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"Study of the Causes and Remedies of Premature Surface Cracking of Asphalt Pavements"

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STUDY OF THE CAUSES AND REMEDIES OF PREMATURE SURFACE CRACKING OF ASPHALT PAVEMENTS

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ABSTRACT

Over the past 120 years, the asphalt industry has evolved to become a multi billion-dollar business achieving significant technological advances and providing better and effective road infrastructure. However, it has also been experiencing a number of problems. One such major problem is a perception, and arguably a reality, that asphalt pavements are not being designed and constructed to meet its long term objective or being cost effective. At the same time, there is a growing backlog of needs due to unexpected early asphalt road deterioration. This deterioration includes several problems such as early cracking, rutting, moisture damage and surface roughness. The result is that at the turn of the century, despite major efforts, better economic and technical solutions for these problems, more work remains to be achieved. On a positive note, however, the pressure to address these problems and develop better solutions has led to a number of key initiatives which are shaping the asphalt industry today. These initiatives include the Strategic Highway Research Program (SHRP), which deals in part with the characterization of asphalt materials and their performance under a wide range of in-service conditions. Also the use of advanced materials such as non-metallic polymeric grid and/or polymer modified asphalt binders to reinforce asphalt layers and/or improve their tensile and shear strengths and the introduction by many agencies of end-result specifications; some agencies are even going to long-term performance based specifications have contributed to an improvement in the pavement performance. There is no doubt that most of these developments, if not all have significant technical and economic potential. One of the unresolved problems is clearly appearance of surface cracks at early stage after construction of new asphalt layers. This paper reviews the state-of-the-art of the problem of surface cracking of asphalt pavements, it assesses theoretical and imperial models and approaches describing the causes and remedies of the cracking problem and provides an in depth analysis to the main causes and mechanisms that induce such cracking. Finally, the paper discusses better ways to minimize and hopefully eliminate the causes of the occurrence of early surface cracks of asphalt pavements.

INTRODUCTION

There is no doubt that asphalt pavements have helped shape the economic and industrial development of first world nations. More than 85% of road networks in the world are asphalt pavements. However, since the construction of asphalt pavements started in the early 20th century, it has also been experiencing a number of problems. One such major problem is a perception and arguably a reality that asphalt pavements are not being designed and constructed to be sufficiently long lasting and cost effective. At the same time, there is a growing backlog of needs due to road deterioration. This deterioration includes such problems as early cracking, rutting, moisture damage, and roughness.

The pavement industry has invested millions of dollars in search for remedies to pavement distress. These remedies included the improvements in the design of asphalt mixes, development of new and engineered asphalt binders, using new materials, and establishment of new research efforts. These remedies were successful in improving the properties of asphalt materials in the laboratories. However, these improvements did not appear in the field performance of the asphalt roads. The research performed to attempt to solve pavement distress problems did, however, result in a number of significant solutions and initiatives such as the Strategic Highway Research Program (SHRP), which in part deals with the characterization of asphalt materials and their performance under a wide range of in-service conditions, and the adoption of gyratory compaction as the main laboratory device for designing asphalt mixes. In addition, new advanced materials are currently being used to reinforce asphalt layers and to improve their tensile and shear strengths such as non-metallic polymeric grid and polymer modified asphalt binders. There is no doubt on the significant technical and economic affect of these improvements. However, such initiatives could be considered more affective and advanced when addressing and solving the initial cause of asphalt pavement deterioration (Halim and Haas, 2004).

CONSTRUCTION INDUCED SURFACE CRACKS

The presence of surface cracks significantly reduces the life of the asphalt pavements. This is because surface cracks are one of the main contributors of the development of the other different types of cracks in the asphalt layers. They accelerate the development of cracking which would ultimately lead to the early failure of the pavement (Halim et al. 1993).

One of the main contributors to surface cracking is the current practice of asphalt compaction that has been used for the past century without any significant change or improvement. Construction cracks have been traditionally recognized to be due to deficiencies in the base stability, the mix temperature during compaction, operator error, or due to the design of the asphalt mix itself. To remedy these surface cracks, the practice was to use pneumatic rubber-tired rollers.

However, even though pavements are normally designed to last 15 to 20 years, the compaction procedure has helped reduce this fatigue life by more than 50% (Halim et al. 1993, Halim et al. 1994, Mostafa and Halim 2004). Hughes (1989) pointed out that better compaction would result in higher strength, durability, resistance to deformation and moisture damage, impermeability, and skid resistance of the asphalt pavement. Bell et al. (1982) pointed out that better compaction would result in extending the service life of the asphalt pavement.

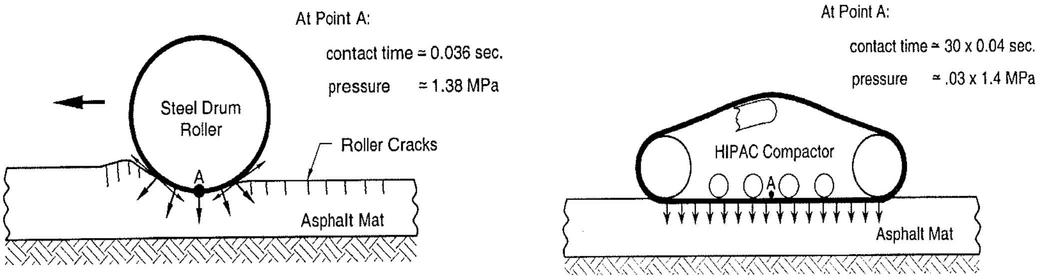
All these statements are true, however the approach of applying them in the past 50 years is not. Past research has assumed that any problems of compaction are related to the mix properties, and that increasing the performance of the pavement would be realized by increasing the density and reducing the percentage of air voids in asphalt mixes. Hughes (1989), for example, stated that the aggregate and asphalt properties as well as their mixture properties affect the ability to achieve the proper compaction level. Therefore, problems due to compaction were often remedied through improving the asphalt mix. Geller (1982) stated that the problems that occur in the asphalt pavements are not due to compaction deficiencies but rather due to the inability to predict the behaviour of the asphalt mixture.

Studies by Abd El Halim et al. (Halim 1985, Halim and Bauer 1986, Halim et al. 1987) have proven that the compaction procedure is the main factor behind the reduction in service life of pavements and behind the appearance of surface cracks. These studies also proved that the solutions of these problems would not be through using pneumatic rubber-tired rollers, but rather to change the methodology concept of compaction. These studies introduced a new concept in compaction by the invention of the asphalt multi-integrated roller (AMIR) which caused a revolution in the research of asphalt pavements.

FORMATION OF CONSTRUCTION CRACKS

This section will attempt to describe the process of formation of the surface cracks and will prove that these cracks are in fact attributed to the compaction process itself. Asphalt pavements are constructed by placing the hot mix asphalt over either the base course or an existing road surface. Compaction is then performed by first using heavy vibratory steel rollers to reach the desired density. Then, multi wheeled pneumatic rubber rollers followed by a light steel roller are used to smooth out the surface. The addition of the pneumatic rubber rollers was considered one of the main achievements in the compaction industry in the last 50 years (Halim et al. 1987).

A mechanistic approach will be used to describe the cause of construction cracks. The interface between the surface of the compacted asphalt mix and that of the compacting device is a key factor in the quality of the compacted product. In case of the typical steel drum roller, the contact between the asphalt mix and the roller drum is a rectangular area 5 to 10 cm long and its width equals to the width of the drum. Although this could be considered as a rectangular area, it actually takes the shape of a cylindrical drum which is the shape of the roller drum. The applied force has both radial and tangential components due to the small curved contact area as shown in Figure 1 (a). At a normal rolling speed of 10 km/h, the contact time between the roller and the mix is approximately 0.03 seconds. The small contact area and load time combine to apply an intense pressure impulse, typically 1.38 MPa, to the asphalt surface. Therefore, conventional compaction equipment presents forces that are both rapidly applied and held for merely a fraction of a second (Halim et al. 1987).



(a) (b)

Figure 1: Schematic of (a) Conventional Steel Drum Roller and (b) AMIR Compactor

EFFECTS OF COMPACTION PROCEDURE

Two major negative effects result from this compaction procedure. First, loads applied rapidly for a short duration time cause asphalt to respond with a high elastic stiffness with relatively small plastic deformation. In order to overcome the increased asphalt stiffness, conventional equipment seeks to increase the applied load or to use vibration. This may cause breakage of the aggregate particles. The second negative effect is that the small contact area causes the application of horizontal forces which causes shoving of the asphalt layer. The radial and tangential forces applied by the steel roller both contain horizontal components as shown in Figure 1. As the roller travels, the horizontal forces push and pull the asphalt in front of and behind the drum respectively, inducing hairline surface cracking, often referred to as "roller checking" with an interrelated dissipation of a significant portion of the applied compaction energy. The initiation of surface cracking at this stage of construction reduces the strength and fatigue resistance of the asphalt layer, and facilitates the development of cracking, which can ultimately lead to the premature failure of the newly constructed pavement. This type of cracking initiates at the top of the pavement and propagates toward the bottom and is the leading cause of all top down cracks. This process has been extensively described in other references of the first author (Abd El Halim et al. 1993, Mostafa and Abd El Halim 2004, Abd El Halim et al. 1994, Abd El Halim 1985, Abd El Halim and Bauer 1986, Abd El Halim et al. 1987). Abd El Halim (Abd El Halim 1985, Abd El Halim and Bauer 1986, Abd El Halim et al. 1987) also showed that the pneumatic-robber rollers do not eliminate these surfaces cracks, and that these cracks are detrimental to long term performance of asphalt pavements.

OTHER FORMS OF CRACKING

Top-down cracking, reflective cracking, fatigue cracking, and thermal cracking are the most widely observed types of cracking in asphalt concrete pavements. Top-down cracking is a type of cracking that initiates at the surface of the pavement due to the movement of wheel loads on the pavement. During the early stages of top-down cracking, it appears as longitudinal cracks along the wheel paths. However, with the further propagation of cracking, secondary transverse cracks begin to form, which further deteriorates the pavement due to moisture action (Baladi et al. 2002).

Baladie et al. (2002) found that mechanistic analysis could be used to determine the factors that cause high tensile stress at the pavement surface, and laboratory experiments could be used to find the factors that result in the low tensile strength of the mix. The causes of top-down cracking are summarized in literature to be load induced stresses and strains, thermal stresses, aging of the binder, and segregation of the asphalt concrete mix (Baladi et al. 2002).

Reflective cracking has been traditionally thought to initiate at the bottom of the asphalt concrete mat at the same location of previously existing cracks in the under layers and then these cracks propagate to the surface. However, Abd El Halim (1985, 1986, 1987)) has shown that this type of cracking is initiated at the surface and then propagates to the bottom of the mat near the existing cracks. It was also proven in these studies that the presence of surface cracking could significantly affect the life of the asphalt concrete mat.

Fatigue cracking can be defined as the fracture phenomenon under repeated fluctuating traffic loading. It is traditionally accepted that these cracks are a result of tensile strains at the bottom of the asphalt concrete layer. These strains result in cracks at the bottom of the layer, which propagates upwards until it appears at the surface of the pavement. Forms of fatigue cracks are longitudinal cracks in the direction of wheel paths. Himeno and Watnabe (1987) introduced a new criterion of fatigue failure, which states "fatigue failure can initiate at the top of the mix slab, when the mix stiffness modulus is low". Low stiffness can result from poor compaction and/or inadequate methods of compaction. In addition, Myers et al. (2001)

showed that fatigue cracks could also initiate at the pavement surface due to tensile stresses resulting from the movement of trucks on the pavement. Their results were based on linear-elastic finite element analysis.

Thermal cracking can be induced by a drop in the temperature. Haas (1970) and Christison (1972) have investigated the basic mechanisms of low temperature cracking. Micro-cracks may develop at the pavement surface under decreasing temperature, which then propagates through the full depth of the asphalt layer with successive thermal cycles. Although the initiation of micro-cracks can be caused by excessively low temperatures, the presence of these cracks due to other reasons, such as compaction, can significantly accelerate the full development of these cracks. The presence of surface cracks developed during construction is not the only reason for the development of the different types of cracking in asphalt pavements. However, these surface cracks serve as catalysts, which accelerate the development of cracking and ultimately the failure of the pavements (Abd El Halim et al. 1993).

Reflective Cracking

Reflective cracking is the result of the appearance of cracks in the pavement surface at the same location of the previously existing cracks before rehabilitation with new asphalt layers. This phenomenon has been studied through several approaches taking in consideration that cracking propagation is either bottom-up or top-down. Pavement surveys led to these two types of cracking propagation which depend on the pavement thickness and stiffness and the stress concentration due to traffic loads and temperature effects. Laboratory simulations of reflective cracking have also conducted to those two types of cracking propagation.

Asphalt concrete overlays are exposed to great strains and stresses when subjected to traffic and thermal loadings. Several authors (Sousa et al. (2000) and de Bondt (2000)) suggest that there exist different mechanisms which originate and cause propagation of cracks in pavement overlays:

- Thermal stresses from thermal fatigue, which occur when temperature variations induce cyclic openings and closures of cracks in the pavement. This provokes stress concentrations in the overlay.
- Thermal stresses as a result of rapid cooling down of the top layer, implying critical tensile stresses on overlay.
- Repetitive traffic loads induce additional distress in the overlay and increase the rate of crack propagation, independently if these cracks are originated from thermal stresses;
- Soil movements – settlements (downwards).

The literature review also revealed that temperature variations, daily and seasonal, and associated thermal stresses could be one of the causes of premature overlay cracking, affecting the predictive overlay service life of asphalt concrete layers. In regions that experience large daily temperatures variations or extremely low temperatures, thermal conditions play a major role in the reflective cracking response of a multilayered pavement structure. On the one hand, binder properties (stiffness, ageing, penetration, etc) are sensitive to temperature variations. On the other hand the combination of the two most important effects – wheel loads passing above (or near) the crack and the tension increase in the material above the crack (in the overlay) due a rapid decrease of temperatures – have been identified as the most likely causes of high states of stress and strain above the crack and responsible for reflective cracking (Shalaby et al, 1990).

Daily temperature variations have an important influence in the pavement thermal state in a depth of few centimeters below the surface. Depending on the level of temperature variation, stress is induced in the overlay in two different ways, which need to be distinguished: through restrained shrinkage of the overlay and through the existing movements of slabs, due to the thermal shrinking phenomenon (Minhoto et al, 2005).

Models for Reflective Cracking

The development of models to predict reflective cracking has been a concern for many researchers who, by using several different approaches, try to model cracking propagation to the pavement overlay. The best known approach uses fracture mechanics to model cracking propagation through numerical simulation with finite elements and crack tip elements to evaluate the stress intensity factors. Once these factors are identified, it is possible to compute the number of load repetitions necessary for the crack in the model to propagate over the overlay thickness. This calculation uses the Paris law which relates cracking propagation speed to the stress intensity factors.

Examples of the applications of that approach are depicted in detail by Scarpas et al. (1996), who simulated the vertical cracking propagation as well as the debonding between the overlay and the old pavement, concluding that the vertical propagation is more severe than the debonding case. Shalaby et at. (1996) also used fracture mechanics to simulate four distinct crack types: a) vertical cracks which initiate from the top of the pavement and propagates downwards through pavement overlay; b) cracks which are originated from hair line cracks initiated during the compaction process; c) vertical cracks originated at the bottom of the overlay and that propagate upwards to the top of the pavement; d) full depth cracks that originate at the pavement edges or within the layer. The numerical simulation to evaluate the stress intensity factors allowed concluding that the first two types of cracks led to identical values and that there exist some differences in relation to the third type of cracking. Laboratory tests carried out in notched slabs showed that cracking propagation from bottom is faster than from top.

Recently, Pais and Pereira (2000a) introduced a new concept to consider cracking reflection in pavement overlays based on the cracking activity. In a first step the crack activity before pavement overlay is used to calibrate the finite element model to estimate the crack activity after overlay. The cracking activity before overlay (Figure 2) can be measured in situ by using a crack activity meter which give the differential movements between the edges of the cracks. The cracking activity calculated in the finite element analysis (Figure 3) is applied to asphalt concrete specimens to evaluate the reflective cracking resistance, as stated by Pais and Pereira (2000b), which is compared to the design traffic.

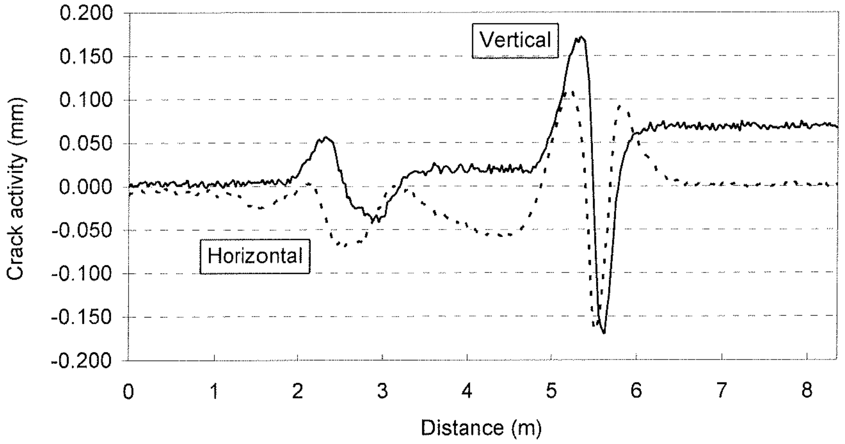


Figure 2: Crack activity before overlay

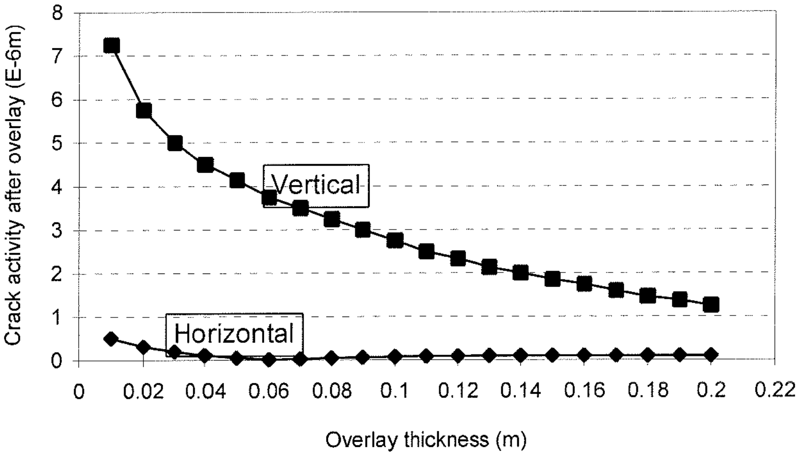


Figure 3: Crack activity after overlay

Further developments (Sousa et al, 2002) were carried out by applying the von Mises strain deviator failure criterion to consider the simultaneously effect of horizontal and vertical movements in the zone above existing cracks. The parameter for the von Mises strain deviator was derived from four point bending fatigue tests in strain control mode. This method seemed to be easily used and utilizes typical parameters (fatigue test results) to predict the pavement overlay life. The developed model for von Mises strain, ε_{VM} , is expressed by:

$$\varepsilon_{\mathrm{VM}}\ (1x10^{-6}) = a * [Overlay\ \ thickness\ \ (m)]^{b} \tag{1}$$

$$a = \prod_{i=1}^{6} [a_{1i} * \ln(X_i) + a_{2i}] \tag{2}$$

$$b = \prod_{i=1}^{6} [b_{1i} * \ln(X_i) + b_{2i}] \tag{3}$$

The a_{ij} and b_{ij} coefficients are shown in Table 1 and were obtained by a statistical analysis of the modelling of more than 300 pavement configurations.

Table 1 – Statistical coefficients for the von Mises model [R^2=0.98]

i	X_i	a_{1i}	a_{2i}	b_{1i}	b_{2i}
1	Cracked thickness (m)	-1.038E-04	-1.446E-01	7.169E-03	1.314E-01
2	Granular thickness (m)	2.777E-01	-4.022E+00	9.773E-05	-6.368E-01
3	Overlay modulus (MPa)	-1.173E+00	1.212E+01	-4.946E-01	7.069E+00
4	Cracked modulus (MPa)	1.281E+00	5.070E-01	3.923E-02	2.641E+00
5	Granular modulus (MPa)	-5.160E-01	6.964E+00	3.265E-02	-1.287E+00
6	Subgrade modulus (MPa)	-1.775E-01	2.385E+00	1.875E-03	-8.167E-01

Recent work by Minhoto et al. (2006) combining traffic and temperature variation effects proposed a model to evaluate the reflective cracking in asphalt pavements based on the schematic representation of Figure 4.

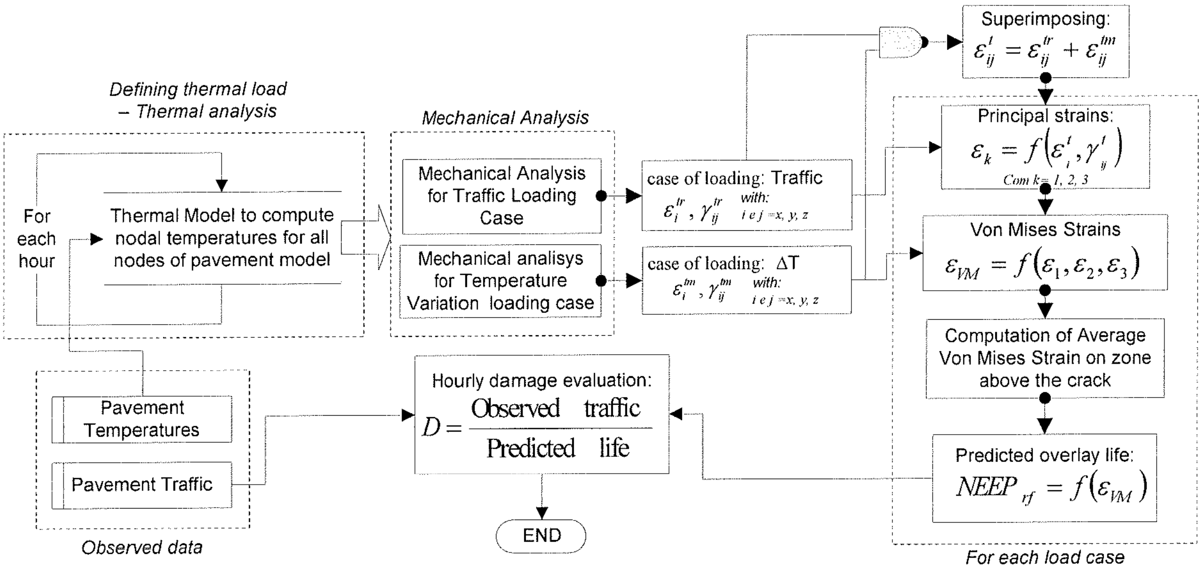


Figure 4: Model for combining traffic and temperature effects for reflective cracking

The development of this study was based on the numerical simulation of the overlay behavior, using three-dimensional finite-element analysis, considering the simultaneous loading of traffic and temperature variation and considering the most predominant type of overlay distress observed in situ: reflective cracking. A mechanistic-based overlay design method was used to predict the reflective cracking overlay life. The occurrence of temperature variations in pavements leads to an increase of the reflective cracking phenomenon, due to the stress and strain states created by temperature, which provokes the premature distress of the overlay.

The model considers the elastic behavior for traffic effects and the visco-elastic behavior for temperature variations effect. The studies carried out take into consideration one-year traffic profile and temperature variation as studied by Minhoto et al. (2003). The temperature distribution in a pavement was obtained through in situ measurements, using a temperature-recording equipment (Datalogger associated with thermocouples). The option for the use of in situ measurements is desirable because real temperatures can be reliably measured and used in stress calculation models. However, this method is relatively slow and only provides information about temperatures throughout the observed period.

IMPLICATIONS OF CRACKS ON THE ENVIRONMENT

One of the main negative effects of pavement cracks is the moisture induced damage or stripping in asphalt pavements. Newly constructed asphalt pavements are designed to have air voids between 3 to 5%. It is usually constructed at higher air voids content that may reach between 8 to 10%. In addition to the high air void content, the surface cracks caused by the conventional steel drum rollers used for compaction enable the infiltration of water through the pavement layers. Stripping of the asphalt material from the surface of the aggregate or loss of adhesion is one of the most common types of pavement distresses known in the asphalt pavement field and is subject to wide research efforts (Mostafa and Halim 2004, Mostafa 2005, Brown et al. 1999). It often accelerates the pavement deterioration and reduces its life.

Asphalt layers are expected to serve as waterproofing layer for the entire pavement structure. Thus, the one of the main functions of the asphalt layer is the protection of the base and sub-base layers in addition to the prevention of the infiltration of salts, oils and other chemical that may exist on the road surface. However, the presence of cracks leads to higher surface permeability. Subsequently, these cracks will allow water and other harmful fluids to penetrate the top layer into the main body of the highway structure. These fluids would eventually become pollutants to the soil and water resources adjacent to the paved roads. Polluted water and soil can be harmful to people, animals and plants. Clearly, this would have adverse effects on the environment and could threaten the well being of the communities.

Therefore, it is important to control the construction induced cracks not only for the structural integrity of the pavement but also to insure that the finished asphalt layer meets the environmental adequacy in terms of the proper protection of the underlying layers. An exponential relationship was found between permeability and air voids (Mostafa and Halim 2004). Consequently, when the asphalt pavements are properly compacted, cracks are eliminated and air voids could be reduced to less than 7%, which would reduce the intrusion of water into the asphalt pavements. In addition to the direct effect on the environment the construction induced cracks result in serious deterioration of the pavement which lead to early failure and waste of initial investment. Hence, rehabilitation and/or new construction of the damaged road will require new materials which are in short supply.

THE NEW CONCEPT: AMIR COMPACTOR

The relative rigidity parameter (*R*) influences the transfer of stresses in pavement systems between the loading compactor and the various components of the multi-phase elastic material or the multi-component elastic structure. Abd El Halim (1985) pointed out the importance of understanding the relationship between the numerical value of the parameter *R* and the physical terms contained in the equation of relative rigidity using the theory of relative rigidity. The application of the equation in the asphalt pavement field provided a new mechanistic approach for the prediction of construction-induced cracks. This approach was the main inspiration that led to the development of the AMIR roller.

The reason for surface cracking has been attributed to the incompatibility between the geometry and relative rigidity of the soft, flat asphalt layer and the hard, cylindrical steel drums of conventional rollers (Abd El Halim 1985). The Asphalt Multi-Integrated Roller (AMIR) prototype shown in Figure 2, was designed and fabricated by Carleton University and the National Research Council of Canada in 1989 to overcome these incompatibilities. AMIR uses a multi-layered belt composed of specialized rubber compounds to create a single flat contact plate of approximately 3 m^2 for compaction. In addition, the rubber belt is flexible, providing a closer match in rigidity to the asphalt surface. Due to the large contact area, the stress applied to the asphalt mat is relatively low at 41.6 Kpa. This is compared with stresses of 1.38 MPa applied by typical steel drum rollers. However, for the same rolling speed, the AMIR load duration is 30 times longer than conventional steel rollers. Figure 1 (b) shows a schematic drawing of the belt and the forces acting on the asphalt pavement. The AMIR prototype is well described in the following references (Abd El Halim et al. 1994, Abd El Halim 1985, Abd El Halim and Bauer 1986, Abd El Halim et al. 1987).

Figure 2: Photo of AMIR Prototype

Based on AMIR technology, the HIPAC compactor was designed and fabricated by Pioneer Road Services in Australia in early 1998. Significant operational modifications were implemented to the HIPAC device in order to produce a regular production, commercially available compactor. The HIPAC is double-belted and has greater manoeuvrability than the AMIR compactor. A more descriptive development program of HIPAC is available in other references (Rickard et al. 1999). A photo of the HIPAC compactor is shown in Figure 3.

The compaction pressure of the device is low and is applied gradually over a long duration in order to keep the initial stiffness response of the asphalt is low. The applied stress from the compactor is more efficiently utilized because it is not "fighting" against a large initial damped elastic stiffness response that occurs with rapid, short duration loading. The long load duration also compensates for the low applied pressure by allowing visco-plastic flow of the asphalt, providing efficient particle contact and expulsion of entrained air. Furthermore, the large contact area minimizes horizontal forces applied to the asphalt mat and provides a high degree of confinement during compaction. This, in turn, eliminates roller induced cracking, reduces surface permeability, and increases tensile strength and resistance to fatigue damage. The elimination of surface cracking also permits the full compaction energy to be applied to the pavement layer. Figure 4(a) shows the construction cracks formed by compaction using the steel drum roller, while construction cracks are significantly reduced when asphalt is compacted by the AMIR roller in Figure 4 (b). Figure 5 (a) shows the surface cracks formed on sand using the steel drum roller, while Figure 5 (b) shows how these surface cracks are significantly reduced when using the AMIR roller. This further proves that surface cracks are actually a function of the type of compaction used rather than the type of material being compacted.

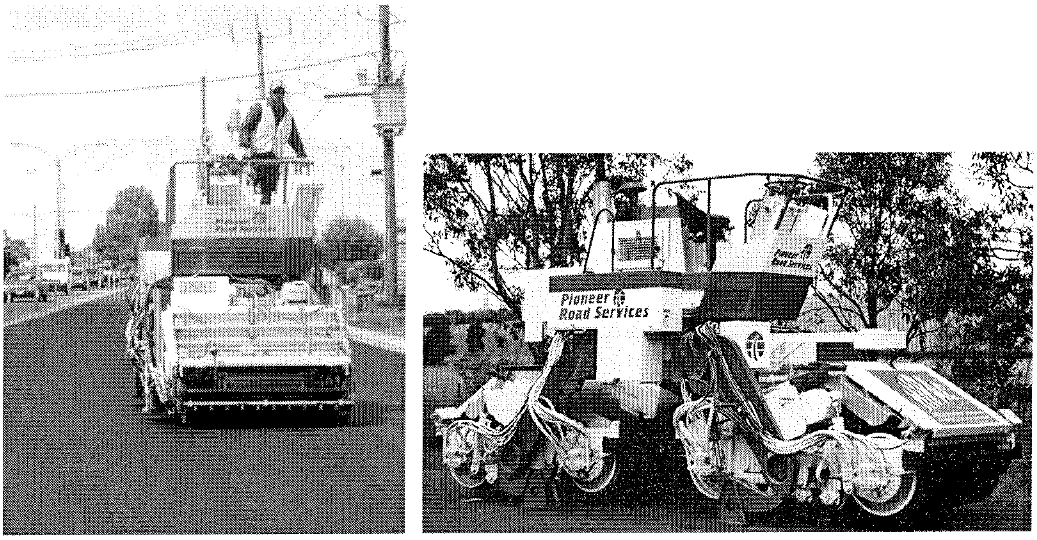


Figure 3: Photos of HIPAC Prototype


(a) (b)

Figure 4: Asphalt Compacted by (a) Steel Drum Roller and (b) AMIR Roller

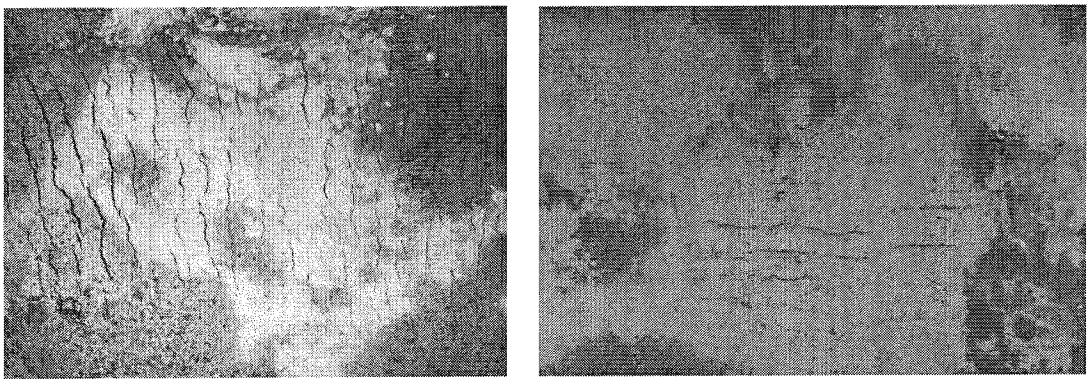

(a) (b)

Figure 5: Sand Compacted by (a) Steel Drum Roller and (b) AMIR Roller

CONCLUSION

This paper presented a summary of a long term research work performed through the last 20 years. It showed how proper compaction of fresh asphalt mixes using the new AMIR compactor, along with its many advantages, is able to protect the environment from the severe and detrimental effects of surface cracking to our environment. AMIR compactor has been proven to successfully prevent surface cracks that are induced due to the conventional method of compaction. Due to the fact that AMIR is successful in preventing surface cracks, the adverse effects accompanied with surface cracks are also prevented. Infiltration of harmful material that are washed by precipitation and dissolved into it is substantially reduced. This result not only has a significant economic effect in terms of saving losses in capital invested in pavement structures, but also has important environmental effects.

REFERENCES

Abd El Halim, A.O. (1985). *Influence of Relative Rigidity on the Problem on Reflection Crackin*", TRR 1007, pp.53-58, USA.

Abd El Halim, A.O. and Bauer, G.E. (1986). *Premature Failure of Asphalt Overlays at Time of Construction.*

Abd El Halim, A.O., Phang, W. and Haas, R.C. (1987). *Realizing Structural Design Objectives Through Minimizing Of Construction Induced Cracking*, Proc., Sixth International Conference on Structural Design of Asphalt Pavements, Ann Arbor, U.S.A., July 13-16, Vol. I., pp.965-970.

Abd El Halim, A.O., Phang, W. and Haas, R.C. (1993). Unwanted Legacy of Asphalt Pavement Compaction. *Journal of Transportation Engineering*, Vol. 119, No. 6, November/December. pp. 914-932.

Abd El Halim, A.O., Haas, R. and Svec, O.J. (1994). *Improved Asphalt Pavement Performance Through a New Method of Compaction.* Proceedings - 17th ARRB Conference, Part. 3. pp. 175-191.

Abd El Halim, A.O., and R. Haas (2004). Process and Case Illustration of Construction Innovation: From Concept to Commercial Realization, *Journal of ASCE Construction Engineering and Management*, Volume 130, Issue 4, pp. 570-575.

Abd El Halim, A.O, and Mostafa, A. (2006). Asphalt Multi-Integrated Rollers and Steel Drum Compactors, Evaluating Effect of Compaction on Permeability of Asphalt Pavements, Transportation Research Record: *Journal of the Transportation Research Board*, No. 1967, TRB, Washington D.C., pp. 173-189.

Baladi GY, Schorsch M, Svasdisant T. (2002). Determining the Causes of Top-Down Cracking in Bituminous Pavements, MDOT-PRCE-MSU-2003-110, Michigan State University.

Bekheet, W., Y. Hassan, and A.O. Abd El Halim (2001). Modelling In-situ Shear Strength Testing of Asphalt Concrete Pavements Using The Finite Element Method, *Canadian Journal of Civil Engineering*, 28, pp. 541-544, 2001.

Bell, C. A., Hicks, G., and Wilson, J. E. (1982). "Effect of percent compaction on asphalt mixture life." Placement and compaction of asphalt mixtures: ASTM STP 829, *American Society for Testing and Materials*, Philadelphia, Pa.

Brown, A. B., J. W. Sparks, and G. e. Marsh (1999). Objective Appraisal of Stripping of Asphalt from Aggregate Mixtures, STP 240. *American Society for testing and Materials, Philadelphia*, Pa. Pp. 59-74.

Christison T. J. (1972). The Response of Asphalt Concrete Pavements to Low Temperature, Dissertation Submitted in Partial Fulfillment for Requirements for the Ph.D. in Civil Engineering, University of Alberta, Canada.

de Bondt, A. (2000). *Effect of Reinforcement Properties.* Proceedings PRO11. 4th International RILEM Conference on Reflective Cracking in Pavements – Research in Practice. Edited by A. O. Abd El Halim, D. 5. A. Taylor and El H. H. Mohamed. RILEM. Ottawa, Ontario, Canada, pp 13-22.

Emery, J. (2006). *Evaluation and Mitigation of Asphalt Pavement Top-Down Cracking*, 2006 Annual Conference of the Transportation Association of Canada, Charlottetown, Prince Edward Island.

Finn, F. N. (1967). Factors involved in the design of asphaltic pavement surfaces. NCHRP Rep. 39. *Transportation Research Board*, National Research Council, Washington, D.C.

Finn, F. N., and Epps, J. A. (1980). *Compaction of hot mix asphalt concrete.* Res. Rep. 214-21, Texas Transportation Institute, College Station, Tex.

Geller, M. (1982). Compaction equipment for asphalt mixtures. Placement and compaction of asphalt mixtures: ASTM STP 829, *American Society for Testing and Materials*, Philadelphia, Pa.

Hass, R.C.G. (1970). *Low Temperature Pavement Cracking in Canada: The Problem and its Treatment*, C.G.R.A. Ad Hoc Committee on Low Temperature Behavior of Flexible Pavements, Annual Convention of Canadian Good Roads Assoc.

Himeno K, Watnabe T. (1987). *Design of Asphalt Pavements*, Six International Conference on Structural Design of Asphalt Pavements, Ann-Arbour, Michigan.

Hughes, C. S. (1989). Compaction of asphalt pavement. NCHRP Rep. 152. *Transportation Research Board*, National Research Council, Washington, D.C.

Kandil, K, A. O. Abd El Halim, Y. Hassan, and A. Mostafa, (2006). Improving Mechanical Properties Of Asphalt Concrete Mixes Through Use Of Polymer-Modified Asphalt Cements, *Journal of Canadian Society for Civil Engineering*.

Marker, V. (1972). *Construction methods--symposium on thick lift construction.* Proc. Association of Asphalt Paving Technologist, 41,354.

Minhoto, M.J.C., Pais, J.C., Pereira, P.A.A., Picado-Santos, L.G. (2003). *Low-temperature influence in the predicted of pavement overlay life*, Asphalt Rubber 2003 Conference, Brasilia, Brasil, p. 167-180.

Minhoto, M.J.C., Pais, J.C., Pereira, P.A.A., Picado-Santos, L.G. (2005). Predicting asphalt pavement temperature with a three-dimensional finite element method, *Journal of the Transportation Research Board*, n° 1919, pp. 96-110.

Minhoto, M.J.C., Pais, J.C., Pereira, P.A.A. (2006). *Influence of temperature variation on the reflective cracking behaviour of asphalt overlays*, Asphalt Rubber 2006 Conference, Palm Springs, USA, p. 209-230.

Mohamed, E. H. and Abd El Halim, A.O. (1993). Differential Thermal Expansion and Contraction: A Mechanistic Approach to Adhesion in Asphalt Concrete. *Canadian Journal of Civil Engineering*, Vol. 20, No.3, pp. 366-373.

Mostafa, A., A. O. A. Halim (2004). *Evaluating the Effect of Surface Cracks on Moisture Induced Damage Using Different Standard Test Methods for Airfield Asphalt Pavement Mixes,* CTAA pp 318-339, Montreal, QC.

Mostafa, Abdelzaher E. A. (2005). The Stripping Susceptibility of Airfield Asphalt Mixes: The Development of Guidelines for a Laboratory Test Method, a Ph.D. thesis Submitted In partial fulfilment of the requirements for the degree of Doctor of Philosophy, Carleton University, Ottawa, Canada.

Myers, L. A., R. Roque, and B. Birgisson. (2001). Propagation Mechanisms for Surface-Initiated Longitudinal Wheel path Cracks. *Transportation Research Record* No. 1778, pp. 113–122.

Pais, J.C., Pereira, P.A.A. (2000a). *Prediction of existing reflective cracking potential of flexible pavements*, Fourth International RILEM Conference and Exhibition on Reflective Cracking in Pavements, Ottawa, p. 155-164.

Pais, J.C., Pereira, P.A.A. (2000b). *Evaluation of reflective cracking resistance in bituminous mixtures*, Fourth International RILEM Conference and Exhibition on Reflective Cracking in Pavements, Ottawa, p. 93-102.

Rickards I, Goodman S, Pagiani J, Abd El Halim AO, Haas R. (1999). Practical Realization of a New Concept for Asphalt Compaction, *Transportation Research Record* No. 1654, pp. 27-35.

Scarpas A, A.H. de Bondt, A.A.A. Molenaar, G. Gaarkeuken (1996). *Finite elements modelling of cracking in pavements. Reflective Cracking in Pavements.* Editted by L. Francken, E. Beuving and A.A.A. Molenaar. Published by E&FN Spon, 2-6 Boundary Row, London.

Shalaby A., A. O. A. Halim, S. Easa (1996). *Influence of thermal stresses on construction-induced cracks*. Reflective Cracking in Pavements. Editted by L. Francken, E. Beuving and A.A.A. Molenaar. Published by E&FN Spon, 2-6 Boundary Row, London.

Shalaby A., Abd el Halim A.O and O.J. Svec (1990). Low-temperature stresses and fracture analysis of asphalt overlays. Proceedings. In Transportation Research Record: *Journal of the Transportation Research Record,* N° 1539, TRB, National Research Council. Washington, D.C., pp 132-139.

Sousa, J.B., Pais, J.C., Stubstad, R.N. (2000). *Mode of loading in reflective and flexural fatigue Cracking - a numeric evaluation*, Fourth International RILEM Conference and Exhibition on Reflective Cracking in Pavements, Ottawa, p. 23-35.

Sousa, J.B., Pais, J.C., Saim, R., Way, G.B., Stubstad, R.N. (2002). Development of a mechanistic-empirical based overlay design method for reflective cracking, *Transportation Research Board*, p. 209-217.