

# Review of Low-Temperature Crack (LTC) Developments in Asphalt Pavements

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## **ABSTRACT**

The article presents a review of low-temperature crack (LTC) developments in asphalt pavements commonly observed in regions affected by cold weather. The cold weather contributes significantly towards the development of these low-temperature cracks (LTCs). Since the 1960s, many studies have been published, proposing various cracking mechanisms. The simplistic reason for the development of cracks in low temperatures is thermal stresses, due to contractions and a drop in the pavement's strength. However, other factors such as frost action also play a significant role. The impact of frost action on LTCs depends on the type of soil and water/moisture content. In addition to frost action, other factors also contribute directly or indirectly to the development of cracks. A comprehensive review of various types of cracks and their mechanism of development is given in the article. It is concluded that, to develop remedies, it is vital to understand the types of cracks.

## **1. INTRODUCTION**

A typical asphalt pavement consists of layers, starting from natural ground, ballast, core/lining, filter, shoulder/erosion protection, embankment, subbase, base course, asphalt binder course, and asphalt wearing course, as shown in Figure 1.

There are various causes of pavement deterioration such as overloading, seepage, improper or poor road surface drainage, insufficient road maintenance, poor design, and adverse climatic conditions [1]. This work focuses on adverse climatic conditions, particularly cold weather.

Cold weather accelerates the deterioration of the transportation infrastructure system, particularly roadways. The pavements are subject to extremely cold weather conditions because of environmental factors such as oxidation, thermal cracking, subgrade softening, freeze-thaw damage, joint deterioration (spalling), and scaling [2].

The severe cold weather is responsible for low-temperature cracks (LTCs) on the asphalt pavement, due to differential thermal contraction. It has been observed that an instant drop in surface temperature of more than 9.5°C (15°F) can result in the development of cracks, due to surface contractions [3].

LTCs are common in Alaska, Canada, Norway, Russia, the United States, Arctic regions, and other locations experiencing severely cold weather. LTCs are the result of thermal contractions, which build transverse stresses exceeding the tensile strength of the pavement's material, leading to failures such as LTC. The daily temperature cycle accompanying the

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repeated heating and cooling also aids LTC formation across the road and down the pavement structure. LTC forms even when traffic load and volume are not high. LTC is just the initiation, helping water to seep through into the pavement structure, causing a reduction in subbase strength and the loss of fines. This further leads to deterioration, to the extent that potholes are formed [4, 5]. In addition, the freezing temperature of the surrounding air causes surface deterioration [6]. Furthermore, the fluctuation in temperature enhances the development of LTCs [7]. [4] has reported that de-icing materials (such as salts and others) cause water seepage through the LTC and defrost the subgrade. The fine grain material in the subgrade mixes with water, creating a gap. This results in a depression, hence reducing the service life of the pavement.



Figure 1: A typical asphalt pavement.

The LTC has been extensively studied [5], for example its mechanism [8, 9], laboratory experiments' methods [10, 11], field investigation [12], different influencing factors [9, 13, 14], corrective maintenance to increase the cracking resistance [15-17] and the assessment of cracking potential through empirical and mechanical models [10, 18, 19].

The governing principle of the LTC is shown in Figure 2. The strength of the pavement's material varies with temperature and has a decreasing trend in low as well as high temperatures. As shown in Figure 2, thermal stresses rise exponentially as the temperature drops and can be related to thermal contractions. The estimated cracking temperature is the point at which thermal stresses surpass the strength. This point is highlighted in Figure 2.

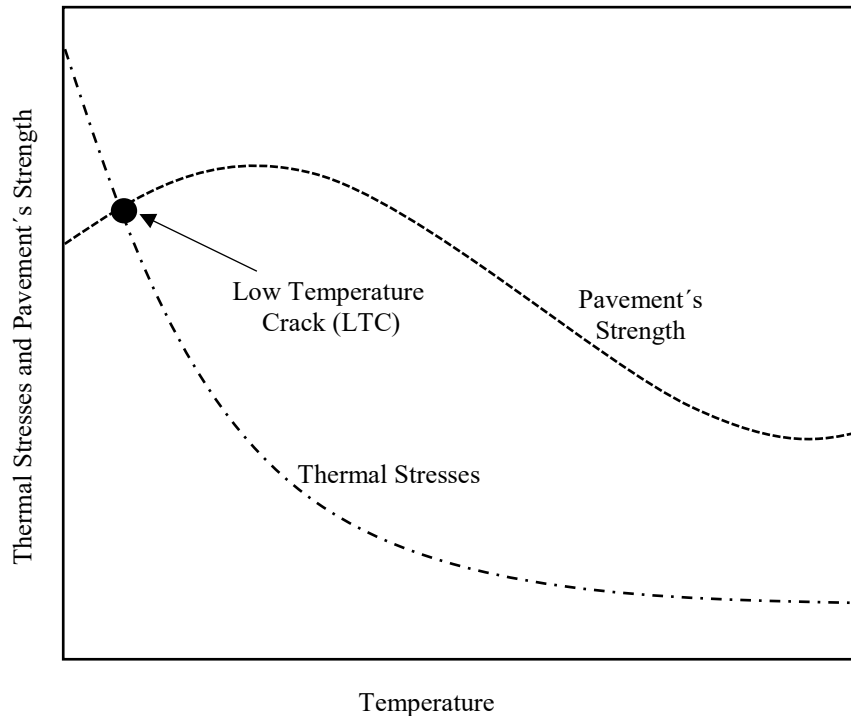


Figure 2: The governing principle of low-temperature cracking (LTC) [4, 19].

## 2. HISTORICAL PERSPECTIVE

The research on low-temperature cracking began in the 1960s. [20] worked on the characteristics of pavements undergoing low temperature cracking. They found that the low temperature is not the only cause of cracking; it is also caused by variations in mixes and climate. [7] discussed the early studies on road cracking. [21] explained the thermal cracking mechanism, which involves shrinkage due to different temperatures in the asphalt pavement and the subgrade. [22] observed that the characteristics of the asphalt binder and mix change with time. [23] identified that thermal cracking mainly happens because of the subgrade and subbase materials in cold weather. They observed that cracks on the northern Minnesota road surfaces were deep enough to pass through the subgrades, reaching the base soil. [24, 25] experimentally proved that the coefficients of thermal expansion and contraction differ and vary with temperature. [4, 26] presented three causes of low-temperature cracking. First, tensile stress build-up, due to the temperature drop, exceeds the tensile strength of the pavement. Second, cracks develop in the subgrades, due to freezing and shrinking. Finally, the cracks propagate through the pavement, due to the freezing and shrinking of the subbase. They proved that pavements with a high stiffness modulus are more prone to developing cracks at low temperatures.

LTCs were observed in the Ste Anne Test Road, built in Manitoba in 1967 [7, 27]. In this study, thermal contraction coefficients and breaking stresses were calculated. The results showed that the predicted temperature was consistently lower than the actual temperature at

which LTCs would occur. It was also concluded that the LTCs also depend on the subgrade and type of asphalt binder used in the pavement. They also noticed that initial cracking occurred on the pavement surface at the minimum surface temperature for the day. Pavements with sandy subgrade material were also observed to undergo more cracking than those with clay subgrade soil [4, 7].

[28] recommended eliminating specific asphalt binders with poor low-temperature performance. [4, 29] presented a model to identify low temperature cracking. This model calculated the pavement temperature by the air temperature and solar radiation values. The low-temperature cracking was predicted by using the mix stiffness in this model and then compared favorably to actual cracking that has occurred on test roads in Ontario and Manitoba.

[30] explained the factors that affect LTCs such as climate, subgrade type, asphalt properties, mix design and properties, pavement design, the age of the pavement and traffic. [31] designed a computer program and used the viscosity, coefficient of thermal contraction and temperature susceptibility data, in order to predict the LTCs. Similarly, [32] also provided a computer program, COLD, and reported that fracture strength is affected by the aggregate type and may be increased by up to 10-15%. The COLD computer program was used to investigate fracture temperature by using the daily air and pavement temperature, initial temperature gradient, stiffness modulus, tensile strength values, and thermal properties of the asphalt concrete layer. The COLD model demonstrated that the effect on LTCs of aggregate type was small, compared to the effect of asphalt viscosity. [4, 33] found that each asphalt source type has specific stress-strain characteristics. Asphalt with a higher value of failure strain provides more resistance against LTCs.

[4, 34] performed a statistical analysis that comprises many variables such as minimum temperature, Pen Vis Number (PVN), asphalt layer thickness, coefficient of thermal contraction, base thickness, subbase thickness, road width, overlay age (construction year), asphalt content, consistencies of binder, and stiffness and stresses of binder at various temperatures. This analysis included four regression models, consisting of particular variables. The first regression model included minimum temperature, which is believed to be the main reason for LTCs. The two-variable model consisted of PVN and minimum temperature. The three-variable model comprised minimum temperature, PVN, and coefficient of thermal contraction. The four-variable regression model consisted of the highest correlation coefficient of  $R^2=0.70$  with minimum temperature, PVN, the coefficient of thermal contraction, and pavement layer thickness.

[4, 7] explained the many factors which may contribute to LTCs such as pavement age, granular base layers, degree-days of temperature below freezing, the rate of change of temperature, and pavement layer thickness. According to [35], the stiffness of an asphalt mixture is a most significant factor in LTCs. Binder stiffness may reduce with aging, hence increasing the chances of forming LTCs. [35] also stated that cracks in the existing pavement layer might appear through new overlays. They also suggested the use of polymer modified asphalt aids against thermal cracking performance. Other factors, such as the use of lime and aging of the HMA (Hot-mix asphalt concrete), may also contribute to reducing LTCs.

[36] reported on porous asphalt pavement performance in cold regions in Minnesota and included the study of durability, maintenance requirements, hydrologic benefits, and environmental considerations of a full-depth porous asphalt pavement, installed on a low-volume roadway in a cold climate. In this project, they constructed two porous asphalt test

cells on the low-volume road test loop. One porous asphalt cell was constructed over a sand subgrade and one over a clay subgrade. The cross-slope data indicated that both pavement cells had undergone seasonal vertical distortion (rutting). This rutting could have resulted from seasonal (frost/moisture) influences, heavy vehicle loading, and/or the movement of open-graded base material.

A comprehensive study on LTCs of typical Alaskan asphalt paving material was presented by [5], who showed the behavior of Alaskan asphalt binders and mixtures in freezing temperatures, through experiments. Similarly, the Superpave project in the US and the ‘Frostschutz’ system developed in Germany are looking into preventing freezing/thawing in the lower layers [37].

### 3. FROST ACTION (IN SUBGRADE)

Subgrade is the soil supporting the pavement. It is important to know which soils are susceptible to frost heave or frost action. Frost action is defined as the expansion and ultimate consolidation of fine-grained soils due to freezing and thawing [2]. Frost action depends on factors such as the type of soil, moisture/water content, and fluctuation in temperatures (freezing/thawing).

#### 3.1. Type of soil

Frost action varies with the soil’s hydraulic properties such as capillarity and permeability [2, 38]. Soils with high permeability and low capillarity, such as sands and gravels, are least prone to frost susceptibility. Soils such as gravel and sands with very fine sands are more susceptible to frost action due to moderate capillarity and permeability. Very fine sands, silty sands and silts are fine-grained soils that enhance the fluid flow by capillary actions through their pores and promote severe frost action severely. Soils with high capillarity and low permeability such as clays (heavy, lean, silty, and sandy) undergo little frost action. The relationship between frost action and the hydraulic properties (capillarity and permeability) of various types of soils is shown in Figure 3.

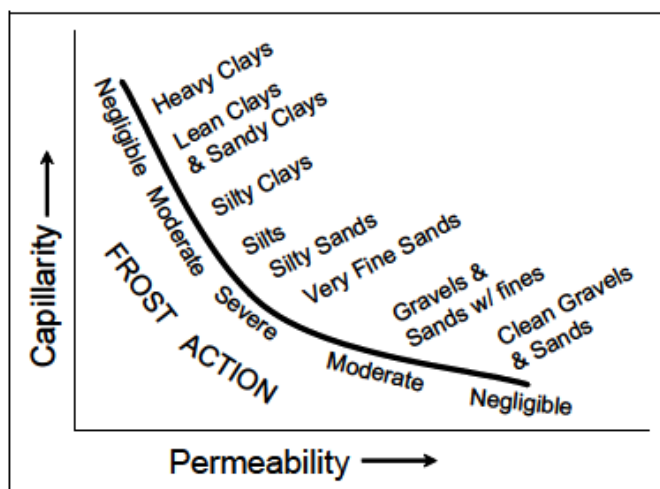


Figure 3: Relationship between frost action and hydraulic properties (capillarity and permeability) of various types of soils [2].

### 3.2. Moisture/water content

Water seeps into the pavement by various means such as cracks in the pavement surface, permeable surface, pavement edges, lateral movement of the shoulder, percolating water, high water table close to pavement surface and liquid and vapor movement from the water table [4, 39].

The presence of water/moisture in the subgrade, base, or asphalt layer is the major cause of LTCs. It causes frost heave and loss of stability, due to thawing and softening of the subgrade. Soil types and their characteristics, pavement types and traffic conditions also play a part.

The severity of frost action depends upon the amount of soil water. Frost action may happen in two phases: (1) freezing of the soil water (2) thawing of the soil water. The freezing phase results in heaving of the road surface, and the thawing phase causes softening of the roadbed.

Frost heaving begins with the formation of ice lenses in the soil, as shown in Figure 4. These ice lenses form when free water within the soil freezes. The frozen soil water expands by 9% volume. In certain cases, the lens grows as water is fed from the water table due to the capillary action. The growing lens pushes the pavement surface, resulting in the development of LTCs, as shown in Figure 4 [2, 3, 40].

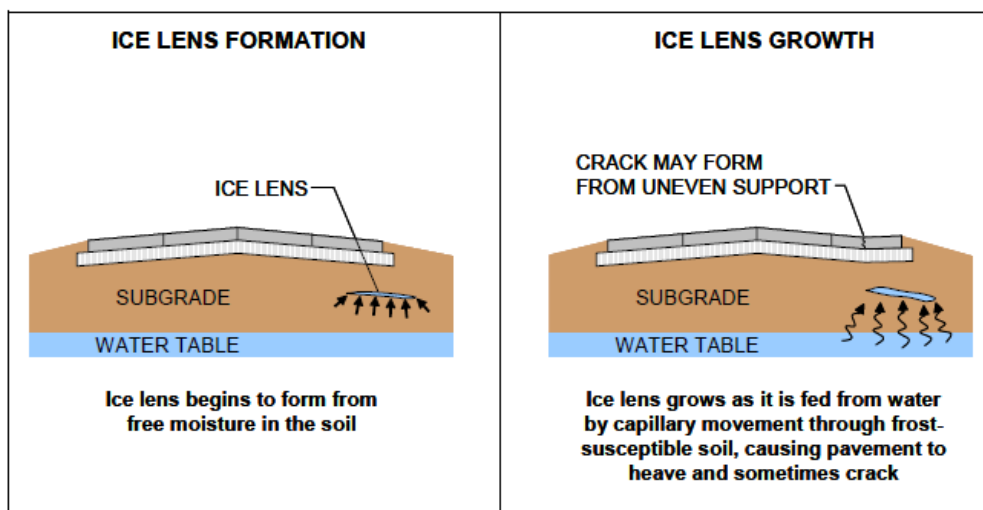


Figure 4: Ice lens formation and frost heaving [2].

## 4. LOW-TEMPERATURE CRACKS (LTC)

This section covers the different types of cracks that may result from cold climate conditions. The following defects are discussed: fatigue cracks, block cracks, edge cracks, longitudinal cracks, reflection cracks, transverse cracks, patching and potholes, rutting, corrugations, shoving, depressions, swells, raveling, and polished aggregate.

### 4.1. Fatigue cracks

Fatigue cracks are interconnected and develop into many-sided, sharp-angled pieces, usually less than 0.3 meters (m) on the longest side, as shown in Figure 5. These cracks are also called alligator cracks. Extreme climate conditions and heavily loaded vehicles are the main causes

of fatigue cracking. A weak and thin surface and base also contribute to the cracks' development. This cracking may lead to structural failure and water seepage through the cracks and can further degrade to form potholes [41].



Figure 5: Alligator cracks on the asphalt pavement [42].

#### 4.2. Block cracks

Block cracks appear in the form of interconnected rectangular pieces, as shown in Figure 6. Water can seep through the block cracks, which range in size from approximately 0.1 m<sup>2</sup> to 10 m<sup>2</sup>. These cracks develop in pavements where the asphalt mix is very dry and there are absorptive aggregates [41, 43].

#### 4.3. Edge cracks

Very common in cold regions, edge cracks have been identified as long and arching and a combination of longitudinal and crocodile cracks near the edge of the pavement, as shown in Figure 7.

The following are possible causes that may result in edge cracking.

- The muddy material on the side of the road does not allow the water to escape from the base beneath the pavement edge after it enters through the cracks. This water softens the subgrade and base under the pavement.

- The surface and base are both relatively very thin; therefore; they cannot tolerate the stress of traffic.
- If water ponds on the shoulder near the pavement edge, then it seeps into the base and softens it. This results in the edge of the pavement breaking off and raveling away.
- The shoulder's muddy material is more frost susceptible and accommodates more ice lenses and snow. This snow melts during spring, and water seeps into the subgrade.
- Edge cracks normally develop in narrow roads. Heavy traffic (i.e. trucks, which are wider and tend to drive near the edge of the road) results in the heaviest load on the edge of the road. The wheel load near the edge of the road bends the pavement down when the base and shoulder material is weak during the spring thaw. The passing traffic in the narrow road also results in bending the pavement down, and tension cracks develop. These tension cracks become wider and propagate with repeated loading.
- The edge cracks allow surface water to sieve into the base and weaken it further. More water softens the base and subgrade, which leads to more cracks [44].



Figure 6: Block cracks in the asphalt pavement.

#### 4.4. Longitudinal cracks

Longitudinal cracking forms in the direction of the traffic flow or predominantly parallel to the pavement centerline, as shown in Figure 8. The possible causes of these cracks are poorly constructed paving joints, shrinkage of the asphalt layer, daily temperature cycling, cracks in an underlying layer that reflect up through the pavement, and longitudinal segregation, caused by improper operation by the paver.





Figure 7: Edge cracks in the asphalt pavement [44].



Figure 8: Longitudinal cracks in the asphalt pavement.

#### 4.5. Reflection cracking

These cracks develop over an existing crack or joint. They occur directly over the underlying cracks or joints and the process is also known as “joint reflection cracking”, as shown in Figure 9. This type of crack forms due to the differential movement between the asphalt and concrete layers, because of thermal and moisture changes, or shrinkage cracking in the subgrade and reflection up through the surface layers, or too thin flexible pavement surface.



Figure 9: Reflection cracks on the asphalt pavement.

#### 4.6. Transverse cracks

Transverse cracks are predominantly perpendicular to the pavement centerline or laydown direction, as shown in Figure 10. Possible causes of transverse cracks are shrinkage of the hot mix asphalt (HMA) material surface due to low temperatures or asphalt binder hardening.



Figure 10: Transverse cracks in the asphalt pavement.

#### 4.7. Patching and potholes

Patches are localized areas of the pavement, greater than 0.1m<sup>2</sup>, that have been removed and replaced for utility work or the repair of distressed areas, as shown in Figure 11.



Figure 11: Patch on the asphalt pavement.



Figure 12: Pothole (filled with water) on an asphalt pavement.

Potholes are bowl-shaped depressions in the pavement surface, as shown in Figure 12. They are generally of varying sizes and have sharp edges. They develop on roads with thin surface courses. They are usually caused when severe alligator cracking increases. They cause roughness and are a major cause of accidents, especially in poor visibility. Potholes also lead to further deterioration by collecting rainwater, which seeps directly into the subgrade (see Figure 12). Possible causes of potholes are as follows:

- Continued deterioration such as thawing of a frozen subgrade, cracking, raveling, or a failed patch after pieces of the original pavement surface have been dislodged.
- Poor surface mixtures.
- Weak spots in the base or subgrade.
- The severity of the surrounding distress and traffic action, which accelerates the formation of potholes.

#### 4.8. Rutting

Ruts are longitudinal surface depressions in the wheel path, as shown in Figure 13. Rutting can develop due to inadequate compaction in one or more layers in the pavement. A narrow rut is the result of surface failure, while wide ruts are the result of subgrade failure. The ruts may fill with water, especially due to melting ice and snow, and may cause further damage to the roadway. Rutting is classified into two types: mix rutting and subgrade rutting. Mix rutting is rutting on the pavement surface. However, subgrade rutting's impact is deeper in the subgrade. Rutting is dangerous for vehicles because tires may stick in the rut and the vehicle may go off the road [41, 43].



Figure 13: Rutting on the asphalt pavement [45].

#### 4.9. Corrugations

Corrugation appears as wash boarding, due to surface distortion, as shown in Figure 14. The possible causes of corrugation are: low air voids, high fine aggregate contents, excessive

moisture or contamination in the granular base, smooth or rounded aggregate, incorrect asphalt grade, frost action, and black ice [41, 43].



Figure 14: Corrugations on the asphalt pavement [41].

#### 4.10. Shoving

Shoving is the localized bulging of the pavement, as shown in Figure 15, and results from the plastic movement of the asphalt concrete surface. The possible causes of shoving are similar to those of corrugations. Shoving has a significant impact on braking or accelerating vehicles. It is usually located on hills or curves, or at intersections [41, 43].

#### 4.11. Depressions

Depressions are small, bowl-shaped areas in the pavement, as shown in Figure 16. They represent surface roughness and can be a hazard to vehicles. Depressions may also have cracks and can hold water. They develop due to localized consolidation or the instability of the supporting layers under the surface course.

#### 4.12. Swells

Swells are localized upward bulges on the pavement surface, as shown in Figure 17, and develop due to the expansion of the supporting layers in the subgrade. Swells are very common in cold regions, as the expansion is caused by frost heaving or by moisture [43].



Figure 15: Shoving on the asphalt pavement.

#### 4.13. Raveling

Raveling is the wearing away of the pavement surface, as shown in Figure 18. Raveling develops due to insufficient adhesion between the asphalt and aggregate, resulting in the dislodging of aggregate particles and loss of the asphalt binder. It ranges from the loss of fines to the loss of some coarse aggregate and creates roughness. Raveling is very common in cold regions, due to the use of chained tires, especially by heavy traffic.

#### 4.14. Polished aggregates

Polished aggregate occurs when the surface binder becomes worn away, due to traffic, and exposes the coarse aggregate, as shown in Figure 19. This results in low friction and will be dangerous for vehicles. It may occur through the use of studded tires, which are commonly used in winter in snowy and icy conditions in cold-climate countries.



Figure 16: Depression in the asphalt pavement.



Figure 17: Swells in the asphalt pavement.



Figure 18: Raveling on the asphalt pavement.

## 5. CONCLUSION

The severe cold weather contributes significantly to the development of low-temperature cracks (LTCs) on asphalt pavements, resulting in poorer road conditions. The cracks and potholes in poor road conditions create many problems such as hindering traffic flow and traffic safety, increasing fuel costs and time delay and causing damage to vehicles. Therefore, it is essential that road cracks are identified at an early stage before the problem becomes too severe and the pavement collapses.

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