of FAA reports on airport pavements (1, 2, 3, 4, 5, 6).

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Design of Civil Airfield Pavements for Seasonal Frost and Permafrost Conditions

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The principal adverse effects of frost action on pavements are roughness and cracking, which are caused by the upheaval of the pavement during freezing and the weakening of the subgrade and base course and loss of supporting capacity during thaw. Design procedures for pavement section thicknesses to minimize these effects in both flexible and rigid pavements in areas of seasonal frost and permafrost conditions have been developed for the Federal Aviation Administration. The design charts are based on a classification of frost-susceptible soils and the depths to which freezing and thawing will occur for the specific location. Design procedures for pavements incorporating extruded polystyrene insulation have also been developed.

In the United States, only the more southerly states have climatic conditions that provide relative freedom from effects of seasonal frost action. Yet the current Federal Aviation Administration (FAA) criteria for airport pavement design do not account adequately for the detrimental effects of frost action on pavements. These criteria do not provide design alternatives based on degree of roughness, proposed use, or funding available, and they often result in unsatisfactory performance or excessive life-cycle cost of pavements. In addition, these criteria do not recognize parameters known to affect the depth of frost penetration, which has a major influence on the severity of some of the detrimental effects of seasonal frost conditions.

Permafrost is widespread in Alaska and affects pavement design in most of that state, but the current FAA standards provide no criteria or guidance applicable to the design and construction of pavements in areas of permafrost. This is a subject for which existing technology needs further development; however, available information could be adapted for incorporation into FAA design criteria.

Recognizing the need for updating their criteria, the FAA requested that a study be carried out that would draw on existing technology and provide the needed adaptation of currently available guidelines and design procedures for application to airports that serve civil aircraft. The primary objects of the study, the results of which are summarized here, were to

1. Delineate the frost susceptibility of the various FAA soil groups;
2. Provide a methodology for the determination of frost-penetration depths;
3. Develop methods of engineering design based on various levels of frost protection;
4. Prepare design curves for flexible and rigid pavements for various levels of frost protection;
5. Provide guidance on construction control, new materials, and construction techniques to reduce the detrimental effects of frost on pavement performance;
6. Present appropriate testing procedures necessary for the use of the design methods; and
7. Provide methods for engineering design of pavements in permafrost areas.

EFFECTS OF FROST ACTION ON PAVEMENTS

The principal adverse effects of frost action are roughness and cracking, caused by the upheaval of the pavement surface during freezing and by the weakening of the subgrade and base course and loss of supporting capacity during thaw. Frost heave, the raising of the pavement in winter, is caused by the freezing of the soil moisture. In its most damaging form, it is associated with ice segregation, the formation of lenses of ice in the subgrade or base course or both. Frost heave may not be detrimental if adjacent areas of a pavement are heaved by equal amounts, but nonuniform heave can result in extremely severe roughness and in the cracking of both flexible and rigid pavements. Small structures inserted in paved areas, such as fueling hydrants and light bases, may be progressively heaved to levels significantly above the surrounding pavement. The degree of uniformity of pavement heave is enhanced by horizontally uniform soil characteristics and moisture conditions, uniform surface exposure to sun and wind, and uniformity of pavement color and of the thickness and types of materials in adjacent pavement cross sections. Thaw weakening, which causes a loss in pavement supporting capacity, is experienced when frozen soil containing a significant amount of ice thaws. The extreme acceleration in the rate of pavement damage under traffic during the spring is shown in Figure 1 (1) by the deterioration in the serviceability of the flexible pavements in the AASHO Road Test. Pavement roughness and cracking can be caused by severe nonuniform frost heave or by inability of the pavement to support traffic during the thawing season. Cracking of asphalt pavements can also be caused by thermal contraction. As the temperature decreases to low levels, the pavement is partially restrained by friction at the contact with the base course; consequently, the asphalt mixture, embrittled by the low temperature, fails in tension.

SOIL CLASSIFICATION FOR PAVEMENT DESIGN IN FROST AREAS

Because the method of design for pavements recommended here is based on the method used in frost areas by the U.S. Army Corps of Engineers, the classification of frost-susceptible soils on which the Corps' design method is based should be adapted to the FAA soil classification system also. However, no problems are foreseen in the use of the frost design soil classification (Table 1) with the FAA system of classifying soils; both rely on grain-size distribution and Atterberg limits for the division of soils into the four frost groups, FG1 through FG4, by which the soils are ranked approximately in order of increasing severity of frost effects.

DEPTH OF FREEZING AND THAWING

While the depth to which a pavement section will freeze, or (in permafrost areas) to which thawing will take place, can be calculated by several methods, it is recommended that the FAA use the modified Berggren equations (2), which can be expressed as

$$X = \lambda\,(173\ 000knF/L)^{1/2} \qquad (1)$$

or

$$X = \lambda\,(173\ 000knI/L)^{1/2} \qquad (2)$$

where

- X = depth of freeze or thaw (m),
- k = thermal conductivity of soil (W/mK),
- L = volumetric latent heat of fusion (J/m^3),
- n = conversion factor for air index to surface index (dimensionless),
- F = air-freezing index [degree-days (C)],
- I = air-thawing index [degree-days (C)], and
- λ = coefficient that takes into consideration the effect of temperature changes in the soil mass.

The use of Equations 1 and 2 requires the calculation of the design air-freezing and thawing indexes respectively, the cumulative number of degree-days below (or above) freezing for one season. The solution of Equation 1 is shown in Figure 2 (3), which gives the depth of freezing of pavement and granular base as a function of the freezing index and the moisture content and dry unit weight of the base.

THICKNESS OF PAVEMENT SECTION: SEASONAL FROST AREAS

In seasonal frost areas, the design process seeks to determine the minimum combined thickness of pavement surfacing material, freeze-thaw-durable stabilized base, and clean granular non-frost-susceptible base that will adequately control heave-related surface roughness and prevent premature pavement failure caused by thaw weakening of the subgrade. Two approaches are available to meet this object. The principle of the first is to limit the advance of the freezing front into the frost-susceptible subgrade to a small amount and thereby restrict differential pavement heave to small acceptable values. By experience, it has been found that this object will be achieved if the depth of subgrade freezing does not exceed about one-fourth the base thickness. The design thickness of base needed to thus limit subgrade freezing is shown in Figure 3 (3) and can be calculated as follows:

$$c = a - p \qquad (3)$$

where

- a = combined thickness of pavement and non-frost-susceptible base for zero frost penetration into subgrade and
- p = pavement thickness, and

$$r = W_s/W_b \qquad (4)$$

where

- W_s = water content of base and
- W_b = water content of subgrade

and $r \le 3$. For example, if c = 160 cm (5.2 ft) and r = 2.0, then the design base thickness (b) = 106 cm (3.51 ft) and s = 26 cm (10 in). Experience has shown that this thickness of base will also adequately control subgrade thaw weakening, which may be neglected in the proportioning of pavement section elements by other design criteria.

In cold areas with high freezing indexes, the thickness required by use of Figure 3 may be impractically great, but if the subgrade soils are uniform in properties and moisture contents throughout a paved area, a second method of design may be feasible. This method relies on uniformity of soil conditions to reasonably restrict differential heave and only determines the minimum combined thickness of pavement and base for adequate support of aircraft loads during the period when the subgrade is weakened by thawing. From traffic tests on airport pavements in the 1940s and experience with pavements since that time, equivalent-design California bearing ratio values applicable to the design of flexible pavements for year-round use can be inferred for subgrade soils subject to freezing and thawing. These inferred values have been used to develop design charts for various civil aircraft currently in use. Figure 4 shows typical design charts, applicable to B-747 aircraft, for flexible pavement. For proportioning rigid pavements, the modulus of reaction necessary for the design equation can be obtained from Figure 5 (3).

A third method of design [Figure 6 (4)] can also be used that proportions the base to restrict freezing of the subgrade under conditions less severe than the design freezing index that is usually used for Figures 4 and 5. If more roughness can be tolerated in an occasional colder winter, this method, which provides an inter-

Figure 1. Typical performance data of two test sections of AASHO Road Test.

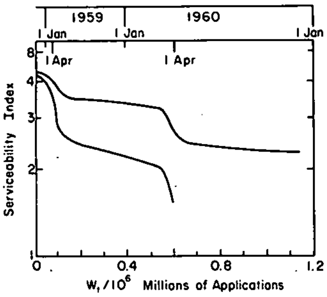


Figure 2. Depth of freezing into granular, non-frost-susceptible soil beneath pavements kept free of snow and ice.

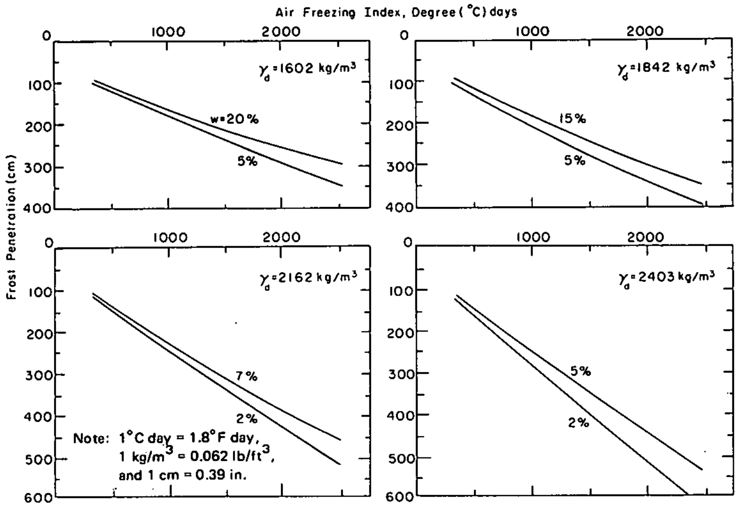


Table 1. Soil classification for frost design.

Frost Group	Description	Typical Soil Types: Percentage Finer Than 0.02 mm by Mass	Unified Soil Classification System	FAA Soil Classification System
FG1	Gravelly soils	3 to 10	GW, GP, GW-GM, and GP-GM	E-1, E-2, E-4, and E-5
FG2	Gravelly soils	10 to 20	GM, GW-GM, and GP-GM	E-1, E-2, E-4, and E-5
	Sands	3 to 15	SW, SP, and SM SW-SM, and SP-SM	E-1 through E-5
FG3	Gravelly soils	>20	GM and GC	E-2, E-4, and E-5
	Sands, except very fine silty sands	>15	SM and SC	E-2 through E-5
	Clays having PI > 12	—	CL and CH	E-7, E-8, E-10, E-11, and E-12
FG4	All silts	—	ML and MH	E-6 through E-12
	Very fine silty sands	>15	SM	E-2 through E-5
	Clays having PI < 12	—	CL and CL-ML	E-6 and E-7
	Varved clays and other fine-grained, banded sediments	—	CL and ML	E-7 and E-6
			CL, ML, and SM	E-6, E-7, and E-2 through E-5
			CL, CH, and ML	E-7, E-8, E-10, E-11, E-12, and E-6
			CL, CH, ML, and SM	E-6, E-7, E-8, E-10, E-11, E-12, and E-2 through E-5

Figure 3. Design depth of non-frost-susceptible base for limited subgrade frost penetration.

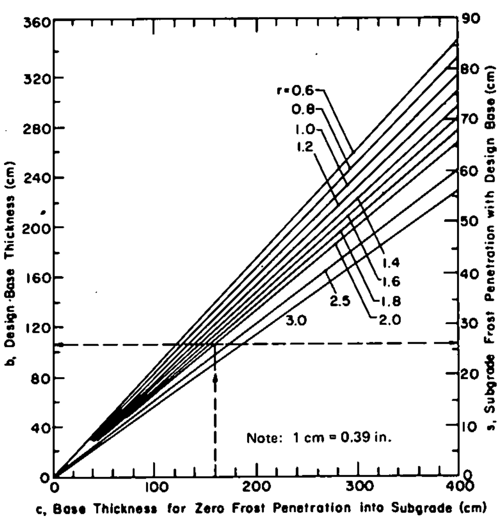


Figure 4. Reduced-subgrade-strength design charts for flexible pavements used by B-747 aircraft.

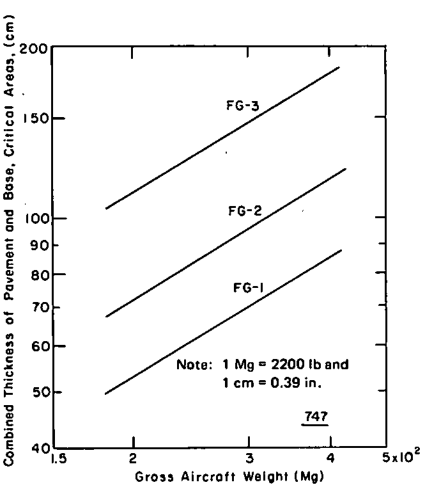


Figure 5. Modulus of reaction for reduced-subgrade-strength design of rigid airport pavements.

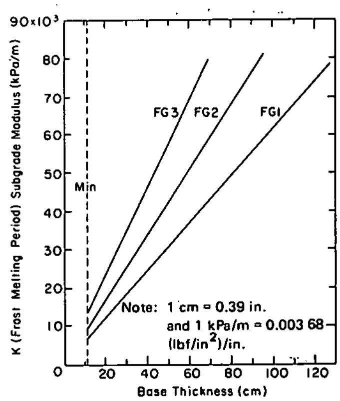


Figure 6. Nomogram for determining indexes for reduced subgrade frost-protection method.

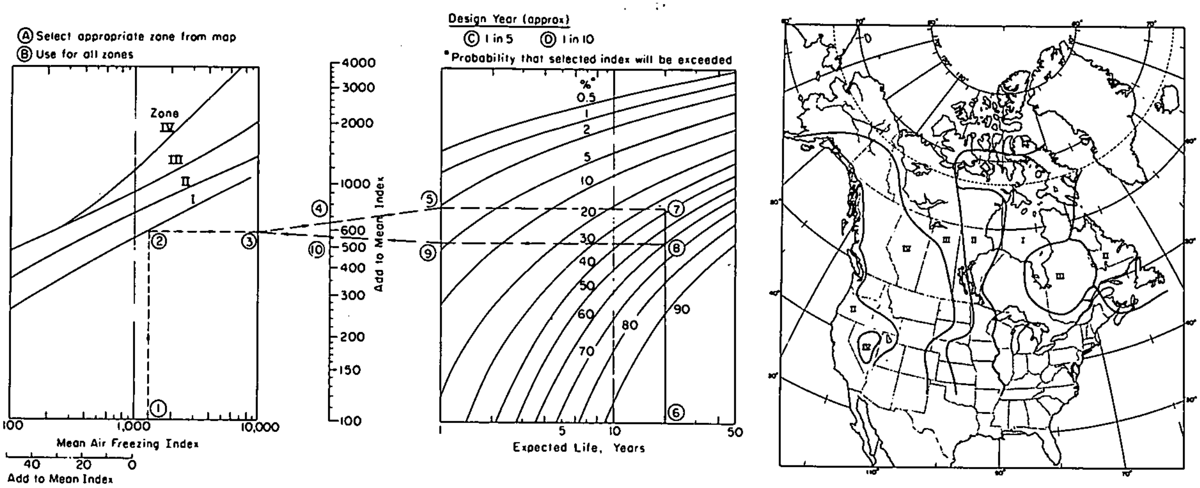
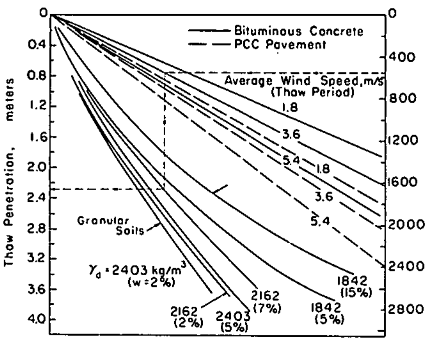


Figure 7. Depth of thaw in granular, non-frost-susceptible soil beneath pavements.



Note: 1 m/s = 2.24 mph, 1°C day = 1.8°F day, 1 kg/m^3 = 0.062 lb/ft^3, and 1 m = 3.3 ft.

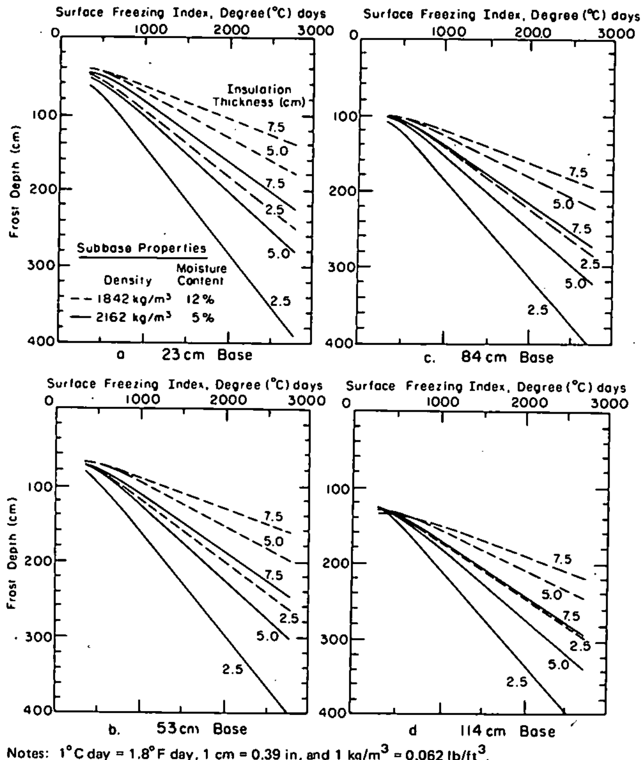
mediate degree of protection against differential heave, may be adopted.

THICKNESS OF PAVEMENT SECTION: PERMAFROST AREAS

In permafrost areas, the upper layers of soil thaw in summer and refreeze in winter, and hence pavements must be designed to minimize the adverse effects of both frost heave and thaw weakening. In arctic areas with low thawing indexes, the design requirements may be met by making the base thick enough to prevent seasonal thawing of the subgrade [Figure 7 (5)]. However, as the thawing index increases, the thickness needed becomes excessive, although synthetic insulation can be used to decrease the requirements for the granular base. If, however, subgrade thawing is expected, the minimum base thickness should be that given by design charts such as Figure 4.

The most difficult problem facing the designer is found in subarctic areas where not only is the depth of seasonal freezing very great, but the depth of thawing beneath a pavement may exceed the depth of refreezing. In this case, progressive lowering of the top of the permafrost may be inevitable and lead to large cumulative settlements as the high-ice-content permafrost thaws. However, degradation of the permafrost may be slowed or even prevented by the following measures: (a) use of high-moisture-retaining material such as sand in the base course, (b) painting the pavement white to control surface reflectance, or (c) use of polystyrene insulation (which cannot prevent permafrost degradation, but can beneficially retard it).

Figure 8. Total depth of frost penetration through 7.5-cm (3-in) asphalt pavement, base, insulation, and subbase.



Notes: 1°C day = 1.8°F day, 1 cm = 0.39 in, and 1 kg/m^3 = 0.062 lb/ft^3.
Base density = 2162 kg/m^3 (135 lb/ft^3) and moisture content = 5%.

DESIGN OF PAVEMENTS INCORPORATING EXTRUDED POLYSTYRENE INSULATION

An insulated pavement system is composed of conventional surfacing, base, and subbase layers above an insulating material of suitable properties and thickness to restrict or prevent the advance of subfreezing temperatures into a frost-susceptible subgrade (or, in permafrost areas, to retard subgrade thawing). Unless the thickness of insulation and overlaying layers is sufficient to prevent subgrade freezing, additional layers of granular materials are placed between the insulation and the subgrade to partially contain the portion of the frost zone that extends below the insulation. Considering only the thermal efficiency of the insulated pavement system, a given thickness of granular material placed below the insulating layer is much more effective than the same thickness of the material placed above the insulation. Hence, the thickness of the pavement and base above the insulation should be the minimum that meets structural requirements, and the thickness of the insulation and additional granular material should be based on the placement of the latter beneath the insulation.

Alternative combinations of thicknesses of insulation and underlying granular material required to completely contain the zone of freezing can be determined from Figure 8, which shows the total depth of frost for various freezing indexes and thicknesses of insulation; the thickness of granular material needed to contain the zone of freezing is the total depth of frost less the total thickness of cover material and insulation. For pavements in seasonal frost areas, experience has shown, however, that limited subgrade freezing may not have detrimental consequences. Accordingly, the total depth of frost given by Figure 8 may be taken as the value a in Figure 3 and a new combined thickness of pavement, base, insulation, and subbase determined. The thickness of the granular material needed beneath the insulation is obtained by subtracting the previously established thicknesses of upper base and insulation.

ACKNOWLEDGMENT

This paper is a summary of a report by Berg to FAA (6).

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Abridgment

Design and Construction of Airport Pavements on Expansive Soils

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The pavements of airports (e.g., runways, taxiways, ramps, parking aprons, and such) are a vital part of the overall facility, and therefore pavement construction and maintenance costs are important in the planning and operation of airports. Premature failure of these pavements (manifested as surface roughness) affects operational limitations, accelerates aircraft fatigue, and reduces safety; on the other hand, initial construction and material costs prohibit deliberate overdesign.

A major cause of premature pavement failure is underlying expansive soils that by shrinking and swelling cause surface roughness. Although current Federal Aviation Administration (FAA) design procedures (1) do not adequately treat the design of pavements over expansive soils, recognition that these soils are a significant engineering problem took place many years ago, and a concentrated effort to solve this problem was begun in 1965.

OBJECTS AND SCOPE

This investigation reviewed the current engineering literature and synthesized from it a design procedure for stabilizing expansive soils beneath airport pavements. To do this, the study was divided into specific areas:

1. Methods of identifying and classifying the types of soil that are considered expansive and cause early pavement distress;
2. Laboratory and field test methods to determine the level of expansion and shrinkage, i.e., prediction of heave; and
3. The design of stabilized soil layers including (a) selection of the type and amount of stabilizing agent (such as lime, cement, or asphalt), (b) test methods to determine the physical properties of stabilized soil, (c) test methods to determine the durability of stabilized soil, and (d) field construction criteria and procedures.

The conclusions and recommendations are based on the current literature, without laboratory verification. Soil-volume changes caused by factors such as frost heave and salt heave were not studied.

CONCLUSIONS AND RECOMMENDATIONS

Expansive Soil Design

Engineering problems associated with expansive soils are significant and warrant the implementation of special design procedures to supplement those normally used. Expansive soils may be detected by observing the performance of structures, but when such observations are impossible or inconclusive, other means are needed. An economical and fast test is desirable to provide an early indication that special testing and design are needed. The current identification and classification systems are based on correlations of simple index properties—the plasticity index and the linear shrinkage—with values of swell measured in the laboratory. In the initial investi-