Frost Action

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The effects of frost action on transportation facilities are costly and disruptive. During the 20th century, great strides were made in understanding and controlling these effects. For example, the relationship between fine soils and thaw weakening was well understood, the mechanisms of frost jacking and frost heaving were documented, and physical and numerical models were developed to the point that they have become useful tools.

DESIGNING FOR IMPACTS OF FROST

Certain design techniques can reduce or eliminate the impacts of frost. The best-known and most widely employed technique is the use of low-fines soils and frost protection. By avoiding fine soils, one can eliminate moisture migration, frost heaving, and the resulting thaw weakening.

Frost protection entails placing non-frost-susceptible soils at an adequate thickness to reduce the strain in the frost-susceptible soil layers to an acceptable level. This technique was first used to design runway pavement structures during World War II.

Drains are commonly used to minimize the impacts of frost. These drains provide a migration path for water during the spring thaw to reduce soil pore pressures and thus maintain the strength of the embankment. The drains come in several forms, including lateral drains, edge drains, and open-graded base courses. All of these techniques have to be proved successful and are documented in the literature. The use of insulation in combination with drains to protect frost-susceptible soils against freezing proved to be extremely effective.

Geotextiles are becoming a common means of controlling the movement of fines and strengthening the pavement structure. Research has shown that, when properly used, geotextiles can reduce embankment thickness and improve pavement life in cold regions. In many cases, marginal aggregates can be used in combination with geotextiles without compromising the pavement life.

While these and other design techniques reduce the impacts of frost on transportation facilities, improvements can be expected in the 21st century. Soil additives show promise as a cost-effective means of controlling moisture migration, frost heaving, and thaw weakening. A better understanding of moisture migration through freezing soils may lead to the development of design techniques that are less expensive and more effective than existing methods.

LOAD RESTRICTIONS

Load restrictions are a common means of controlling damage on thaw-weakened pavement structures. By limiting axle loads, damage to the pavement is reduced, but perhaps more important, trucks often seek alternate routes.

In regions of the country where pavements are constructed in wet, freezing environments, springtime load restrictions are used by many highway agencies as a preservation strategy to reduce distress caused to the pavement by truckloads. This approach is used as an alternative to designing and constructing a more costly pavement section that is capable of carrying the legal limit regardless of the time of year.

During the spring, the air temperature rises, thawing the ground, which in turn increases the liquid moisture content of the ground. At the same time, as the heave subsides and the base and soils begin to consolidate, a dramatic decrease in pavement strength occurs. Soils and aggregate base materials are in a weakened state during and immediately following the thaw period. A recent survey of agencies indicated that most states affected by freezing climates have some method for dealing with springtime damage. The methods used for determining the time at which to place load restrictions range from calendar date, to visual observations, to subsurface temperature measurements, to deflection testing. Types of restrictions include load limits for certain axle configurations, complete shutdown, and reduced speed limits.

Many agencies base their decisions to impose load restrictions on visual observation of conditions that indicate the potential for springtime load-related damage (such as pumping near cracks and shoulders). The down side of this approach is that by the time the thawing process manifests itself at the surface, significant damage may already have taken place.

Numerous schemes have been developed for determining the level and duration of load restrictions. The Canadian Good Roads Association developed a procedure using the Benkleman beam during the 1950s. This procedure was based on the relationship among deflection, actual pavement rebound, and pavement life. Load restrictions were established by monitoring the deflection and using this relationship. Several states employed a similar approach.

The Dynaflect and Road Rater replaced the Benkleman beam in the 1970s. These devices proved faster and less expensive. Further, by providing information about the curvature of the deflection bowl, these devices enabled engineers to assess the strength of the pavement structure during thaw weakening. As a result, pavement engineers realized that total deflection was not a particularly good indicator of the damage being done to pavement. Using models developed by Kelvin, Boussinesq, Burmister, and others, designers were able to assess the stresses and strains in each pavement layer. The result was the ability to better predict the damage from thaw weakening.

The primary drawback of these devices was the low vibratory loading. Low loads did not allow engineers to evaluate the materials at depth. Further, the vibratory loading often resulted in liquefaction of the soils near saturation and unrealistically high damage predictions.

The falling weight deflectometer (FWD) came into favor during the 1980s. This device drops a load onto the pavement in such a manner as to simulate a tire loading. The FWD is the preferred device today. Through use of the FWD, researchers and engineers have been able to analyze the impacts of thaw weakening more accurately. Many states have been able to determine the extent and duration of load restrictions much more precisely. As a result, we now understand that the maximum damage may occur shortly after thawing begins, well before the maximum deflection. However, use of the FWD for establishing load restrictions is expensive.

Many states are using the FWD to assess whether to apply load restrictions. In most instances, air or ground temperature serves as the basis for the determination. This methodology has proved to be cost-effective and is easily understood.

During the new century, we can expect to see the use of heavy vehicle simulators, rolling wheel simulators, and other such devices to better understand the relationships among loads, thaw weakening, and pavement life. Modeling using data from these devices will allow engineers to better understand and predict the damage due to frost action. These devices will also be used to explore new design alternatives that will reduce the need for load restrictions.

Spring load restrictions cause disruptions to freight haulers, and agencies are now attempting to study the associated costs and benefits. Load restrictions may result in the need to make increased trips along a restricted route or to follow alternate, potentially longer routes. Both situations lead to increased costs to the haulers that are passed on to the consumer. Although it is clear that agencies will continue to deal with spring load restrictions into the near future, it is crucial for practitioners and researchers to continue striving for better solutions to this problem.

PHYSICAL MODELING

Physical modeling has remained an important tool for understanding frost action. Several physical models were employed during the 20th century. In the frost chamber, for example, a sample is frozen from the top down with an available water supply, and the frost heave is measured. The frost chamber has allowed researchers to gain an understanding of moisture migration through the soil and to classify soils by their susceptibility to frost action. Another example is triaxial tests, which led to an understanding of the relationships between soil strength and moisture content. These tests range from the standard triaxial tests to resilient modulus testing devices. In each case, a sample is loaded with a deviator stress and a confining pressure. Samples are prepared at a specific moisture content. Often, the pore pressures are measured to help understand the mechanisms that result in moisture weakening. In some cases, the frost chamber and the triaxial tests have been combined to provide a more realistic picture of the impacts of freezing soil and thaw weakening.

Recent developments in centrifuge testing show great promise. With this technique, moisture migration can be physically modeled both rapidly and accurately.

NUMERICAL MODELING

Numerical modeling enables researchers and design engineers to model the thermal characteristics of soil, as well as the soil’s potential to heave. These models range in simplicity from the Modified Berggren Equation, which estimates the depth of freeze or thaw, to Frost, which models the thermal regime in the soil, as well as moisture migration.

Thermal models are the most common models used in cold regions. They typically use finite-difference or finite-element techniques to estimate the thermal regime in the ground. These models are capable of one-, two-, and three-dimensional analysis. While one-dimensional analysis is often adequate, improvements in computer hardware and software are rapidly reducing the difficulty and time required to process three-dimensional thermal models.

The most difficult part of thermal analysis is estimating the input boundary conditions, such as ground surface temperatures. While we have many years of air temperature data, few data on ground surface temperatures are readily available. Surface temperature models are, to date, inadequate.

The Frost model, developed by the U.S. Army Cold Regions Research and Engineering Laboratory, models both soil temperature and moisture transport. As a result, it can be used to estimate frost heave. The results of Frost have been encouraging. However, a common complaint has been the difficulty of determining the moisture transport parameters required by the model. Centrifuge modeling offers hope of providing this information.

While numerical modeling has advanced during the 20th century, considerable work remains to be done in this area. Surface temperature modeling, moisture transport modeling, and soil strength estimations are but a few of the most important areas to be explored in the coming century.

SUMMARY

Understanding of frost action matured during the latter part of the 20th century. We now understand the relationships among fine soils, moisture, frost heave, and thaw weakening. However, as quality materials become more difficult to obtain, pressure to use marginal materials will increase. Through soil additives, moisture barriers, drains, and other innovative methods, it will become possible to counteract the impacts of frost in transportation facilities.

As transportation costs rise, pressure to eliminate load restrictions on weak roads will increase. Consequently, it will be necessary to seek cost-effective means of building transportation facilities that can survive heavy traffic without disruption.

The 21st century holds promise for resolving these and other issues surrounding frost damage. However, continued focused research will be required if frost damage is to be eliminated.