文章编号:1000-0240(2002)05-0593-08

Cold Region Pavements

(寒区路面)

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Abstract: The article mainly discusses several essential problems of cold region pavement, including thermal cracking of asphalt concrete, cracking deterioration and heaving, frost heave, seasonal and long term roughness induced by different frost heave, frost heave cracking, bearing capacity loss during spring thaw. The reason for these problems is that cold region pavements are subjected to intense solicitation by climatic and environmental factors. The author offers several models corresponding to the solicitation. Furthermore in conclusion of the article the author indicates future research for cold region.

Key words: thermal cracking; crack deterioration; frost heave; frost heave cracking

CLC number: U419.92 **Document code**: A

1 Introduction

Cold region pavements are subjected to intense solicitation by climatic and environmental factors. The three main factors contributing to pavement deterioration in cold climate are: Thermal contraction and fracture in bound layers, volume change caused by frost heave and bearing capacity loss during spring thaw. These factors are likely to reduce both the functional and the structural levels of service of pavements. They are considered to be important causes of pavement deterioration in cold climates.

2 Cold Region Pavement Problems

2.1 Thermal cracking of asphalt concrete

Bound materials are sensitive to temperature variations. As temperature drops, asphalt concretes tend to contract. In the absence of joints, the contraction is restrained and tensile stresses build-up in the material. If the stresses exceed the strength of the material, a thermal crack is initiated. Since flexible pavements are infinite along their longitudinal axis, stresses tend to develop along this axis. Therefore, thermal cracks occur transversally and are thus also called transverse cracks. Figure 1 illustrates the build-up of stress and strength in bound materials subjected to progressive cooling. As temperature drops in the material, stress and strength increase following parallel courses until the glass transition temperature is reached. Above that temperature, the asphalt cement is in a fluid state and stress relaxation without fracture occurs under thermal stress. Below that temperature, asphalt cement is in a glassy state and stresses cannot be relaxed. The strength of the material is thus reduced and cracking can occur.

According to Vinson *et al.*[1], the factors affecting low temperature cracking of asphalt concrete pavements can be grouped in three main categories:

Material related factors:

(1) The temperature-stiffness and the temperature-strength relationships of the asphalt cement;

(2) Aggregate type and gradation;

Received date: 2002-06-12; **Modified date**: 2002-08-10

(3) Asphalt cement content.

Environment related factors:

(1) Temperature (the colder the surface temperature, the greater the incidence of thermal cracking);

(2) Rate of cooling;

(3) Pavement age (hardening of asphalt cement with age).

Pavement structure and geometry:

(1) Pavement width (Thermal cracks are more closely spaced on narrow roads);

(2) Pavement thickness (Thicker pavements resist better thermal cracking);

(3) Friction between the AC layer and the base course;

(4) Subgrade type (Pavement on cohesive subgrades are less subjected to thermal cracking);

(5) Construction flaws.

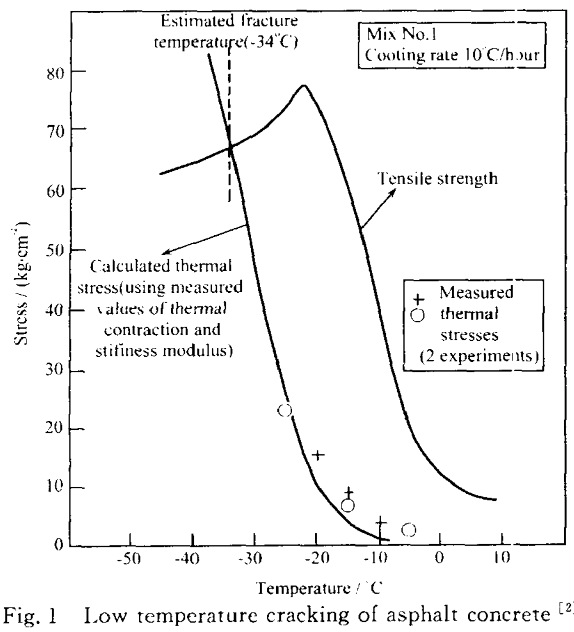

Fig. 1 Low temperature cracking of asphalt concrete [2]

2.2 Crack deterioration and heaving

Once cracks are initiated in the asphalt concrete surface, pavement deterioration is accelerated. The reduction of the layer stiffness in the vicinity of the crack combined with base material weakening caused by water infiltration amplify pavement damage caused by truck traffic. As a result, secondary cracks are initiated and the main crack tends to become faulted and depressed.

Another frost related problem has been observed on cracked pavements where deicing salt are used to maintain the surface free of ice during winter. Short wavelength surface deformation resulting from frost heaving along transverse cracks seriously affects driving conditions at the end of winter. Several cases are reported and studied each winter in Canada. Profile measurements along a line perpendicular to the crack indicate that frost heave tend to be maximum at short distance (approximately 300 mm) on both side of the crack which is generally slightly depressed. The measured difference in elevation of the crack area compared with the surrounding uncracked pavement surface has been found to be as much as 90 mm.

Recent studies conducted at Laval University[3,4] have shown that ice segregation can occur in pavement granular layers (usually considered non-frost susceptible) near cracks and that deicing salt plays a major role in the process. It appears that salt concentration gradient and the resulting gradient in freezing temperature can effectively replace the temperature gradient in the ice segregation process in salt free frost susceptible soil. Moreover, it seems that the saline gradient can contribute to increase the frost susceptibility of granular materials. Figure 2 is a schematic illustration of the ice enrichment process.

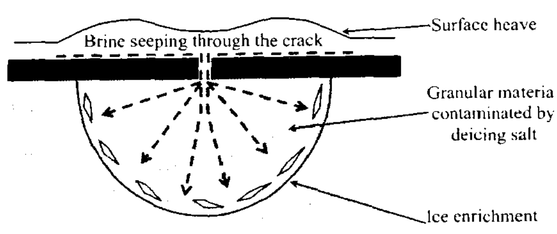

Fig. 2 Frost heaving in granular bases contaminated by deicing salt

2.3 Frost heave

During winter, frost penetrates in pavement materials and subgrade soils. While progressing in the pavement structure, frost cause interstitial water to expand and can also cause segregation ice to form in the unbound granular materials. Notwithstanding the fact that these phenomena are generally considered insignificant in pavement granular materials, they cause the materials to loosen.

Heaving of pavement surfaces reaching 10～15 mm have been observed on experimental test sites before the frost front reached the subgrade soil. When the frost front reaches frost susceptible subgrade soils, water is sucked toward the frozen fringe where ice lenses are formed. Heave of the pavement surface resulting from these phenomena can reach and even exceed 150 mm for climatic conditions prevailing in Canada.

2.4 Differential frost action

The problem with frost heave is mainly due to the fact that the phenomenon is rarely uniform. As a result, pavement becomes distorted during winter causing increased roughness and cracking of the pavement surface. Differential frost heaving can be attributed to four major causes. The first cause, described by Peterson and Krantz[5], is associated with the instability of the one-dimensional freezing process. It was found that the one-dimensional frost heave has the propensity to evolve into multi-dimensional differential frost heave as a function of soil properties and environmental conditions. The other causes of differential heaving are the variability in the frost susceptibility characteristics of the subgrade soil (including moisture availability), the variability of the thermal regime and the topography of the surface and/or the geometric characteristics of an earth structure[3].

2.5 Seasonal and long term roughness induced by differential frost heave

Surface distortions have a significant impact on the service level of roadways. Long wavelength distortions induce oscillations of the vehicle, making driving uncomfortable. Short wavelength distortions induce vibrations in the steering system and increase the risk of accidents. In general, surface distortions increase the dynamic forces acting on the moving vehicle and reduce adherence in curves and braking situations. They also cause the suspension to absorb energy increasing thus the fuel consumption and vehicle maintenance. Finally, rough surfaces amplify dynamic loading of the pavement increasing thus the associated pavement deterioration.

Figure 3 shows raw profiles measured during summer and winter for a road test section near Quebec City (Canada). The average frost heave of 40 mm was added to the winter profile to compensate the absence of absolute elevation reference for the profile measurements. The winter profile for the test section follows a close resemblance to the summer profile. However, it is characterized by a succession of 10 m long humps.

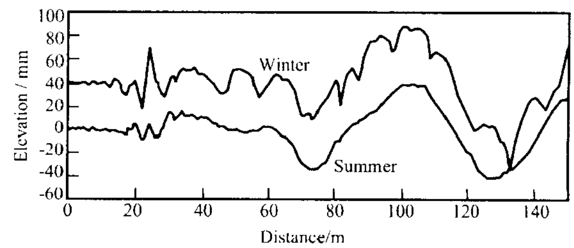

Fig. 3 Summer and winter profiles on a road test section near Quebec City

Researches recently conducted at Laval University (Canada)[6] have shown that seasonal and long-term development of road roughness can be related to the variability of subgrade soil properties.

2.6 Frost heave cracking

As illustrated in figure 4, snow accumulation on the pavement sides affect the thermal regime and result in a greater frost penetration at the center of the pavement than at the edge of the pavement. The transverse differential heaving can be assimilated to a bending moment[7,8] imposed to the pavement transverse section. It is likely to generate excessive tensile stresses and initiate longitudinal or meandering cracks. Road users are not directly affected by the phenomena but the resulting cracks can be highly detrimental to the structural performance of the pavement because they intercept running surface water[9].

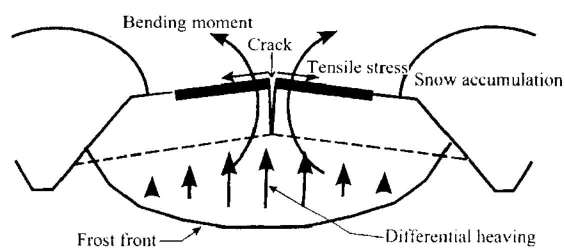

Fig. 4 Transverse differential heaving

Longitudinal cracking will occur when tensile stresses induced in pavement by the bending action (σ_F) exceed the low temperature tensile strength of the asphalt layer (σ_R). The ratio σ_F/σ_R is defined as the solicitation index and will be used to relate the mechanical action of transverse differential heaving to the deterioration of the pavement surface by longitudinal cracking[10].

2.7 Bearing capacity loss during spring thaw

During spring, thaw penetrates into the pavement structure and releases the water accumulated in the interstitial and segregation ice. High water contents combined with lower densities are essentially responsible for the weakening of pavement materials and subgrade soils. The strength is then progressively recovered as soils and materials consolidate (drain) over time.

Many authors consider spring thaw as being the most important damage factor for pavement subjected to frost action[11~14]. Several studies have been conducted to quantify the loss of bearing capacity and it's effect on pavement performance. Based on several studies conducted using California Bearing Ratio (CBR) tests, plate bearing tests and Falling Weight Deflectometer (FWD) tests, the loss of bearing capacity of the subgrade soil is ranging from 20 to 60% depending, among other factors, on soil type. White and Coree[11] have reported that 60% of pavement failures during the AASHO road test occurred during spring. Moreover, based on a fatigue criterion and measurements done on several test sections in Quebec, St-Laurent and Roy[15] have established that the relative damage caused by a given load during springtime is between 1,5 and 3 times higher than the average annual damage. Figure 5 shows the importance of spring thaw bearing capacity loss in the accumulation of fatigue damage on an experimental test road in Quebec, Canada.

Figure 6 illustrates that frost heave and thaw consolidation (as a function of time) can be divided in four distinct phases. In figure 6 (bottom), these phases are illustrated in a density-moisture space. Assuming initial density and water content near

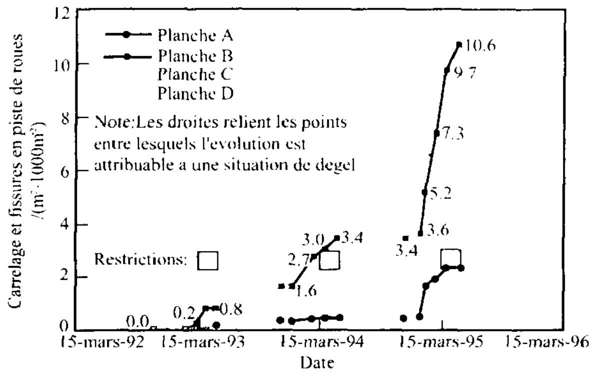

Fig. 5 Accumulation of fatigue damage on four experimental sections of Highway 10 in Fleurimont, Quebec [Source: Quebec Ministry of Transportation]. The squares on the figure correspond to the load restriction periods

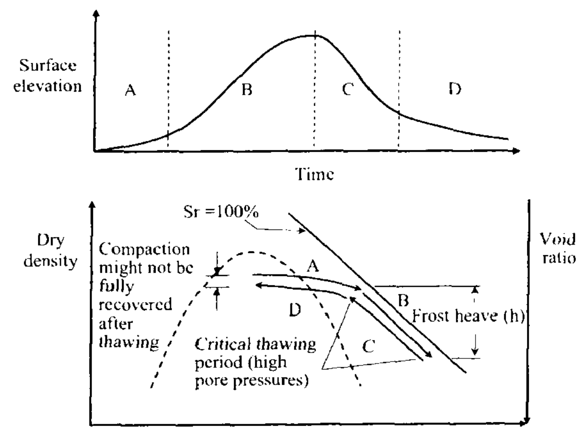

Fig. 6 Volume change with time (top) and moisture density relationship (bottom) during the four phases of the freeze-thaw process

optimal conditions, frost penetration generates high suction at the segregation front. Available water is then forced to flow toward the freezing front increasing the water content of the freezing soils (phase A). During the ice segregation process, water is pumped through the frozen fringe causing an important volume increase (reduction of the soil dry density) near the segregation front (phase B). During the second phase, the soil structure is essentially supported by frozen water.

When thaw progresses through the soil layer, water is gradually released from interstitial and segregation ice. This phase, denoted C on the figure, is considered as the critical period during the thawing process. At the scale of a very small soil element located at the thaw front, the effective soil strength tends toward zero due to high pore pressures prevailing at that location. If the amount of ice in the soil element and if the thaw rate tend to be low while the drainage capacity and, as a result, the consolidation rate are high, the effect of the strength loss of the soil element is going to be short and limited to a small area. Therefore, the weakening occurring at the thaw front is going to have a limited effect on the bearing capacity of the soil layer. Increasing ice content and/or thaw rate combined with decreasing drainage capacity will cause the thickness of the weakened area and the duration of the weakening to increase. The effect on the bearing capacity of the layer can then be considerable.

After pore pressures are dissipated in the thawed soil, drainage of interstitial water will continue until equilibrium is reached between the flow gradient and soil suction. During that phase (D), additional settlement is caused by increasing matric suction.

Thaw weakening is thus a complex process, which is essentially a function of three major factors:

(1) The amount of frost heave occurring in the considered layer.

(2) The rate at which the layer is thawing.

(3) The rate at which the layer consolidates.

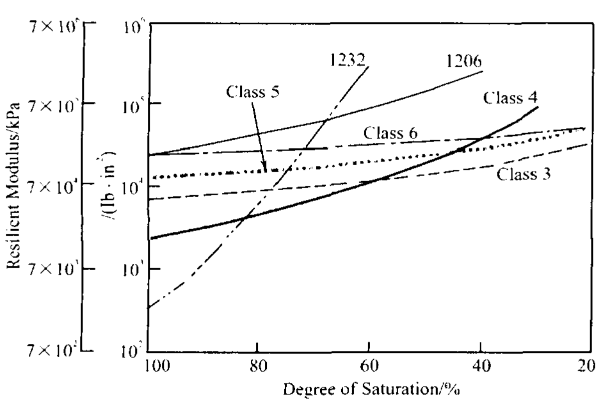

Fig. 7 Influence of the degree of saturation on the resilient modulus of pavement granular materials[16]

Several authors have attempted to characterize soil and material mechanical behavior during the thawing process. The studies are based on laboratory resilient modulus measurement or field observations using deflection testing. The models developed are generally based on empirical relationships between moisture content and resilient modulus[16] or between backcalculated elastic modulus and pavement condition during spring thaw[15].

2.8 Predictive tools

Several models are available in the literature to help predict pavement response to solicitation by load and climate. These models vary in complexity, ranging from simple statistical models to complex thermo-mechanical models. Table 1 gives a short summary of some commonly used models.

Performance prediction remains one of the main challenges for pavement engineering in cold climates. Load related deterioration models can easily be adapted to seasonal frost conditions by integrating damage prediction over a full seasonal cycle. This type of approach allows accounting for increased bearing capacity during winter and reduced bearing capacity during spring in predicting fatigue and permanent deformation caused by load repetition. A few other models allow for the empirical prediction of pavement serviceability loss as a function of factors related to seasonal frost conditions. Recent research work done at Laval University has led to the development of mechanistic-empirical models relating roughness development and non-wheel path longitudinal cracking with differential frost heaving[6,10].

2.9 Design considerations and approaches

Several strategies can be used to improve pavement performance in frost conditions. As shown in Table 2, these strategies must be adapted as a function of the main factor affecting pavement deterioration (Differential frost heave or bearing capacity loss during spring). Several mitigation techniques can be considered to adapt the pavement structure or to neutralize the problem.

2.10 Design procedures for pavements in frost conditions

The state of practice and knowledge in the field of pavement design in frost conditions shows that the discipline is still essentially based on em-

Table 1 Pavement response models

Type of response	Input parameters	Typical Output	Examples
Temperature	• Surface temperature (freezing/thawing index) • Material characteristics • Thermal conductivity • Heat capacity • Latent heat	Frost depth Thaw depth	• Modified Berggren • Numerical solutions of Fourier s thermal diffusion equation • Heat balance models • FHWA integrated climatic model
Moisture	• Hydraulic conductivity Hydraulic gradients Segregation potential Moisture-suction characteristic curve Soil characteristics	• Frozen and unfrozen water content • Pore pressure	• Darcy s law • Water potential model • Richard s model • FHWA integrated climatic model
Volume change	• Temperature regime • Moisture regime • Frost susceptibility (segregation potential) • Consolidation coefficient • Overburden pressure	• Frost heave • Thaw settlement	• Coupled heat and mass transfer models • Segregation potential model • SSR model (Finland)
Load related	• Load characteristics • Layer thickness • Material characteristics (modulus and Poison ratio) • Seasonal variations of material characteristics	• Tensile strains at the bottom of the asphalt concrete • Compressive strains on subgrade soil	• Odermark-Boussinesq • Burminster

Table 2 Summary of mitigation techniques for cold region problems on pavements

Deterioration factor	Type of intervention	Mitigation techniques
Differential heaving	Adaptation of pavement structure	Increase pavement thickness (sub-base)
		Increase cracking resistance of asphalt concrete
	Problem neutralization	Drainage
		Pavement insulation
		Subgrade soil homogenization
		Remove and replace frost susceptible subgrade soil
		Chemical stabilization of subgrade soi
Bearing capacity loss	Adaptation of pavement structure	Increase pavement rigidity
		Increase pavement thickness (base layer)
	Problem neutralization	Drainage
		Pavement insulation
		Remove and replace frost susceptible subgrade soil
		Chemical stabilization of subgrade soil

pirical foundations [17~19]. Some methods use more rational procedures. For example, design procedures used in France, Finland, Norway and the one proposed by the Cold Region Research Engineering Laboratory in United-States, use site-specific calculation to assess the value of a frost action indicator (frost heave, frost penetration, etc.). The indicator is then compared with a pre-established threshold or "acceptable" value. If needed, the structure is modified until the value of the indicator reaches an acceptable value. These methods are interesting since they allow modifying certain design parameters as a function of the value of the indicator. Threshold values are however based on local experience, conferring thus to these approaches a strong empirical connotation. It is besides presumed that the threshold value is an optimal value below which the road will have a poor performance and beyond which the pavement will be over-designed. Moreover, these approaches do not so allow establishing the consequences, in term of gain or losses of performance, of not meeting the threshold.

The AASHTO [20] and the Ontario (OPAC) methods include procedures allowing for the determination of a serviceability loss associated specifically with frost action. The principle of these approaches is very interesting although they use composite performance indices (PSI or RCI) as dependent variables. These variables are good indicators of the global quality of the road but, because they integrate several deterioration modes, they do not allow for the establishment relationship between pavement distresses and specific design parameters.

The AASHTO method also includes a procedure to integrate pavement damage caused by traffic on a bi-weekly or a monthly basis. This procedure constitutes a rationale approach to take into consideration the seasonal variation of the bearing capacity of subgrade soils. A similar approach can be used to compute incremental damage caused by traffic to pavement structure as a function of seasonal variations in soil and material characteristics. Several authors have described mechanistic-empirical design procedure to analyze pavement damage in seasonal frost conditions [21]. These methods are yet incomplete since they do not allow taking into consideration damages caused by frost heave.

Recent developments in Finland [22] and at the Cold Region Research and Engineering Laboratory (CRREL) [12] as well as concepts proposed by other authors[23~25] suggest the use of performance-based criteria for pavement design in frost conditions. None of the proposed approaches allow however to calculate a life expectancy and to quantify a service offered to the users according to criteria specific to frost action. Therefore, they do not so allow for a real optimization of the structural characteristics of the pavement in a seasonal frost context. Doré and Rioux[18] have recently proposed a pavement mechanistic empirical design model that takes into consideration frost heave as well as seasonal damage caused by traffic. As illustrated in Figure 8, the model includes mechanistic procedures to assess differential frost heave coupled with related performance models.

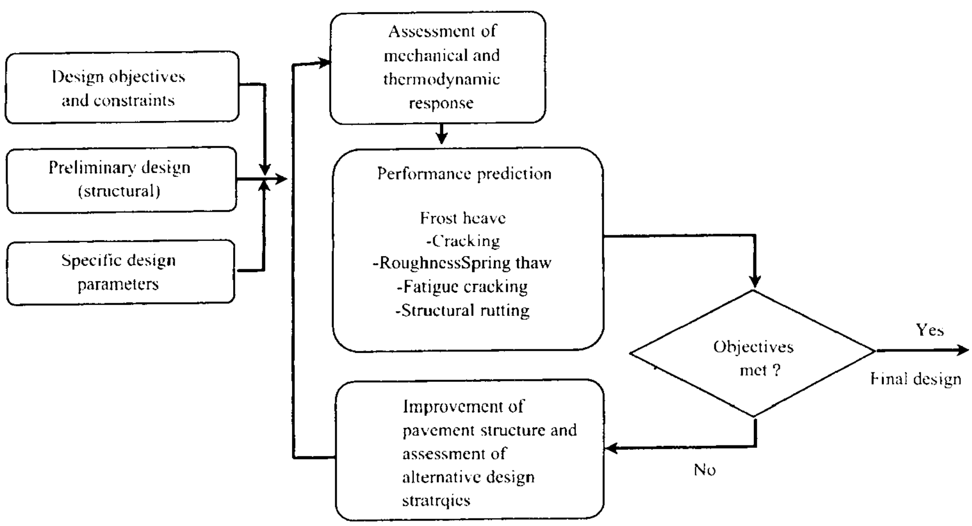

Fig. 8 Conceptual outline of the proposed frost design procedure for pavements subjected to seasonal frost [18]

3 Conclusion

Frost action is a major cause of pavement deterioration in seasonal frost areas. The main problems affecting pavements are thermal cracking of asphalt concretes, differential heave and bearing capacity loss during spring thaw. Several predictive tools are available to assess the thermo-mechanical response and performance of pavements subjected to solicitation by climate and traffic. Research is however still needed to improve pavement performance in cold climates. Future research should focus on the development of performance prediction models specific to frost action, material characterization with respect to their behavior during freezing and thawing and pavement design tools allowing for the optimization of pavement structures subjected to freeze thaw cycles. The development of cost effective mitigation techniques for most problems related to frost action is also required.

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