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# FINITE-ELEMENT MODELLING OF CRACK SEALANT FLEXIBLE PAVEMENT

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**Abstract.** This paper documents the use of finite element analyses techniques to determine the failure mechanism in a crack sealant pavement under moving loads. The flexible pavement that is modelled is on a medium-strength subgrade. The stress-strain response of the medium soft clay is simulated using an elastic-plastic model. The three-dimensionality of the failure surface under actual wheel loads with wander requires that computationally intensive three-dimensional models is used. The finite element techniques employed are verified against available failure data of the laboratory testing samples. The paper will discuss the advantages and limitations of the crack sealant models that are currently used in pavement analysis. In addition, the paper will also discuss efficient finite-element techniques that can be used for crack sealant pavement analysis that will reduce the computational time without sacrificing accuracy.

**Keywords**: crack sealant, finite element, stress & strain, modelling, flexible pavement, elastic analysis, moving load.

## 1. Introduction

Three-dimensional finite element analysis tools are increasingly viewed as the best approach to answering certain fundamental questions about pavement performance [1–3], but the tedious processing and time required to accurately model crack sealant pavement have hampered the use of these analyses.

While two-dimensional axi-symmetric models can be utilised for a single wheel load analysis, such a constraint would lead to an inaccurate three-dimensional analysis, particularly for crack sealant pavements subjected to multiple-wheel loads and wander.

The objective of this paper is to discuss finite-element modelling strategies that can be used for analysing crack sealant pavement systems. The goal of this paper is to discover a less computationally intensive model that will maintain the accuracy of an infinitely integrated model. To accomplish this task, a reduced integration element is used that would take advantage of the ANSYS modelling software. The material model employed for the clay and gravelly material is an elasto-plastic Drucker-Prager model. In addition, meshing strategies for pavements and issues of mesh crack sealant and element aspect ratios required for accuracy is discussed. To accommodate the memory constraints, mesh gradation and infinite elements are used which reduce computation time with a reduced overall model size. In addition, the use of symmetry in the model is explored by demonstrating the ability to predict pavement responses for symmetrically loaded conditions.

Before further research on the behaviour of the crack sealant pavement structure under single and multiple loads can be completed, the material model utilised was to be validated. This was accomplished by utilising elasto-plastic material models in ANSYS [4]. The final goal of this study is to develop a working model of a crack sealant flexible pavement structure capable to model pavement failures caused by heavy loads of moving lorries.

## 2. Review of crack sealant pavement practice

In this section, the experiments are emphasised more than other subjects, because the practices are very important. There is a widespread acknowledgement in Iran that bituminous pavement cracks are formed from the top down crack [5]. The top open cracks normally are associated with environmental conditions such as heat, cold thermal movements etc. They are also caused by overloaded tire contact stresses exceeding the limiting strain of the asphalt materials. These cracks are normally wide open and crack sealing from the top is possible and relatively easy. This paragraph describes the Iranian method (materials, machines and procedures) for sealing top down cracks.

Crack sealing should be designed to serve three basic purposes:

- to prevent the ingress of surface water into the base course and underlying layers;
- to restrain the pumping out of fines and so maintain a uniform support;
- to serve as a stress absorbing system.

There is a widespread acknowledgement in Iran that bituminous pavement cracks are either the top open or the top closed type. Sealing cracks in pavements with an asphalt surface is a preventive maintenance activity performed by most highway agencies.

A range of materials and methods are in use within Iran for this purpose. The choice of a specific material/method depends on the country managers' understanding of the historical performance of various materials, pavement type (flexible or composite), regional conditions, and availability of operating funds.

### 2.1. Priming of cracks

Prime should be jetted into the open cracks using a compressed air propulsion. An inverted prime, such as MSP 1, is recommended. A schematic drawing of the equipment is shown in Fig 1.

Essentially, the process consists of a blowpipe with a nozzle to direct the jet of compressed air mixed with prime into the crack. A venturi device is fitted inside the blowpipe to create a pressure differential for sucking in the prime from a storage vessel.

A closed pressure vessel prime tank, where the air space above the prime was pressurised using a tap-off from the same compressed air source, can be used [6]. This arrangement generates similar head losses across the venturi as across the prime, and with the prime at a slightly higher pressure than the downstream end of the venturi, a constant rate of prime feed can be obtained. A needle and seed valve can be installed in the prime line for the fine adjustment of the air to prime ratio. A complete shut-off valve should be added to isolate the injector from the compressed air. This is most important when public traffic occupies the same carriageway, as the prime injectors have a considerable 'shooting range' of up to 10 m.

Three types of sealant can be used:

- Warm bitumen-rubber sealant or cold emulsion sealant (main seal);
- Final seal (rubber crumb slurry);
- Wide crack in fills.

### 3. Use of finite element model

As stresses and strains are used more and more to predict pavement distresses, and thus the relative condition of the various layers and pavement structure, the need for consideration of non-linear material behaviour becomes increasingly important. The stress state dependency on granular materials, and strain based on subgrade soil models must be considered for an accurate estimation of true pavement response [7].

Previous flexible pavement models used multi-layer elastic analysis, which assumes static loading, whereas in reality pavements are subjected to both static and moving loads. However, asphalt mixtures are visco-elastic material; crack sealant material and clays exhibit plasticity. The model used in the study conducted by Zaghloul and White incorporated an elasto-plastic model for the base, sub-base and subgrade and a visco-elastic model for the asphalt layer and crack sealant material. Zaghloul and White [8] researched the ability of three-dimensional dynamic finite element programs (ABAQUS [9]) to predict the response of moving loads on pavement structures. In their study, the granular material was modelled using the Drucker-Prager model. This assigns elastic properties to materials at low stress levels and plastic properties when the stress level reaches the yield stress. The crack sealant material was modelled using the Cam-Clay model. The validation of their model was accomplished by testing the model's ability to predict deformations under static and dynamic load conditions. The final results show that their model was capable of simulating truckloads and realistic deformation predictions were obtained.

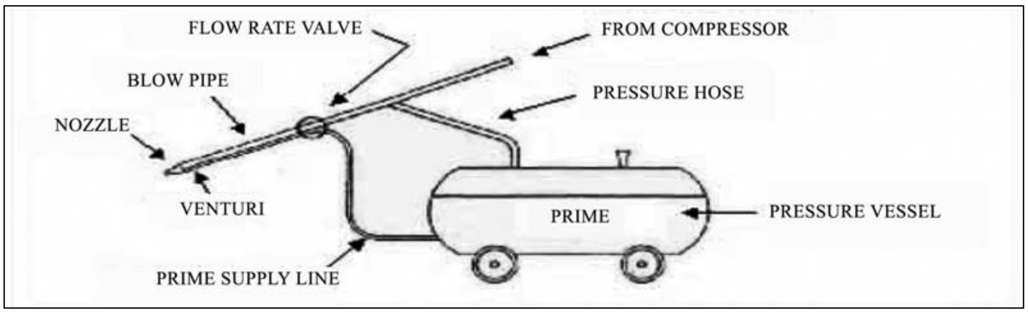

**Fig 1.** Prime injector

ANSYS [9], a commercial finite element modelling program, has been widely applied for pavement analysis. Chen et al [1] did a comprehensive study of various pavement analysis programs and showed that the results from ANSYS program were comparable to those from other programs. Zaghloul and White [8] simulated the pavement responses under FWD loading for flexible pavements using three-dimensional dynamic analysis in ANSYS. The main capabilities of ANSYS in solving pavement engineering problems include:

- Linear and non-linear elastic, visco-elastic, and elasto-plastic material modelling;
- Two-dimensional and three-dimensional calculation;
- Static, harmonic dynamic and transient dynamic loading simulation;
- Interface modelling with friction;
- Cracking propagation modelling;
- Thermal gradient analysis.

ANSYS provides many element types that are useful for pavement analysis. An infinite element model can be used to model the infinite boundary conditions in the horizontal and vertical directions of a pavement system. ANSYS also includes many material models such as linear elastic, visco-elastic, hypo-elastic and elasto-plastic models.

### 3.1. Model geometry

The mesh comprises four layers of the pavement structure as shown in Fig 2, with each layer assumed to be perfectly bonded. The pavement section is comprised of asphalt concrete, crushed aggregate, uncrushed aggregate and cohesive soils. The thickness of each layer is as follows: 10 cm of asphalt surface, 15 cm of crushed aggregate for the base layer, 30 cm of uncrushed aggregate for the subbase layer and 150 cm of Dupont clay, which forms the subgrade. Dimension of cracks is 2 ×3 cm.

The finite element mesh developed has the following dimensions: 10 m in x-direction (length), 3 m in the y-direction (height), and 15 m in the z-direction (width). The degree of mesh refinement is the most important factor when estimating an accurate stress field in the cracked and crack sealant pavement. The finest mesh is required near the loads to capture the steep stress and strain gradients. The mesh presented in Fig 3 has 21 676 nodes, 4526 three-dimensional reduced integration elements and 336 three-dimensional reduced infinite elements. The use of infinite elements allows the displacement and stress fields to decay to zero at infinity [10], providing a good alternative to boundary truncation.

### 3.2. Material properties, linear elastic model

In this research, the finite element models were designed particularly for testing configuration. The horizontal and vertical boundaries were modelled using infinite elements. No displacement in horizontal direction along the symmetry axis was allowed. At locations farther from the load, the mesh was modelled to be coarser to reduce the number of elements and, therefore, the computation burden.

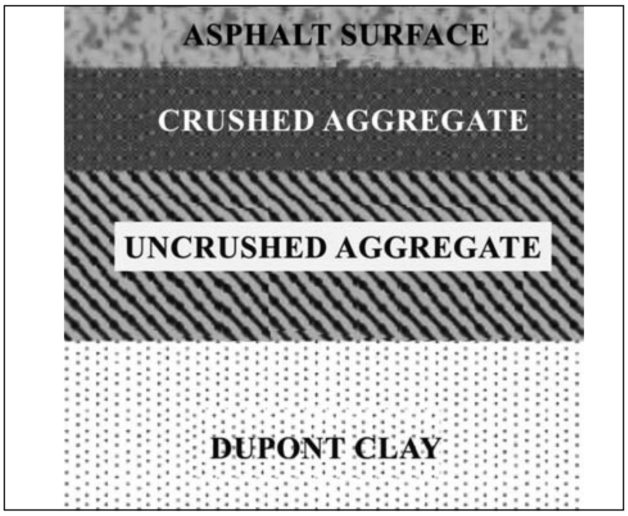

**Fig 2.** Pavement cross-section

ANSYS can be applied to simulate material discontinuities (cracking, stripping and debonding) in pavements. It allows the user to define the modulus for each element.

The pavement material is divided into 4 groups: asphalt mixtures, granular materials, crack sealant material and cohesive soils. Asphalt mixtures and crack sealant material were modelled as elastic materials. Granular materials, which consist of base and subbase, are modelled using the Mohr-Coulomb material model. This is an elastic-plastic model in which granular materials are assumed to behave as elastic materials for low stress levels. When the stress level reaches a certain yield stress, the material will start to behave as a plastic material. The yield surface is specified using a friction angle. The medium strength subgrade, Dupont clay is modelled using a Von-Mises model. The ultimate shear strength is specified. All the material models also require elastic material properties, which include the specification of the modulus of elasticity and Poisson's ratio.

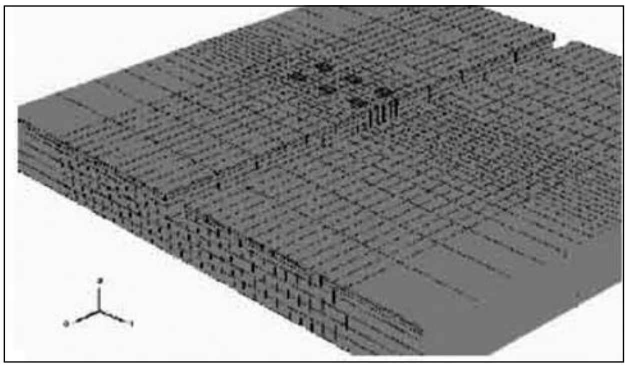

**Fig 3.** Finite-element mesh with trench

### 3.3. Model analysis

Since the boundary conditions have a significant influence on predicting the response of the model, the model is constrained at the bottom and on the sides, which do not have infinite elements. In order to verify the model, a static punch test is simulated using the mesh (Fig 4) and the results compared with a test done at the laboratory. In the model, a 6-wheel configuration is used to apply a static load. The wheel spacing is 120 cm dual (transversely between the wheels) and 80 cm tandem (longitudinally between the wheels) and the closest wheel to the trench is at a distance of 50 cm. The load vs deflection curve obtained from ANSYS is compared with experimental data obtained from a laboratory test. The model created can be seen in Fig 5.

The results of the static load in Fig 6. The data of the finite element model is compared with the values obtained from the laboratory test. The load-deformation plots shown in Fig 6 are the load vs deflection values obtained from the finite element analysis of the wheel closest to and furthest from the crack. Due to the use of an elastic model for the surface layer, no visible failure load is predicted. Since this study will be used mainly to determine the response of the underlying layers rather than the surface layer, the model is suitable for further studies with a moving wheel load.

### 3.4. Moving-wheel model

After validating the model under the static punch load, the model was run using one dynamic wheel load, taken as a pressure load moving across the top of the mesh. The most common way of applying wheel loads in a finite element analysis is to apply pressure loads to a circular or rectangular equivalent contact area with a uniform tire pressure [11].

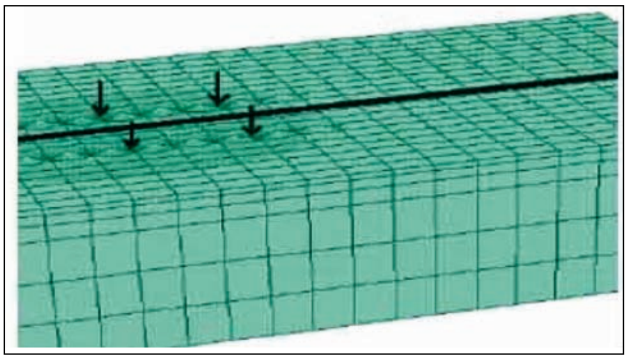

**Fig 4.** Line of symmetry

A pressure load equal to 35 KN/cm² was applied to the element, which was created to be of the same size as the wheel imprint of a large airplane, about 30 cm by 45 cm. The contact area was approximated to a rectangle. The rectangular element used to apply the contact pressure was then subjected to a velocity boundary condition of 15 km/h to simulate the moving wheel load. This model was found to require a long computation time and was further refined by removing the infinite elements. The results of further verification studies found that the inclusion of infinite elements is not necessary in achieving accurate results and the mesh could be further simplified by reducing the geometrical size and therefore the number of elements. To determine if the reduction in mesh size resulted in any loss in accuracy, further tests were conducted and are described in the next section. Fig 7 shows the load vs deflection values obtained from finite element analysis of that simulating moving load.

### 4. Discussion

The relations of the strain under asphalt layer (S) and crack with (c) are calculated with a power regression as per statistical data.

Static load

$$S = -2{,}388C^2 + 12C + 130\,. \tag{1}$$

Moving load

$$S = -1{,}223C^2 + 16C + 178\,. \tag{2}$$

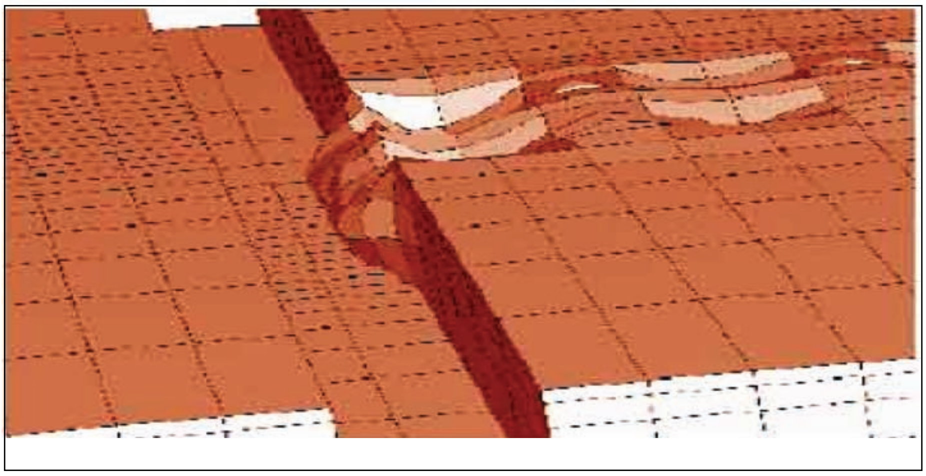

**Fig 5.** Modelled cracked pavement

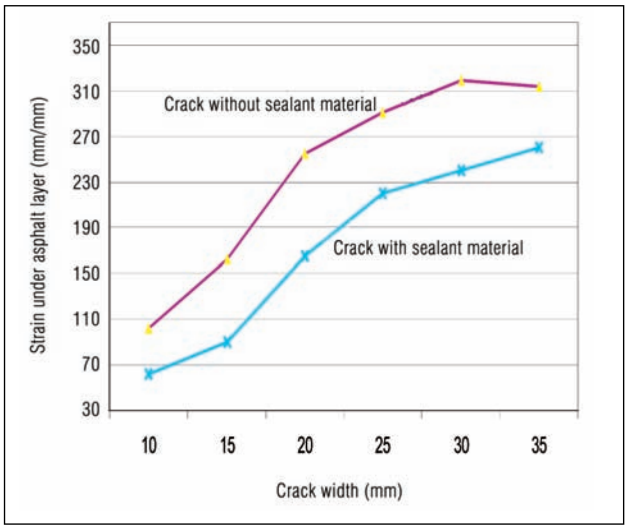

**Fig 6.** Load vs deflection value obtained from finite element software (static load)

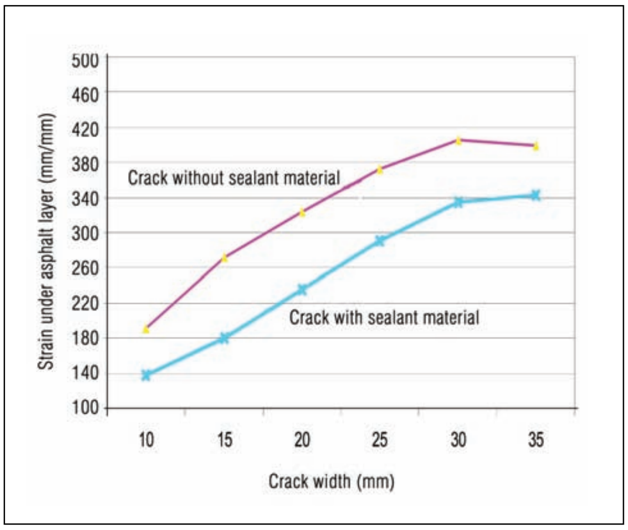

**Fig 7.** Load vs deflection value obtained from finite element software (moving load 15 km/h)

The study led to the following major findings:

- Crack sealant pavement reduces deflection and increases pavement life.
- Crack sealant pavement reduces deflection about 15 %.
- It increases crack width up to 10 % and strain of pavement about 20 %.

Effects might be different if loads of different magnitudes are applied, or at a different temperature. The relationship between the vertical stress and displacement changes with the normal stress and temperature. Also, the effect of the environment could not be considered in this analysis.

## 5. Conclusion

The paper presents the modelling of three-dimensional analysis of cracking pavements. The issues of mesh construction, mesh refinement, element aspect ratios and material non-linearities are discussed. Each of these factors affect the overall time efficiency. For the three-dimensional problems, a careful balance is required to meet the demands of solution time and memory without sacrificing accuracy. Careful planning of the finite-element model is needed to ensure an economical design with accurate results. This study is aimed to determine the effect of crack sealent condition.

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