CHAPTER 2

DEFINITIONS AND THERMAL PROPERTIES

2-1. Definitions.

Definitions of certain specialized terms applicable to arctic and subarctic regions are contained in TM 5-852/AFR 88-19, Volume 1. Following are additional terms used specifically in heat-transfer calculations.

a. Thermal conductivity, K. The quantity of heat flow in a unit time through a unit area of a substance caused by a unit thermal gradient.

b. Specific heat, c. The quantity of heat absorbed (or given up) by a unit weight of a substance when its temperature is increased (or decreased) by 1 degree Fahrenheit (°F) divided by the quantity of heat absorbed (or given up) by a unit weight of water when its temperature is increased (or decreased) by 1°F.

c. Volumetric heat capacity, C. The quantity of heat required to change the temperature of a unit volume by 1°F.

—*For unfrozen soils,*

$$C_u = \gamma_d \left(c + 1.0 \frac{w}{100}\right). \qquad \text{(eq 2-1)}$$

—*For frozen soils,*

$$C_f = \gamma_d \left(c + 0.5 \frac{w}{100}\right). \qquad \text{(eq 2-2)}$$

—*Average values for most soils,*

$$C_{avg} = \gamma_d \left(c + 0.75 \frac{w}{100}\right). \qquad \text{(eq 2-3)}$$

where c = specific heat of the soil solids (0.17 for most soils)

γ_d = dry unit weight of soil

w = water content of soil in percent of dry weight.

d. Volumetric latent heat of fusion, L. The quantity of heat required to melt the ice (or freeze the water) in a unit volume of soil without a change in temperature—in British thermal units (Btu) per cubic foot (ft^3):

$$L = 144\, \gamma_d \frac{w}{100} \qquad \text{(eq 2-4)}$$

e. thermal resistance, R. The reciprocal of the time rate of heat flow through a unit area of a soil layer of given thickness d per unit temperature difference:

$$R = \frac{d}{K} \qquad \text{(eq 2-5)}$$

f. Thermal diffusivity, a. An indicator of how easily a material will undergo temperature change:

$$a = \frac{K}{C} \qquad \text{(eq 2-6)}$$

g. Thermal ratio, α.

$$\alpha = \frac{v_o}{v_s} \qquad \text{(eq 2-7)}$$

where

v_o = absolute value of the difference between the mean annual temperature below the ground surface and 32°F.

v_s = one of two possible meanings, depending on the problem being studied:

(1) $v_s = nF/t$ (or nI/t)

where

n = conversion factor from air index to surface index

F = air freezing index

I = air thawing index

t = length of freezing (or thawing) season.

(2) v_s = absolute value of the difference between the mean annual ground surface temperature and 32°F.

(3) In the first case, v_s is useful for computing the seasonal depth of freeze or thaw. In the second case, it is useful in computing multiyear freeze or thaw depths that may develop as a result of some long-term change in the heat balance at the ground surface.

h. Fusion parameter, μ.

$$\mu = \frac{C}{L} v_s \quad \text{(eq 2-8)}$$

where v_s has the two possible meanings noted above.

i. "Lambda" coefficient, λ. A factor allowing for heat capacity and initial temperature of the ground (see fig. 3-1).

$$\lambda = f(\alpha, \mu) \quad \text{(eq 2-9)}$$

j. Thermal regime. The temperature pattern existing in a soil body in relation to seasonal variations.

k. British thermal unit, Btu. The quantity of heat required to raise the temperature of 1 pound (lb) of water 1°F at about 40°F.

2-2. Thermal properties of soils and other construction materials.

a. The basic thermal properties of soils and other construction materials used to calculate depths of freeze and thaw are specific heat, thermal conductivity and volumetric latent heat of fusion. Other terms used in heat-flow calculations are derived from these data and the elements of weight, length, temperature and time.

b. the specific heat of most dry soils near the freezing point may be assumed to be constant at the value of 0.17 Btu/lb °F. Specific heats of various materials are given in table 2-1; see the *ASHRAE Guide and Data Book* of the American

*Table 2-1. Specific heat values of various materials**
(U.S. Army Corps of Engineers).

Material	Temperature (°F)	Specific heat (Btu/lb °F)
Aluminum	-27.4	0.20
Asbestos fibers	--	0.25
Concrete (avg. stone)	--	0.20
Concrete (dams)	--	0.22
Copper	44.6	0.20
Corkboard	91	0.43
	-19	0.29
Cork, granulated	--	0.42
Fiberglas board	111	0.24
	-22	0.19
Foamglas	-20	0.16
Glass block, expanded	112	0.18
Glass sheets	--	0.20
Glass wool	--	0.16
Ice	32	0.48
Iron (alpha)	44.6	0.11
Masonry	--	0.22
Mineral wool	--	0.22
Perlite, expanded	--	0.22
Polystyrene, cellular foam	--	0.27
Polyurethane foam	--	0.25
Sawdust	--	0.60
Snow	--	0.50
Steel	--	0.12
Straw	--	0.35
Water	--	1.00
Woods (avg.)	68	0.33
Woods fiberboard	148	0.34

* Specific heat values shown to nearest 0.01. Average values listed where temperature is not shown.

Society of Heating and Air Conditioning Engineers for the specific heat values of common materials.

c. The thermal conductivity of soils is dependent upon a number of factors: density; moisture content; particle shape; temperature; solid, liquid and vapor constituents; and the state of the pore water, whether frozen or unfrozen. Average values, expressed in Btu/ft hour °F, for frozen and unfrozen granular soils, silts and clays should be read from figures 2-1 through 2-4. The charts for sands and gravels are applicable when the silt and clay content together make up less than 20% of the soil solids. The charts for silt and clay are applicable when that fraction is at least 50%. For intermediate silt-clay fractions, it is recommended that the simple average of the values for the two sets of charts be used. In all cases, the error in the thermal conductivity estimates may be ±25%, and even higher when the percentage of quartz grains in the soil is exceptionally high or low. Figures 2-5 and 2-6 present estimates of the average thermal conductivity of frozen and unfrozen peat. An excellent source of data for dry construction materials is the *ASHRAE Guide and Data Book.* Thermal conductivity values for a number of common construction materials are listed in table 2-2.

d. The latent heat of fusion is the amount of heat required to cause a phase change in soil moisture. This amount of heat does not change the temperature of the system when freezing or thawing takes place. The gravimetric latent heat of fusion of water is assumed to be 144 Btu/lb. The amount of heat energy required to convert 1 ft of water to ice is (144 × 62.4 =) 9000 Btu/ft^3 and to change 1 ft^3 of ice to water is (144 × 0.917 × 62.4 =) 8240 Btu/ft^3. (Note: The density of water 62.4 lb/ft^3 and that of pure ice is 57.2 lb.ft^3).

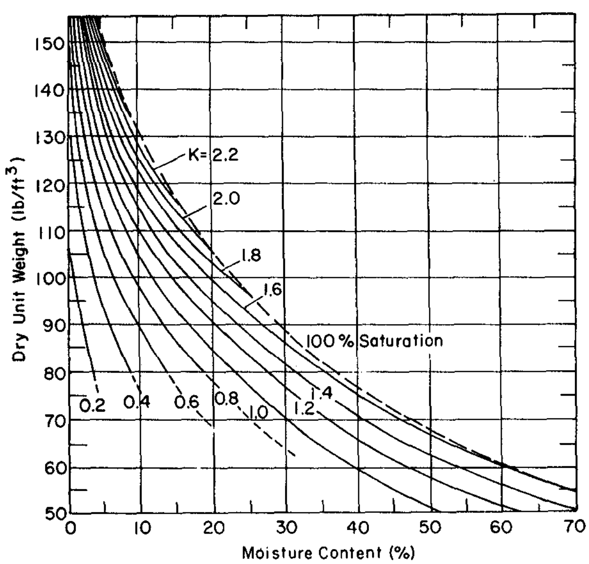
e. Figures 2-7 and 2-8 may be used to determine the average volumetric heat capacity and volumetric latent heat of fusion, respectively, of moist soils.

f. The following *example* illustrates the significance of latent heat of fusion relative to the volumetric heat capacity for a moist soil. Assume a soil having a dry unit weight of 120 lb/ft^3 and a water content of 15 percent. Its volumetric latent heat of fusion, L, is (144 × 120 × 0.15 =) 2592 Btu/ft^3 and its average volumetric heat capacity, C, is (120[0.17 + 0.75 × 0.15] =) 33.9 Btu/ft^3 °F. The quantity of heat required to change the phase of pore water in 1 ft^3 of this soil at 32°F is the same as that required to cause a temperature change of (2592/33.9 =) 76.4°F when a phase change is not involved.

2-3. Fundamental considerations.

a. Theoretical basis. The freezing or thawing of soils is the result of removing or adding heat to an existing soil mass. The movement of heat is always in the direction of lower temperature. The time rate of change of heat content depends on the temperature differential in the direction of heat flow and on the thermal properties of the soil.

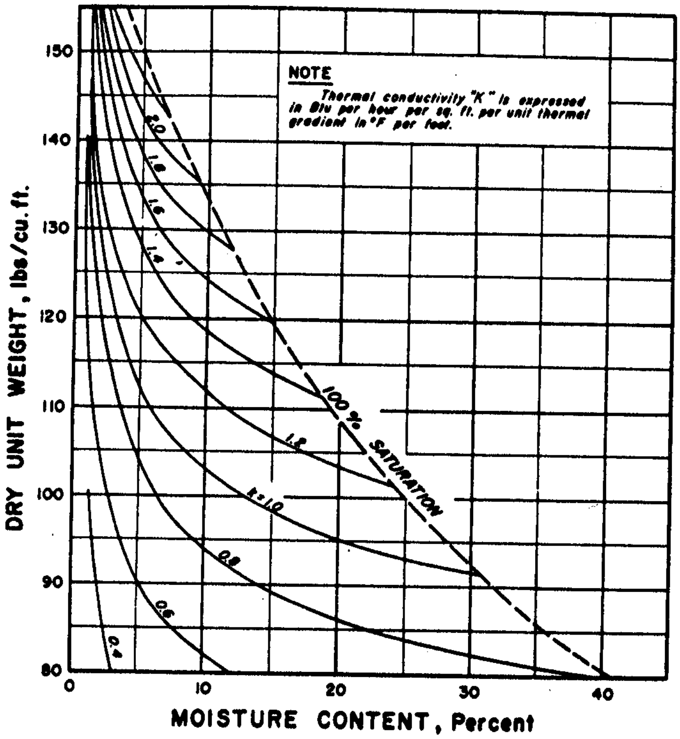
b. Physical factors and data required. Calculation of the depth of freeze or thaw is based on knowledge of the physical and thermal properties of the soil in the profile, the existing thermal regime, and the nature and duration of boundary conditions



Thermal conductivity K is expressed in Btu per hour per square foot per unit thermal gradient in °F per foot.
Dashed line represents extrapolation.

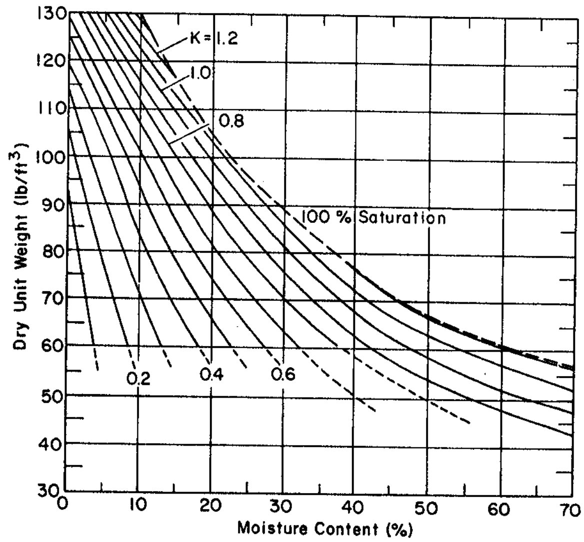
(U.S. Army Corps of Engineers)

Figure 2-1. Average thermal conductivity for sands and gravels, frozen.



(U.S. Army Corps of Engineers)

Figure 2-2. Average thermal conductivity for sands and gravels, unfrozen.



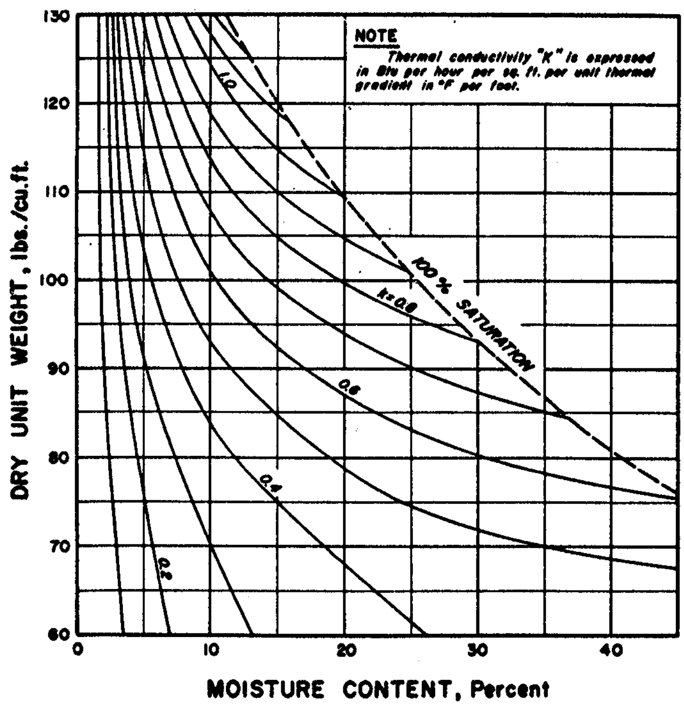
γ_d	w 90	120	100% saturated
50	N/A	N/A	1.20
40	1.00	N/A	1.23
30		0.98	1.26
20		0.61	1.26
pure ice			1.26

Thermal conductivity K is expressed in Btu per hour per square foot per unit thermal gradient in °F per foot.

Dashed line represents extrapolation.

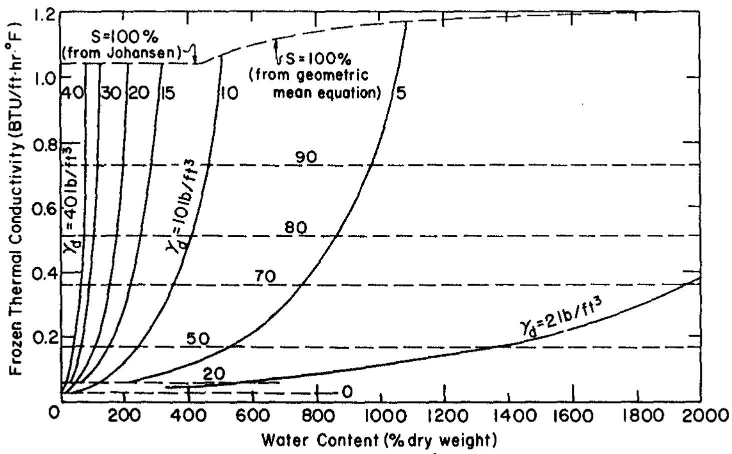
(U.S. Army Corps of Engineers)

Figure 2-3. Average thermal conductivity for silt and clay soils, frozen.



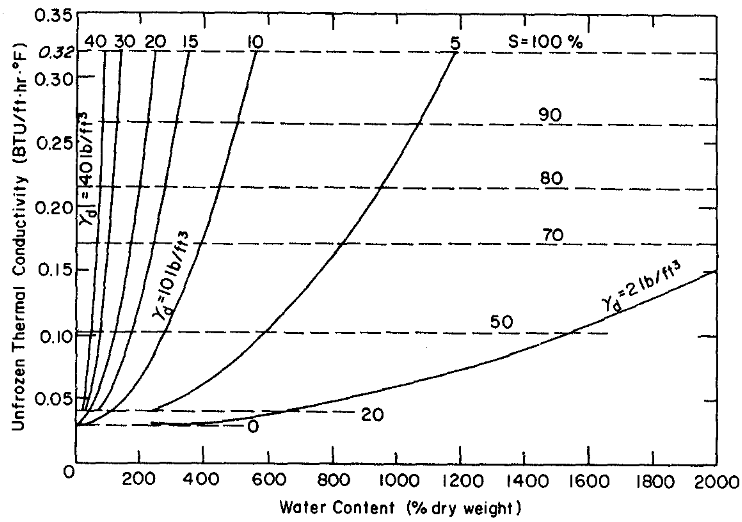
(U.S. Army Corps of Engineers)

Figure 2-4. Average thermal conductivity for silt and clay soils, unfrozen.



(U.S. Army Corps of Engineers)

Figure 2-5. Average thermal conductivity for peat, frozen.



(U.S. Army Corps of Engineers)

Figure 2-6. Average thermal conductivity for peat, unfrozen.

causing a change in the thermal regime. Data pertinent to the soil profile include grain-size distribution, classification, density, water or ice content, and temperature of each soil stratum. Knowledge of the thermal properties of all the materials in the heat flow path is also required. Measured or assumed temperatures within the soil mass determine the initial conditions. If surface temperatures can be assumed to be spatially uniform and the thermal influence of any buried structures can be considered negligible, one-dimensional heat flow may be assumed, thereby simplifying the problem and its solution.

2-4. Freezing and thawing indexes.

a. Physical concept and quantitative measurement. The penetration of freezing or thawing temperatures into soil partly depends on the magnitude and duration of the temperature differential at the air-ground interface. The magnitude of the temperature differential is expressed as the number of degrees that the temperature in the air

Table 2-2. Thermal properties of construction materials (U.S. Army Corps of Engineers).

Type of material	*Description*	*Unit weight (lb/ft³)*	*k conductivity* (Btu/ft²·hr·°F per in.)*	*K conductivity (Btu/ft·hr·°F)*
Asphalt paving mixture	Mix with 6% by weight cut-back asphalt	*138*	10.3	0.86
Concrete	With sand and gravel or stone aggregate (oven-dried)	*140*	9.0	0.75
	With sand and gravel or stone aggregate (not dried)	*140*	12.0	1.00
	With lightweight aggregates, including expanded shale, clay or slate; expanded slags; cinders; pumice; perlite; vermiculite; also cellular concretes.	*120*	5.2	0.43
		100	3.6	0.30
		80	2.5	0.21
		60	1.7	0.14
		40	1.15	0.096
		30	0.90	0.075
		20	0.70	0.058
Wood	Maple, oak and similar hardwoods	*45*	*1.10*	0.092
	Fir, pine and similar softwoods	*32*	0.80	0.067
Building boards	Asbestos-cement board	*120*	4.0	0.33
	Plywood	*34*	0.80	0.067
	Wood fiberboard, laminated or homogeneous	*26,33*	0.42,0.55	0.035,0.046
	Wood fiber-hardboard type	*65*	1.40	0.12
Blanket and batt insulation	Mineral wool, fibrous form, processed from rock, slag, or glass	*1.5-4.0*	0.27	0.022
	Wood fiber	*3.2-3.6*	0.25	0.021
Board and slab insulation	Cellular glass	*9.0*	†0.39	0.032
	Corkboard (without added binder)	*6.5-8.0*	†0.27	0.022
	Glass fiber	*9.5-11.0*	0.25	0.021
	Wood or cane fiber-interior finish (plank, tile, lath)	*15.0*	0.35	0.029
	Expanded polystyrene	*1.6*	0.29	0.024
	Expanded ureaformaldehyde	*1.0*	0.25	--
	Expanded perlite	*9.5-11.5*	0.34	--
	Polyurethane foam	*1.5-3.0*	0.17	--
	Mineral wool with resin binder	*15.0*	**0.28	0.023
	Mineral wool with asphalt binder	*15.0*	**0.31	0.026

Table 2-2. Thermal properties of construction materials, Continued

Type of material	Description	Unit weight (lb/ft³)	k conductivity* (Btu/ft²·hr·°F per in.)	K conductivity (Btu/ft·hr·°F)
Loose fill insulation	Cork, granulated	5-12	0.25-0.36	--
	Expanded perlite	3-4	0.28	--
	Mineral wool (glass, slag, or rock)	2-5	0.30	0.025
	Sawdust or shavings	8-15	0.45	0.037
	Straw	7-8	0.32	
	Vermiculite (expanded)	7.0-8.2	0.48	0.040
	Wood fiber: redwood, hemlock, or fir	2.0-3.5	0.30	0.025
Miscellaneous	Aluminum	168	1416	118
	Copper	549	2640	220
	Ductile iron	468	360	30
	Glass	164	5.5	0.46
	Ice	57	**15.4	1.28
	Snow, new, loose	5.3	0.6	0.05
	Snow on ground	18.7	1.56	0.13
	Snow, drifted and compacted	31.2	4.8	0.40
	Steel	487	310	25.8
	Water, average	62.4	4.2	0.35

* Values for k are for dry building materials at a mean temperature of 75°F except as noted; wet conditions will adversely affect values of many of these materials.

† Mean temperature of 60°F.

** Mean temperature of 32°F.

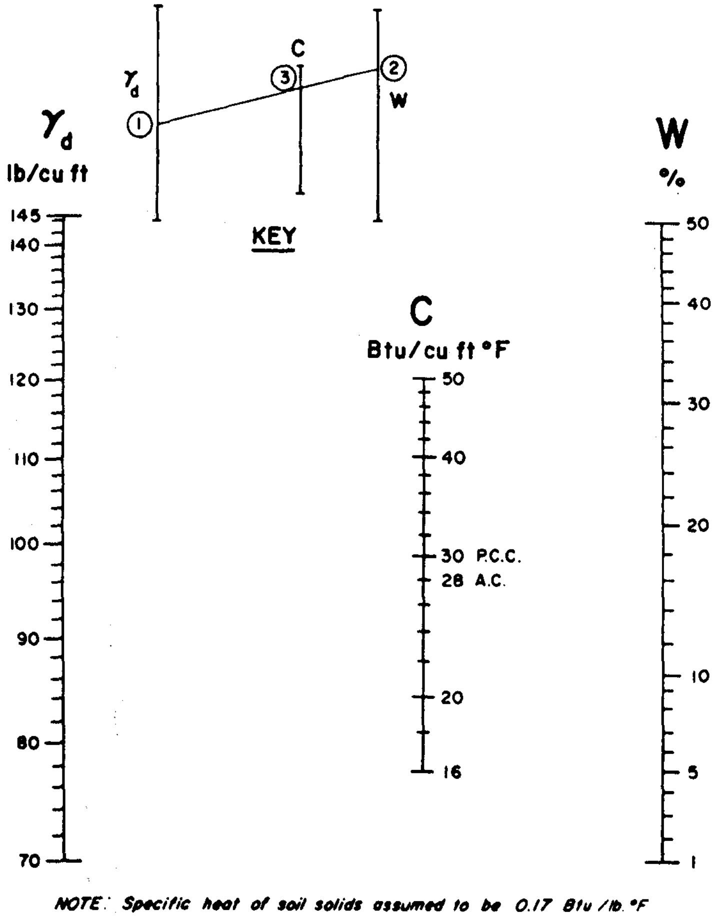
or at the ground surface is above (positive) or below (negative) 32°F, the assumed freezing point of water. The duration is expressed in days.

b. Air freezing index (F) and air thawing index (I). The air freezing and air thawing indexes, as defined in TM 5-852-1/AFR 88-19, Volume 1, may be determined by the following methods.

(1) Summation of degree-days of freeze and thaw from average daily temperatures. If T_1 is the maximum daily air temperature and T_2 is the minimum daily air temperature, the average daily air temperature $\overline{T}$, may be taken as $1/2\,(T_1 + T_2)$, and the number of degree-days for the day is $(\overline{T} - 32)$. The summation of the degree-days for a freezing or thawing season gives the air freezing or air thawing index. Table 2-3 illustrates the method used to obtain the summation of degree-days for a 1-week period, assuming that -456 degree-days had been accumulated since freezing began. An average daily temperature based on hourly temperatures would be slightly more accurate, but such precision is not usually warranted. The negative sign, indicating freezing degree-days, is usually omitted.

(2) Calculation from average monthly temperatures. The freezing or thawing index may be calculated by determining the area between the 32°F line and the curve of average monthly temperature and time, taken over the appropriate season. The area may be determined by planimeter or a simple approximation rule (Simpson's rule, midordinate rule, etc.). The areas are expressed in units of degree-days, resulting in a summation of degree-days or a freezing or thawing index. For an example refer to figure 2-9, a plot of the monthly average temperatures at Fairbanks, Alaska, from September 1949 to October 1950. Determination of areas by planimeter gave a freezing index of -5240 degree-days and a thawing index of +3420 degree-days. The use of Simpson's rule gave a freezing index of -5390 and a thawing index of +3460 degree-days. Either pair of indices is adequate for computations.

c. Surface-freezing and surface-thawing indexes. For determining the heat flow within the soil, it is neces-



(U.S. Army Corps of Engineers)

Figure 2-7. Average volumetric heat capacity for soils.

sary to determine or estimate the temperature condition at the ground surface. Since air temperatures are generally available and surface temperatures are not, a correlation between these temperatures helps establish the thermal boundary condition at the ground surface. The combined effects of radiative, convective and conductive heat exchange at the air-ground interface often must be considered in determining surface temperature.

d. Correlation of air and surface indexes. No simple correlation exists between air and surface indexes. The difference between air and surface temperatures at any specific time is influenced by latitude, cloud cover, time of year, time of day, atmospheric humidity and stability, wind speed, snow cover and ground surface characteristics, and subsurface thermal properties. Heat balance algorithms that approximate many of these interrelationships exist but they are often unwieldly to use and the inputs are often difficult to characterize. It is recommended that the ratio of surface index to air index, designated as the "n-factor," be used to represent a monthly or seasonal correlation. Reliable determination of the n-factor for a specific location requires concurrent observations of air and surface temperatures throughout a number of complete freezing and thawing seasons plus anticipation of future changes to conditions existing during the period of measurement. Such determination is often not feasible, so n-factors must generally be estimated conservatively from n-factors tabulated for other, preferably similar, sites.

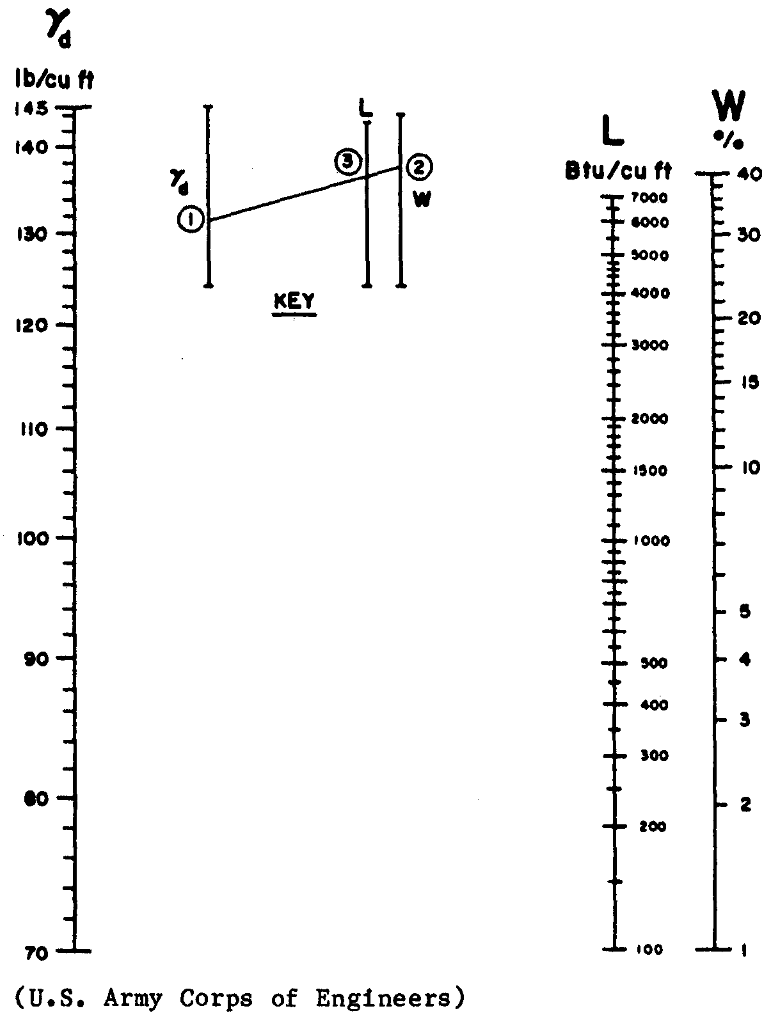
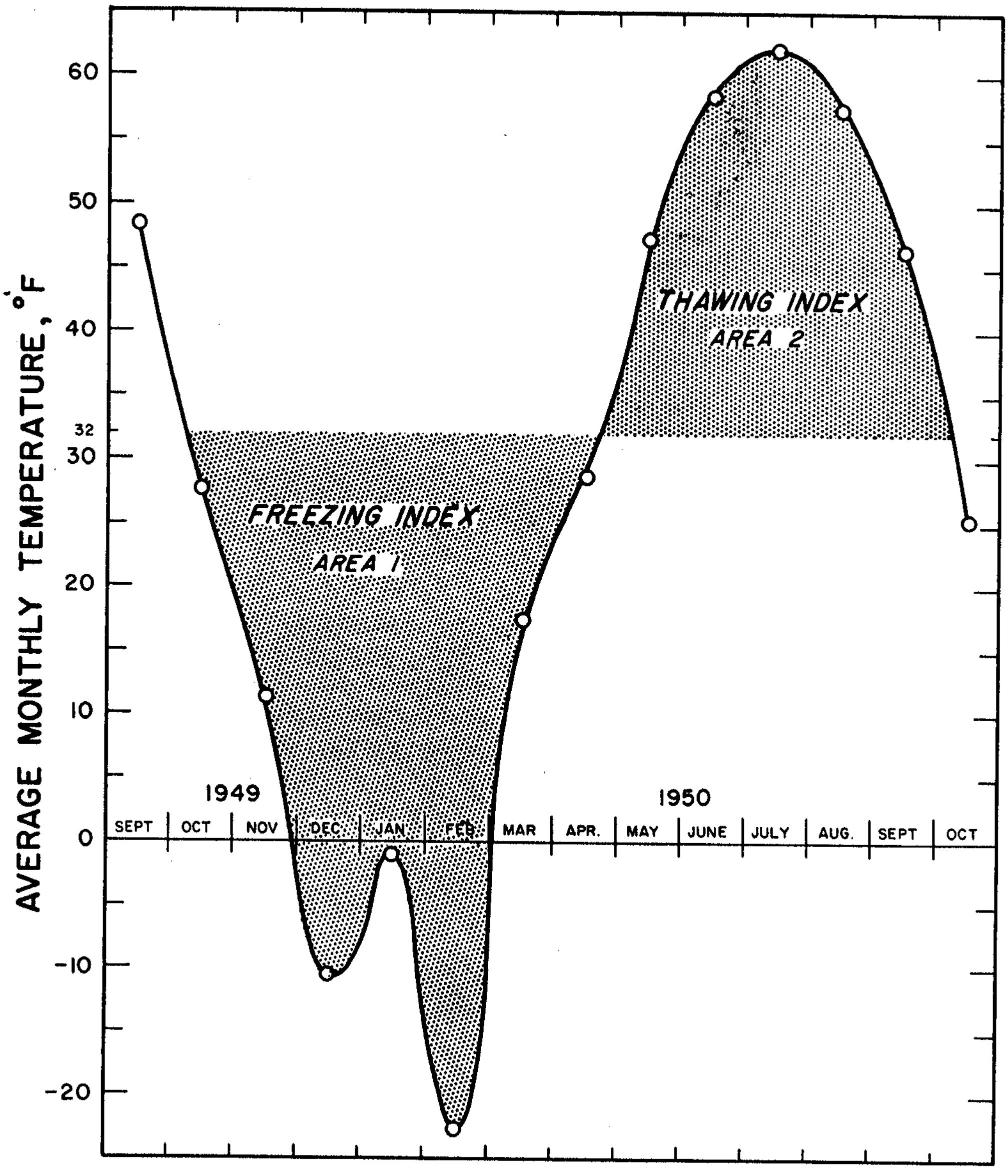


Figure 2-8. Volumetric latent heat for soils.

Table 2-3. Calculation of cumulative degree-days (U.S. Army Corps of Engineers).

Day	Temperature (°F) Maximum	Minimum	Average	Degree-days per day	Cumulative degree-days
1	29	1	15	-17	-473*
2	9	-11	- 1	-33	-506
3	10	- 8	1	-31	-537
4	15	- 1	7	-25	-562
5	30	16	23	- 9	-571
6	38	30	34	2	-569
7	30	18	24	- 8	-577

*Prior accumulation of -456 degree-days assumed.



(U.S. Army Corps of Engineers)

Figure 2-9. Average monthly temperatures versus time at Fairbanks, Alaska.

(1) *Freezing conditions.* The n-factor is very significant in analytical ground studies. It generally increases with wind speed. Snow cover reflects a large part of incoming solar radiation resulting in higher freezing indexes at the snow surface, but its insulating effect can greatly reduce the freezing index at the ground surface. The effects of turf or an organic ground cover on the heat flow processes at the air-ground interface are extremely variable and difficult to evaluate. On the basis of observations and studies made to date, the n-factors given for average conditions in table 2-4 should be used to convert the air freezing index to the surface freezing index in the absence of specific measurements at the site of planned construction.

(2) *Thawing conditions.* The n-factor for thawing conditions is affected by the same factors as those for freezing conditions. It is the ratio of surface degree-days of thaw (degrees above 32°F) to air degree-days of thaw.

Incoming shortwave radiation may introduce heat into the surface to an extent that the surface becomes a source of heat conducted not only downward but upward into the air. In such a case the n-factor may become significantly larger than 1.0. The effect of latitude is not particularly significant in arctic and subarctic areas, but consideration should be given to the effect of wind speed. Recommended curves for n-factors versus wind speed for portland-cement-concrete and bituminous-concrete pavements are shown in figure 2-10 and are based on field studies conducted in Alaska and Greenland. The n-factors given for average conditions in table 2-4 should be used to convert air thawing indexes to surface thawing indexes in the absence of specific measurements at the planned construction sites.

e. Design indexes. For design of permanent pavements, the design freezing (or thawing) index should be the average air freezing (or thawing) index of the three coldest winters (or warmest summers) in the latest 30 years of

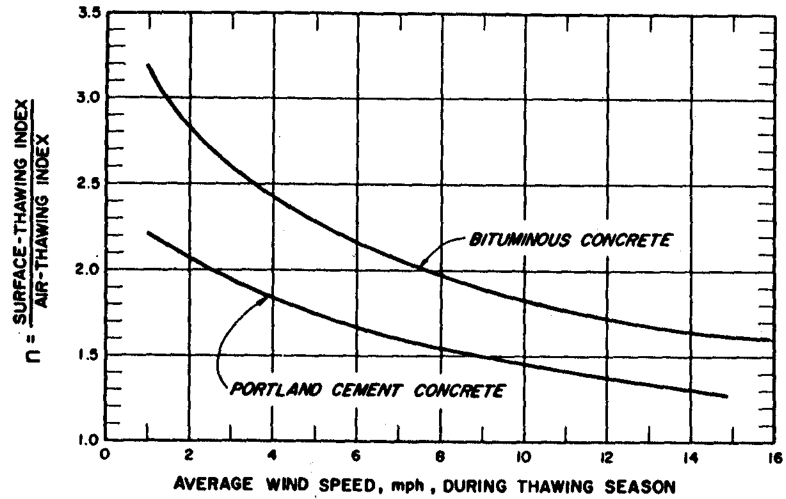
Table 2-4. n-factors for freeze and thaw (ratio of surface index to air index) (U.S. Army Corps of Engineers).

*Type of surface**	*For freezing conditions*	*For thawing conditions*
Snow surface	1.0	--
Portland-cement concrete	0.75	1.5
Bituminous pavement	0.7	1.6 to 2†
Bare soil	0.7	1.4 to 2†
Shaded surface	0.9	1.0
Turf	0.5	0.8
Tree-covered	0.3**	0.4

* Surface exposed directly to sun or air without any overlying dust, soil, snow or ice, except as noted otherwise, and with no building heat involved.

† Use lowest value except in extremely high latitudes or at high elevations where a major portion of summer heating is from solar radiation.

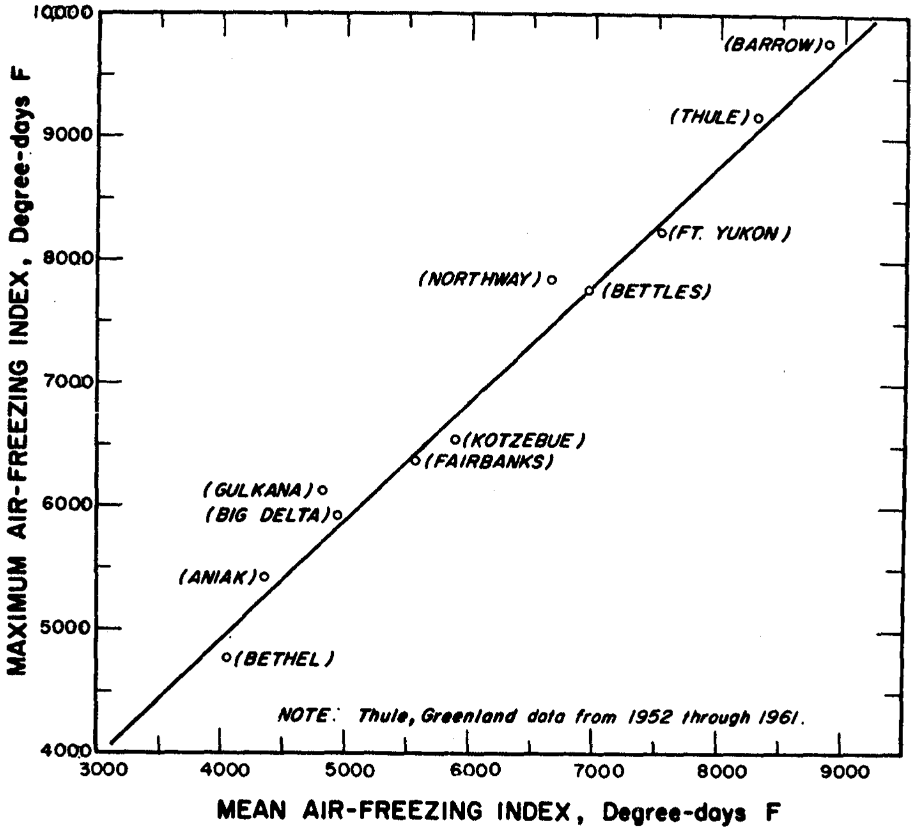
** Data from Fairbanks, Alaska, for single season with snow cover permitted to accumulate naturally.



(U.S. Army Corps of Engineers)

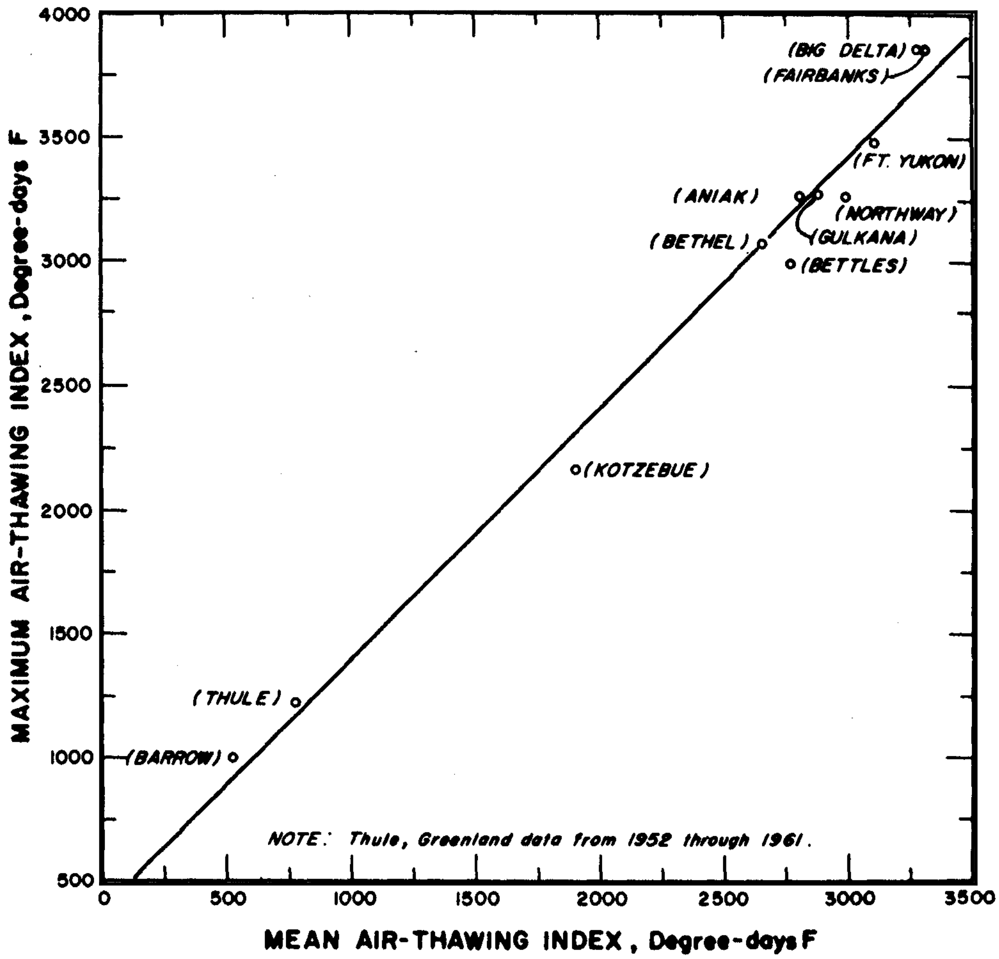
Figure 2-10. Relationship between wind speed and n-factor during thawing season.

record. If 30 years of record are not available, the air freezing (or thawing) index for the coldest winter (or warmest summer) in the latest 10-year period may be used. For design of foundations for average permanent structures, the design freezing (or thawing) index should be computed for the coldest (or warmest) winter in 30 years of record or should be estimated to correspond with this frequency if the number of years of record is limited. Periods of record used should be the latest available. To avoid the necessity for adopting a new and only slightly different freezing (or thawing) index each year, the design index at a site with continuing construction need not be changed more often than once in 5 years unless the more recent temperature records indicate a significant change. The distribution of design freezing and thawing index values in North America is presented in TM 5-852-1/AFR 88-19, Volume 1. The relatively linear relationship between recorded maximum indexes and mean freezing and thawing indexes shown in figures 2-11 and 2-12 may be used in conjunction with distribution of mean and freezing and thawing indexes in TM 5-852-1/AFR 88-19, Volume 1 to determine the design index values for arctic and subarctic regions.



(U.S. Army Corps of Engineers)

Figure 2-11. Relationship between mean freezing index and maximum freezing index for 10 years of record, 1953-1962 (arctic and subarctic regions).



(U.S. Army Corps of Engineers)

Figure 2-12. Relationship between mean thawing index and maximum thawing index for 10 years of record, 1953-1962 (arctic and subarctic regions).