ASPHALT LAYERS TRAFFIC LOAD INDUCED CRACK GENESIS AND PROPAGATION

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ABSTRACT

This paper describes a study that combines pavement finite elements method analysis together with fracture and material mechanics in order to identify and describe the main physical and theoretical principles that ultimately define the mechanisms that cause asphalt layers traffic load induced crack propagation.

To achieve this goal, the StratCalc finite elements method model was applied, and several adaptations in both the 2D and 3D domains were developed and implemented with the goal of better adjusting each analysis and its corresponding results to the different sets of constraints and problems that are addressed along this document.

It is possible to conclude that the top down and alligator distresses are caused by shear stresses that occur at the periphery of the tire/pavement contact area. It is also concluded that the microcracks that will eventually evolve to surface cracking originate in the binder, due to the fatigue caused by repeated traffic loads, and that these microcracks do not necessarily occur at depths that coincide with the pavements surface.

Keywords: Finite elements method, crack genesis and propagation, top down and alligator cracking, fracture mechanics, fatigue.

1. FRACTURE MECHANICS AND PAVEMENT CRACKING

Structural cracks and their associated progression are described by fracture mechanics, whose basic principle is that there are three distinct forms (Figure 1) of genesis and development of any given crack in a structural element that is subjected to cyclic loads, such as the case of the asphalt layers that are applied in flexible pavements.

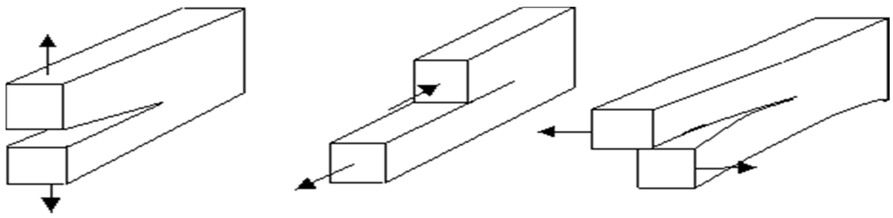
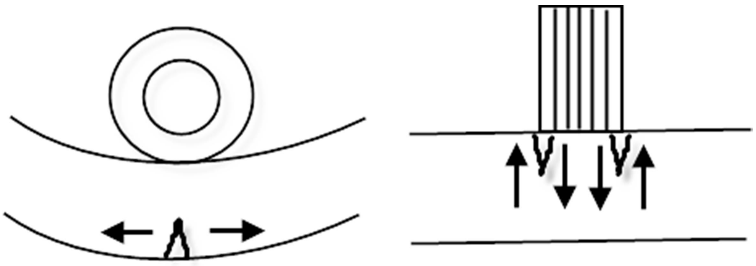


FIGURE 1 Fracture modes

The three possible fracture modes are differentiaded as follows:

- **Mode I**: also known as opening mode. The fracture is caused by the action of tensile stresses acting perpendicularly to a given plane.
- **Mode II**: usually referred to as in plane shear mode. The fracture is caused by the action of shear stresses parallel to its own plane.
- **Mode III**: the third mode, or out of plane shear mode, corresponds to fractures that are caused by shear stresses acting perpendicular to the fracture.

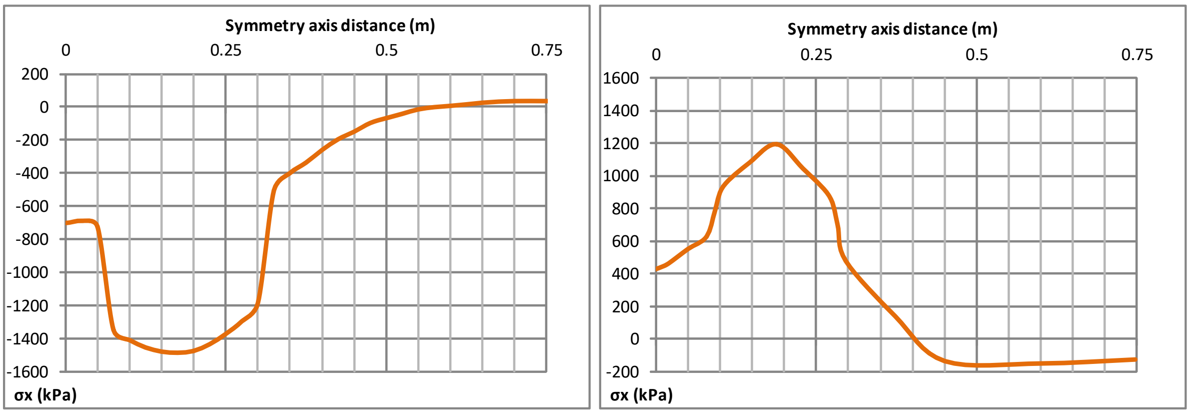
When applying these basic principles to flexible pavement structures, it is possible to ascertain that the fractures originating from Mode I occur at the lower face of asphalt layers directly under the wheel load, given the fact that this is the section in which tensile stresses of higher magnitude are located (in the longitudinal and transverse directions). Fractures that originate from Modes II and III (due to shear stresses) occur closer to the pavements surface, in vertical alignaments that coincide with the perimeter of the tires imprint on the pavement (Figure 2), since it is in these sections that higher magnitude shear stresses will arise.



a) Mode I b) Modes II and III

FIGURE 2 Fracture modes applied to asphalt layers under traffic loads

Normal tensile stresses are also present at the surface of the pavement, but they seem insuficcient to initiate a Mode I corresponding crack in the asphalt layer, especially when the magnitude of these stresses is compared to their bottom face counterpart (Figure 3). For example, when applying the 130 kN equivalent standard axle to an example flexible pavement, the maximum normal transverse tensile stress at the surface is of about 50 KPa, while at the bottom face of the bonded asphalt layers this value is of 1200 kPa.



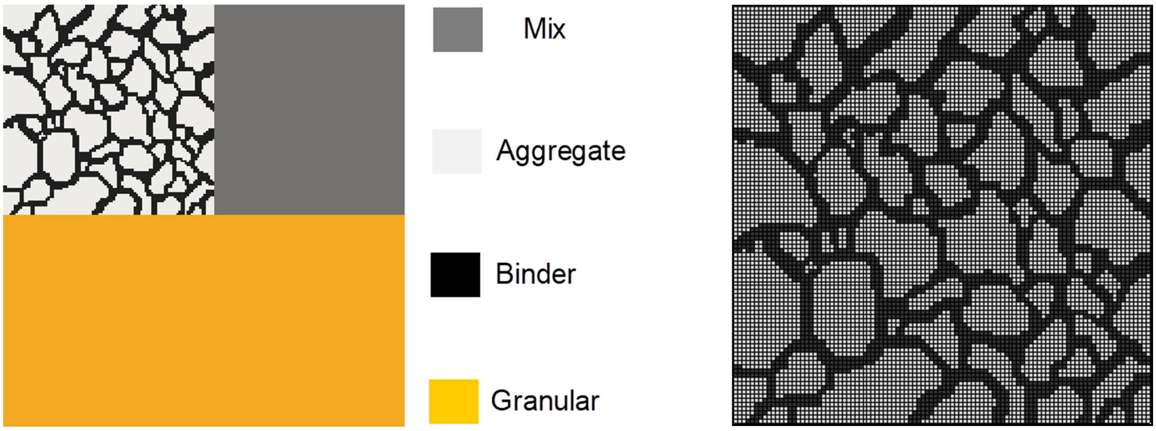
a) Upper face (surface) b) Lower face of the asphalt layers

FIGURE 3 Transverse stresses along the alignment that intercepts load centers

2. DETAILED MODELING OF A FLEXIBLE PAVEMENT

In order to better understand the physical process that is behind the emergence of microcracks in asphalt layers, a 2D finite element model of a flexible pavement structure was created using the StratCalc model [1]. The use of a very high level of finite elements discretization enables to differentiate between binder and aggregate in the section of the pavement where the displacements, strains and stresses of higher magnitude are located, i.e., directly underneath the load (Figure 4). Due to the symmetry of the considered structure, only

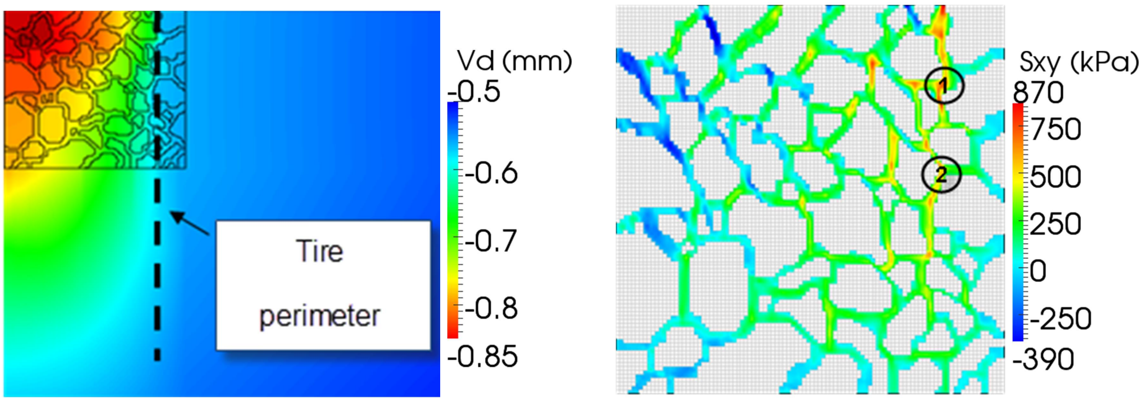
50% of the pavement needs to be effectively modeled. This particular finite element mesh apllies four noded quadrilateral finite elements, the dimension of the master finite element side in the detailed section (Figure 4 b) is of one millimeter, therefore, each of these finite elements will cover an area of one squared millimeter.



a) Pavement structure (partial) b) Binder and aggregate finite elements

FIGURE 4 Detailed 2D finite element modeling of a flexible pavement

The vertical displacements magnitude displays a very clear frontier in the alignment defined by the perimeter of the load applied to the surface of the pavement. This fact clearly emphasizys the higher value of the deflections verified in sections located directly under the load in regard to the ones that occur in the remaining structure (Figure 5).



a) Vertical displacements b) Shear stress of the binder in the detailed section

FIGURE 5 Coincidental alignment of the tire perimeter and of higher magnitude shear

As initially admitted, these results confirm that the sections where shear stresses of greater magnitude occur are located in close proximity to these same vertical alignments. It is in the perimeter of the tire/pavement surface contact area that the microcracks that derive from fracture Modes II and III will appear and ultimately develop into the top down and alligator cracking distresses. However, in order for microcracks to originate or for already existing cracks to increase in length, it will be necessary that the acting stresses in the materials that form the asphalt layer (binder and aggregate) are beyond the limits defined by their corresponding strengths.

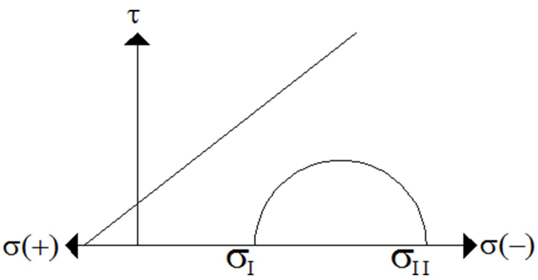
Binders possess lower tensile and shear strengths than those of its aggregate counterpart, so naturally it will be in the binder that the microcracks that will eventually evolve into various forms of pavement cracking will initially appear. Points n. º 1 and n. º 2 identified in Figure 5 are located in close proximity with the vertical alignment of the tire imprint perimeter; their corresponding stress states and principal stresses are as follows:

$\sigma_{P1}(kPa)=\begin{bmatrix}-598.0 & 397.7\\ 397.7 & -1103.0\end{bmatrix}$, σ_I = -379.4 kPa and σ_{II} = -1321.6 kPa

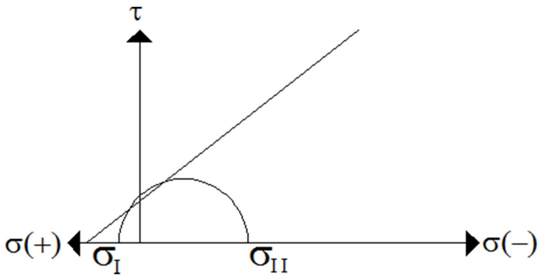
$\sigma_{P2}(kPa)=\begin{bmatrix}12.8 & 154.7\\ 154.7 & -327.4\end{bmatrix}$, σ_I = 72.6 kPa and σ_{II} = -387.2 kPa

Considering cohesion c of 297 kPa and internal friction Φ of 38.13º for the binder (1), it is possible to define the Mohr circle for both of these points (Figure 6).

$$\tau = c + \sigma.\tan(\Phi) \qquad (1)$$



a) Point n.º 1



b) Point n.º 2

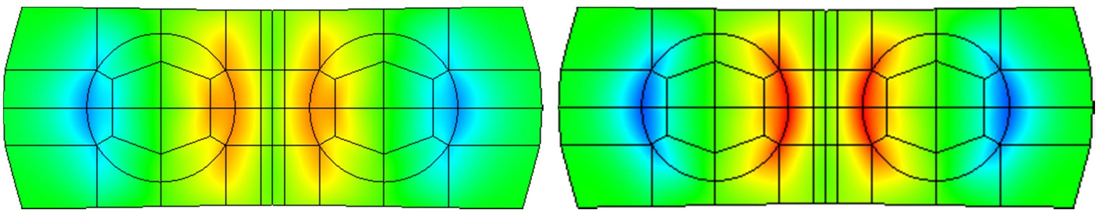
FIGURE 6 Representation of points n.º 1 and n.º 2 Mohr circles

Stresses for point n. º 1 (located closer to the surface) are within admissible limits, while for point n. º 2 these have been exceeded, hence, the occurance of a rupture or crack in the specific location of point n. º 2 is inevitable.

3. CRACK ORIGINS AND DEVELOPMENT

According to this information, it is plausible to assume that the early stage asphalt microcracks caused by shear stress (corresponding to fracture modes II and III) can be located at any depth of the critical vertical alignments defined by the perimeter of the tires. Overtime, they will gradually evolve and progress toward the surface of the pavement until they become visible. Top down cracking may possibly initiate inside the asphalt layer and not at the pavement surface as the distress designation itself might suggest. It is even possible that several crack foci can occur simultaneously in the same vertical alignment and that with load repetition these microcracks eventually interconnect to form a single crack that reaches the pavement surface.

This assumption is corroborated by a supplementary three dimensional finite pavement model, in which the same pavement and load considered to obtain the results depicted in Figure 3 (in this model aggregates and binder are not differentiated; the asphalt mix is modeled as a homogeneous mass). Shear stresses display higher magnitude at mid asphalt depth than closer to the pavement surface (Figure 7), once again suggesting that asphalt layer cracks that derive from Modes II and III do not necessarily originate at the top of the pavement.



a) at $^{1}/_{5}$ asphalt depth b) at $^{2}/_{5}$ asphalt depth

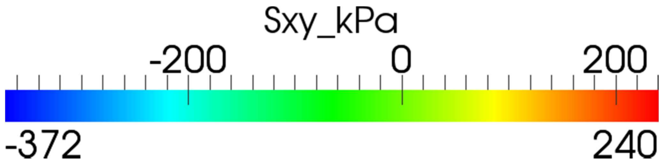
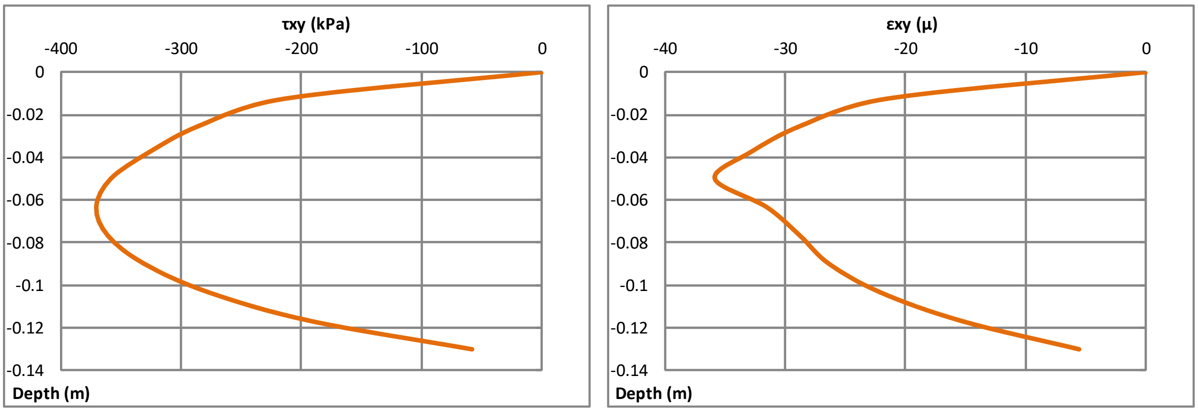


FIGURE 7 Varying transverse/vertical directions shear stress with depth

Both shear stresses and strains will vary significantelly with depth, achieving their maximum magnitudes at approximately five centimeters from the surface (Figure 8).



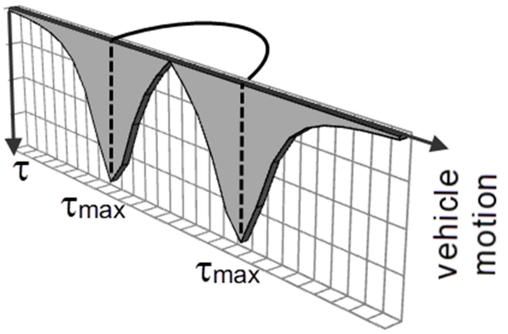
a) Shear stress b) Shear strain

FIGURE 8 Asphalt mix shear stress and strain in depth at the edge of the load

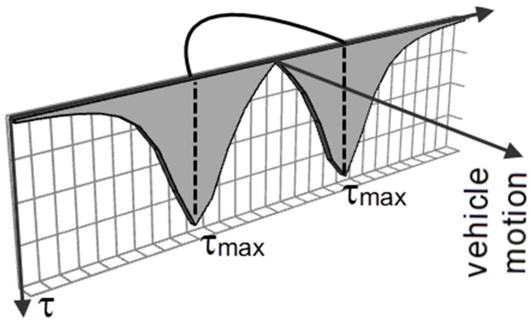
When the maximum allowable stress in any given fiber is exceeded, it ruptures thus creating a discontinuity. This disruption has the direct consequence of eliminating the contribution of that particular section where the rupture occurred in opposing the displacements and stresses applied by traffic loads, hence overloading the adjacent binder fibers. This fact increases the probability that once again stresses higher than the maximum allowable ones are applied. Supplementary microcracks can be formed or the extent of an already existing crack might be increased. This fact implies an endless cycle in which the fatigue consumption associated to traffic loads causes the development of existing cracks as well as the appearance and development of new ones. Cracks in the longitudinal direction are usually the first to manifest themselves, because the maximum shear stress between the longitudinal and vertical planes is achieved twice; first when the front tire limit is directly over a particular section, and then after further motion of the vehicle, when it is the rear tire limit that is positioned over that exact same section.

The maximum longitudinal/vertical shear stress will have to be accounted twice for each single moving load. For this reason, the fatigue consumption rate that occurs between the vertical and longitudinal planes is exactly double its equivalent for shear stress between the vertical and transverse planes, as well as for the fatigue caused by repetition of normal tensile stresses in the longitudinal and transverse directions at the bottom face of asphalt layers, thus justifying the appearance of the top down cracking distress before other load induced distresses.

At roads that count with more than one lane per direction, longitudinal cracking will occur (Figure 9), preferably on the slower speed lanes, where there is a higher incidence of heavier vehicles traffic in comparison with the remaining lanes.



a) Longitudinal/vertical planes shear



b) Transverse/vertical planes shear

c) Weel path longitudinal cracking at the slower speed lane

FIGURE 9 Maximum shear at the tire limits

With continued traffic loading, fatigue consumption in the transverse direction will also ensue, thus causing the appearance of ruptures and cracks parallel to the transverse direction. These transverse cracks, when added to the already existing ones in the longitudinal direction, will form the distress known as alligator cracking. The time required for transverse cracks to appear after the first longitudinal cracks have manifested themselves, will be inferior to that which elapsed until the initial cracks arose, given the fact that the already cracked asphalt layer has at this point already lost its original structural integrity, and will therefore display higher vertical displacements (consequently, higher strains and stresses) for the exact same loads.

REFERENCES

[1] Rowe, G. and Raposo, S. Load Format Comparison with StratCalc: A 3D Finite Element Method Pavement Analysis Model, International Conference on Highway Pavements and Airfield Technology 2017, Philadelphia, United States of America, pp. 107-118. 2017.