Development of potholes from cracks in flexible pavements

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A Thesis

in

School For Building

Presented in Partial Fulfilment of the Requirements

for the Degree of Master of Applied Science

in Engineering at Concordia University

Montreal, Quebec

October 1998

0-612-39100-0

Abstract

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Pothole is a localized loss of material or depression on road pavement surface. The development of cracks and the formation of potholes on road surface are widespread problems in road construction and maintenance. The objective of this study is to develop mathematical models to compute stresses and deflections associated with the cracks in flexible pavement and the formation of potholes.

A crack on a flexible pavement surface is a prerequisite for a pothole formation and progression. Three types of cracks, namely, transverse, longitudinal and alligator cracks are taken into consideration. As stated in the objective, mathematical models have been developed to compute stresses and deflections associated with cracks in flexible pavement and formation of potholes. A special case of blowout of asphalt pavement layer lying on an impermeable concrete base, due to water pressure in the cracks, is studied and a mathematical model is proposed. The mathematical formulations are applied to typical

pavement models and the results are reported in examples and graphs.

A set of computer programs is developed for each proposed mathematical model to calculate stresses and deflections.

This thesis is organized in chapters to report the results of the research work in an orderly manner.

Acknowledgements

I would like to express my gratefulness and thanks to Dr. B. Ashtakala for supervising me through all stages of this thesis. His assistance and guidance were not only helpful but made it possible for successful completion of this thesis.

I would like to convey my love and devotion to my family to whom this thesis is dedicated, for their cooperation, patience and support throughout my study period.

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AC	Asphalt Concrete
a	Radius of crack
A	Distance of loaded beam
b	Breadth of beam
β	The reaction of the foundation
c	Distance of crack from the edge of the pavement
D	EI
E	Young's Modulus for AC layer
h	Thickness of AC layer
I	Moment of inertia
k	Modulus of support
L	Total length of beam
λ	Constant for calcalations
p	Tire pressure
p_i	Ice pressure
p_t	Total pressure $(p + p_i)$
Q	Shear stress
r	Point of reference
S_T	Surface energy of asphalt at all grades
σ_{BS}	Bending stress
σ_h	Hoop stress

σ_r	Radial stress
σ_t	Tensile stress
u	Point of reference
ν	Poisson's ratio
x	Point of calculations
y	Deflection at x

SI units

The results presented in this thesis are in Imperial Units (foot-pound). The following conversions can be used for SI units.

1 inch.	=0.0254 m
1000 lb (1K) force	=4.48 KN
1 psi.	= 6.895 KPa
1000 psi.	= 6.895 MPa
1 psf	= 47.88 Pa
1 pcf	= 157.1 N/m^3

Chapter 1

Introduction

A flexible pavement structure consists of asphalt concrete (AC), base course and subgrade layers from top to bottom. AC layer is dense graded bitumen mix, which is well compacted to form the pavement surface. According to Yoder (1964) high-type asphalt concrete pavements are used where high loads are anticipated. In areas of high air temperature, the heavier grades are used, whereas for colder climates, the lighter grades are used. The stability of AC mixture is made up of both cohesion and internal friction. Cohesion and internal friction in turn depend upon gradation of the aggregate, density of mix and quantity of asphalt. The base layer consists of granular material. The subgrade consists of well-compacted soil.

1.1 Pavement Distress

According to Yoder (1964) pavement distress can be classified into two different types of failures. The first, structural failure, includes a collapse of the pavement structure or a breakdown of one or more of the pavement components of such magnitude to make the pavement incapable of sustaining the loads imposed upon its surface. The second, classified as functional failure, may or may not be accompanied by structural failure. However the pavement will not carry out its intended function without causing discomfort to passengers or without causing high stresses in the pavement. Sargious (1975) concludes that frost thawing during the springtime can cause pavement distress due to loss in subgrade supporting capacity, even though frost heaving may not have taken place. During the thawing period, frozen soil generally thaws out from above and below. Excessive amounts of water freed by melting soil and ice lenses may soften the material of the layer immediately underneath the pavement. In winter pavements are generally kept free from snow, which is deposited on the shoulder or in side ditches. Snow, a good insulator, is undesirable in these locations in the early part of the thawing season. The reason for this is that when pavement is exposed to the warming sun in the Spring, the soil underneath the pavement will thaw out while the drainage facilities and base-drainage course are still frozen. This may result in the accumulation of large quantities of water beneath the pavement between relatively nonporous surface and the still frozen layer underneath. When heavy traffic moves over the pavement at such locations, it may cause failure in the pavement. There are mainly three types of cracking in pavements.

1. Transverse Cracking
2. Longitudinal cracking
3. Alligator cracking

Transverse cracking is associated with cold temperature. As the pavement is cooled, thermal stresses are induced as a result of AC's tendency to contract, as well as friction between the AC and the base layer that resists contraction. The thermally induced stress gradually increases as temperature decreases until pavement failure occurs.

Longitudinal cracking occurs due to shrinkage. Alligator cracks are caused due to decrease in relative bearing capacity of subgrade in spring season.

1.2 Potholes in flexible pavements

A pothole may be defined as any localized loss of material or depression in the surface of a pavement. To many people, the classic definition of a pothole is a deep hole that suddenly appears with the spring thaw in an asphalt concrete pavement. Or it may be a simple depression in the surface of the pavement caused by poor base support, moisture in the base or a lack of proper preparation during a utility repair.

Various types of cracks such as transverse, longitudinal, and alligator cracks are formed due to temperature changes in the pavement layer and repetitive vehicle loads on the pavement surface. The pavement material fails due to various type of stresses and deflections occurring at the cracks. The cracks start widening forming more crack area, which leads to forming of potholes.

According to O'Flaherty (1988) potholes are not accompanied by distortion of the adjacent surface. They generally result from a cracked bituminous surface, which has allowed moisture to enter and soften the pavement or penetrate horizontally under the bituminous layer. Once water has entered, the cracked surface is prone to disintegrate and lift out under the action of traffic, particularly after rainfall, thereby initiating the formation of a pothole.

1.3 Potholes in Montreal area

Pothole problem in Montreal and vicinity is very severe. Montreal weather is very cold. It ranges from -10°C to -30°C in the winter season. Potholes are formed after the winter season in the spring. Potholes can be seen frequently in Montreal and surrounding areas. Some of the potholes have been photographed and are shown here as examples.

Fig: 1.1 shows disintegration of pavement due to alligator cracking. Pothole has started to form where white mark is shown. This picture was taken at Jarry Street in Montreal, at the crossing of Jarry/Champegneur in front of National Bank on 4-way express way. The pothole is situated 5 feet from the signal intersection. A vehicle (at maximum permissible speed) passing can cause an impact on the pavement. The impact causes disintegration of pavement, which leads to forming of pothole.

Fig: 1.2, shows pothole formation due to transverse cracking. This picture was taken on Saint-Laurent street in front of Russel Rineret, 7915 Saint-Laurent at the corner towards gas station. The dimensions of the pothole are 2.5 ft. in length, 2.0 ft. in width and 3.5 inches in depth.

Fig 1.3 is another example of pothole formation due to alligator cracking. This picture was taken at Chemin Upper Lachine at the corner of Upper Lachine/Addington on the bridge. The dimensions of the pothole are 1.5 ft. in width and 2 inches in depth.

Fig: 1.4 shows a complete formation of pothole. The picture was taken at Ogilivy street in Montreal. The pothole is located at the center of street at crossing of Ogilivy/Birnam on 2-way lane in front of 1000 Ogilivy. The dimensions are 1.5 ft. in length, 1.2 ft. in width and 2.5 inches in depth.

1.4 Objective of the Study

The objective of this study is to develop mathematical models to compute stresses and deflections associated with the cracking of the pavement and the formation of potholes. Also, the objective is to develop a set of graphs which show stresses and deflection for various strengths of pavement material and thickness of AC layer.

1.5 Structure of Thesis

Chapter 1 describes introduction to structure of the flexible pavement and cracking in the pavements. Potholes in the flexible pavements are described and the possible causes of potholes are included. Also, some photographs of potholes in Montreal and vicinity have been shown. Possible causes of pothole formation in each photograph are discussed.

Chapter 2 of this thesis outlines the literature review, describes different types of cracks on the surface of flexible pavement and gives detailed description of pavement failure. The various causes of cracking have been given. This chapter also describes pothole occurrence in the flexible pavements.

Chapter 3 describes the proposed methodology of formation of potholes when a crack is formed on the pavement surface. Three types of cracks, namely, transverse, longitudinal and alligator are considered. In each model stresses and deflections are calculated and the effect on the crack is discussed. Graphs are plotted to show different types of pavement material and thickness of AC layer. The effect of moisture on the pavements is studied and a model is proposed to find the cause of blow out on the pavement surface.

Chapter 4 illustrates the computer program, which has been developed for this study. The flowchart and program instructions on its use are also described.

Chapter 5 gives the conclusions of this study and provides suggestions for further study.

Appendix A shows the printout of the computer program developed for this study and gives the printouts of the results.

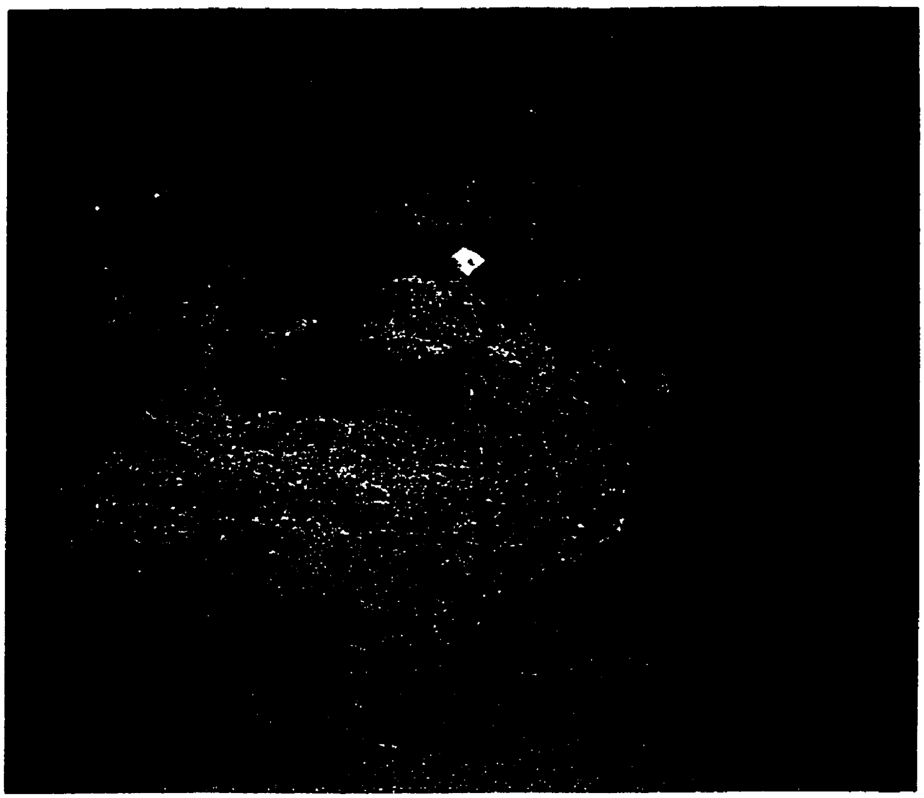


Fig: 1.1 Disintegration of pavement due to alligator cracking

Fig: 1.2 Complete failure of pavement at edge forming pothole

Fig: 1.3 Pothole starts forming due to alligator cracking

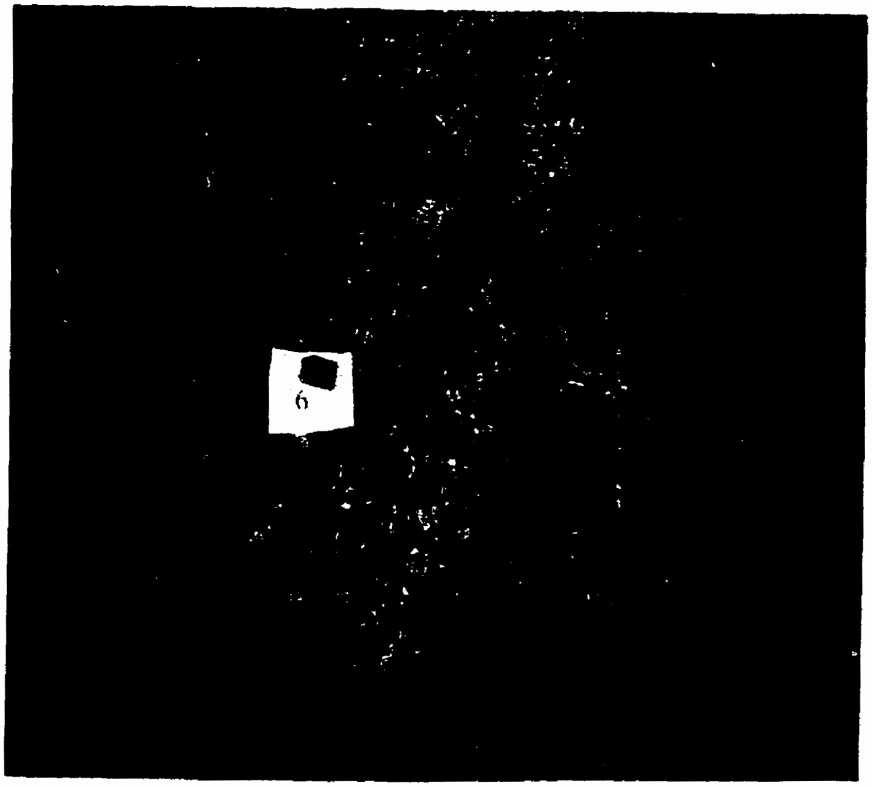


Fig: 1.4 Complete formation of a pothole

Chapter 2

Literature Review

2.1 Introduction

Pothole is defined as any localized loss of material or depression in the surface of a pavement that compromises the riding quality of the pavement. A pothole may simply be a depression on the surface of the pavement caused by poor base support or a hole in the pavement layer. Shahin (1994) adds that potholes are small usually less than 3ft in diameter-bowl-shaped depression in the pavement surface. They generally have sharp edges and vertical sides near the top of the hole. Their growth is accelerated by free moisture collection inside the hole. Potholes are produced when traffic abrades small pieces of the pavement surface. Potholes are most often structurally related distresses and should not be confused with raveling weathering. When high-severity alligator cracking creates holes, they should be identified as potholes, not as weathering. Cracking is the pre-requisite for a pothole to form. After the cracks are formed in the pavement, expansion of the cracks leads to pothole formation. According to Atkins (1983), potholes are relatively small holes in the surface, due to loss of material. The cause may be material failure or faulty workmanship or the use of inappropriate material. Unless attended to promptly, traffic action will widen and deepen the holes, allowing water ingress and increased accident risk. Potholes may also be symptoms of underlying structural failure. These all too common faults in road surfacing present hazards, particularly to two-wheeled vehicles and can damage all classes of vehicles.

2.2 Mechanism of Failure of Flexible Pavement

According to Pavement Design and Evaluation Committee (1965), the performance and life of flexible pavements are governed by failures which may attributed to:

a) Unstable or non-durable materials in the pavement structures

b) Inadequate mix design

c) Inferior construction and maintenance practices

d) Excess traffic loading

e) Environmental factors (temperature, rain, snow)

Through out Canada raw materials, design methods and construction procedures are available to produce stable and durable surface and base course for pavement structures. Thus, sections of pavement, which failed because of inadequate materials or obviously substandard construction or maintenance practices, were not included in the analysis to determine performance relationships. These structural design criteria relate to pavement thickness design problem.

In flexible pavements, some of the types of failures associated with inadequate materials or mix design are map cracking, raveling, stripping, bleeding and shoving of the asphalt concrete surface.

2.3 Cracking in the AC (Asphalt Concrete) pavements

Cracking is a prerequisite for pothole to occur. Wheel loads of vehicular traffic are applied to the pavement structure, which may number several millions over its lifetime. When a load passes over the pavement some deflection of the surface and underlying layers takes place. If the load is excessive or the supporting layers are weak to withstand the load, the load repetitions will cause roughing and cracking which will ultimately result in complete failure. According to Thawat et al. (1987), cracking initiation and progression are predicted for two classes, all cracking and wide cracking, through separate sets of relationships. Cracking results from load repetition or environmental factors. Cracking due to repeated loading occurs primarily as a result of bending deflections. This type of failure is often designated as "fatigue failure". Fatigue in bituminous paving materials has been shown to be a progressive process. Cracks propagate from small flaws inherent in the material until ultimately the amount of cracking reaches an unacceptable level or the remaining section becomes so weak that catastrophic failure occurs. Cracking over 10% of a length of pavement is cause for concern and is critical if it is over 40%. The severity of the cracking observed will depend on the temperature, with cracks tending to close in hot weather and open in cold weather. This crack opening movement can be up to 10 mm. According to O'Flaherty (1988), a fracture is the cracking of the bituminous surface which is a manifestation of volume changes and excessive strains under given traffic loadings or differential foundation support conditions. These cracks can occur abruptly or progressively with time or traffic. With respect to fracture-type failures, these are two main causes to which the durability of the binder is a direct contributing cause: shrinkage and brittleness cracking. Shrinkage cracking results from a volume change in the binder during ageing, due to loss of volatiles, change in temperature, absorption of the binder by porous aggregates, or perhaps some internal structural readjustment such as that described by the term thixotropy. Shrinkage cracks are often found in old bituminous surfaces, which have high binder contents and are not exposed to heavy traffic, e.g. large parking areas. In the case of brittleness cracking, as the binder becomes more brittle with age, the surface initially develops load-associated block cracking in the wheel tracks, edge cracking along the perimeter of the pavement, and general edge spalling of all cracking patterns. Different types of cracking include:

a) Thermal Cracking

b) Fatigue Cracking

c) Reflection Cracking

Thermal cracking according to Owen et al. (1983) includes both low temperature cracking and thermal cracking. The pavement will crack when the computed thermal stress is greater than the fracture strength. Repeated loads and tensile strain in the asphalt layer due to daily temperature cycling cause this. Shahin et al. (1994) includes temperature cracking as the appropriate addition of low temperature cracking, which occurs when the thermal tensile stress exceeds the asphalt concrete tensile strength. The thermal-fatigue cracking, occurs when the thermal-fatigue distress due to daily temperature cycling exceeds the asphalt concrete fatigue resistance.

O'Flaherty (1988) states that the potential for cracking results from the phenomenon of fatigue in bituminous materials. Fatigue has been defined as the phenomenon of fracture under repeated or fluctuating stress having maximum value generally less than the tensile strength of the material. Under traffic loading, bituminous pavement materials in particular are subjected to repeated stress and the possibility of damage by fatigue cracking continually exists. Fatigue cracking is assumed to originate at the bottom of bound pavement layers, and its onset to be controlled by the horizontal strains repeatedly generated at this level by traffic loading. The cracks are assumed to propagate upwards through the bound layers to the pavement surface.

Reflection cracking refers to the cracking of a flexible resurfacing or overlay above underlying cracks or joints. It is caused by base course or subgrade cracking reflection through to the surface layer and probably lead to further pavement damage. The fact that they are reflection cracks is determined by their origin rather than by their form. The importance of this type of pavement distress became apparent to highway engineers in the mid-1950s when many resurfacing projects experienced premature cracking failures in zones of underlying cracks in pavements. According to Samooj et al. (1973) the reflection crack growth is a function of time. Evidently the rate of crack growth is considerably increased by the presence of the temperature stresses. The failure occurs in the following types of cracking.

1. Transverse Cracking
2. Alligator Cracking
3. Longitudinal Cracking

According to O'Flaherty (1988) the performance of a bituminous pavement deteriorates with rising temperature. This is due in part to the fact that the effective resilient moduli of bituminous materials are temperature dependent, and in part because their resistance to deformation drops rapidly with increasing temperature. Wignall (1991) adds that in asphalt concrete pavements a cooling induced shrinkage cannot occur. As a result of the restrained shrinkage tensile stresses are compensated by relaxation. At low temperatures the AC pavements become more elastic and the capability for relaxation decreases. That is the reason for increasing tensile stresses. If the tensile stress reaches the tensile strength, cracking occurs.

2.4 Low Temperature Cracking(Transverse Cracking)

The cause of transverse cracking, Noureldin et al., (1978) is due to the cold-temperature contraction of the asphalt concrete surface layer. The stiffer or harder the AC in pavement, the greater the degree of transverse cracking. Transverse cracks, also known as contraction or shrinkage cracks may result from long term shrinkage, an active clay subgrade or contraction of the surface layer.

Carpenter et al. (1975) include freeze-thaw cycling produced plastic deformation in all samples, and the permanent expansion or contraction is related to the compacted total soil moisture suction. These permanent deformations from freeze-thaw cycling impart a residual tensile stress to the asphalt concrete. During freeze, suction increases and decreases during thawing and this drop is consistent regardless of the thermal activity or plastic deformation and induces residual tensile stresses in the asphalt concrete, forming cracking in the transverse direction of the pavement. According to Hajek et al. (1972) low winter temperatures that induce tensile forces in the asphalt concrete primarily cause transverse cracking of flexible pavements. If the induced tensile forces exceed the tensile strength of the material, cracks are formed because the pavement cannot predominantly contract in the longitudinal direction. Most low temperature cracks are formed in the transverse direction to the highway. The factors influencing transverse cracking are stiffness of asphalt cement, climatic conditions, age of the pavement, thickness of AC layer, and pavement foundations. According to Ford et al. (1974) the occurrence of transverse cracking is increased as failure strain decreases and failure stiffness increases. If the stiffness of the asphalt concrete is increased, the degree or amount of cracking is also increased. Transverse cracks are formed on the surface of the pavement. Thus the major cause of these cracks appears to be the cold-temperature contraction of the asphalt concrete surface layer.

Huang (1993), adds that low-temperature cracking in AC pavements is influenced by material, environmental and pavement structure geometry. Among the environmental factors affecting low-temperature cracking is pavement age. The older the pavement, the greater the incidence of thermal cracking. This is associated with the increase in stiffness of the asphalt cement with age. Low temperature cracking primarily occurs in the transverse direction to the direction of the traffic and is fairly regularly spaced at intervals of 30-60m for new pavements and at less than 5m for older pavements. Low temperature cracking of AC pavement is attributed to tensile stresses that develop in the AC layer as the temperature drops to fairly cold levels. As the pavement cools, it tends to contract; this contraction is resisted by friction between the pavement and base layer, which in turn includes tensile stresses in the pavement. When the thermal induced tensile stress equals the strength of AC, microcracks develop and propagate under cold temperature or cold-temperature cycling.

2.5 Alligator Cracking

Alligator cracks are also known as map cracks, block cracks, crazing cracks, crocodile, chicken wire cracks, fishnet and ladder cracks. A number of cracks are formed on the surface of the pavement. These inter-connected cracks form a series of approximately straight-sided polygons, or 'blocks'. These cracks may be due to shrinkage of age-hardened bitumen, shrinkage of underlying bound courses or reflection through to the surface of base course fatigue cracks. The underlying cause may be inadequate pavement strength and/or loss of wearing course ductility. The cracking pattern is called crazing when the cracks are hair-like and the uncracked area is small, crocodile when the area is up to 300mm in diameter (resembling crocodile skin), map when it is up to 1m in diameter and block when larger than 300mm. Map and block cracks are more likely to be linked with binder ageing rather than with wear and loading. Chicken wire cracks are an advanced form of crazing, which is usually associated with surface deformation. Most of the cracks will probably lead to further pavement damage such as potholes. Ong (1994), has found that the bearing capacity of flexible pavements is reduced considerably during the spring break-up period, partly due to reduction in relative density of the subgade material as a result of frost action, partly by the saturation of the soil caused by thawing and partly by excess pore pressure resulting from the incomplete reconsolidation of the subgrade. When wheel load is applied on the surface of the pavement, the pavement is depressed downward due to less bearing capacity of the subgrade, causing map cracking on the pavement surface. Shahin (1994) adds that alligator cracking is a series of interconnecting cracks caused by fatigue failure of the asphalt concrete surface under repeated traffic loading. Cracking begins at the bottom of the asphalt surface where tensile stress and strain are highest under a wheel load. The crack propagates to the surface initially as a series of parallel longitudinal cracks. After repeated traffic loading, the cracks connect, forming many-sided, sharp-angled pieces that develop a pattern resembling chicken wire or the skin of an alligator. The pieces are generally less than 2ft on the longest side. Alligator cracking occurs only in areas subjected to repeated traffic loading, such as wheel paths. The cracking of this type is considered a major structural distress and is usually accompanied by rutting.

2.6 Longitudinal Cracking

Longitudinal cracks are caused by settlement, rutting or, if near pavement edge, due to shrinkage. These cracks are also known as line cracks.

Edge cracks occur near the pavement edge due to:

i. Embankment or shoulder movement
ii. Inadequate width for the pavement
iii. A very flexible surface course
iv. Subgrade shrinkage due to seasonal drying of shoulders and the outer meter of the pavement
v. Bitumen hardening

Wheelpath cracks along the wheelpath are due to fatigue or excessive settlement. In either case, wheel path cracking is a sign that critical structure condition has been attained. If in the outer wheelpath, they often denote water infiltration from the shoulder into base course and/or subgrade. Shahin (1994) configured that longitudinal cracking is caused by shrinkage of the AC surface due to low temperatures or hardening of the asphalt or a reflection crack caused beneath the surface course. Longitudinal cracks are parallel to the pavement's centerline or lay down direction.

2.7 Moisture in Pavements

According to Wignall (1991), moisture behavior consists of three phases; an entry phase (which occurs quite rapidly), a redistribution phase (when water moves within the material in response to suction and gravity) and finally an evaporative phase, when water, as vapour, leaves a material or moves to other layers. According to Ford et al. (1974) stripping occurs when there is loss of adhesion between the aggregate and the AC which is due primarily to water action. The resulting deterioration can be a serious problem causing a substantial reduction in total pavement performance. External factors such as climate, traffic and construction techniques also contribute to the stripping process.

Adhesion is defined as that physical property or molecular force by which one body sticks to another of a different nature. Stripping is when water, through some mechanism, can cause the bond between aggregate and asphalt to diminish, i.e. the reverse of adhesion. Several mechanisms of stripping have been studied.

These mechanisms are summarized by Magdy et al. (1978), they include detachment, displacement, film rupture and pore pressure. Detachment happens when the AC, with no obvious break in the continuity of the coating, is separated from the aggregate surface by a thin film of water. Displacement occurs where there is discontinuity or break in the asphalt coating and the aggregate, asphalt and free water are all in contact. Pore pressure may cause hydraulic scouring to take place in a saturated pavement, where the impact of tire pressure pushes water into the pavement surface in front of it and then as the tire leaves the spot the water is sucked out.

2.8 Maintenance of flexible pavements

According to Wignall (1991) the routine maintenance of surfaces has essentially two interrelated objectives:

i. Sealing against ingress of water and weathering due to oxidation, ultraviolet light and alternating freeze/thaw conditions and direct surface and subsoil water away from the pavement foundation.

ii. Dealing with the effects of the action of traffic tires and loads that cause abrasions and stresses leading to fatigue failure of the road structure.

Yoder (1964) states that maintenance of bituminous surfaces implies sealing, patching, resurfacing or nonskid treatments. The cause of distress should be determined and then corrected before patching is attempted. If bad ground water conditions exist, the water should be intercepted and removed, or else deterioration will again take place. Likewise, if small areas of unsuitable subgrade exist, they should be removed and replaced with suitable granular material.

Nonskid treatments are necessary when slippery or slick spots develop under the polishing action of traffic or from excessive bitumen on the pavement surface. Skid proofing may be accomplished by the application of a seal and stone chips, and resurfacing by planing the surface.

2.9 Repair of Potholes

According to O'Flaherty (1988) repair to potholes should be carried out before the onset of inclement weather. Any pothole, which is likely to be a potential hazard to traffic should be repaired immediately after detection, if necessary with temporary patches. The patching process requires the squaring of a rectangular area encompassing the sides of the hole, and the removal of all loose or faulty material. The objective is to ensure that the edges of the filled in patch are in contact with good-quality, supportive, pavement materials.

The most durable results are obtained when the backfill is premixed with a dense bitumen-bound material. If unbound gravel or crushed stone is used for backfill, the material needs to be moistened to facilitate its compaction in layers not exceeding 100mm thick with a mechanical tamping machine.

Before applying the final bituminous layer, the surface of the unbound backfill has to be swept clean of dust and loose stones and primed with a bituminous binder. Surface priming is unnecessary in the case of premixed bitumen-bound backfill, although the exposed surfaces of the hole may have to be lightly primed or track coated before the addition of the backfill. The repair work is then completed with the placement of a bituminous material similar to that in the existing surface. In all instances, the amount of patching material used must be chosen to ensure that the surface of the compacted patch is flush with the surrounding road surface.

2.10 Permanent repair of potholes

Cutting out the hole to solid material on both sides to the bottom and filling it with new base and surface material makes permanent repair.

Important steps in permanent repair of untreated potholes are:

i. Surface and base removal to firm support
ii. Application of tack coat
iii. Full depth mixture placed and compacted
iv. Finished patch compacted to the level of surrounding pavement.

Chapter 3

Methodology

3.1 Introduction

As stated, potholes are formed due to loss of material, depression in the surface of pavements, poor base support and the spalling of wide cracking.

The performance and life of flexible pavements are governed by failures, which can be attributed to

a) unstable or non-durable materials in the pavement structure

b) inferior construction and maintenance

c) inadequate mix design

d) excess traffic loading

e) environmental factors

All these factors are mainly affected by load repetitions. Potholes start from cracks in the pavement, and then expand due to breaking of the pavement edges.

3.2 Pothole Initiation and Progression

According to Thawat at el. (1987) initiation of potholes can be expressed as a function of time since it starts 2 to 6 years after wide cracking. As new potholes are formed wide cracking and the existing potholes become enlarged, the pothole distress progresses.

Cracking in pavements is of three types

i. Transverse Cracking

ii. Longitudinal Cracking

iii. Alligator Cracking

Pothole formation due to different types of cracking is shown in Fig: 3.1

Each type of cracking undergoes loading effect in the form of deformation, breaking of pavements, and bending stress development.

3.3 Flexible Pavement Structure

AC layer is a dense graded premixed bitumen mix, which is well compacted to form a high quality pavement surface. The AC consists of a carefully proportional mixture of coarse aggregates, fine aggregates and bitumen.

Base course is granular material and subgrade soil is well compacted. Traffic loads act on the road surface and they are transmitted through the layers stated above until they are supported by the native soil foundation. The axle load from the vehicular traffic is distributed on the asphalt concrete wearing surface as a contact pressure from the wheels. This stress is then distributed through asphalt,

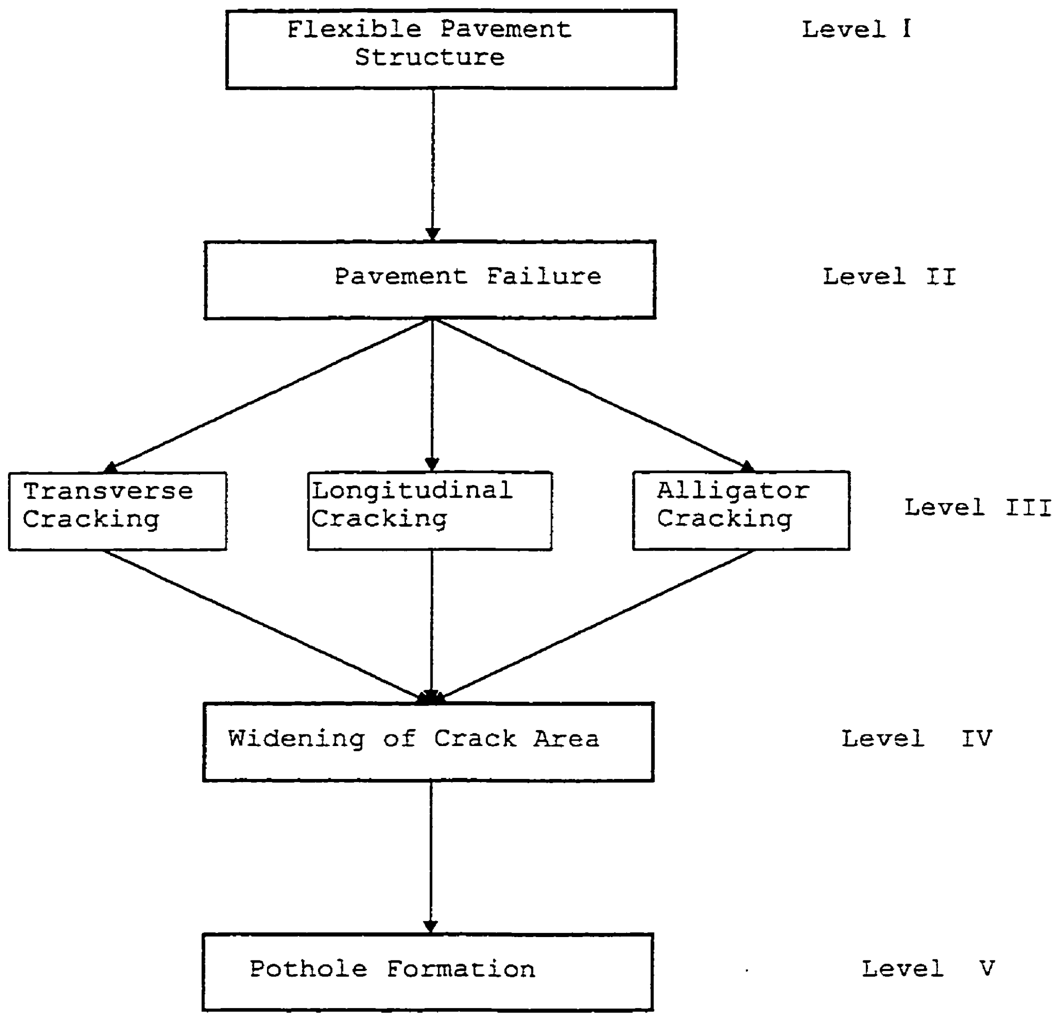


Fig: 3.1 Flow Chart for pothole formation

base and finally subgrade. The superimposed load is distributed over a larger area as the depth increases. The contact area is directly proportional to the axle loads, i.e. the magnitude of contact area increases as the axle load increases on the pavement surface.

3.2 Pothole formation due to transverse cracks

With a transverse crack on the surface of a flexible pavement, the deflection basin under a wheel load shown is in fig: 3.2(b). The middle portion of the deflection basin is concave and the ends of the basin tend to be convex.

A typical deflection basin on a flexible pavement has one concave portion and two convex portions as shown in fig: 3.2(b). The magnitude of the peak deflection is indicative of the support conditions of the pavement and the degree of curvature in the deflection basin is indicative of the state of the layer close to the surface. Also, the crack on the surface can open or close, depending on the deflection basin. The crack goes through a cycle of opening-closing-opening for every wheel that passes over it. The peak crack movement depends upon the degree of curvature of deflection basin.

Due to the repetitive wheel load, the size of the crack becomes larger.

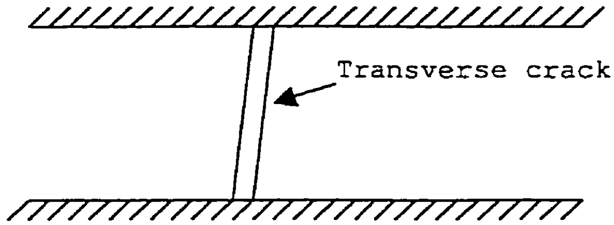


Fig: 3.2(a) Top View for pavement with transverse Crack

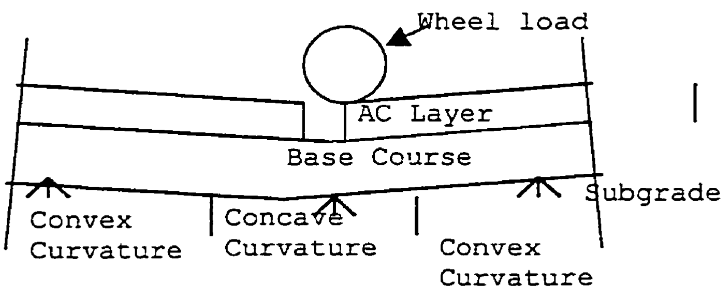


Fig: 3.2 (b) Wheel Load acting on the top of the transverse crack (side view)

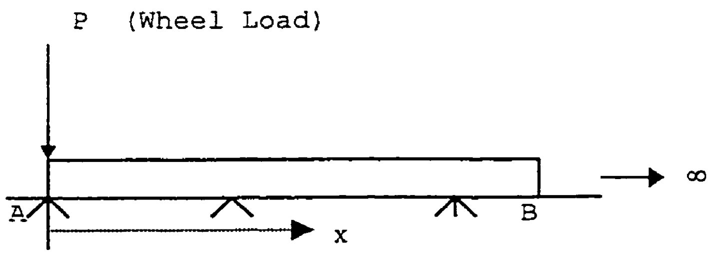


Fig: 3.3 Wheel load on the edge of the crack

This can be simulated as a crack movement through a cantilever beam resting on elastic foundation at the edges. Let *b* be the breadth of beam resting on Winkler foundation. If the length of beam is 1-inch and the deflection of beam is 1-inch.

Let *k* be the modulus of support.

The reaction of the foundation, β can be written as

$$\beta = kb \qquad (1)$$

Assuming the supporting medium with intensity, *q* the deflection, *y* at a point can be written as:

$$q = \beta y \qquad (2)$$

Suppose an infinite small element is enclosed between vertical cross-sections at a distance *dx* apart.

The forces acting on the pavement are shown in fig: 3.5

Let *x* be the application of wheel load to the point of consideration.

Let, Q = shear force

M = bending moment

$$Q - (Q + dQ) + \beta\, ydx = 0 \qquad (3)$$

$$\frac{dQ}{dx} = \beta\, y \qquad (4)$$

$$Q = \frac{dM}{dx} \qquad (5)$$

$$\frac{dQ}{dx} = \frac{d^2M}{dx^2} = \beta\, y \qquad (6)$$

Let, E = Elastic Modulus

I = Moment of inertia

$$EI\frac{d^2y}{dx^2} = -M \tag{7}$$

$$EI\frac{d^3y}{dx^3} = -\frac{dM}{dx} \tag{8}$$

since $Q = \frac{dM}{dx}$ from equation (5)

$$EI\frac{d^3y}{dx^3} = -Q \tag{9}$$

Differentiating equation (9)

$$EI\frac{d^4y}{dx^4} = -\frac{dQ}{dx} \tag{10}$$

Putting equation (4) into equation (10)

$$EI\frac{d^4y}{dx^4} = -\beta y \tag{11}$$

$$\frac{d^4y}{dx^4} + \frac{\beta}{EI}y = 0 \tag{12}$$

Let EI = D (13)

Substituting in equation (12)

$$\frac{d^4y}{dx^4} + \frac{\beta}{D}y = 0 \tag{14}$$

Let λ be constant such that

$$\lambda^4 = \frac{\beta}{4D} \tag{15}$$

$$\lambda = \sqrt[4]{\frac{\beta}{4D}}$$

Therefore equation (14) becomes

$$\frac{d^4y}{dx^4} + 4\lambda^4 y = 0 \tag{16}$$

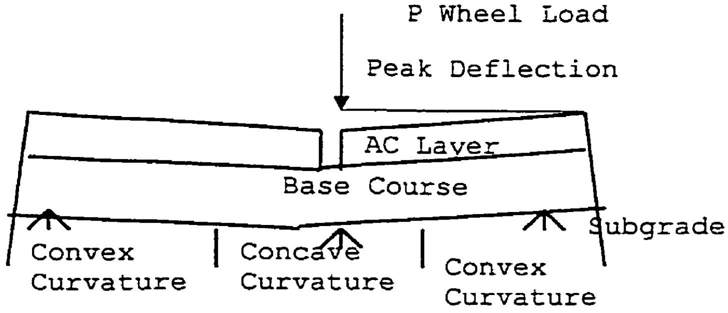


Fig: 3.4 Wheel Loading on Transverse Crack

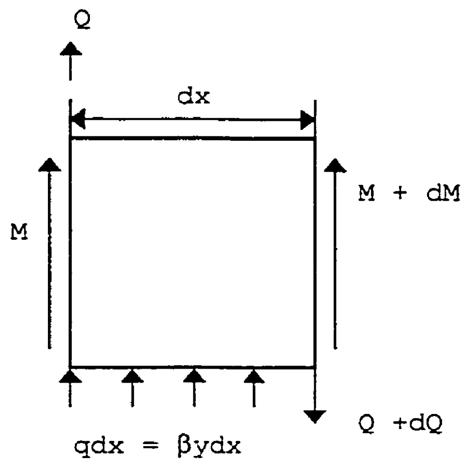


Fig: 3.5 Equilibrium of forces on the element

$$\text{Let } \frac{d^4}{dx^4} = D_1 \qquad (17)$$

Equation (16) in symbolic form is

$$(D_1^4 + 4\lambda^4)y = 0 \qquad (18)$$

Auxiliary Equation (A.E) is

$$(D_1^4 + 4\lambda^4) = 0 \qquad (19)$$

$$(D_1^4 + 4\lambda^2 D_1^2 + 4\lambda^4) - 4\lambda^2 D_1^2 = 0 \qquad (20)$$

$$(D_1^2 + 2\lambda^2)^2 - (2\lambda D_1)^2$$

$$(D_1^2 + 2\lambda D_1 + 2\lambda^2)(D_1^2 - 2\lambda D_1 + 2\lambda^2) \qquad (21)$$

Eithet $(D_1^2 + 2\lambda D_1 + 2\lambda^2) = 0$ or $(D_1^2 - 2\lambda D_1 + 2\lambda^2) = 0$

$$D_1 = \frac{-2\lambda \pm \sqrt{4\lambda^2 - 8\lambda^2}}{2} \text{ and } D_1 = \frac{2\lambda \pm \sqrt{4\lambda^2 - 8\lambda^2}}{2}$$

$D_1 = -\lambda \pm i\lambda$ and $D_1 = \lambda \pm i\lambda$

The complete solution consisting of homogeneous and particular solution is,

$$y_c = e^{\lambda x}\left(C_1 \text{Cos}\lambda x + C_2 \text{Sin}\lambda x\right) + e^{-\lambda x}\left(C_3 \text{Cos}\lambda x + C_4 \text{Sin}\lambda x\right) \qquad (22)$$

Wheel load P is acting on the end of the crack

i.e. at $x = 0$

Consider a point at

$x = +\infty$ (infinite length of pavement)

At, $x = +\infty$

the bending moment, and deflection become zero

i.e. $y = M = 0$

implies that

$C_1 = C_2 = 0$

Therefore equation (22) becomes

$$y_c = e^{-\lambda x}\left[C_3 \mathrm{Cos}\lambda x + C_4 \mathrm{Sin}\lambda x\right] \tag{23}$$

for, calculating C_3, C_4

As P is on the edge of the crack

therefore, $x = 0$ (24)

Bending Moment is zero at $x = 0$, therefore

$$EI\frac{d^2y}{dx^2} = 0 \tag{25}$$

Shear force at $x = 0$ is

$$-Q = P \tag{26}$$

Putting equation (26) in equation (9)

$$EI\frac{d^3y}{dx^3} = P \tag{27}$$

From equation (23)

$$y = e^{-\lambda x}\left(C_3 \mathrm{Cos}\lambda x + C_4 \mathrm{Sin}\lambda x\right)$$

$$\frac{dy}{dx} = \lambda\ e^{-\lambda x}\left[C_4\left(\mathrm{Cos}\lambda\ x - \mathrm{Sin}\lambda\ x\right) - C_3(\mathrm{Sin}\lambda\ x + \mathrm{Cos}\lambda\ x\right] \tag{28}$$

$$\frac{d^2y}{dx^2} = 2\lambda^2 e^{-\lambda\ x}\left[C_4 \mathrm{Cos}\lambda\ x - C_3 \mathrm{Sin}\lambda\ x\right] \tag{29}$$

From equation (25)

$$\frac{d^3y}{dx^3} = 2\lambda^3 e^{-\lambda\ x}\left[C_3\left(\mathrm{Cos}\lambda\ x - \mathrm{Sin}\lambda\ x\right) + C_4(\mathrm{Sin}\lambda\ x + \mathrm{Cos}\lambda\ x\right] \tag{30}$$

Since equation (25)

$$EI\ \frac{d^2y}{dx^2} = 0$$

Substituting equation (29) in equation (25)

$$EI\left[2\lambda^2 e^{-\lambda x}\left(C_4 \mathrm{Cos}\lambda x - C_3 \mathrm{Sin}\lambda x\right)\right] = 0 \tag{31}$$

Either $e^{-\lambda x} = 0$

or

$C_4 \mathrm{Cos}\lambda x = C_3 \mathrm{Sin}\lambda x$

$$C_3 = C_4 \frac{\mathrm{Cos}\lambda x}{\mathrm{Sin}\lambda x} \tag{32}$$

From equation (27)

$$\frac{d^3 y}{dx^3} = \frac{P}{EI} \tag{33}$$

Substituting equation (30) in equation (33)

$$2\lambda^3 e^{-\lambda x}\left[C_3\left(\mathrm{Cos}\lambda x - \mathrm{Sin}\lambda x\right) + C_4\left(\mathrm{Sin}\lambda x + \mathrm{Cos}\lambda x\right)\right] = \frac{P}{EI} \tag{34}$$

Substituting equation (32) in equation (34), gives

$$C_4 = \frac{P\mathrm{Sin}\lambda x}{EI2\lambda^3 e^{-\lambda x}} \tag{35}$$

Since $x = 0$

Therefore $C_4 = 0$ (36)

Putting equation (33) into equation (30)

$$C_3 = \frac{P\mathrm{Sin}\lambda x\mathrm{Cos}\lambda x}{2EI\lambda^3 e^{-\lambda x}\mathrm{Sin}\lambda x}$$

Since $x = 0$ implies

$$C_3 = \frac{P}{EI2\lambda^3} \tag{37}$$

Therefore equation (21) becomes

$$y_c = \frac{e^{-\lambda x}}{2EI\lambda^3}\left(P\mathrm{Cos}\lambda x\right) \tag{38}$$

3.5 Pavement Model for Transverse Cracking

Wheel loading is acting on the edge of the crack.

The following data is assumed:

Thickness of the pavement layer, h = 4inch. (0.10 m)

Wheel load, P = 10,000 lbs. (44.8 KN)

Tire pressure, p = 70 psi. (0.48 MPa)

Wheel load acts on the pavement surface, It has a contact area depending upon the tire pressure. The contact area is calculated as follows:

Contact area is load divided by the tire pressure. The contact area is assumed to be a rectangular.

Contact area = 142.7 inch^2 (0.09 m^2)

Width of tire = 13.5 inch. (0.34 m)

Length of contact area = 10.60 inch. (0.27 m)

Consider a pavement strip of one inch and width 10.6 inches length.

Load on the strip = 743 lbs. (3.33 KN)

Breadth of beam, b = Width of tire as shown in fig: 3.6(b).

= 13.5 inch. (0.34 m)

Elastic Modulus of AC layer, E = 100000 psi. (689.5 MPa)

Modulus of beam, k = 250 pci. (68346.6 N/m^3)

Breadth of beam, b = 13.5 inch. (0.34 m)

Reaction of foundation, β = 3375 psi. (23.27 MPa)

Cross-section of pavement layer

w = 1 inch and h = 4 inch. (0.10 m)

Moment of inertia, M.I = $\frac{wh^3}{12}$ = 5.33 $inch^4$ (2.2×10^{-6} m^4)

$$\lambda = \sqrt[4]{\frac{\beta}{4EI}}$$

= 0.20 $inch^{-1}$ (7.87 m^{-1})

At x = 0

Deflection, y_c as given in equation (38)

$$y_c = \frac{e^{-\lambda x}}{2EI\lambda^3}(P\cos\lambda x)$$

y_c = 0.087 inch (0.002 m)

The Shear Force acting at $x = 0$

$$EI\frac{d^3y}{dx^3} = -Q = P = 743 \text{ lbs } (3.33 \text{ KN})$$

The loaded area taken as (1 * 4) $inch^2$

Shear Stress = $\frac{743}{1 * 4}$

= 186 psi. (1.28 MPa)

3.5(a) <u>Graphs for deflections and shear stresses</u>

The deflections at a transverse crack have been computed for elastic moduli varying from E = 20,000 (137.9 MPa) to 100,000 psi. (689.5 MPa) and for thicknesses varying from 4 (0.10 m) to 12 (0.30 m) inches using the procedure shown in section 3.5. These are shown in fig: 3.7

The shear stresses at a transverse crack have been computed for tire pressures 70 (0.48 MPa) and 100 psi. (0.69 MPa) and for thicknesses varying from 4 (0.10 m) to 12 (0.30 m) inches using the procedure shown in section 3.5. These are shown in fig: 3.8

3.6 Discussion of Results

When wheel load passes on a transverse crack, it develops shear stress of 186 psi. (1.28 MPa) and deflection of 0.087 inches (0.002 m) on the pavement surface. The repetition of wheel load produces shear stress and deflection on each application of wheel load. The edge of the crack starts breaking up to form a larger new crack area. This widening of crack area leads to the formation of pothole.

Deflection in AC layer depends upon its thickness. The larger the thickness of AC layer, the lesser the deflection in the pavement. The strength of an AC layer is directly proportional to the thickness. Strong Pavement material produces less deflection as compared to weak material fig:3.7.

Higher tire pressure produces more shear stress in pavement. Shear stress decreases if the thickness of the AC layer increases fig: 3.8.

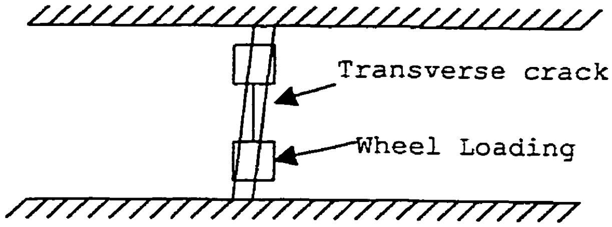


Fig: 3.6(a) Top View for pavement with transverse Crack

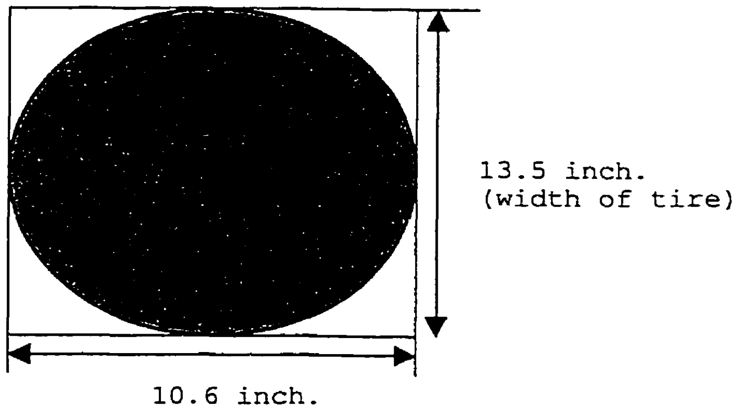


Fig: 3.6(b) Contact area of tire

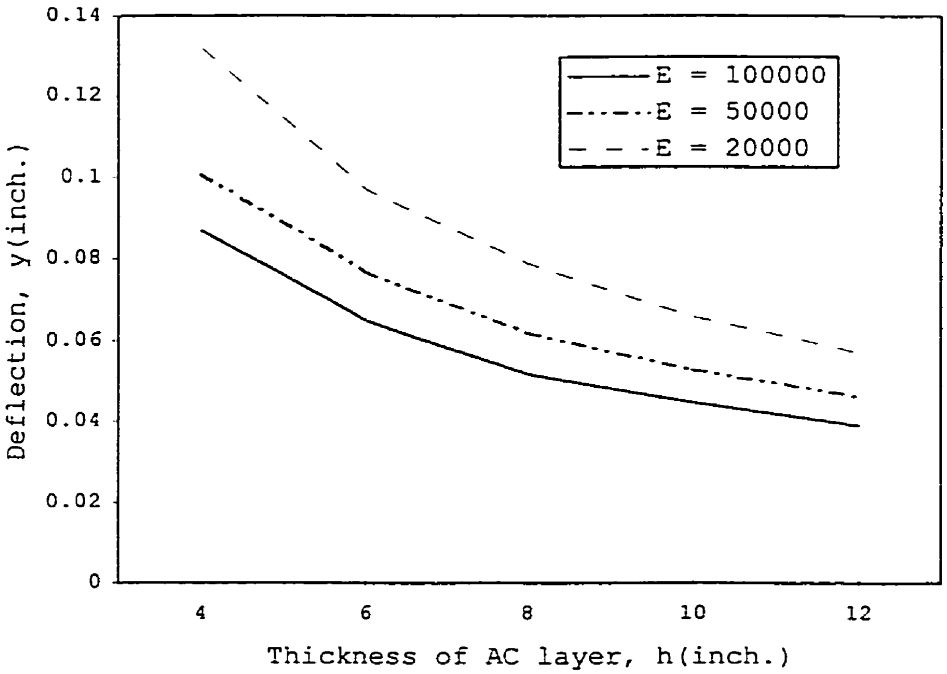


Fig: 3.7 Deflections at a transverse crack

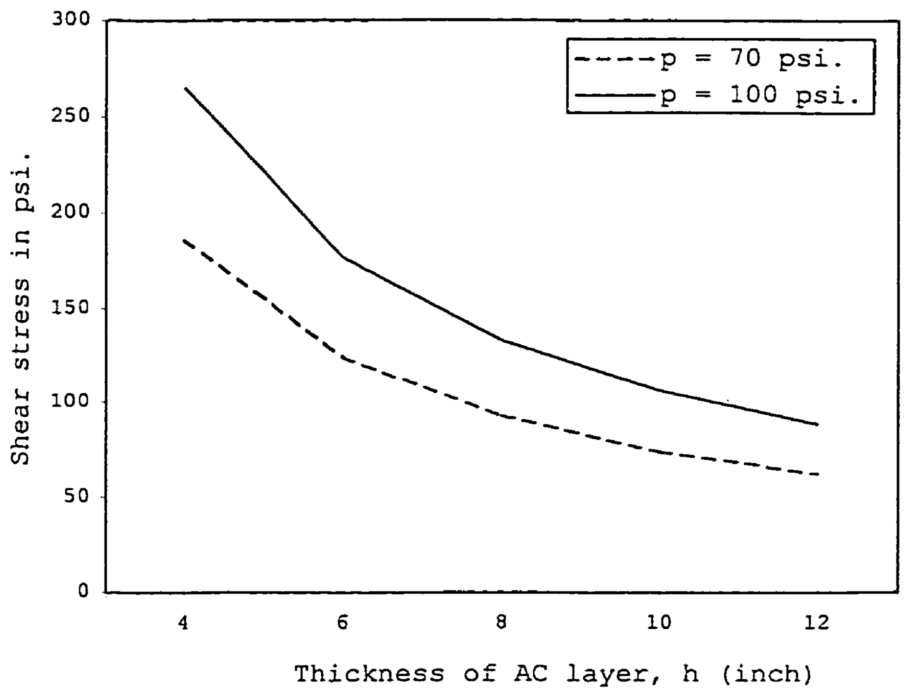


Fig: 3.8 Shear stresses at a transverse crack

3.7 Pothole formation due to longitudinal cracks

Formation of a longitudinal crack on the surface of the flexible pavement allows the water to go inside the crack. When temperature drops to freezing point, the water inside the crack becomes ice.

Pavement model with longitudinal crack is shown in fig: 3.9 The shape of the crack is assumed cylindrical. The depth of the crack is less than the thickness of AC layer by about 1 to 2 inches. The formation of ice lenses in the crack causes volume expansion.

Let,

h denotes hoop direction
r denotes radial direction
z denotes axial direction

E = Modulus of elasticity of AC
υ = Poission ratio

As the external pressure is zero, at a distance r from point O, there are no shear forces involved. According to Nichols (1971) at location r the condition is equilibrium.

$$\sigma_h - \sigma_r - r\frac{d\sigma_r}{dr} = 0 \tag{39}$$

σ_h = hoop stress

σ_r = radial stress

Since deformation is symmetrical, it is constant in σ_h direction.

If u is the deformation the element r,

the elongation in three directions in terms of principle strain can be written as:

$$\varepsilon_h = \frac{u}{r} = \frac{1}{E}\left[\sigma_h - \upsilon(\sigma_r + \sigma_z)\right] \qquad (40)$$

$$\varepsilon_r = \frac{du}{dr} = \frac{1}{E}\left[\sigma_r - \upsilon(\sigma_h + \sigma_z)\right] \qquad (41)$$

$$\varepsilon_z = \frac{1}{E}\left[\sigma_z - \upsilon(\sigma_h + \sigma_r)\right] \qquad (42)$$

Solving simultaneously equations (40) and (41) and

$\sigma_z = 0$, gives:

$$\sigma_h = \frac{E}{1-\upsilon^2}\left[\frac{u}{r} + \upsilon\frac{du}{dr}\right] \qquad (43)$$

$$\sigma_r = \frac{E}{1-\upsilon^2}\left[\frac{du}{dr} + \upsilon\frac{u}{r}\right] \qquad (44)$$

Put equation (43) and (44) in equation (38)

$$\frac{d^2u}{dr^2} + \frac{1}{r}\frac{du}{dr} - \frac{u}{r^2} = 0 \qquad (45)$$

$$u = C_1 r + \frac{C_2}{r^2} \qquad (46)$$

As $(\sigma_r)_{r=c} = 0$ (no external pressure)

$$\sigma_r)_{r=a} = -p_i \qquad (47)$$

Substituting these values in equations (43) and (44)

$$\sigma_h = \frac{1}{c^2 - a^2}\left[a^2 p_i + \left(\frac{ca}{r}\right)^2 p_i\right] \qquad (48)$$

$$\sigma_h = \frac{a^2}{c^2 - a^2}\left[p_i + \frac{c^2}{r^2}p_i\right] \qquad (49)$$

let $\frac{c}{a} = R$

$$\sigma_h = \frac{p_i}{R^2 - 1}\left[1 + \frac{c^2}{r^2}\right] \qquad (50)$$

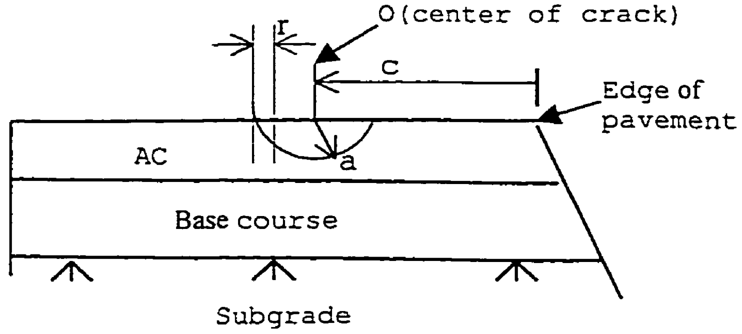


Fig: 3.9 Pavement model with a longitudinal crack

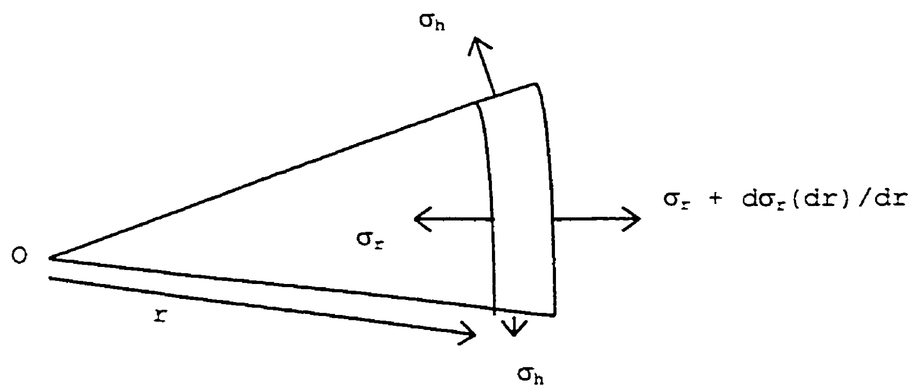


Fig: 3.10 Distribution and application of hoop and radial stresses

Similarly,

$$\sigma_r = \frac{p_i}{R^2 - 1}\left[1 - \frac{c^2}{r^2}\right] \quad (51)$$

When the wheel passes on the crack, the tire pressure, acting on the crack, increases the total internal pressure inside the crack.

Let p be the tire pressure.

The total internal pressure becomes

$$p_t = p_i + p \text{ (tire pressure} \quad (52)$$

Therefore equations (50) and (51), become

$$\sigma_h = \frac{p_t}{R^2 - 1}\left(1 + \frac{c^2}{r^2}\right) \quad (53)$$

$$\sigma_r = \frac{p_t}{R^2 - 1}\left(1 - \frac{c^2}{r^2}\right) \quad (54)$$

The displacement (radial expansion), according to Nichols (1971) is

$$U_0 = \frac{p_t}{E(c^2 - a^2)r}\left[r(1 - \upsilon) + c^2(1 + \upsilon)\right] \quad (55)$$

3.7.1 Pavement model for Longitudinal cracking

Formation of longitudinal crack on the surface of pavement accumulates water inside the crack. When water inside the crack becomes ice, it exerts pressure inside the crack. Tire pressure increases this pressure.

Assuming the breadth of the beam in longitudinal crack as length of the contact area as shown in fig: 3.11

Let unit width of strip of half of width of tire (fig: 3.11) of length as shown in fig: (3.12)

The following data is assumed:

Let a pavement strip of one-inch width and a length of 6 inch as shown in fig. 3.12

Load on the strip = 70*1*6 = 420 lbs. (1.88 KN)

Thickness of AC layer, h = 4 inch. (0.10 m)

Elasticity Modulus of AC, E = 100000 psi. (689.5 MPa)

Ice pressure, p_i = 284 psi.(1.96 MPa) [Mellor et al. (1967)]

Tire pressure, p = 70 psi. (482.65 KPa)

Total pressure exerted by crack, $p_t = p_i + p$

= 354 psi. (2.44 MPa)

Hoop stress as given in equation (53)

$$\sigma_h = \frac{p_t}{R^2 - 1}\left[1 + \frac{c^2}{r^2}\right]$$

σ_h = 361 psi. (2.49 MPa)

Radial stress as given in equation (54)

$$\sigma_r = \frac{p_t}{R^2 - 1}\left[1 - \frac{c^2}{r^2}\right]$$

σ_r = 354 psi. (2.44 MPa)

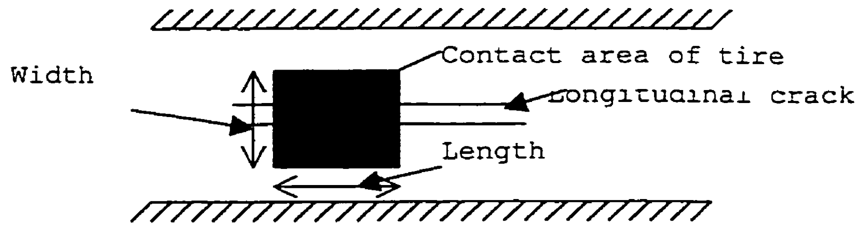


Fig: 3.11 Wheel loading on Longitudinal Crack

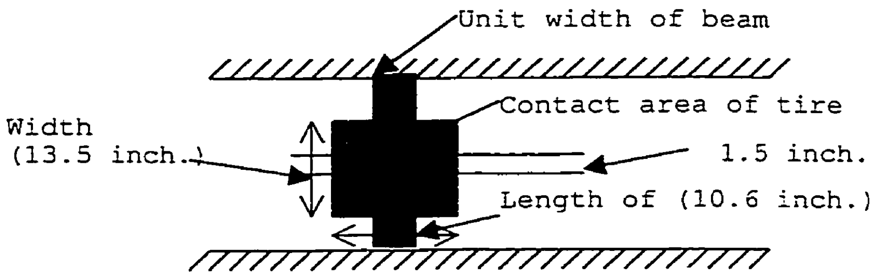


Fig: 3.12 Considered beam on pavement surface

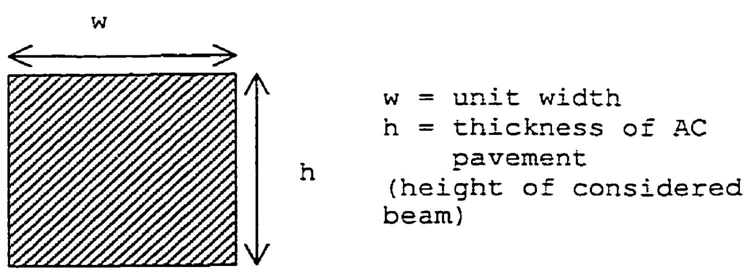


Fig: 3.13 Beam dimensions

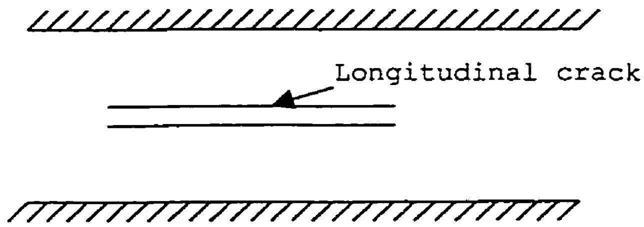


Fig: 3.14 Top View for pavement with Longitudinal Crack

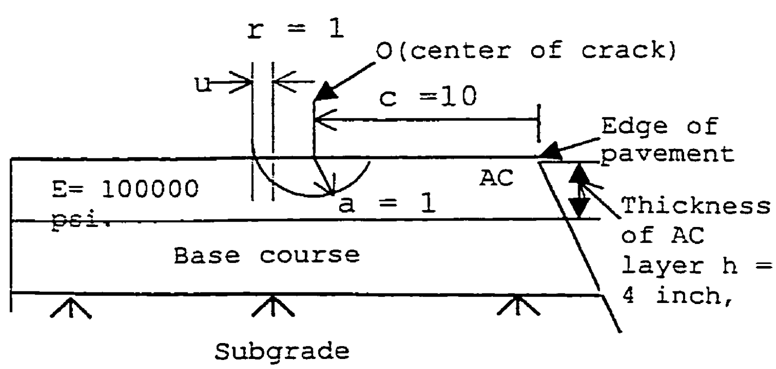


Fig: 3.15 Pavement model with a longitudinal crack

Elongation of crack as in equation (55)

$$U_0 = \frac{p_t}{E(c^2 - a^2)r}\left[r(1 - \upsilon) + c^2(1 + \upsilon)\right]$$

U_o = 0.005 inch. (0.00012 m)

3.8 Pavement Model for calculating bending Stress and deflection

Since the wheel load, passing on longitudinal crack, also produces bending in the pavement,

From equation (22)

$$y = e^{\lambda x}\left[C_1 \mathrm{Cos}\lambda\ x + C_2 \mathrm{Sin}\lambda\ x\right] + e^{-\lambda x}\left[C_3 \mathrm{Cos}\lambda\ x + C_4 \mathrm{Sin}\lambda\ x\right]$$

The infinite length of beam resting on an elastic foundation and subjected to a load P at any point at section x = 0 as shown in figure: (3.3)

At $x = \infty$, $y = M = 0$

Therefore from equation (22) $C_1 = C_2 = 0$

Under load, P

$x = 0$, $\quad \frac{dy}{dx} = 0 \quad$ Therefore, $C_3 = C_4 = C$

Equation (22) becomes

$$y = Ce^{-\lambda x}\left(\mathrm{Sin}\lambda\ x + \mathrm{Cos}\lambda\ x\right) \tag{56}$$

The constant C is determined from condition that

$$Q = -\frac{P}{2} \quad \text{for } x = 0 \tag{57}$$

From equation (9)

$$Q = -EI \frac{d^3y}{dx^3} = -\frac{P}{2}$$

From equations (56) and (57)

$$C = -\frac{P}{8\lambda^3 EI} = \frac{P\lambda}{2\beta} \tag{58}$$

Therefore equation (56) becomes

$$y = \frac{P\lambda}{2\beta} e^{-\lambda x}\left[\mathrm{Sin}\lambda\ x + \mathrm{Cos}\lambda\ x\right] \tag{59}$$

$$= \frac{P\lambda}{\sqrt{2}\beta} e^{-\lambda x}\left[\mathrm{Sin}\left(\lambda\ x + \frac{\pi}{4}\right)\right] \tag{60}$$

The bending moment is given by

$$M = \frac{P}{4\lambda} e^{-\lambda x}\left[\mathrm{Cos}\lambda\ x - \mathrm{Sin}\lambda\ x\right]$$

$$= \frac{P}{2\sqrt{2}\lambda} e^{-\lambda x}\left[\mathrm{Cos}(\alpha x + \frac{\pi}{4}\right] \tag{61}$$

The maximum deflection & moment are under load P at x = 0 are,

$$y_{max} = \frac{P\lambda}{2\beta} \tag{62}$$

$$M_{max} = \frac{P}{4\lambda} \tag{63}$$

The bending stress can be found for neutral axis y^-

Therefore,

$$\sigma_{BS} = \frac{M_{max}}{I} y^- \tag{64}$$

3.8.1 Pavement Model for calculating bending stress & deflection

The wheel load, passing on the crack, also produces bending in the pavement.

Let a pavement strip of one inch. width and a length of a 6 inch. as shown in fig.(3.13)

The load on each strip = 420 lbs. (1.88 KN)

w = 1 inch (0.0254 m), h = 4 inch. (0.10 m)

Moment of Inertia, M.I = $wh^3/12$

$= 5.33\ inch^4\ (2.22 \times 10^{-6}\ m^4)$

Breadth of beam, b = 10.6 inch.(0.269 m)

Modulus of support, k = 250 pci.(68346.6 KN/m^3)

Reaction of foundation, β = 2650 psi. (18.27 MPa)

$$\lambda = \sqrt[4]{\frac{\beta}{4EI}}$$

$= 0.188\ inch^{-1}\ (7.40\ m^{-1})$

Maximum deflection as given in equation (62)

$$y_{max} = \frac{P\lambda}{2\beta}$$

y_{max} = 0.015 inch. (0.00038 m)

Maximum bending moment given in equation (63)

$$M_{max} = \frac{P}{4\lambda}$$

M_{max} = 559 lbs-inch. (63.61 N-m)

Maximum bending stress as given in equation (64)

$$\sigma_{BS} = \frac{M_{max}}{I} \bar{y}$$

σ_{BS} = 202 psi. (1.39 MPa)

3.8(a) Graphs for elongations, hoop stresses, deflections and bending stresses

The elongations at a longitudinal crack have been computed for tire pressures 70 (0.31 MPa) and 100 psi. (0.448 MPa) and for radii of crack varying from 0.5 to 2.5 inches using the procedure shown in section 3.8. These are shown in fig: 3.17.

The hoop stresses at a longitudinal crack have been computed for tire pressures 70 (0.31 MPa) and 100 psi. (0.448 MPa) and for radii of crack varying from 0.5 to 2.5 inches using the procedure shown in section 3.8. These are shown in fig: 3.18.

The deflections at a longitudinal crack have been computed for tire pressures 70 (0.31 Mpa) and 100 psi. (0.448 Mpa) and for thicknesses varying from 4 to 12 inches using the procedure shown in section 3.8. These are shown in fig: 3.19.

The bending stresses at a longitudinal crack have been computed for tire pressures 70 (0.30 Mpa) and 100 psi.

(0.448 Mpa) and for thicknesses varying from 4 to 12 inches using the procedure shown in section 3.8. These are shown in fig: 3.20.

3.9 Discussion of Results

Water in the longitudinal crack becomes ice when temperature drops to freezing and the volume of water increases when it becomes ice. The ice in the crack exerts pressure and tends to increase the crack area by 0.005 inches.

When wheel load passes on the longitudinal crack it enhances the crack pressure. It produces hoop stress of 361 psi. (1.62 MPa), radial stress of 354 psi. (1.59 MPa) and bending stress of 202 psi.(0.90 MPa). This breaks the edges of the crack. The new area is formed as shown in fig: 3.16.

Elongation of crack increases with increase in tire pressure (fig: 3.17). Elongation decreases as the radius of crack increases.

Hoop stress increases as the tire pressure and radius of crack increase. (fig: 3.18)

Increase in tire pressure increases deflection in the pavement. Deflection decreases as thickness of pavement increases.

Bending stress in pavement is more when tire pressure is increased. Increase in thickness of AC layer decreases bending stress (fig: 3.20)

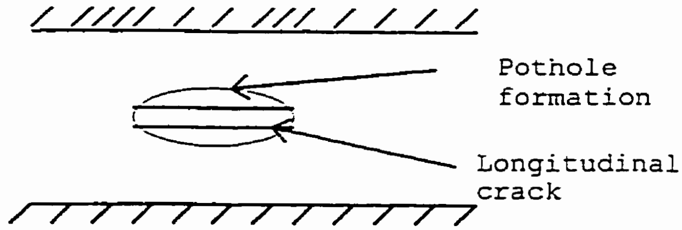


Fig: 3.16 Formation of Pothole

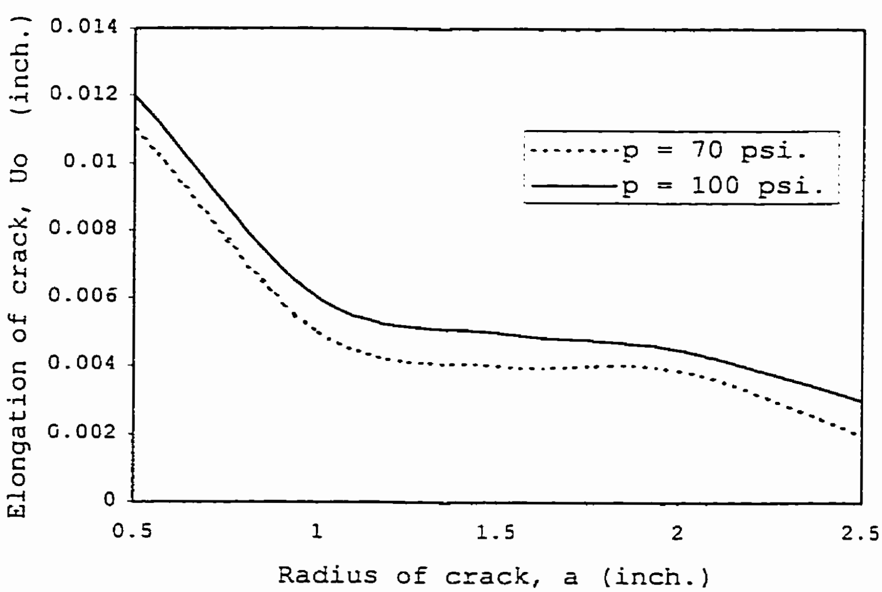


Fig: 3.17 Elongations at a longitudinal crack

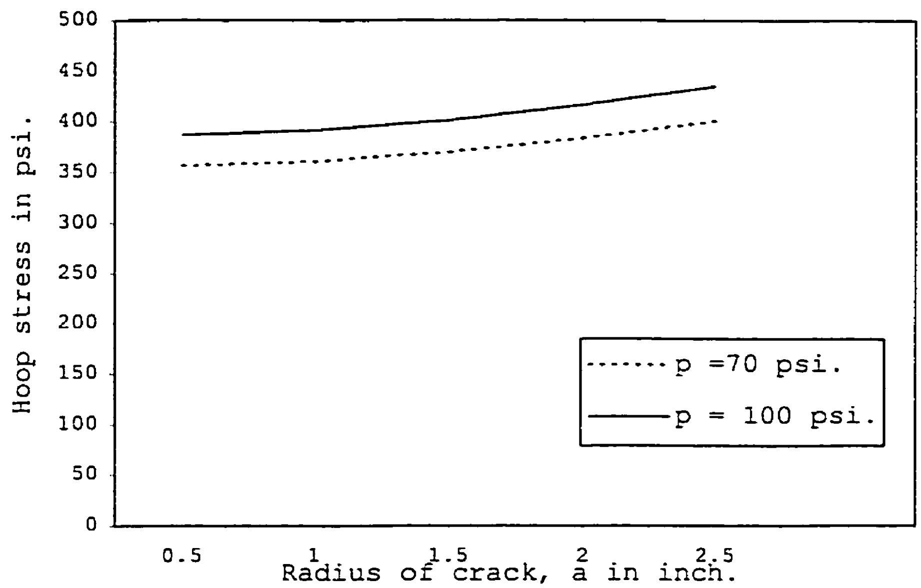


Fig: 3.18 Hoop stresses at a longitudinal crack

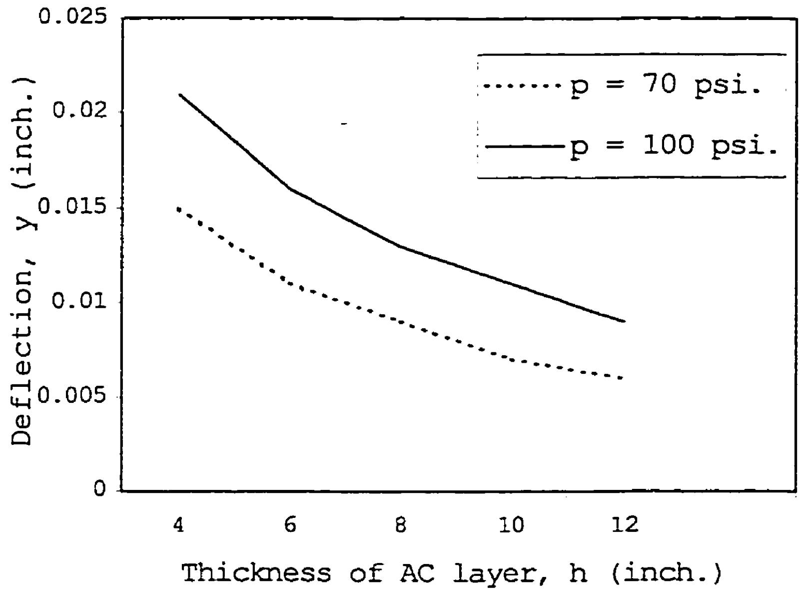


Fig: 3.19 Deflections at a longitudinal crack

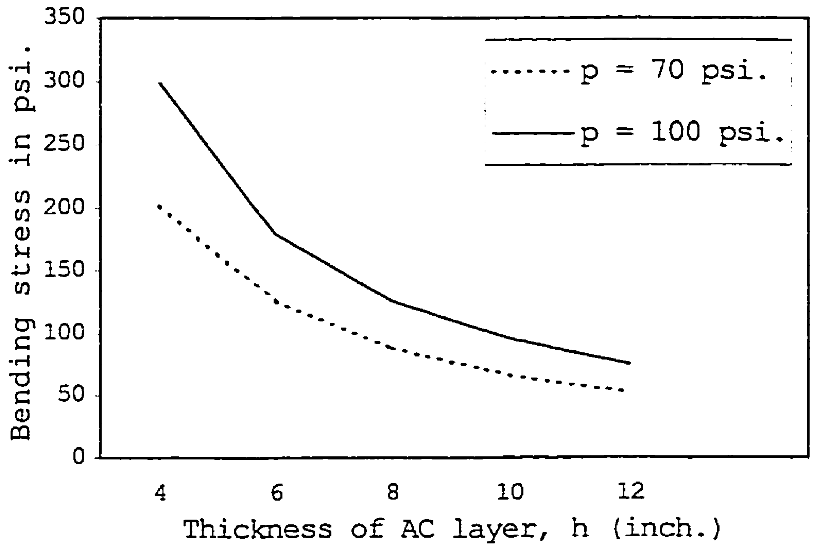


Fig: 3.20 Bending stresses at a longitudinal crack

3.10 Pothole formation due to alligator cracks

Thawing takes place in spring season and is associated with excess of pore pressure produced by melting of ice lenses. The consequences are loss of soil strength due to decrease of effective stress and settlement of ground surface due to drainage of water.

The bearing capacity of flexible pavements is reduced considerably. This is partly a result of a decrease of the relative density of the base course and subgrade material as caused by heave, partly a result of an increase of the degree of saturation of the soil, and partly a result of excess of pore water pressure in the soils caused by rapid melting of ice lenses.

As the wheel load applications on the pavement surface increase, the whole surface will be compressed downwards causing cracking. Cracks due to repetition loads are formed, and this cracking is known as alligator cracking.

In the fracture mechanics approach to the strength of materials, it is recognized that all material particles contain flaws that act as stress raisers.

On the surface of flexible pavement having unit thickness is represented by a microscopic elliptical crack. If the applied load is increased until the tensile strength of the

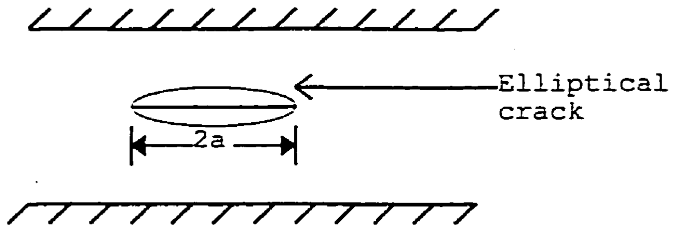


Fig: 3.21 (a) Hairline crack on pavement surface

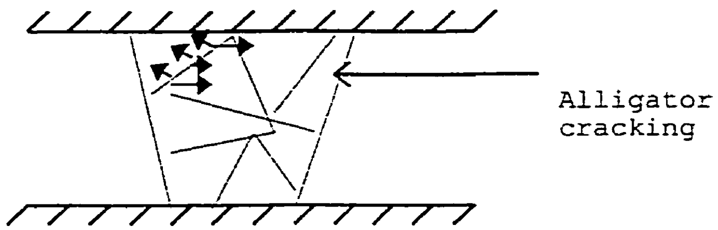


Fig: 3.21 (b) Disintegration of Pavement

pavement is reached. The crack spreads, forming new crack surface.

Let it be assumed that on the surface of the pavement, a hairline crack of elliptical shape is formed. When the applied stress is increased until the strength of pavement is reached, the crack spreads forming new crack surface.

Let radius of crack be 'a'

According to Blight (1973) when length of the crack becomes 2a the volume of the material destressed is equal to the twice the volume of cylinder of radius '*a*' of unit length.

$$v = \pi a^2 * 1 \qquad (65)$$

Therefore, volume of material distressed as the length of crack is 2a, V

$$V = 2v \qquad (66)$$

$$V = 2 * \prod * a^2 * 1$$

$$= 2 \prod a^2 \qquad (67)$$

Strain energy released in enlarging the crack, SE

$$= \frac{1}{2} * \text{Load} * \text{Extension}$$

$$= \frac{1}{2} * \text{Stress} * \text{Area} * \text{Strain} * \text{Length}$$

$$= \frac{1}{2} * \text{Stress} * \text{Area} * \frac{\text{Stress}}{\text{Young's Modulus}} * \text{Length}$$

$$= \frac{1}{2} * \frac{(\text{Stress})^2 * \text{Volume}}{\text{Young's Modulus}}$$

$$= \frac{1}{2} * \frac{\sigma_t^{\,2}}{E} * V \qquad (68)$$

Putting equation (67) in (68)

$$S.E = \frac{1}{2} * \frac{\sigma_t^2}{E} * 2\Pi a^2$$

$$= \frac{\Pi}{E} * \sigma_t^2 * a^2 \quad (69)$$

By the principle of conservation of energy, this energy must reappear as the surface energy S_T of the extended crack.

Therefore, The total energy of the crack per unit depth is:

$$T_E = 2(S_T)2a - \frac{\Pi}{E}\sigma_t^2 a^2 \quad (70)$$

$$= 4S_T a - \frac{\Pi}{E}\sigma_t^2 a^2 \quad (71)$$

The crack expands if

$$\frac{dT_E}{da} = 0 \quad (72)$$

Putting equation (71) in equation (72)

$$4S_T - \frac{\Pi}{E}\sigma_t^2 2a = 0$$

$$2S_T - \frac{\Pi}{E}\sigma_t^2 a = 0 \quad (73)$$

$$\sigma_t^2 = \frac{2S_T E}{\Pi a} \quad (74)$$

$$\sigma_t = \sqrt{\frac{2S_T E}{\Pi a}} \quad (75)$$

Saal et al. (1971) say that the surface energy of asphalt of all grades at all temperature is 11 x 10^{-3}lbf-inch^{-1}. (1.9 N/m).

A hairline crack will expand when minimum stress is developed. As the radius of the crack is small, it requires more stress than a crack with greater radius. That is why if a small crack is formed, it keeps on expanding even at low stress development.

3.10.1 <u>Pavement Model for alligator Cracking</u>

When applied tensile stress exceeds tensile strength, the crack expands forming new cracking area.

Saal et al. (1971) say that surface energy of asphalt of all grades at all temperatures is 11×10^{-3} lbf-inch^{-1} (1.94N/m)

The following data is assumed:

Young's modulus, E = 100,000 psi. (689.5 MPa)

Surface Energy, S_t = 0.011 lbf-inch^{-1} (1.9 N/m)

Radius of crack, a = 0.5 inch. (0.0127 m)

The minimum tensile strength required to expand the crack as given in equation (75)

$$\sigma_t = \sqrt{\frac{2S_T}{\Pi a}}$$

σ_t = 37.41 psi. (0.26 MPa)

When applied stress is 37.4 psi. (0.26 MPa) the crack of 0.5 inches (0.013 m) expands to form a new crack area.

3.10.2 Pavement Model for Bending & Shear Stresses

When the crack becomes sufficiently large, it resembles a transverse or a longitudinal crack. A typical alligator crack surface is as shown in the fig: 3.21.

When wheel load passes on each crack, it produces shear and bending stress at the cracks.

When the alligator crack becomes enlarged to the size of transverse crack, then shear stress & deflection can be calculated in section 3.5.

Therefore,

Shear Stress = 186 psi. (1.28 MPa)

Deflection, y_c = 0.087 inch. (0.002 m)

When the alligator becomes enlarged to the size of longitudinal crack, then bending stress and deflection can be calculated as shown in section 3.7.2.

Therefore,

Bending stress, σ_{BS} = 202 psi. (1.39 MPa)

Deflection, y_c = 0.015 inch. (0.0004 m)

3.10(a) Graph for tensile stresses required for expanding a crack

The tensile stresses required for expanding a crack have been computed for elastic moduli varying from E = 20,000 (137.9 MPa) to E = 100,000 psi. (689.5 MPa) and for radii of crack varying from 0.2 (0.005 m) to 1 (0.0254 m) inches using the procedure shown in section 3.10. These are shown in fig: 3.22.

3.11 Discussion of Results

A hairline crack expands according to the fracture energy concept. A minimum tensile stress of 37.2 psi. (0.26 MPa) is required to expand a typical crack of radius 0.5 inches. (0.013 m) As radius of crack increases, tensile stress required to expand a crack is less (fig: 3.22). This is the reason for the formation and expansion on the surface of a pavement. This increases the radius of crack.

When the hairline crack expands sufficiently it resembles a transverse or a longitudinal crack depending upon the direction of the crack on the pavement surface.

When wheel load passes on alligator crack in transverse direction, it develops shear stress of 186 psi. (1.28 Mpa) and deflection of 0.087 inches (0.002 m) on the pavement surface. Higher tire pressure produces more shear stress in pavement. Strong pavement material produces lesser deflection than weak material (fig: 3.7). Shear stress is lesser if the thickness if AC layer is more (fig: 3.8).

When wheel load passes on alligator crack in longitudinal direction, it produces bending stress of 202 psi.(1.39 Mpa)

Bending stress in pavement is more when tire pressure increases (fig: 3.20). Deflection decreases as the thickness of pavement increases (fig: 3.19).

This process is experienced by all cracks (fig: 3.21). The pavement is disintegrated into pieces. This effect is more noticeable when the number of wheel load repetitions are maximum. When the pavement breaks into pieces, a pothole is formed on the surface of the pavement.

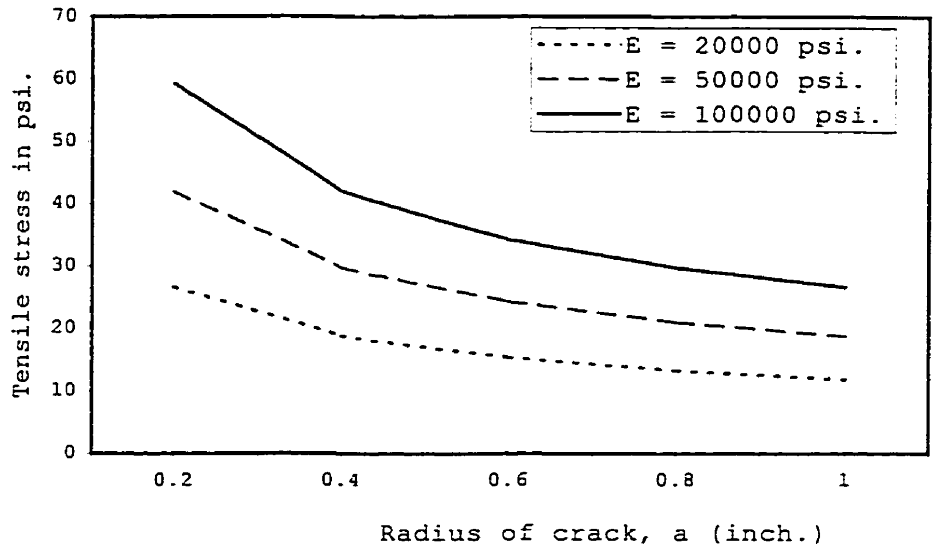


Fig: 3.22 Tensile stresses required for expanding a crack

3.12 Moisture damage in flexible pavement

A small transverse crack on the surface of the flexible pavement with cement concrete base (impermeable) allows the water to enter the pavement when there is heavy rain or flooding.

Flexible pavement (AC) with a cement concrete base is shown in fig: 3.23. AC layer is assumed fully saturated.

A small transverse crack allows water into AC layer. Any applied tire pressure is transmitted as pore water pressure as if an hydraulic system existed beneath pavement. The pressure needs relief and often, lowest resistance is encountered from the surrounding surface course, which is then blow out. According to Lay (1990) in an ideal system the upward pressure is of the same order as tire contact pressure.

As pressure is transmitted from the transverse crack, there is water between AC layer and concrete base. The water pressure is released in the near vicinity. This can be considered as a beam with simple support at one end and fixed on the other side, with partly loaded uniformly distributed load. The beam shown in fig: 3.24 shows the proposed model.

Let R_A and R_B be the reactions and q be the uplift pressure.

$$R_A + R_B = qA \quad (76)$$

$$R_B L - \frac{qA^2}{2} = M_1 \quad (77)$$

The bending moment at $0 < x < A$

$$M = EI\frac{d^2y}{dx^2} = R_A x + M_1 - q\frac{x^2}{2} \quad (78)$$

$$EI\frac{dy}{dx} = \frac{1}{2}R_A x^2 + M_1 x - q\frac{x^3}{6} + C_1 \quad (79)$$

$$EIy = \frac{1}{6}R_A x^3 + \frac{1}{2}M_1 x^2 - q\frac{x^4}{24} + C_1 x + C_2 \quad (80)$$

Since $x = 0$, $y = 0$ and $\frac{dy}{dx} = 0$

Therefore $C_1 = 0 = C_2$

For $A < x < L$

$$M_1 = EI\frac{d^2y}{dx^2} = R_B(L - x) \quad (81)$$

$$EI\frac{dy}{dx} = R_B L x - R_B\frac{x^2}{2} + C_3 \quad (82)$$

$$EIy = \frac{1}{2}R_B L x^2 - R_B\frac{x^3}{6} + C_3 x + C_4 \quad (83)$$

At $x = A$,

Slopes for $0 < x < A$ and $A < x < L$ are equal

Equating equations (79) and (82)

$$\frac{1}{2}R_A A^2 + M_1 A - q\frac{A^3}{6} = R_B L A - R_B\frac{A^2}{2} + C_3 \quad (84)$$

$$C_3 = \frac{1}{2}R_A A^2 + M_1 A - q\frac{A^3}{6} - R_B L A + \frac{1}{2}R_B A^2 \quad (85)$$

At $x = L$, $y = 0$

Substituting these values in equation (83)

$$EI * 0 = \frac{1}{2} R_B L^3 - \frac{1}{6} R_B L^3 + C_3 L + C_4 \tag{86}$$

$$C_4 = -\frac{1}{3} R_B L^3 - C_3 L \tag{87}$$

At x = A,

Deflections for 0 < x < A and A < x < L are equal

Therefore,

Equating equations (80) and (83) at x = A

$$\frac{1}{6} R_A A^3 + \frac{1}{2} M_1 A^2 - W \frac{A^4}{24} = \frac{1}{2} R_B L A^2 - \frac{1}{6} R_B A^3 + C_3 A + C_4 \tag{88}$$

From equation (81)

$$R_B = qA - R_A \tag{89}$$

Substituting equation (89) into equation (77)

$$(qA - R_A)L - q \frac{A^2}{2} = M_1 \tag{90}$$

Substituting equation (89) and (88) in equation (85),

$$C_3 = -\frac{qA^3}{6} \tag{91}$$

Substituting equation (91) in equation (87)

$$C_4 = -\frac{1}{3}(qA - R_A)L^3 + q \frac{A^3}{6} L \tag{92}$$

Now substituting equations (90) and (92) in equation (88)

$$R_A = \frac{qA}{8L^3}(A^3 + 8L^3 - 4A^2L) \tag{93}$$

From equation (76)

$$R_A + R_B = qA$$

Substituting equation (93) in equation (76)

$$R_B = \frac{qA^3}{8L^3}(4L - A) \qquad (94)$$

From equation (80) as $C_1 = 0 = C_2$

$$EIy = \frac{1}{6}R_A A x^3 + M_1 - \frac{qx^4}{24} \qquad (95)$$

Substituting equation (77) in (95)

$$EIy = \frac{1}{6}R_A x^3 + \frac{1}{2}\left(R_B L - \frac{qA^2}{2}\right)x^2 - \frac{qx^4}{24} \qquad (96)$$

From equation (76)

$$R_A = qA - R_B \qquad (97)$$

Substituting equation (97) in (96)

$$y = \frac{1}{24EI}\left[4R_B(3Lx^2 - x^3) - qx^4 - 2qAx^2(3A - 2x)\right] \qquad (98)$$

The deflection y is obtained from equation (98)

Bending moment at any point between $0 < x < A$

From equation (78)

$$M = R_A x + M_1 - q\frac{x^2}{2}$$

Substituting equation (77) and (97) in above equation

$$M = R_B(L - x) + \frac{q}{2}(2Ax - A^2 - x^2) \qquad (99)$$

Bending moment is obtained from equation (99)

Let y^- be the position of neutral axis.

Therefore, Bending stress

$$\sigma_{BS} = \frac{M}{I}y^- \qquad (100)$$

3.13 Pavement model for moisture damage

Transverse crack on the flexible pavement surface allows the water to pass through the AC layer. The impermeable concrete base doesn't allow water to pass through. The water between AC layer and impermeable base course exerts pressure in upward direction, which causes blow up of AC layer.

The following data is assumed:

Modulus of elasticity, E = 100000 psi. (689.5 MPa)

Tire pressure, p = 70 psi. (0.48 MPa)

Width of beam, w = 1 inch. (0.0254 m)

Thickness of AC layer, h = 4 inch. (0.10 m)

Load per inch acting on beam, q = 910 lbs/inch. (176.4 N/m)

Moment of inertia, $I = wh^3/12$

$= 5.33$ inch.^{4} (0.000002 m^4)

The reaction as given in equation (94)

$$R_B = \frac{qA^3}{8L^3}(4L - A)$$

R_B = 1623 lbs. (7.27 KN)

Bending moment at x = 7 inch. by using equation (99)

$$M = R_A(L - x) + \frac{q}{2}(2Ax - A^2 - x^2)$$

M = 9588 lbs-inch. (1091.04 N-m)

The position of neutral axis, $\bar{y}$ = 2 inch. (0.05 m)

Therefore, Bending stress as given in equation (100)

$$\sigma_{BS} = \frac{M}{I} \bar{y}$$

σ_{BS} = 3598 psi. (24.81 MPa)

Deflection at this point as given in equation (98)

$$y = \frac{1}{24EI} [4R_B(3Lx^2 - x^3) - qx^4 - 2qAx^2(3A - 2x)]$$

y = 0.895 inch. (0.023 m)

3.13(a) Graphs for deflections and bending stresses

The deflections in moisture damage model have been computed for elastic moduli varying from E = 20,000 (137.9 MPa) to 100,000 psi. (689.5 MPa) and for thicknesses varying from 4 (0.10 m) to 6 inches (0.15 m) using the procedure shown in section 3.13. These are shown in fig: 3.28.

The bending stresses in moisture damage model have been computed for tire pressures 70 (0.48 MPa) and 100 psi. (0.69 MPa) and for thicknesses varying from 4 (0.10 m) to 12 inches (0.30 m) using the procedure shown in section 3.13. These are shown in fig: 3.29

3.14 Discussion of Results

Due to moisture, the relative strength of AC layer decreases. When wheel load passes on a small transverse crack, this applied pressure is transmitted as pore water pressure. This pressure needs instant relief and there is no modulus of support for the AC layer. The deflection in the upward direction for the pavement is 0.895 inches (0.023 m) and a large bending stress of 3598 psi. (24.81 MPa) This causes sudden blow out in the upward direction in the near vicinity of the transverse crack. Therefore, AC layer blows out forming pothole (fig: 3.27).

Deflection is less in stronger material than in weaker material. It decreases with increase in thickness of AC layer (fig: 3.28).

Bending stress is more when tire pressure increases. It decreases with increase in thickness of AC layer (fig:3.29).

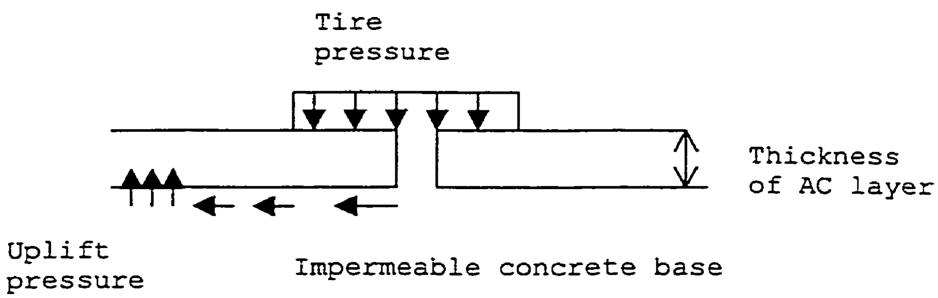


Fig: 3.23 Upward pressure acting on pavement surface

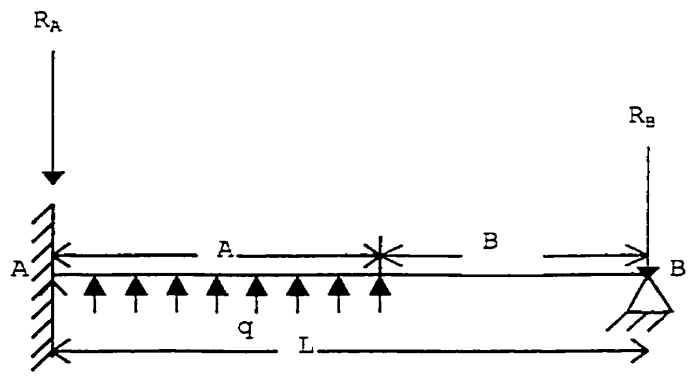


Fig: 3.24 Proposed beam model

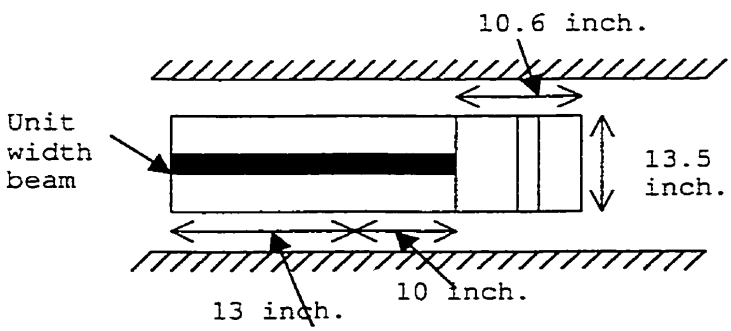


Fig: 3.25 Wheel loading on transverse Crack

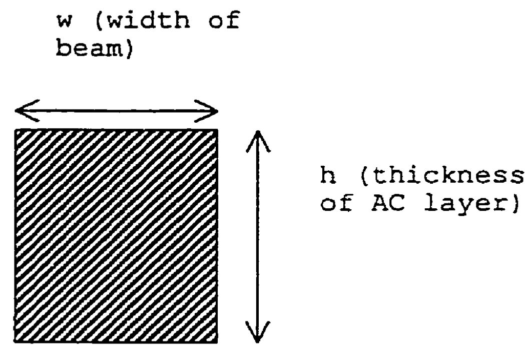


Fig: 3.26 Beam dimensions

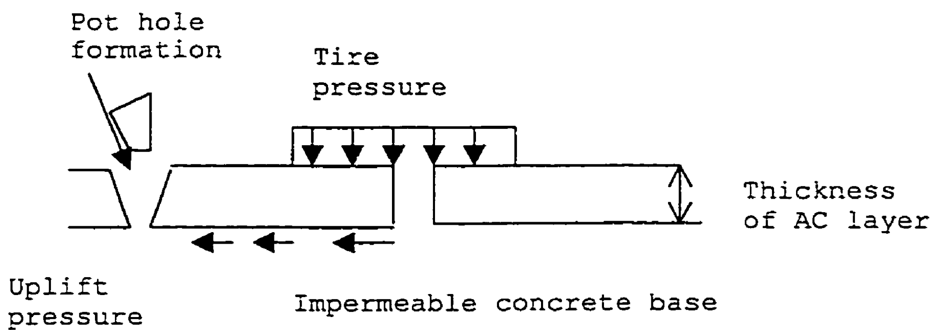


Fig: 3.27 Blow out from AC surface forming pothole

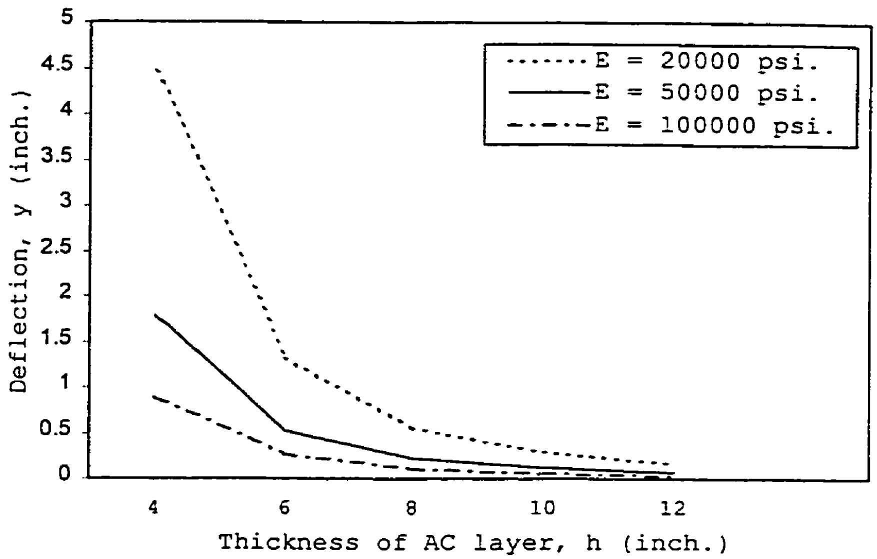


Fig: 3.28 Deflections in Moisture damage model

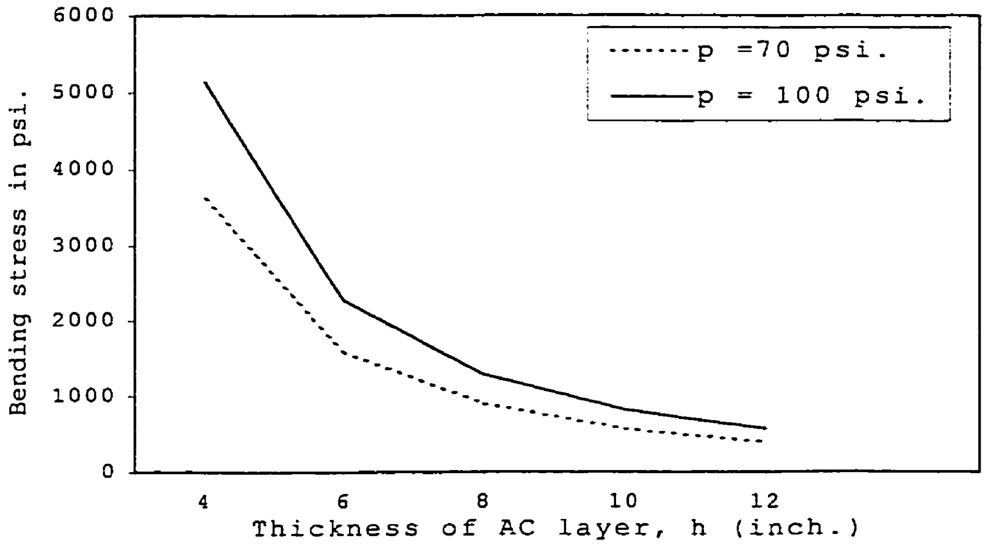


Fig: 3.29 Bending stresses in Moisture damage model

3.15 General discussion

Three types of cracks, namely, transverse, longitudinal and alligator cracks are identified as the starting points for the formation of potholes in a flexible pavement (asphalt concrete pavement). The repetitive wheel loads of trucks are largely responsible for breaking up the material at the edges of the cracks. A transverse crack is perpendicular to the direction of motion of the wheel whereas a longitudinal crack is parallel to the direction of motion. Alligator cracks are hairline cracks which gradually expand to become wider cracks, similar to transverse or longitudinal cracks. However, they can be at any other angle to the direction of the motion of the wheel. When a wheel load passes over a crack, different types of stresses and deflections are produced in the pavement material due to shear and bending movements of the elements near the cracks.

Mathematical models have been developed to determine the shear stress, bending stress and deflections. The magnitudes of stresses and deflections developed in the pavement are dependent on the thickness of the pavement layer, wheel load, tire pressure, elastic modulus and modulus of base support. Specific values for these parameters are assumed and the magnitudes of stresses and deflections are obtained by using mathematical models. In order to show the range of stresses and deflections developed in the pavement, a range of values for the above parameters are assumed. The results are shown in graphs associated with different models.

Freezing and thawing of water in cracks is contributing factor in the formation of potholes. This has been taken into consideration in the case of longitudinal cracks with ice expansion in the cavity. For this case, radial and hoop stresses developed in the material surrounding the cracks are calculated.

Similarly, the minimum tensile stress required to expand a hairline alligator crack is calculated. Mathematical models are developed assuming the specific conditions.

The breaking of flexible pavement material when water in a transverse crack is subjected to tire pressure is a special case where the pavement layer lies on top of an impermeable base such as cement concrete base. A mathematical model is developed to compute the bending stress and deflection associated with the blowout of pavement material.

In all the above cases, the emphasis is placed on the methods to calculate stresses and deflections rather than on exact numerical values.

When the pavement is newly laid, the flexibility and the strength of the material is sufficient to prevent the formations of cracks. However, as the time elapses, the pavement material becomes brittle and it is subjected to fatigue under repetitive loads. Cracks appear at this stage. The results presented in this thesis show stresses and deflections that are responsible for breaking up the pavement material at the edges of cracks. This disintegration of material contributes to the expansion of cracks and the formation of potholes.

Chapter 4

Computer program

4.1 Introduction

Four mathematical models have been developed to show the mechanism of potholes. In each model stresses and deflections are determined. The programs are written in C/C++. The flowcharts and explanations of the program are presented in the following sections.

4.2 Program Capabilities

The program developed for this study is capable of solving the following four different problems as contained in ITEM 1 through ITEM 4.

4.2.1 Item 1

It deals with the Transverse cracks Mathematical model. The user is asked to enter the following data

When the above required data is supplied, it calculates the deflection and the shear stress.

i. Height of AC layer, h in inch.

ii. Enter width of beam, w in inch.

iii. Enter modulus of support, k in pci.

iv. Enter width of tire in inch.

v. Enter tire pressure, p in psi.

vi. Enter the value of x in inch.

When the above required data is supplied, it calculates the deflection and shear stress.

4.2.2 Item 2

The hoop stress, radial stress, elongation, bending stress and deflection are calculated in longitudinal crack mathematical model by using the following data:

i. Enter value of a, in inch.

ii. Enter value of c, in inch.

iii. Enter r in inch.

iv. Enter ice pressure, pi in psi.

v. Enter tire pressure, p in psi.

vi. Enter poisson's ratio, v

vii. Enter E value in psi.

viii. Enter modulus of support, k in pci.

When the required data is entered the hoop stress, radial stress and deflection can be found.

4.2.3 Item 3

The tensile stress required for the crack to expand in alligator crack mathematical model and maximum deflection and maximum bending stress in the pavement are determined using the following data.

i. Enter value of h in inch.

ii. Enter value of U (S_T as in model development) in lbf/inch.

iii. Radius of crack, a in inches.

When the above data is entered, the tensile stress required for a crack to expand can be calculated.

4.2.4 Item 4

This deals with moisture damage mathematical model. The user is asked to enter the following data

i. Enter value of h in inch.

ii. Enter width of beam, w in inch.

iii. Enter modulus of support, k in pci.

iv. Enter width of tire in inch.

v. Enter tire pressure, p in psi.

vi. Enter the value of x in inch.

vii. Enter young's modulus, E in psi.

When the above data is supplied, the bending stress and deflection are computed.

4.3 Program Instructions

The program is started by entering Borland C/C++ TLAM and by pressing the return/enter key. Then program executes by clicking on run command.

The menu screen will appear. By typing the required ITEM (mathematical model) that needs to be solved and pressing the return/enter key the program will ask for the input data. As soon as the input data is fed the program will start execution and results will be obtained. ITEM 5 will exit the program.

4.4 Flow Chart

The algorithm for developing the computer program used in this study is presented in the flow chart as shown in figure 5.1. The flow chart describes the logic and sequential steps of the program. It is designed to develop and organize for writing the program efficiently. It also makes the reader understand the program clearly and easily.

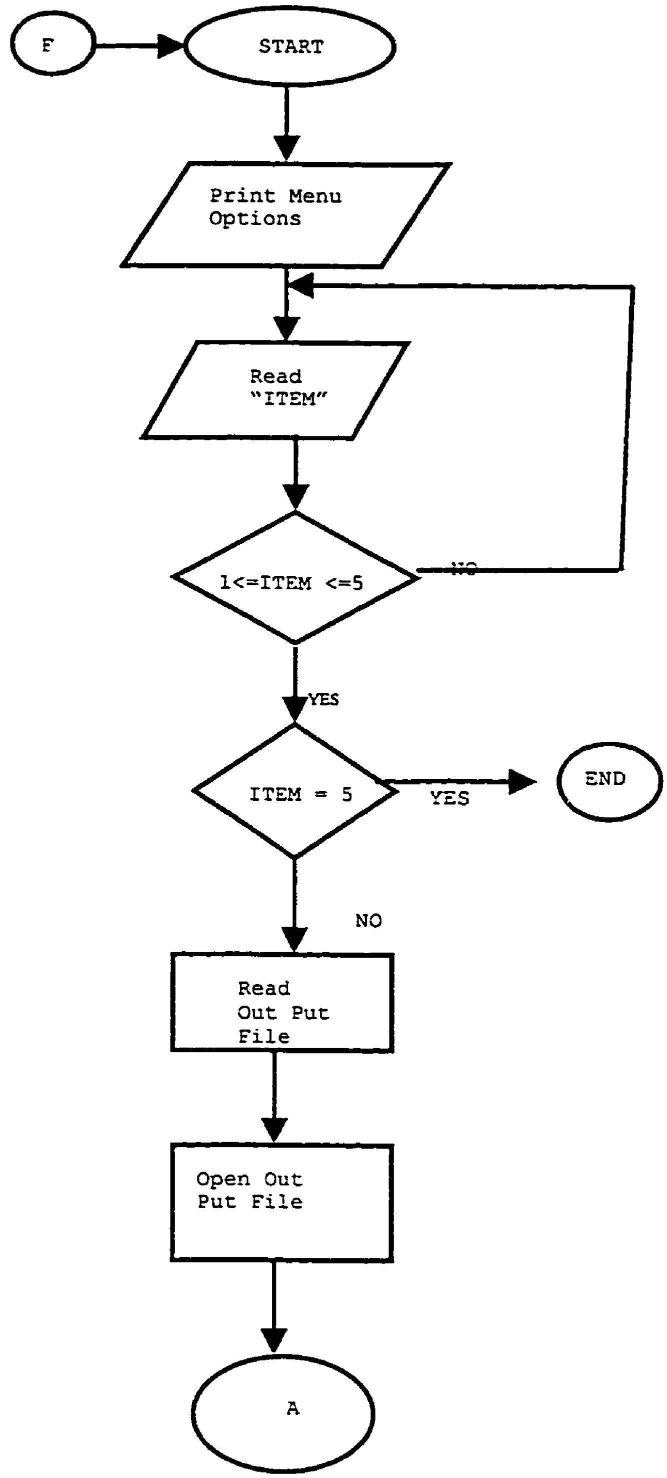


Figure 4.1: Flow Chart

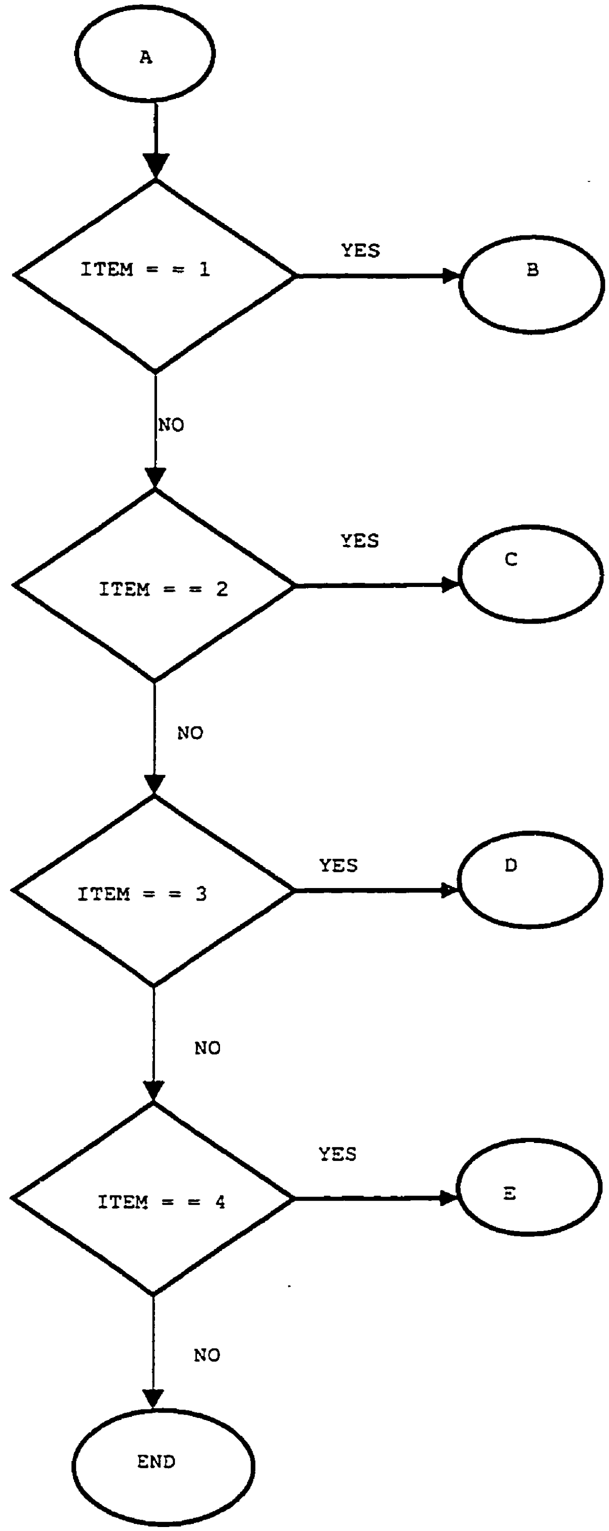


Figure 4.1{a}

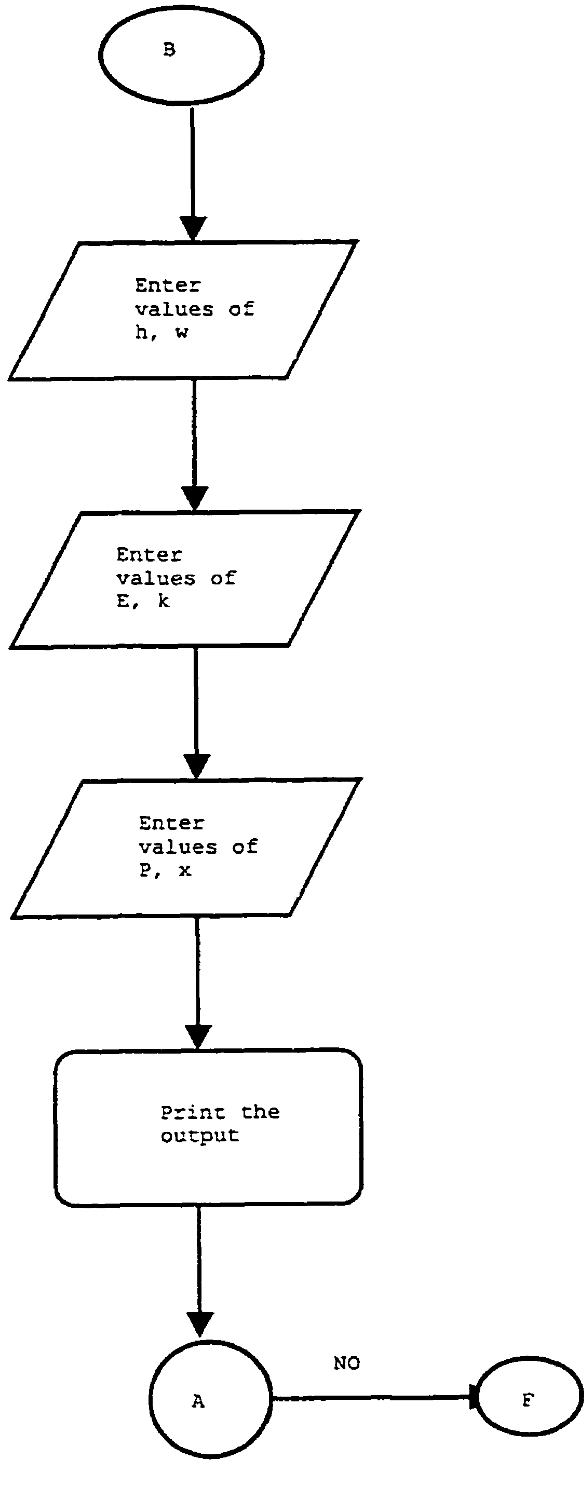

B
Enter values of h, w
Enter values of E, k
Enter values of P, x
Print the output
A
NO
F

Figure: 4.1{b}

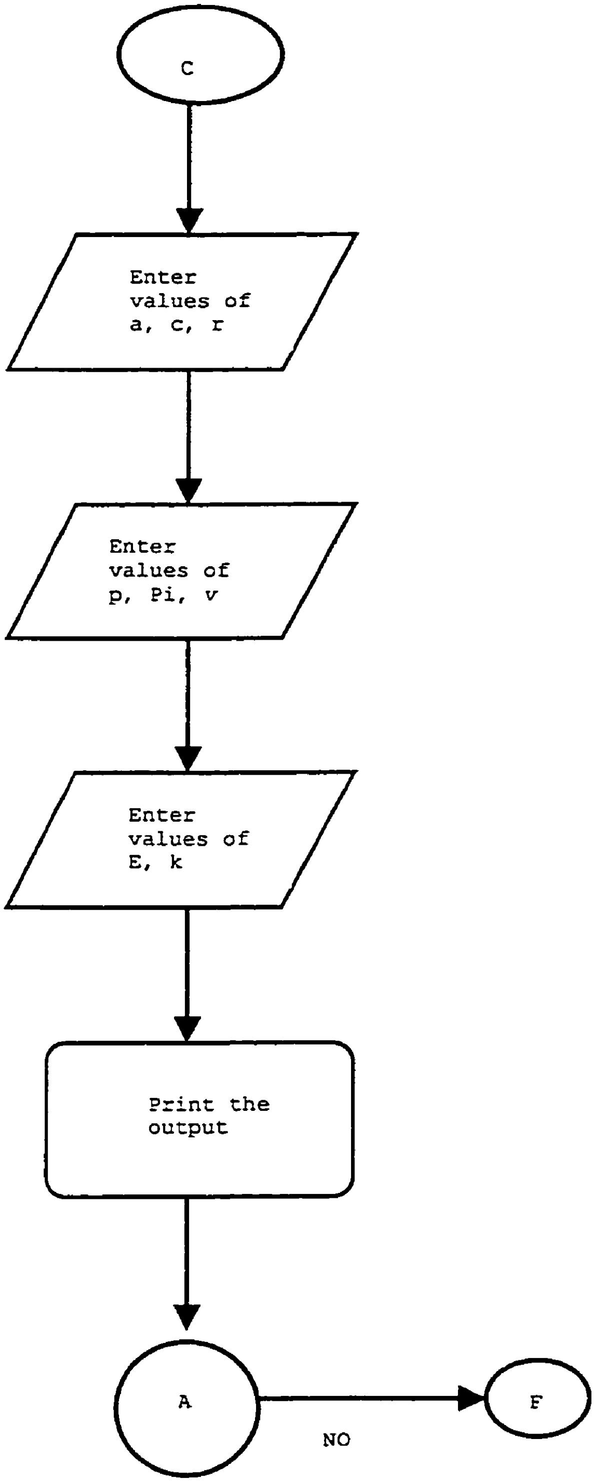
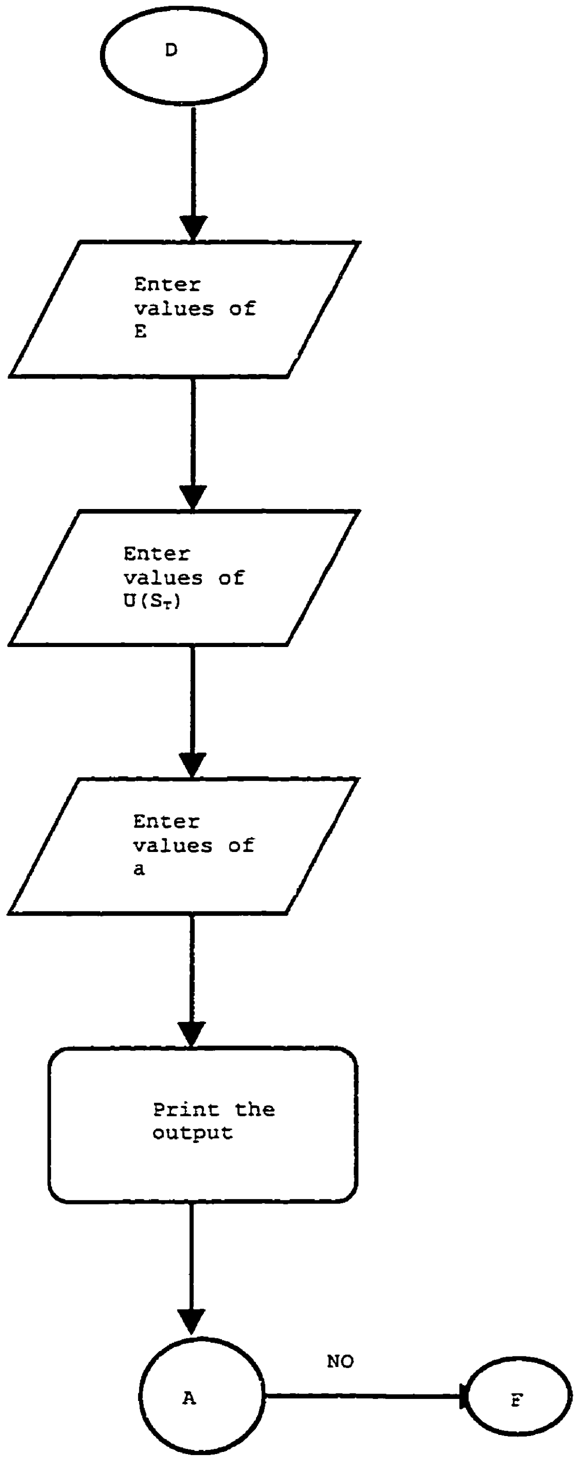

C
Enter
values of
a, c, r
Enter
values of
p, Pi, v
Enter
values of
E, k
Print the
output
A
NO
F

Figure: 4.1{c}



D
Enter values of E
Enter values of U(ST)
Enter values of a
Print the output
A
NO
F

Figure: 4.1{d}

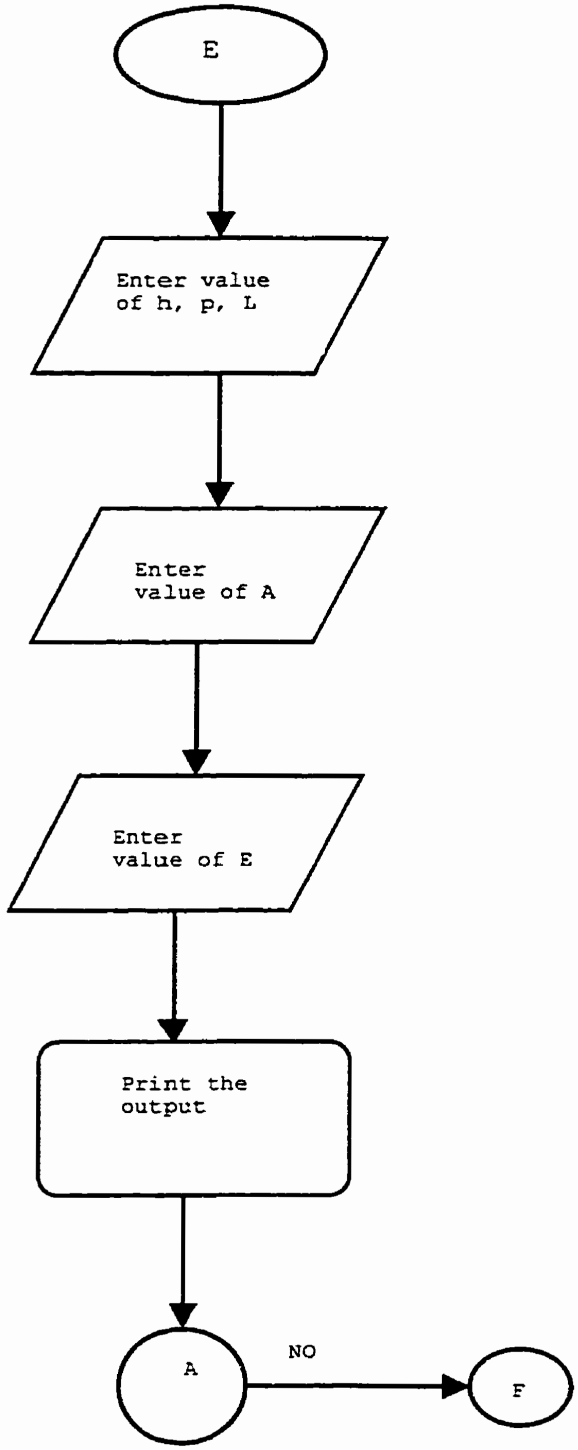

E
Enter value
of h, p, L
Enter
value of A
Enter
value of E
Print the
output
A
NO
F

Figure: 4.1{e}

Chapter 5

Conclusions and Future Recommendations

The research work deals with the formation of potholes starting from different types of cracks in flexible pavement layer (AC layer). The conclusions and recommendations for future study are as follows.

5.1 Conclusions

The following conclusions can be drawn from this study.

i. Wheel loading plays a significant role in pavement failure. It produces stresses and deflections in the pavement at the edges of a crack, which lead to the formation of potholes. Pavement failure depends upon the thickness of AC layer and material properties of the pavement.

ii. When the water in a crack becomes ice, it increases the crack area. The crack is widened due to ice formation and expansion. Due to wheel loading the crack deforms and the stress developed breaks the pavement at the edges of the crack. Continuous breaking and increasing area create potholes on the surface of the pavement. Hoop and radial stresses developed in the crack depend on the tire pressure acting on the crack. Elongation depends upon the E and v of the pavement.

iii. Hairline alligator cracks, once formed, expand without further increase in applied tensile stress because larger cracks need less tensile stress than small cracks to expand. As the crack expands, bending stress and deflections are produced under wheel loads on the pavement. This causes disintegration of the pavement. Stress required for the expansion of the crack depends upon on the radius of the crack and the E value of the AC layer.

iv. Moisture decreases the relative strength of AC layer. When the wheel load acts on the crack, the applied pressure is transmitted as pore pressure. This pressure requires dissipation instantaneously. As there is no support for the pavement, it blows out in upward direction within the crack, forming a pothole. A series of potholes are formed on the surface of pavement as blow outs continue.

5.2 Topic for Future Research

This work has been carried out for different types of cracks occurring in the pavement, under specified conditions. The combined effect of all these cracks occurring under the same weather and loading conditions will be an useful project for further research work. Also, in ice expansion (longitudinal crack) model is considered in AC layer. Further studies can be carried out for deeper cracks which penetrate into the base course.

The alligator cracks are assumed to expand into longitudinal and transverse cracks. In addition to these cracks, consideration of diagonal cracks on the surface of a flexible surface will make the study more comprehensive.

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Appendix A

Computer Program

The computer program developed for the study of this thesis has been written in Borland C/C^{++} language is shown in this apendix.

When this program runs, the menu screen as shown in fig: A.1 appears on the screen. The user has five choices for calculating results for four models (1-4) or quit this program. When the specific choice is entered it asks for required parameters which are shown in fig: A.2-A.5.

When the results are obtained, the program asks the user to wait as "Please wait" and then returns to main menu screen (fig: A.1).

The complete computer program is given on page A.8.

Type of Problem: Your choice (1-5)

1. Transverse Crack

2. Longitudinal Crack

3. Alligator Crack

4. Moisture damage

5. Quit

Your choice:

Figure: A.1 Main menu screen

Your choice: 1

Enter value of h: 4

Enter width of beam w: 1

Enter modulus of support k: 250

Enter width of tire: 13.5

Enter tire pressure p: 70

Enter the value of x: 0

The deflection at x is = 0.087

Shear stress at x is = 184.87

Please wait…………………….

Figure: A.2: Input data and results for "Your choice 1"

Your choice: 2

Enter value of a: 1

Enter value of c: 10

Enter r: 1

Enter ice pressure pi: 284

Enter tire pressure p: 70

The Hoop Stress = 361

The Radial Stress = 354

ELONGATION AT THIS POINT

Enter poison's ratio v: .5

Enter E value: 100000

The Elongation: 0.005

BENDING AND DEFLECTION AT THIS POINT

Enter modulus of support k: 250

Max. Deflection: 0.15

Max. Bending Stress: 202

Please wait.....................

Figure A.3 Input data and results for "Your Choice 2"

Your Choice: 3

Enter Value E in: 100000

Enter value of U in: .015

The crack will spread if S = 43.69

Please wait..................

Figure A.4 Input and results for "Your Choice 4"

Your Choice: 4

Enter Value of h: 4

Enter tire pressure p: 70

Enter total length of beam, L: 23

Enter length of loaded beam, A: 7

Enter value, E: 100000

The Reaction Rb is = 146.77

BENDING STRESS AT THIS POINT

The Bending Moment, M = 2348

The Bending Stress = 881

The deflection y = 0.13

Please wait......................

Figure: A.5 Input data and results for "Your Choice 4"

COMPUTER PROGRAM

```
#include<stdio.h>

#include<dos.h>

#include<stdlib.h>

#include<ctype.h>

#include<math.h>

#include<conio.h>

void Moisture_destruction(void);

void Transverse_cracking(void);

void Alligator_cracking(void);

void Longitudinal_cracking(void);

# define PI 3.142

main()

{

 int choice;

 clrscr();

 textbackground(BLUE);

textcolor(WHITE);

kk :clrscr();

printf("\n\n\n\t\t\tMECHANISM OF POTHOLES");

printf("\n\n\t1.Transverse cracking");
```

```
printf("\n\n\t2.Longitudinal Cracking");
printf("\n\n\t3.Alligator cracking");
printf("\n\n\t4.Special case");
printf("\n\n\t5.Quit");
printf("\n\n\n\n\tYour Choice = ");
scanf("%d",&choice);
switch(choice)
{
     case 1:
          clrscr();
          Transverse_cracking();
          clrscr();
          break;
     case 2:
          clrscr();
          Longitudinal_cracking();
          clrscr();
          break;
     case 3:
          clrscr();
          Alligator_cracking();
          clrscr();
          break;
     case 4:
```

```
          clrscr();
          Moisture_destruction();
          clrscr();
          break;
          default:
     exit(0);
 }
     goto kk;
}
 void Moisture_destruction(void)
{
/* To calculate the Max. Bending Stress due moisture effect
*/
float Rb, A, q, L, x, Mx, y, I, h, Bs, p, E, m ;
/*
* RB is the reaction at simply supported beam in lbs
* A is the length in inch the water pressure is acting
*  q is the load/inch acting on the beam
* x is the distance in inches the bending stress is to be
  calculated
* Mx is the bending moment lb-inch at x
* y is the deflection at x
* h is thcikness of Ac layer in inches
* w is the width in inches of the cross section
```

```
* L is the total length of beam
*/
clrscr();
printf("Enter value of h: ");
scanf("%f", &h);
I = 1*h*h*h/12;
printf("Enter tire pressure p: ");
scanf("%f",&p);
printf("Enter total length of beam, L: ");
scanf("%f",&L);
printf("Enter length of loaded beam, A: ");
scanf("%f",&A);
q = p*A;
printf("Enter value, E:  ");
scanf("%f",&E);
Rb = (q*A*A*A)*(4.0*L-A)/(8.0*L*L*L);
printf("\n The reaction Rb is =   %f", Rb);
printf("\n\n\n BENDING STRESS AT THIS POINT: ");
printf("\nEnter the point of consideration, x: ");
scanf("%f",&x);
Mx = Rb*(L-x);
printf("\nThe Bending Moment, Mx=  %f", Mx);
Bs = (Mx*h)/(2*I);
printf("\n The Bending Stress Bs=  %f",Bs);
```

```
printf("\n\n\nDEFLECTION AT THIS POINT: ");
m = 1/(6*E*I);
y = m*((Rb*(3*L*x*x-x*x*x-2*L*L*L))+(q*A*A*A*(L-x)));
printf("\n The deflection y=   %f",y);
printf("\n\n\n\nPlease wait......");
sleep(7);
return ;
}
void Longitudinal_cracking(void)
{
 /* Program to calculate the hoop stress and radial stress
   due to expansion of crack due to ice formation in winter
 */
float c, a, R, p, pi, X, Y, r, Pt, E, Uo, v, Rf, SL, BSmax,
ymax, Mmax, I, h, L, k;
/*
 * c is the distamnce from the edge of the pavement in
   inch.
 * a is the radius of the crack in inch
 * pi is the ice pressure in psi
 * p is the tire pressure in psi
 * v is the poisson's ratio
 * X is the hoop stress in psi
 * Y is the radial stress
```

```
*/
printf("Enter value of a: ");
scanf("%f", &a );
printf("Enter value of c: ");
scanf("%f", &c);
printf("Enter r: ");
scanf("%f", &r);
printf("Enter ice pressure pi: ");
scanf("%f", &p);
printf("Enter Tire Pressure p: ");
scanf("%f", &p);
Pt =(pi + p);
X = (Pt/(R*R-1))*(1+(c*c/r*r));
Y = (Pt/(R*R-1))*(1-(c*c/r*r));
printf("\nThe Hoop Stress=   %f", X);
printf("\nThe Radial Stress=  %f", Y);
printf("\n\n\n ELONGATION AT THIS POINT: ");
printf("\n\nEnter poisson's ration v:  ");
scanf("%f", &v);
printf("Enter E value:   ");
scanf("%f", &E);
Uo = (Pt*(r*(1-v)+c*c*(1+v)))/(E*r*(c*c-a*a));
printf("\nThe Elongation=     %f", Uo);
printf("\n\n\n BENDING AND DEFLECTION AT THIS POINT: ");
```

```
printf("\n\nEnter Modulud of support:   ");
scanf("%f", &k);
I = (1*h*h*h)/12;
Rf = k*10.6;
L = pow((Rf/(4*E*I)), 0.25);
SL = p*1*6;
ymax = (SL*L)/(2*Rf);
Mmax = SL/(4*L);
BSmax = (Mmax*h)/(I*2);
printf("\nThe Max. Deflection=     %f", ymax);
printf("\nThe Max bending Stress=     %f", BSmax);
printf("\n\n\n\nPlease wait......");
sleep(5);
return ;
}
/* Program to calculate the deflection of the pavement due
to repetition of load */
void Alligator_cracking(void)
{
 /* To find the critical stress for the crack to spread */
 float E, a, S, u;
 /*
 * E is young's modulus of AC in psi
 * sqrt(a) is the radius of the crack in inches
```

```
 * S is critical tensile stress in psi
 * u is the surface energy of AC lbf/inch
 */
printf("\n\n\n\nEnter value of E in :");
scanf("%f", &E );
printf("Enter value of u in  :");
scanf("%f", &u);
printf("Enter value of a  :");
scanf("%f", &a);
S=sqrt((2*E*u)/(PI*a));
printf("\n The crack will spread if S =  %f", S);
printf("\n\n\n\nPlease wait......");
sleep(5);
return ;
}
void Transverse_cracking(void)
{
float E, I,L, p, x, k, w, h, y, t, m, Rf, SL, tw, b, Lca,
 SF;
/*
 E is the young's Modulus in psi
* I is Moment of Inertia in inch**4
* L represents the Lamda in the model  in inverse inch
* x is the distance from the edge of the pavement in inch
```

```
* k is the modulus of base course  in pci
* tw is the width of the tire in inches
* h is the height of the AC layer in inch
* y is the deflection of the pavement due to load in inch
*/
printf("\nEnter the value of h: ");
scanf("%f", &h);
printf("\nEnter width of beam w: ");
scanf("%f", &w);
I = ((w*h*h*h)/12);
printf("\nThe MI, I=   %f", I);
printf("\n\nEnter value of E: ");
scanf("%f", &E);
printf("\nEnter modulus of support k: ");
scanf("%f", &k);
printf("\nEnter width of tire tw: ");
scanf("%f", &tw);
Rf = (k*tw);
L = pow((Rf/(4*E*I)), 0.25);
Lca = 142.7/tw;
printf("\nEnter tire pressure p: ");
scanf("%f", &p);
SL = p*1*Lca;
printf("\nEnter the vaue x: ");scanf("%f", &x);
```

```
y = (exp(-L*x))*(SL*cos(L*x*PI/180))/(2*E*I*L*L*L);

printf("\n\nThe deflection at x is =    %f", y);

SF = SL/(w*h);

printf("\n\nShear Force at x is =     %f", SF);

printf("\n\n\n\nPlease wait......");

sleep(5);

return ;

}
```