, in the case of newly placed concrete, in providing for a flow of heat which may offset in large measure the cooling produced by low air temperatures.

In the case of small concrete structures or elements, the heat stored and the heat generated per cubic foot are the same as in the larger structures. The same phenomena are involved but the reduction in size increases the surfaceto-volume ratio, thus greatly increasing the rate at which temperature changes can take place. Increased protection is required to provide the same curing conditions. The influence of size is illustrated by figure 4. Two concrete cubes, protected only by 2-inch lumber forms, were exposed to freezing conditions, with a thermometer placed at the centre of the face next to the form (4). The face temperature of the 1-foot cube dropped below freezing in $5\frac{1}{2}$ hours, whereas the face temperature of the 3-foot cube remained above 50°F after 36 hours.

The cases just cited show that the temperature conditions within a concrete mass are not alone determined by the external weather conditions, but can be greatly influenced by the effects of scale and of heat exchange with connecting masses. Other important factors are the degree of insulation interposed between the concrete and the weather, and the rate and amount of heat generation within the concrete mass. The prediction of temperatures in the concrete involves recognition of a basic heat exchange situation in which temperatures can change only through changes in the store of heat energy within the mass.

Weather elements can influence the temperature of concrete only insofar as they change the store of internal heat. Their importance and influence are determined by the extent to which they affect the various components of the over-all heat exchange between the concrete mass and its surroundings.

The components of the basic heat exchange between the concrete mass and its environment are shown diagrammatically in figure 5. The store of heat within the concrete is made up of sensible heat in an amount which is reflected directly by the temperature. To this store is added the heat of hydration the rate of release of which is a function of time and temperature for a given mix. The heat exchange with connecting bodies may be either a gain or a loss but, as is the case with all heat flows, can take place only in the direction of decreasing temperatures.

Conduction-convection exchange, which is frequently the most important one, takes place between the concrete mass and the air, and is affected by air temperature and air speed. In winter this will normally be a heat loss. A further component of heat exchange from the surface of the concrete or its enclosure occurs as a net radiation exchange with the sun and sky. When the sun is shining there may be a heat gain regardless of the temperature of the concrete, a heat gain or loss on cloudy days, and a loss on clear nights to the sky. During the daytime there can be diffuse radiation produced by the scattering and reflection of some of the direct radiation coming from the sun by matter in the atmosphere, by the ground, and by surrounding objects. In addition there can be a radiation exchange between the concrete and its surroundings, the direction of which is determined by the respective temperatures.

The component of heat exchange due to change of state of water is the only one shown that does not result in the direct transfer of heat energy. Evaporation occurring on or within the concrete takes up the latent heat of vaporization which is then carried off by the escaping vapour. Conversely, during a condensation process, this latent heat is carried in the vapour and is given up at the condensing surface as heat energy. This component of the heat exchange will be affected by the vapour pressure differences between the concrete and the atmosphere, and by air movement. The evaporation-condensation exchange enters not only into the thermal picture as just discussed, but affects also the moisture store leading to drying, or, in special cases, to wetting, depending on the direction of the driving potential.

Attention has been directed thus far mainly to the exchange of heat between the concrete and its surroundings. There will also be a flow of heat from one part of the concrete to another, according to a pattern determined by the temperatures produced throughout the mass, and by the thermal properties of the concrete itself.

The aspect of winter concreting with which this session is concerned is essentially that of predicting the conditions which the concrete will experience during its curing period, and may be considered in two distinct parts:

(a) prediction of the environmental conditions to which the concrete mass will be subjected, and

(b) prediction of conditions throughout the concrete resulting from a given set of environmental conditions.

Refinement in the selection of protection depends upon the accuracy with which the conditions, which the concrete is likely to experience, can be predicted in advance of the curing period. This will involve an attempt to predict weather conditions since other environmental factors will be known or can be determined.

III GENERAL CHARACTERISTICS OF WINTER WEATHER

1. The Nature of Weather

Weather and climate are determined primarily by the heat balance between the atmosphere and the surface of the earth, and all changes that occur in weather can be traced to the single physical factor: heat (5). The earth acts as a heat reservoir and its surface is an intermediary in all heat transactions between it and the atmosphere.

Radiation is the primary process governing the warming and the cooling of the earth's surface. In summer the surface gains heat from solar radiation by day and loses heat by outgoing radiation at night, the amount varying with the type of surface. In winter, the incoming radiation is reduced by day owing to the reduced angle of incidende of the sun's rays, their longer path through atmosphere, and the shorter period of sunlight. The amount of incoming radiation reaching the earth may be reduced to a small quantity through reflection by clouds. The actual amount absorbed may be reduced substantially by snow cover. On a winter night the outgoing radiation is also small due to the reduced temperature of the earth's surface from which the heat must be drawn. Under conditions leading to a net loss outward the ground surface temperature may be reduced below that of the adjacent air and the soil layers.

The most important observed and measured physical properties of weather are air temperature, wind, vapour content, air pressure, state of sky, and precipitation. These are the fluctuating components of weather and climate. The relatively static influences on large-scale weather are the geographical factors such as latitude, altitude, land and water distribution, vegetation, and nature of the soil.

The characteristics of weather and climate may be defined by the individual elements as they vary with time of day, seasin, and place. Certain properties are more usefully described by calculated values involving combinations of one or more of the simple elements. These are referred to as combined elements, examples being: relative humidity, equivalent temperature, cooling power and drying power. Special characteristics such as variability, frequency and probability are called derived elements and are obtained from statistical analyses of weather data.

The recording of weather data is usually carried out under "undisturbed conditions", well above the surface of the ground, in order to describe conditions over a large region. Local influences are, therefore, largely eliminated. The physical condition of the atmosphere, described by these data, at a given time and place, constitutes the weather. The average state of the atmosphere in a given region, as reflected by the average of data extending over many years, constitutes the climate of that region.

2. Winter Weather Characteristics and Data

(a) Temperatures. - The most important weather element in winter concreting is temperature. The daily and annual temperature variations follow closely the changes on the earth's surface which are, in turn, determined by the heat exchange processes already mentioned. Despite the lower degree of radiation heat exchange in winter, its influence is still marked. This is illustrated in figure 6 in which the temperature amplitude is shown to decrease considerably with the occurrence of clouds which reflect and absorb both incoming and outgoing radiation (5). Temperature amplitude is also affected by latitude, altitude, and nearness to large bodies of water.

Of particular concern in winter concrete work are minimum temperatures. The monthly averages of daily minimum temperatures indicate only generally the severity of winter conditions.

Such data may be inadequate since the variation from mean values may be very great. Examples of such variations are given in Table I.

The lowest temperature on record for the thirty-year period for the month of December, for example, differs by 48°F from the mean daily minimum, and by 21°F from the mean monthly minimum. Such large deviations are not unusual, particularly in continental-type climates.

Another important characteristic of winter temperatures is the rate and degree of temperature change. The amplitudes shown by daily marches of temperature are based on average values and again deviations may be very great. Cases of very rapid temperature changes occur just east of the Rocky Mountains in Western Canada where the severe continental winter weather is frequently modified by warm Chinook ("foehn") winds descending eastward over the mountains to the plains. Temperature rises of 40°F in 15 minutes are not unusual, and in extreme cases the thermometer has been known to rise 30°F in three minutes (6). Temperature drops, although less rapid, can be almost as marked. Such weather phenomena are often associated with high altitudes and certain inland regions. On the other hand, sudden changes from "cold spells" to "warm spells" are more often associated with the time of year in certain areas.

Duration and frequency of below-freezing temperatures, and "threshold" dates showing the probable first occurrence of frost, are of special interest in winter concreting. Figure 7 shows the march of minimum temperatures for the month of October in Montreal based on records from 1874 to 1954 (7). The average minimum temperature remains above 32°F for the whole month, but the low minimum falls below the freezing point for most of this period. The probability when frost might first be expected is October 3rd, and a drop in temperature below 25°F is not to be expected until October 17th. Weather records also provide data from which the frequency of "frost-days" and the duration of frost-free periods can be calculated.

(b) Wind. - The important characteristics of wind are speed and direction, both of which may show great variability, and both of which are directly connected with changes in weather. Most weather station data show a fairly regular daily variation in direction. At high altitudes, or near large bodies of water, this may occur as one prevailing wind during the day and an opposite one at night. In mountainous regions a regular cycle of two opposing winds, one downhill and one uphill, can result from effects of solar radiation. The direction of a prevailing wind may vary considerably through the influence of such factors as local topography.

Variations from mean wind speeds may be very great, as illustrated in Table II.

The variation from month to month is very small but the difference between the mean and the maximum for each of the winter months is very great.

(c) Low Temperatures and High Winds. - The severity of winter weather, from the point of view of cooling, is greatly accentuated by the simultaneous occurrence of high winds and low temperatures. It becomes necessary, therefore, to consider particular values of wind speed with various temperatures. Such data are not available from independent records of temperature and wind, and can only be obtained from records obtained simultaneously in point of time. Such combinations of data, although required for certain purposes, particularly for establishing cooling effects, are obtained from normal weather records through rather laborious analyses. Such an analysis was made to compare the severity of winter weather in two Canadian cities, Churchill and Saskatoon. In figure 8 is plotted the average frequency distribution of winds at various speeds for 10°F temperature range for these two localities, based on the period indicated. It can be seen that at Saskatoon practically all the wind speed occurrences during December, January and February fall in the range 0 to 19 m.p.h., the wind speed average being 10.7 m.p.h. At Churchill the occurrences are spread over 0 to 34 m.p.h., the average for the same period being 14.7 m.p.h. It is to be noted that the frequency of wind speed occurrence is greater at low temperatures for Churchill than for Saskatoon. It is therefore evident that there is a much greater probability of the simultaneous occurrence of high winds and low temperatures at Churchill than at Saskatoon.

(d) Other Elements. - Humidity, cloudiness, and precipitation are generally of secondary importance to the winter environment of concrete. Snow cover, however, tends to accentuate extremes of temperature by radiating strongly at night and reflecting incoming radiation strongly during the day. This property of snow also tends to prolong low temperatures in early spring. Snow cover decreases depth of frost penetration but, except in continental climes, variability in amount and distribution is so great that prediction is difficult. The duration of snow cover and frequency of snowfall are, however, significant factors. The moderating effect of cloudiness, mentioned before, may warrant the use of data on duration and frequency of sunshine during winter months.

3. Combined Elements

Only a few combined elements have been developed on a quantitative basis. An example of a useful combined element is relative humidity. Others of interest in certain connections are cooling power and drying power. Formulae for these combined elements for particular situations are reviewed by Conrad and Pollak (8) and Landsberg (5).

Such equations are of interest because they illustrate how two or more individual elements may be combined to produce a single value for use in place of the original elements in determining a heating or cooling rate for a specific set of circumstances taken into account in the equation. They must not, however, be applied to situations other than those for which they are intended.

Certain instruments such as the Kata-Thermometer and the Davos Frigorimeter (5), measure cooling powers useful in certain specific applications which are defined by the characteristics of instruments constructed in a standard way. Similar instruments might be used on a continuous record basis to provide a single stream of data, thus avoiding the laborious procedure required in combining several individual elements through an equation.

The formulae for cooling power are, in effect, expressions for the rate of heat loss under a particular set of circumstances, the included weather elements alone being considered as varying. A substantial number of variables other than weather elements can also affect the rate of heat loss from a concrete mass and must be taken into account. Each combination of these elements would require a separate cooling power equation and the value of combining the weather elements into a single expression no longer serves a useful purpose for the general case. It becomes more convenient to introduce the selected values of the weather elements into the heat flow equations. A similar situation exists with respect to the application of drying power equations. Unlike heat flow, however, satisfactory equations for moisture flow for the general case have yet to be developed.

IV MICROCLIMATIC AND OTHER ENVIRONMENTAL INFLUENCES

1. General Features of Small-scale Climate

The weather data obtained from meteorological observations under "undisturbed conditions" are valid only for large-scale climate. They do not represent the actual conditions near the ground or near some local body or structure which may exert a considerably modifying influence on the weather elements. The equalizing influences that operate in the upper atmosphere diminish progressively with increasing proximity to the ground. Near the ground the air layer is a zone of disturbances and variations due to such variable factors as vegetation, soil conditions, topography, and buildings.

The dimensions and range of small-scale climate are determined by the particular environmental situation. Geiger (9) considers the air layer up to two metres above the ground surface as the zone that is influenced by variations of the ground and other surroundings, and refers to this environment as the microclimate. In this zone a particular object, such as a mass of concrete, is conditioned by this environment which may differ substantially from the undisturbed weather. The more familiar terms "local", "urban" (10) and "spot" climates (5) are commonly employed for specific areas affected principally by peculiarities of topography, trees, water bodies, and groups of buildings (10). "Site" climate is used to describe the environment at as building site where the additional factors of size, shape, and nearness of buildings exert a special influence on weather (5).

A significant feature of small scale climate is the great variation that can exist in a relatively small area. An illustration of this is the frequently quoted example of winter temperature differences in Toronto shown in figure 9 (11). The topographic and temperature profiles show the gradual decrease of temperature with distance from the lake shore, and the remarkable temperature "low" in the valley seven miles away, the difference between this temperature and the lakeshore temperature being 30°F.

2. Characteristics of Microclimate

Temperature, more than any other climatic element, reacts sensitively to the natural setting. Nest to it wind speed is subject to very large microclimatic variations (12). The ground surface warms through incoming radiation and cools by outgoing radiation at night. The air layer next to the ground, as a result of radiation gains and losses at the surface, shows a greater temperature amplitude than the higher layers of air. Temperatures taken at the top of a weather station tower may, therefore, be considerably higher at night than those near the ground surface, and correspondingly lower during the day.

When conditions are such as to produce a net loss of heat by radiation from the ground surface, a situation which occurs on a clear winter night, the air layer next to the ground becomes a stable layer owing to the greater density of colder air. This accounts for the frequent lowering of wind speed with decreasing temperature in winter. The stability of this stratification is disturbed by any warming process through the initiation of convection. Even during cooling some mixing occurs through so-called "coldness convection" caused by the descent of cooled air and dust particles (9). The occurrence of wind destroys the stratification and the resultant mixing raises the ground surface temperature. Air stratification leads to the occurrence of "cold air dams" and "frost holes" where temperatures may be very considerably below the normal air temperatures.

In the cooling process air convection or wind operates in two ways. As previously mentioned it tends to destroy stratification and thereby reduces the hazard of frost. However, wind increases the heat transfer rate from a surface to the adjacent air, thus increasing the cooling rate for a given temperature.

3. Intensification of Frost

Freezing temperatures become more extreme on a microclimatic scale as a result of a number of factors (9). A clear sky on a winter night favours outward radiation and results in lower surface temperatures. A reduction of the moisture content has the same effect since water vapour increases the counter-radiation of the atmosphere at night. Still air fosters air stratification with the coldest air next to the horizontal surface. Poor heat conductivity of the soil prevents daytime storage of heat and retards heat flow to the surface during cooling. Rapid cooling due to strong evaporation is a contributory factor. Cold air floods due to local advection, as mentioned earlier, are also factors in intensification of frost. The absence of natural protection afforded by vegetation also contributes to lower ground surface temperatures.

4. Site Climate

On a winter concreting job the environmental factors are the natural topography and vegetation and the man-made structures and excavations. A clearing in a forested area or a site surrounded by buildings in a city is provided with a wind break. Heated buildings provide heat which may prevent excessively low temperatures on a cold winter night. They also supply heat to the ground. The pollution of air over a city is also a modifying influence through counter-radiation effects.

The clearing of snow cover tends to intensify extremes of surface temperatures, whether ground, rock, or other material. The general activities on a job site may contribute to the modification of weather conditions. Buildings and clearings may, through unfavourable orientation, accentuate wind speed, or may act as "cold air dams". Excavations become "frost holes" if left exposed for some time, but if fresh, may exert a moderating influence on the change in temperature of a material placed in contact with it. Gullies and ravines may drain away cold air or build up cold air dams, depending on orientation. In general, convex surfaces have a moderate microclimate and concave surfaces have an extreme one in winter.

5. Ground and Rock Temperatures

The thermal conductivity and the heat storage properties of soil and exposed rock are frequently of importance to winter concrete work (13). Concrete may be placed directly in an excavation or on rock, and may either gain or lose heat depending on the relative temperatures. It is common practice to warm such surfaces before placing concrete on them in cold weather.

Even in extreme winter climates the frost penetration is usually limited to a few feet. Figure 10 shows soil temperatures at various depths during a cold winter in Western Canada (14). Despite the very low air temperatures, the depth of frost penetration is only 6 feet. A covering of vegetation, snow or straw will appreciably lower the depth of frost penetration (15).

Figure 11 shows air and rock temperatures during February, March and April at a job site in Eastern Canada. The rock was kept bare of overburden and snow for a 5-foot radius (4). Although air temperatures were fairly low, frost penetration was limited to less than 3 feet.

Cases where ground temperatures are of importance in winter concrete work are perhaps limited. They are, however, not restricted to cases of direct contact or embedment in the ground, but may be of importance in situations where heat exchange may take place with the ground through an intermediate body or structure.

V HEAT FLOW WITH SPECIAL REFERENCE TO COOLING CONCRETE

Once the conditions of exposure of a cooling concrete mass have been established, which is the first half of the problem of predicting conditions within the concrete, there remains the problem of analysing the heat flow condition which will be produced by any given situation. Once it is possible to predict the result of any given situation, the selection of some form of protection, or the determination of the modifications to the conditions which will lead to a desired result, can follow readily.

1. Heat Transfer by Conduction

Heat flow within a concrete mass can be assumed to take place entirely by conduction. The one possible exception to this is the transfer of latent heat carried by vapour diffusing within the concrete mass. Heat flow by conduction is always assumed to follow a simple flow law as stated by Fourier:

$$q = - k \frac{dt}{dx}$$

where, in English units,

q = Btu per sq. ft. per hr.
t = temperature in ^oF.
x = distance in the direction of flow, ft.
k = coefficient of conductivity.
$\frac{dt}{dx}$ = temperature gradient

This simple equation, when integrated for the simple case of a steady-state flow in one direction, leads to the equation:

$$q = \frac{k}{L} (t_1 - t_2),$$

giving the flow rate in Btu per square foot per hour through L feet of material having a coefficient of conductivity k and with temperatures t_1 and t_2 maintained on either side.

The case of a combination of plane slabs of different materials through which the heat must flow in a normal direction, i.e., through the materials in series, can be handled readily by the adoption of the resistance concept. The conductances of each of a number of layers is given by $\frac{k_1}{L_1}$, $\frac{k_2}{L_2}$ ------, and their respective resistances by the reciprocals of these conductances.
The equation for n layers becomes

$$q = C\ (t_1 - t_2),$$

where

C = conductance of the combination, and

$$1/C = \text{resistance of the combination}$$
$$= \frac{L_1}{k_1} + \frac{L_2}{k_2} \text{ --------- } + \frac{L_n}{k_n}$$

The steady-state equation is used extensively in the calculation of heat transfer through building sections. There are extensive data on the coefficients for various materials. The only major complication in such calculations, when dealing with steady-state conduction in one dimension in solids, is that created by the presence of moisture. Most of the coefficients available have been determined for dry materials. Coefficients are quoted for some wet materials on the assumption that the role of moisture can be accounted for simply by the use of an increased coefficient in the conduction equation. This may lead to serious error if the temperature gradient gives to a migration of moisture through a process of evaporation and condensation within the material. This more complicated situation is only now being well recognized, and has not yet been reduced to a working basis for calculation. Much attention has been paid to the role of moisture in heat transmission by Cammerer (16) Johansson (17), and others.

The added mechanism of latent heat transfer is unlikely to be important in wet, setting concrete, but may play an important role in the heat transfer through materials used as formwork, or as insulating or protective covering, which are likely to contain moisture. This mechanism need not be considered further, beyond recognizing it as a complication, and that it is still a matter for research.

2. Heat Transfer by Convection and Radiation

The additional mechanisms of heat transfer, convection and radiation, operate along with conduction in most cases.

This combined situation exists at an air boundary or across an air space or an air cell within a material or combination of materials. There usually exists a temperature gradient within the surface air film which, because of the difference in density created, leads to a circulation of the air which then acts as a transport mechanism for heat. Meanwhile, some conduction also occurs from one air layer to the next. When occurring naturally over surfaces in a still air field, in which the air motion is produced solely by the influence of the surface temperature, this mechanism is known as free convection and is expressed by an equation of the form:

$$q_c = b(t_a - t_s)^{5/4},$$

where

q_c = Btu per sq. ft. per hr.,
b = constant for any given arrangement,
t_a = air temperature in undisturbed air,
t_s = surface temperature.

This heat transfer may be expressed by an equivalent conduction equation form:

$$q_c = h_c(t_a - t_s),$$

where

$$h_c = b(t_a - t_s)^{1/4}.$$

The heat exchange occurring by radiation between a body surface and another surface at a different temperature is given by the Stefan-Boltzmann equation:

$$q_r = \sigma F(T_1^4 - T_2^4),$$

where

σ = constant
F = factor introduced to account for the geometric relationship between the two surfaces exchanging radiant energy, and for the effects of the deviation of the surfaces from black-body conditions.

T_1 and T_2 are the absolute temperatures of the two surfaces exchanging energy.

This may also be reduced to the form of a conductance equation.

$$q_r = h_r (T_1 - T_2)$$

where

$$h_r = \sigma F(T_1^2 + T_2^2)(T_1 + T_2).$$

3. Combined Film Coefficients

The heat transfer by conduction-convection and by radiation at the air boundary of a body can be handled by a simple coefficient $h = h_c + h_r$ which, when multiplied by the air-to-surface temperature difference, gives the heat transfer rate. This is rational if the temperature of the external radiating surface, T_2, is equal to air temperature. The coefficients h_c and h_r are not true coefficients since they are functions of temperature, but they, or their sum, can be assigned constant values for certain ranges of conditions with little loss in precision.

A value of 2.0 is commonly assigned to the conductance of a surface for still air conditions at exterior building surfaces, and with surrounding bodies at air temperature. Under similar conditions, but with wind which produces a "forced convection" at the surface, in combination with radiation exchange, the surface conductance is given approximately by the relationship

$$h = 2 + 0.4V$$

where

V = wind speed in m.p.h. (18).

The marked effect of wind in increasing the conductance may be noted, a 20 m.p.h. wind increasing the effective conductance from 2 to 10.

Evaporation from a wet surface can result in an increased transfer of heat as a result of water taking up the latent heat of vaporization as it is evaporated. This is the action which produces the lowered temperature when a thermometer is fitted with a wetted wick around the bulb. Little has been done as yet in the development of a rational basis for calculation of heat transfer from wetted surfaces.

The reduction of convection and radiation to equivalent conductances becomes a great convenience in many problems since the over-all heat transfer can be treated as a conduction throughout. Such a reduction is usually readily accomplished when the radiation exchange is with surrounding bodies, but the combined mechanisms become much more difficult to handle when the radiation exchange is with the sky. Solutions by trial-and-error are possible but are in many cases not practical. It is necessary in using them to assume a surface temperature, then to calculate the heat exchanges between the surface at that temperature and the air and sky, and to check this with the heat flow in the body to the surface, correcting the assumed surface temperature until a balance is obtained. This procedure becomes unpractical when the heat flow is transient or periodic.

One device developed in building work is that of sol-air temperature. It is defined as the temperature of the outdoor air, which in the absence of all radiation exchanges, would give the same rate of heat entry into the surface as would exist with the actual combination of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings, and the convective heat exchange with the outdoor air (19). The combination of the solar radiation gain with the conduction-convection at the surface is thus dealt with as a conductance, using sol-air temperature in place of outdoor temperature in the calculations.

4. Cooling of a Concrete Mass

Within the concrete mass, together with its formwork and protective cover, the heat transfer can be dealt with as a conduction. Any air spaces existing within this arrangement can readily be assigned appropriate conductances as is done for air spaces in building constructions. The actual situation, however, may be far from simple. Complications are introduced by the transient nature of the flow, by the production of heat of hydration within the mass, and by the three-dimensional flow which will exist in most cases. While the differential equations for conduction for the general case can be set up, solutions can be found readily for only a limited number of cases, notably the simpler cases in two and three dimensions, such as those involving pipes and spheres. Many cases of two-dimensional steady-state flow can be dealt with by relaxation methods.

In the case of transient and periodic flow, solutions are available for a number of the simpler cases involving flow in one dimension. The case of a slab of a single material at one temperature with one or both plane surfaces suddenly changed to, and held at, some other temperature, can be solved. Solutions are available also, and have been reduced to chart form, for the case of slabs of uniform material at one temperature suddenly immersed in a fluid at some other temperature. This brings in fluid film resistance. This method can be applied to brick-shaped objects by combining the results found for three slabs of thicknesses equal to the length, width and depth, or to a column of rectangular section by considering two equivalent slabs. The cases in which the temperatures of the solid surfaces are not held constant, and are not determined by immersion in a constant temperature fluid but follow some other pattern, and those in which the slab is a compound of one of several materials having different properties, can best be dealt by a graphical method developed by Schmidt. All of these methods can be found in standard textbooks providing comprehensive treatment of heat transfer, such as that of McAdams (20).

Cases in concreting will usually involve both surface heat exchange conditions and at least one other material used as formwork or cover, in addition to the concrete. Under certain conditions, simplifying assumptions enable solutions to be found. In the case of a plane concrete wall between forms, for example, the formwork may, under certain limited conditions, be reduced for purposes of calculation to an equivalent added thickness of concrete. Under certain other conditions, when the heat storage capacity of the formwork or other cover is small, it may be considered along with the air film resistance in an equivalent fluid film, and the "fluid immersion" solution used.

Still another type of simplification may be possible in the case of heavily insulated bodies, when the conductivity of the body is relatively so great that the temperature differences throughout the body are never great, under the reduced heat flow permitted by the cover. Under these conditions, and neglecting heat storage in the cover, a fairly simple transient solution is possible.

The coefficients of conductivity for the elements of the enclosure and for the concrete must be known. When both heat storage capacity and flow in a material must be taken into account, the coefficient, thermal diffusivity, given by $\frac{k}{\rho C_p}$ must be known. This coefficient expresses the ratio of conductivity to thermal capacity. Conductivity data for most building materials, of the type which might be used for formwork or insulation, are reasonably well established, although the presence of water may be a complicating factor as previously mentioned.

Heat generated by hydration within the concrete adds to the internal heat available to make up the heat lost from the mass. The rate at which it is released depends however upon the rate of hydration of the cement, which is in turn a function of temperature for a given mix. The total heat released up to the development of a given degree of hydration can be determined but the introduction of heat release as a function of time and temperature may be difficult if not impossible to handle in the general case.

The heat of hydration can however be dealt with relatively easily in the case of a heavily insulated mass in which no account need be taken of differences in temperature throughout the mass.

5. Quantitative Methods Reported

(a) Early Studies of Yoshida. - The first major contribution to a quantitative approach appears to be that of Yoshida in 1920 (21). He carried out experiments to determine the thermal constants for various mixes of concrete and on the rate of cooling under various exposure conditions. Mathematical formulae were developed to predict the temperature at any point in the concrete mass at a given time after placing, and under a given set of exposure conditions. These formulae were then used to predict the temperature-time relationships for various sizes and shapes of newly placed concrete with some surface protection. The heat generated by the hydration of the cement was neglected in very small masses and was assumed to be accounted for in the diffusivity term of the concrete for larger masses. This assumption does not appear entirely sound since the effect of heat generation more properly enters into the equations as a temperature.

(b) Method of Tuthill, Glover, Spencer, and Bierce. - The method used by Tuthill et al (22) for predicting temperatures in insulated concrete masses after placing involves essentially solutions to the case of a solid at one temperature immersed in a fluid at some lower temperature. The solutions are obtained from the available charts given for this case. The effect of heat generation was handled by a stepwise computation, utilizing the fact that solutions of this nature obey the law of superposition. The method provided for dealing with two- and three-dimentional flow and with varying outside temperatures. These workers also devised methods for predicting the surface temperature of thin slabs placed on soil. The thickness of concrete was replaced by an equivalent thickness of soil and the combination treated as a semi-infinite solid. The heat supplied by the initial placing temperature excess above the surroundings, the heat generation in the concrete and the heat supplied to the surface by the initial soil temperature gradient were assumed to be applied at the surface below the insulation. Again a stepwise computation was necessary to account for changing rates of heat generation and changing air temperatures. Using this method the protection required for concrete work can be calculated without any undue amount of labour. More extensive data on heat generation as a time-temperature function would perhaps permit greater accuracy.

(c) Method of Nerenst, Rastrup and Idorn. - These authors (23) have developed methods by which the temperature of cooling concrete may be predicted, as well as the state of hydration of the cement. The state of hydration indicates the strength attained by the hardening concrete which in turn indicates the resistance to freezing and whether the forms may be stripped.

The calculation of the temperature generally follows the principle that sufficient insulation is applied so that no large temperature gradients occur in the concrete mass. A heat balance can then be written by equating the heat loss from the concrete through the insulation to the heat generated minus the heat stored by heating the concrete. The temperature change during short time intervals can then be calculated and the temperature at any time can be ascertained. Quite extensive data have been obtained for the heat generation rates for three Danish cements at various temperatures. The heat generation rate to be used for each time interval is then taken as that corresponding to the temperature at the end of the preceding interval. To facilitate the computations, cooling factors have been calculated for various shapes. This cooling factor (total heat transfer at the concrete surface per degree temperature difference, divided by the thermal capacity of the concrete element) expresses the rate at which the element will cool with unit temperature difference between the concrete and air. For a given cement type and content, a given initial temperature, a given cooling factor, and a given outside temperature, the time-temperature relationship can be established. The hydration time at the actual concrete temperature is referred to an equivalent hydration time at either $0^{o}C$. or $15^{o}C$. The strength-versus-hydration times have been determined for these temperatures so that the estimation of strength and freezing resistance is thus simplified.

Graphs have been prepared for three cements, three placing temperatures, and three outside air temperatures showing, for any given cooling factor, the time passing before the concrete reaches $0^{o}C$., the equivalent hydration time at $0^{o}C$. and $15^{o}C$., whether freezing resistance has been attained, the percentage of the 28-day strength, and whether or not the forms may be stripped. The authors also indicate that, by measuring temperatures in hardening concrete, the equivalent hydration time can be calculated to indicate the concrete properties.

The quantitative approach developed by these authors represents at once a refinement and a simplification which permits direct application to field work.

6. Typical Cooling Curves for Various Conditions

Cooling curves are shown in figure 12 for a concrete wall 1 foot thick for four different sets of conditions. The concrete is assumed to be typical, placed at a temperature of 60°F. and exposed to air at 30°F. The cases have been selected to show on a comparative basis the effect of varying the insulating value of the formwork or cover and of changes in wind speed. Time-temperature curves are shown for the midplane position and for the surface of the concrete just inside the formwork. Case (i) represents a metal form providing practically no resistance to heat flow and with an air film conductance corresponding to a 10 m.p.h. wind. Case (ii) represents a form providing slightly better protection with relatively still air outside. Case (iii) represents a 1.0 inch wood form with a 10 m.p.h. wind outside. Case (iv) represents a high degree of insulation corresponding to two inches of mineral wool. A method similar to that of Tuthill et al was used for cases (i), (ii) and (iii), while in case (iv) temperatures were calculated neglecting any temperature gradient in the concrete. Exposure conditions have been assumed to be identical on both sides of the wall and the air temperature has been assumed to remain constant. The results are therefore not fully representative of an actual case but do show the relative cooling rates and the variations which can be expected between the centre and the surface of the wall with various surface conditions. Very rapid cooling is seen to occur in case (i) and quite rapid cooling also in case (ii). The value of insulation is quite definitely shown.

The variations in temperature through the wall at various times after placing are shown in figure 13 for the conditions of case (i), i.e. with a highly conducting form and wind.

VI PRACTICAL CONSIDERATIONS IN THE USE OF WEATHER DATA

It is clear that it will be an impossibility to devise a system capable of taking into account all the factors having some significance in the cooling of concrete, either from the point of view of weather or of the resulting heat exchange with the concrete mass. The situation lends itself to the acceptance of air temperatures as the primary weather factor with the heat exchange being dealt with in terms of conduction theory.

The effect of surface air motion is then taken into account in establishing design values for the air film conductance. Such values are already available from building work.

The situation with respect to radiant heat exchange is rather more complicated but it, too, can be handled. Radiation exchange with the surroundings can be taken into account by suitable adjustments to the air film conductance, while that with the sky might be handled by adjustments to design air temperatures in a manner similar to that already developed in building work using the sol-air temperature concept.

There already exists from the work of Tuthill et al and of Nerenst et al, taken in combination with existing meteorological data for any location, the basis for the practical prediction of protection requirements.

Any rational approach toward taking into account the effects of moisture must be recognized as being extremely difficult. The primary phenomenon is flow similar to heat flow but with some further complications of its own arising from change of state and the interdependence with temperature and heat flow. Evaporation of moisture within or at the surface of the concrete plus its enclosure can appreciably influence the heat flow and temperature patterns because of the latent heat involved which can, following evaporation, be carried off by the diffusing vapour. Moisture may directly influence the conductivity, especially of the materials used as formwork or cover. Finally, the maintenance of suitable moisture conditions may require that steps be taken to conserve moisture in a manner similar to that done for heat. The very great complications involved, coupled with the limited development to date of adequate theory dealing with moisture, make it unlikely that the moisture effects can be dealt with directly in any design procedure that may be established.

It is important to keep in mind that the design of protection involves anticipation of the conditions that will exist during the curing period. Since the accuracy with which the weather factors can be predicted in advance for a period of several days can never be great, it follows that the methods of using such data need not be much more precise. This is, in a sense, a fortunate circumstance since the achievement of precision in the application of data is, as has been amply shown, usually very difficult and frequently impossible. Approximations in the heat flow theory, such as have been discussed, are therefore acceptable, and the problem becomes one of selecting methods which are of sufficient accuracy yet are simple enough to be workable in practice.

In view of the difficulties in prediction of the pertinent weather factors, it will be necessary to introduce a substantial margin of safety in the design of protection. It seems probable that the practical requirements of achieving a workable system of design may make it necessary to neglect variation in the pertinent weather factors throughout the period for which protection is required, and to design on the basis of constant conditions. The approximations introduced by this procedure will be greater in the case of poorly protected or poorly insulated concrete than in that which is well insulated.

Practical considerations make it necessary to distinguish clearly between the use which can be made of statistical weather data, of forecast information, and of a knowledge of the influence of microclimate and other local or site factors. The basic design weather factors will always have to be evaluated on the basis of a statistical analysis of weather data. This basic design data, applying to a given period, may then be modified in the light of 30-day or other long-range forecast information, to the extent that this is available and can be relied upon. A further adjustment can be made to the basic design data to account for the influence of local conditions. This will be largely a matter of judgment.

Twenty-four- and 48-hour forecasts become of secondary importance since they will not provide for the prediction of conditions over an adequately long period for curing purposes. They may be of little value in the case of large jobs for which concrete is being placed continuously over long periods and where the protection to be provided must be arranged for well in advance of the time it may be needed. On small-scale jobs, however, where emergency protection can be provided on short notice, such forecasts may be of value.

Substantial use may be made of statistical data in connection with work for which no particular protection is to be provided, in establishing such information as the limits of frost-free periods and the probabilities that freezing temperatures will be encountered within a construction period. Again such information might be used in conjunction with data from long-range forecasts.

VII THE ROLE OF THE LABORATORY

Since weather consists of a constant interplay of fluctuating climatic elements, and varies widely through the influence of local factors, its reproduction in the laboratory has little merit for purposes of prediction in winter concreting. The simulation of certain weather conditions has found use in comparative testing, as for example, the weatherometer and apparatus for freeze-thaw cycling and wetting-drying cycling. In the present case, however, laboratory investigations must be largely restricted to the determination of fundamental quantities and coefficients, the study of phenomena, and the development of simple methods for estimating the protection required, cooling rates, and time for stripping of forms.

The most obvious role of the laboratory is in the determination of the basic properties of individual materials involved in providing winter protection. These include thermal conductivity, heat capacity and diffusivity of the ingredients, the fresh concrete itself, the formwork, the various types of insulation, and the materials constituting the bed into which the concrete is placed. The amount and rate of production of heat of hydration must be determined in the laboratory.

Approximations and assumptions made for purposes of simplification of heat flow calculations may create a need for establishing "coefficients" for use in such simplified equations, which are, in effect, functions to which single values are assigned for a particular range of conditions. In many cases such coefficients might best be evaluated by experiment.

Laboratory work may also be directed toward the development of model and analog techniques for the solution of complicated heat flow cases.

Finally, it may be possible in the laboratory to establish limited weather conditions for purposes of assessing approximations which may be under consideration. It is not apparent that large-scale laboratory facilities capable of producing simulated weather conditions involving several of the weather factors simultaneously will be sufficiently useful to justify setting them up where they do not already exist.

VIII DEVELOPMENT FOR THE FUTURE

The problems ahead which are most immediately evident are these:

1. The further development of approximate but adequate methods for solving the various heat flow situations which can arise in winter concreting;
2. Study of the relative importance of the various weather factors, particularly those involved in the radiation environment and in moisture transfer, and ways in which these may be handled in design;
3. Consideration of the types of statistical data which will be useful and the development of these by climatologists;
4. Further consideration of the ways in which forecast data can be useful;
5. Study and development of practical information describing the characteristics of microclimate and of the effects of local and site conditions.

It seems clear that the concrete engineer will seldom have an adequate knowledge of climatology on the one hand, or of heat transfer calculations on the other. The requirements for developments in both of these fields as aids to winter concreting practice are sufficiently involved to offer a challenge to specialists in either field, who must together determine what is possible. At the same time the concrete engineer must make his contribution in determining what will be useful and practical. A three-way partnership in development must therefore be established.

ACKNOWLEDGMENTS

This paper summarizes many discussions on the subject of winter concreting held within the Division of Building Research of the National Research Council of Canada from which it is a contribution. The author gratefully acknowledges the special assistance given to him in the preparation of this paper by Mr. Donald W. Boyd, Climatologist to the Division, Mr. K.R. Solvason, Dr. N.B. Hutcheon, Assistant Director, and Mr. R.F. Legget, the Director, with whose approval the paper is published.

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Table I

Minimum Temperatures at Ottawa, Canada

Based on Years 1921 - 1950

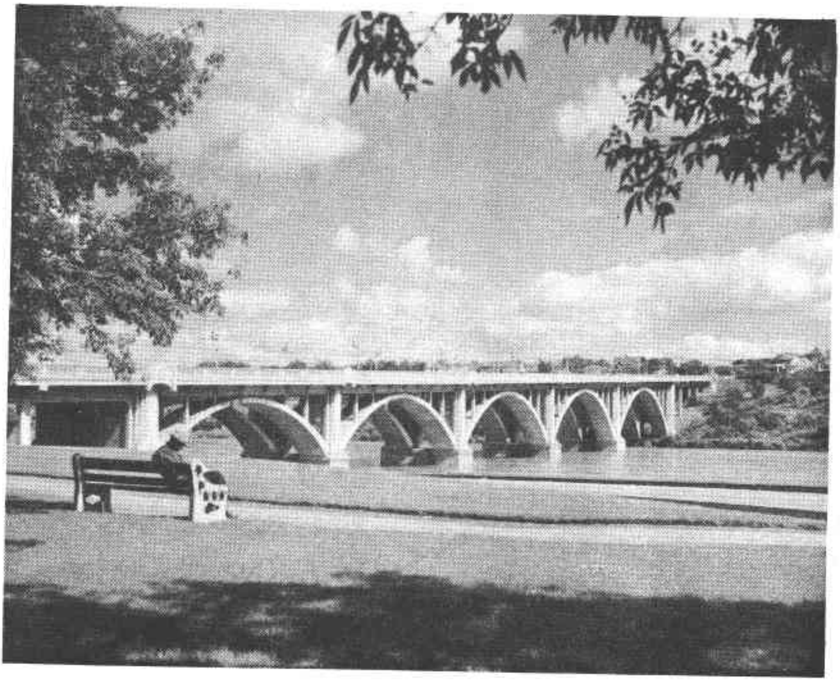
Minimum Temperature (°F.)	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Mean daily	36.8	26.3	10.1	3.2	3.2	16.8	31.2
Mean monthly	20.2	5.4	-17.0	-22.6	-19.8	-9.1	16.0
30-year	9	-11	-38	-34	-35	-34	-5

Table II

Wind Speeds at Ottawa, Canada.

Based on Years 1939-1954

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Mean Wind Speed (m.p.h.)	10.0	10.8	10.8	11.0	11.4	11.5	11.4
Mean Monthly Max.	30	32	32	32	32	33	31
16-year Max.	45	48	42	48	54	41	44



RILEM 56 A 1.pl:
Fig.1. The Broadway Bridge, Saskatoon (Photograph courtesy of Canada Cement Company).

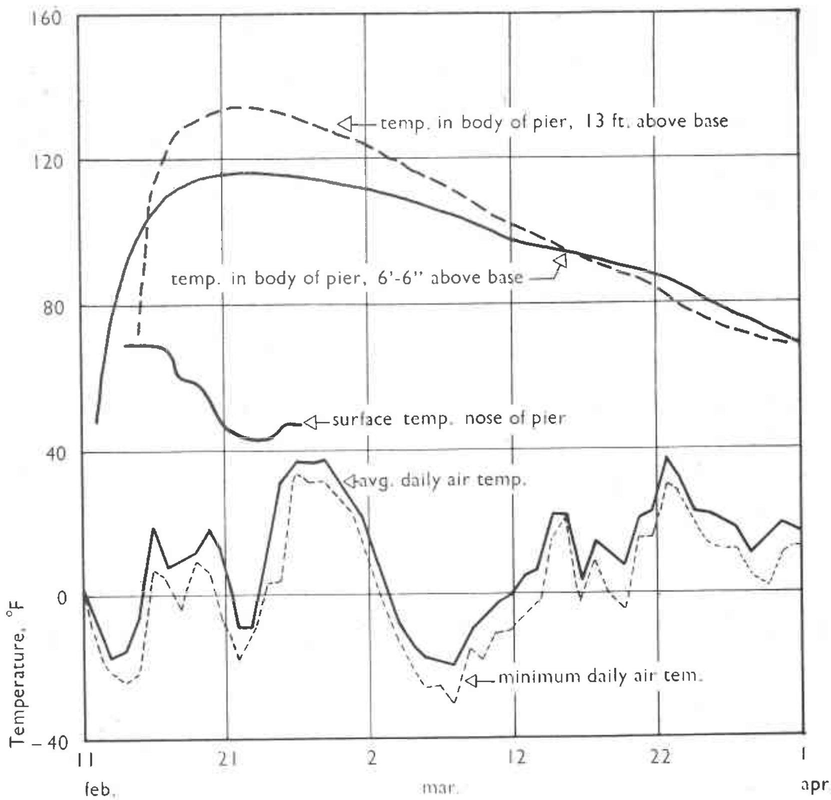


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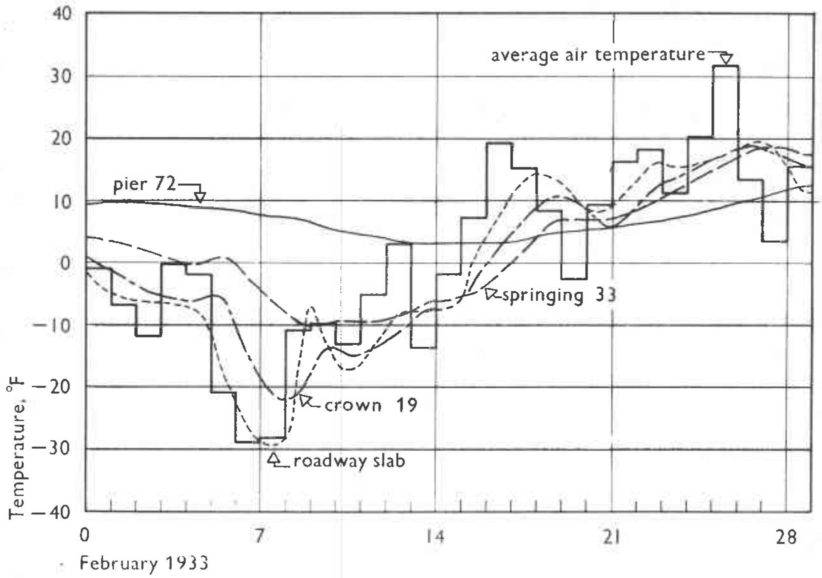
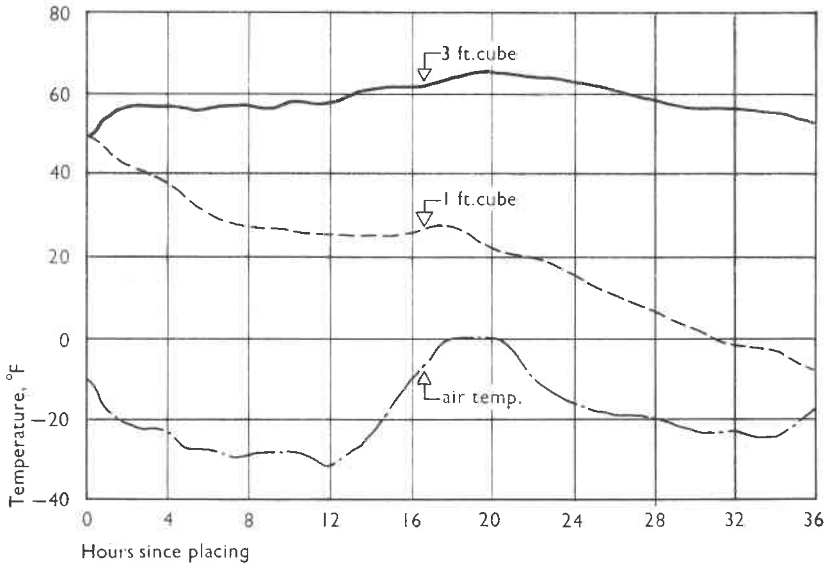
Fig.2. Air and Concrete Temperature in Bridge Pier. (From C.J. Mackenzie, "The Broadway Bridge, Saskatoon", Engng. J., vol. 17, 1934, p.3-18).



RILEM 56 A 1.d2:
Fig. 3. Temperature in Concrete Elements of Bridge Showing Influence of River Water. (From C.J. Mackenzie, "The Broadway Bridge, Saskatoon", Engng. J., vol. 17, 1934, p.3-18).



RILEM 56 A 1.d3:
Fig.4. Freezing Rate for Different Masses of Concrete (6-bag mix; 2-inch wood form protection; temperatures taken at concrete next to form). (Reproduced with permission of Hydro-Electric Power Commission of Ontario).

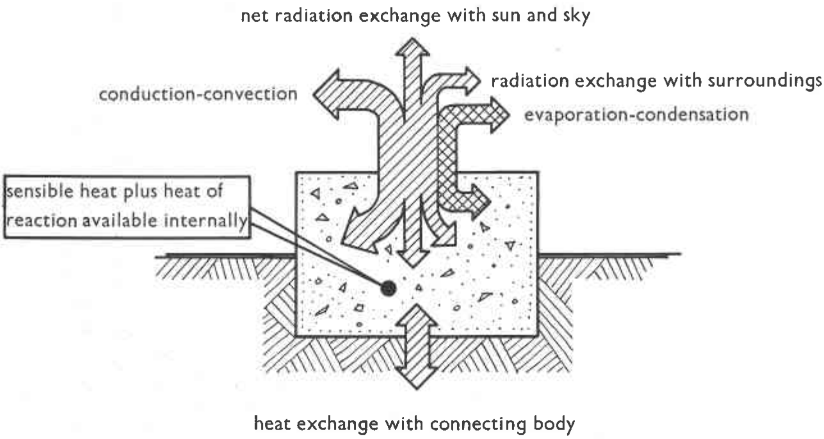


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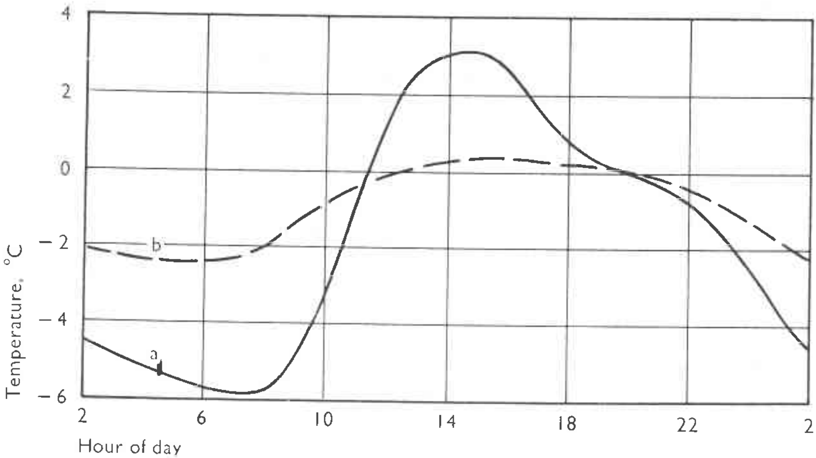
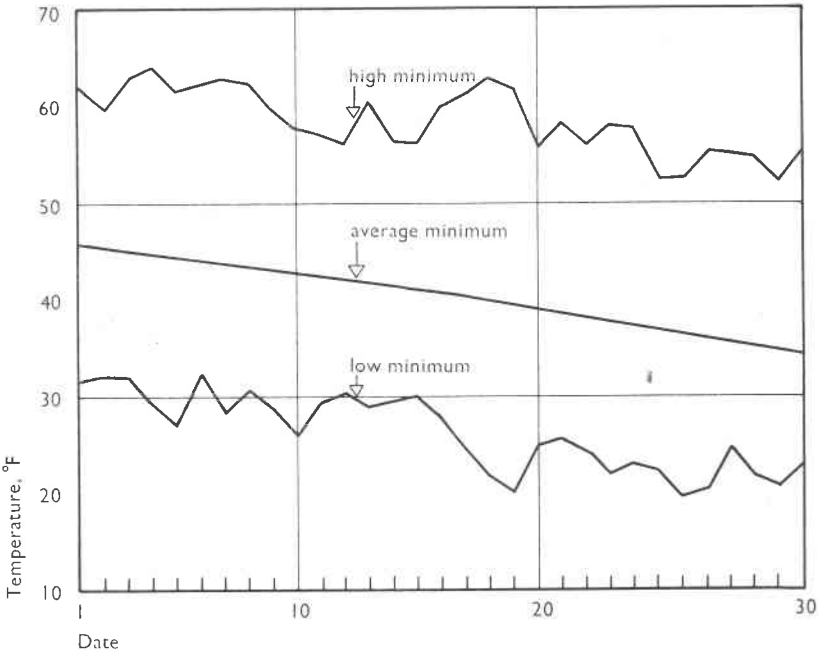
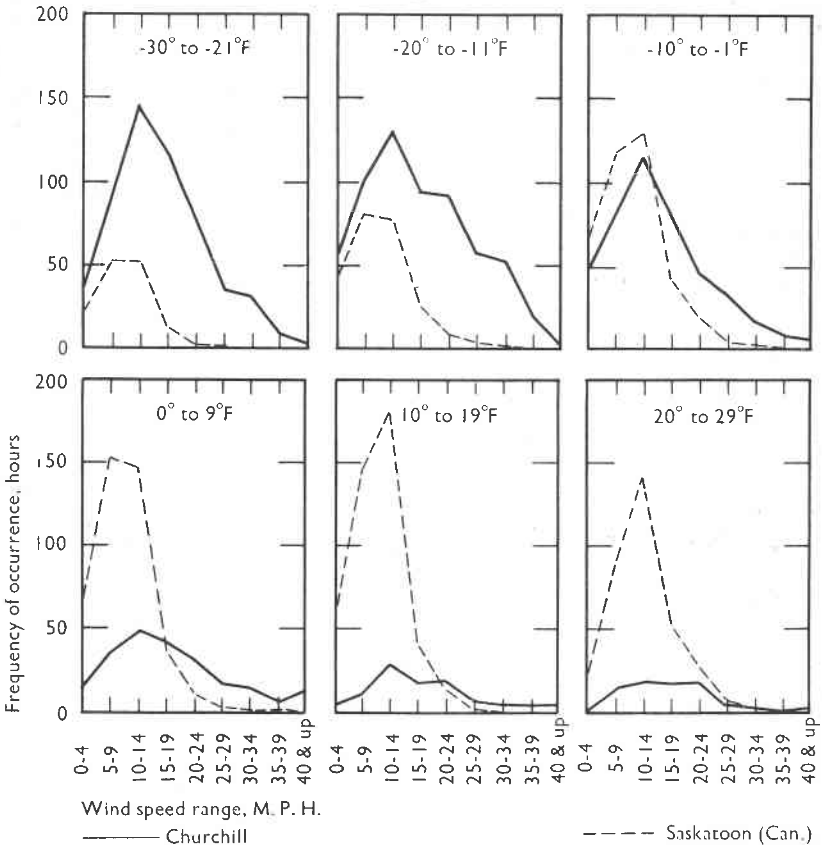
Fig.5. Thermal Exchange Between Fresh Concrete and Its Environment.



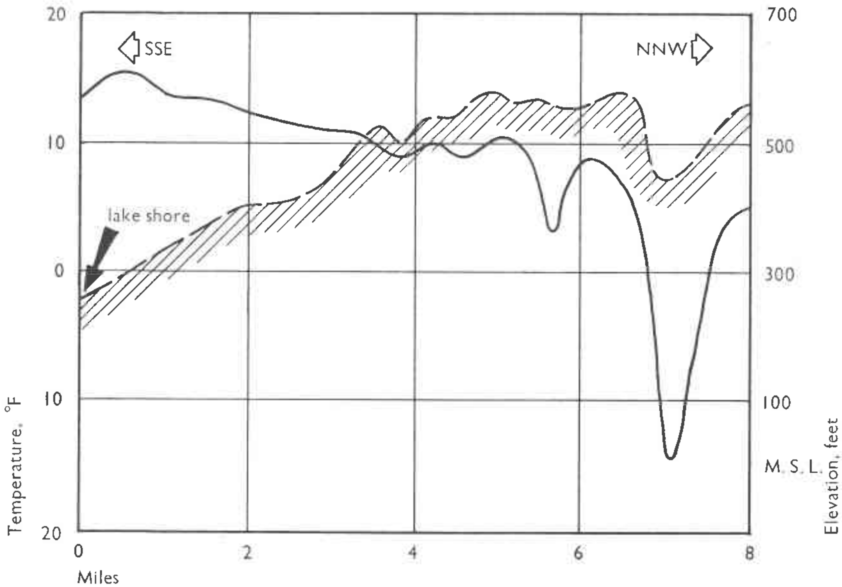
RILEM 56 A 1.d4:
Fig.6. Daily Temperature Variation on (a) bright and (b) cloudy days. (From H. Landsberg, "Physical Climatology". School of Mineral Industries. The Pennsylvania State College, State College, Penn., 195o, 283 p).



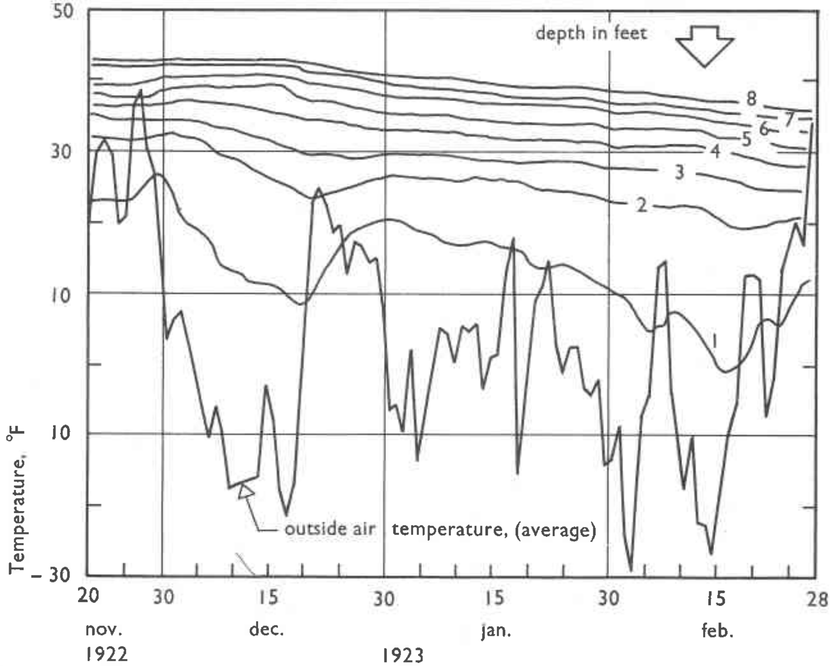
RILEM 56 A 1.d5:
Fig.7. Minimum Temperatures for October in Montreal, Canada. (From R.W. Longley, "The Climate of Montreal", Meteor. Div., Air Services Branch, Dept. of Transport, Canada 1954, 46 p.).



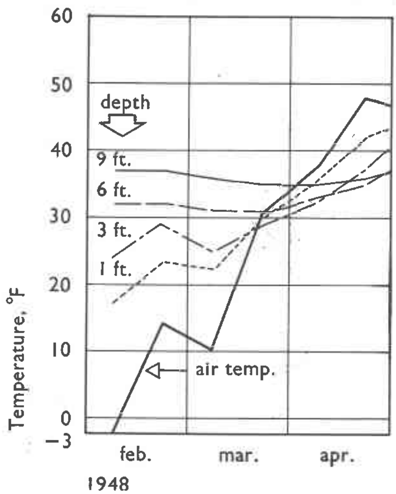
RILEM 56 A 1.d6:
Fig.8. Average Frequency Distribution of Winds at Various Speeds for 10 °F. Temperature Ranges (readings from 1951 to 1954, December, January and February).



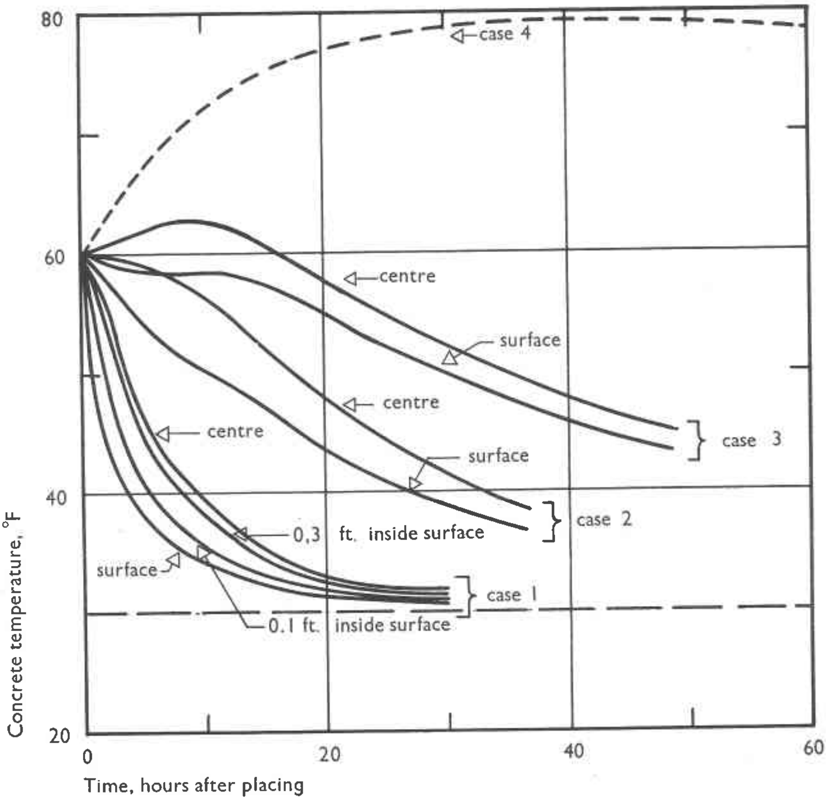
RILEM 56 A 1.d7:
Fig.9. Temperature on a Clear Night Across Toronto, Canada.
(Courtesy Architectural Forum. Copyright Time Inc.,1947).



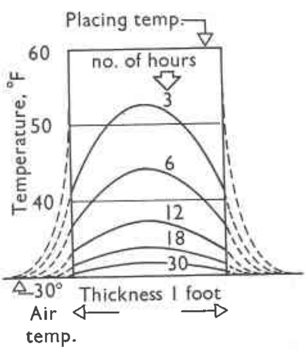
RILEM 56 A 1.d8:
Fig.1o. Winter Soil Temperatures at Various Depths, Saskatoon, Canada, November 2o, 1922, to February 28, 1923. (From E.L. Harrington, "Soil Temperatures in Saskatchewan", Soil Sc., vol. 25, no.3, March 1928, p. 183-194).



RILEM 56 A 1.d9:
Fig.11. Rock Temperatures in Winter, Aquasabon Development, Canada. (Reproduced with permission of Hydro-Electric Power Commision of Ontario).



RILEM 56 A 1.d10:
Fig.12. Temperature in a One-foot Thick Concrete Wall Exposed on Both Sides (initial placing temperature 60 °F.; air temperature 30 °F.).



RILEM 56 A 1.d11:
Fig.13. Temperatures at Various Times in a One-foot Thick Wall Placed at 60 °F. and Exposed to Air 30 °F. with 10 m.p.h. Wind Speed.