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Simplified Numerical Modeling for Asphalt Mixes

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Abstract: Even though, asphalt mixes are classified as a visco-plastic and anisotropic material for simplicity and practicality those properties are commonly neglected and most design methods were based on the assumption that asphalt mixes behave as an elastic and isotropic material. Many sophisticated numerical models were developed to address these issues; unfortunately these models have many parameters, which make them difficult to apply. This study investigated the utilization of a simple visco-elasto-plastic model that had been used successfully in predicting sea ice distresses under different wind loads. The model parameters were fitted using the static creep/flow time test results by simple regression analysis. Then the Sea Ice model was compared to results from the Burger model, which is a widely used model for predicting deformation in asphalt pavements. It was observed that Sea Ice model had better predictions. Further, to validate the utilization of the model, an asphalt mix was tested using cyclic loading setup. Results illustrated that Sea Ice model could be used effectively in predicting deformation in asphalt mixes under static and cyclic loading conditions. The model parameters are easily determined and can be adopted in any numerical method and used to predict deformation in asphalt mixes on a larger scale.

Key words*: Asphalt mixes, Deformation, Flow time, Flow number, Numerical modeling.*

Introduction

Although asphalt mixes are considered a visco-plastic and anisotropic material, since it is a temperature, time, and aggregates orientation dependent. Designers have neglected those properties and considered asphalt mixes as an elastic and isotropic material, to simplify design methods. Nowadays asphalt pavements are subjected to different and harsher loading conditions. Despite the adjusting design factors, the current design methods, which were developed using simple yielding models, cannot predict yielding (failure) efficiently as before. Plastic deformation known as rutting is the major distress that is facing the industry, but no simple and effective solution is in sight. For that a need for a more realistic approach (model) is required to account for the visco-plastic behavior and the anisotropic nature of asphalt mixes, to prevent failures and any undesired effect due to permanent deformations. Once such material models are developed and adopted in the design methodologies, improvement of performance and reduction in maintenance shall be accomplished.

Many recent studies were conducted to simulate asphalt mixes responses to different types of loading. A study by Buttlar et al. [1] suggested that most existing analysis models do not directly account for the continuous grading of properties in flexible pavements. They presented an application of numerical model embedded in a finite element analysis for pavement analysis. Masad et al. [2] suggested an approach that utilized an anisotropic non-associated flow rule based on the Drucker–Prager yield surface. The model parameters were related to the experimental measurements of aggregate characteristics and microstructure damage measured using X-ray tomography and image analysis techniques.

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Tashman et al. [3] developed a microstructure-based viscoplastic continuum model for predicting permanent deformation of asphalt mixes. This model accounted for strain rate dependency, confining pressure dependency, dilation, aggregate friction, anisotropy, and damage, which influence the permanent deformation of asphalt mixes at high temperatures. The developed model predictions were in a good agreement with the experimental measurements. Collop et al. [4] investigated the use of discrete element modeling (DEM) by utilizing Burger model in their analysis. They argued that the behavior of the mixture would be dominated by asphalt binder and complex aggregate interlock effects would be minimized. It was found that tested mixes dilated when the ratio of compressive to tensile contact stiffness increases as a function of loading time.

Many models [5-6] have been developed that approximated the response of the asphalt materials under different loading conditions. These models simulated an HMA sample as two components, coarse aggregates as elliptical particles and mastic (fine aggregates and asphalt binder). The simulations were run using FEA software (i.e. ABAQUS) to calculate material responses to loads. Although, most of these models were developed to predict pavement permanent deformation, these models proved that FEA is a powerful tool that can be used successfully for simulating the response of asphalt mixes under different loading conditions.

A study by Kettil et al. [7] modeled and simulated inelastic deformation in road structures leading to rutting. The developed models accounted for the time and temperature dependent deformation of the asphalt mixes as well as the friction and cyclic compaction of the unbound layers. Their models had been used in simulations of a complete road structure exposed to cyclic mechanical and thermal loads. Simulation results were similar to permanent deformation observed in reality. Wang and Birgisson [8] presented a time domain boundary element method to model the quasi-static linear viscoelastic behavior of asphalt pavements. They suggested that fundamental solution could be derived in terms of elemental displacement discontinuities and a boundary integral equation was formulated in the time domain. Their Numerical experiments were conducted to demonstrate application of the method in pavement engineering.

Bandyopadhyaya et al. [9] attempted to develop a numerical model for predicting the mechanical behavior of asphalt mixes. In this work the irregular shaped aggregates were obtained by tracing out the original aggregate shapes from cross-sectional images of asphalt mix samples and detecting the aggregate boundaries by image processing techniques. The asphalt binder, air voids and small sized aggregates together were assumed to behave like a viscoelastic material idealized by a Prony series and its properties were determined from relaxation tests performed in the laboratory. The overall behavior of the asphalt mix in terms of displacement at failure exhibited good match between experimental and computational results.

Chazallon et al. [10] presented a finite element program, for the modeling of rutting of flexible pavements, using non-linear elastic models, to determine the stress field in the pavement. Stress paths were derived and used to calculate permanent deformations and displacements, using a Drucker–Prager yield surface. Ye et al. [11] studied the nonlinear visco-elastoplastic behavior of asphalt mastic (asphalt and fine materials) by conducting a series of uniaxial compression creep tests conducted under different temperatures and stress levels. Burger model was used in their simulation. It was shown that the presented model had better agreement with experiments. Zelelew and Papagiannakis [12] utilized Burger model to predict deformation in asphalt mixes measured by uniaxial creep test. Simulation results were compared to the laboratory results. It was observed that axial strain curves were similar in shape.

A different approach was adopted by Tabakovic et al. [13], where they studied the applicability of a cohesive zone model for simulating the response of asphalt mixes subjected to quasi-static loading. The Dugdale traction law was implemented within a finite volume code in for simulation. Numerical results agreed well with the experimental data.

Recently, more sophisticated approaches have been developed. Dai [14] evaluated 2D and 3D micromechanical finite element models to predict the viscoelastic properties of asphalt mixes. The internal microstructure of asphalt mixtures was captured with X-ray computed tomography. The generalized Maxwell model was applied for viscoelastic asphalt matrix with calibrated parameters from the nonlinear regression analysis of the lab test data. The simulations were conducted for the uniaxial compression under sinusoidal cyclic loading. Overall, results from 2D and 3D micromechanical models were compared with lab test data of the asphalt mixture specimens, it was observed that their model predictions were close to test results with better prediction by 3D simulations. Further, Mirzahosseini et al. [15] evaluated permanent deformation in asphalt mixes using two branches of soft computing techniques: multi expression programming (MEP) and multilayer perceptron (MLP) of artificial neural networks. The trends of the results were confirmed with the experimental study results and those of previous studies, they argued that the observed agreement between the predicted and measured flow number values validated the efficiency of the proposed correlations. In addition, MEP-based straightforward formulas were found more practical for the engineering applications compared with the complicated equations provided by MLP.

Unfortunately, simple models that under/overestimate the behavior of asphalt mixes under different loading conditions or very sophisticated and efficient numerical models that contain multiple parameter and user dependent were developed, which proved to be hard on the industry to utilize.

Scope

In an effort to develop simplified predictive model to determine deformation especially permanent deformation in asphalt mixes, a simple visco-elasto-plastic model was selected, which was used successfully to predict Sea Ice distresses under different wind load. The model was fitted to predict deformation in asphalt mixes, using a simple test setup (Static Creep/Flow Time Test) to determine its parameters. To check the validity of this model, its results were checked against measured deformation in a different test setup (Flow Number Test).

Sea Ice Model

It was found that Sea Ice exhibits some of time-dependent processes namely delayed elastic recovery and creeping. In the same time, the numerous experiments show that ice strength has a dynamic value depending non-linearly upon the strain rate. From another side, different processes as gravity and drainage desalinate the Sea Ice [16-18]. The axial strain can be superposed into three terms in according with Sinha [19] as,

$$e_T = e_e + e_d + e_v \tag{1}$$

where, e_T is the total strain, e_e is the instantaneous elastic strain, e_d is the delayed elastic recovery, and e_v permanent or viscous strain. Further, Sinha [19] had proposed the strain-stress relation the describe Sea Ice behavior under loading as follows,

$$e_T = \frac{\sigma}{E} + c \left(\frac{d_0}{d}\right)_0 \left(\frac{\sigma}{E}\right)^s \cdot \left[1 - e^{-(a_t \cdot t)^b}\right] + e^{\cdot}_{vo} \cdot t \cdot \left(\frac{\sigma}{\sigma_0}\right)^n \tag{2}$$

where,
σ is the applied stress (kPa),
E is the mix stiffness (kPa),
c is a material constant,
b is a time exponent for delayed elastic strain,
a_T is a material constant (s^{-1}),
d is an average grain diameter (mm),
d_o is a grain diameter (mm),
s is the stress exponent for grain-bound sliding,
n is the degree of viscosity power law, and
$e^{\cdot}_{vo}$ is the viscous strain rate (s^{-1}).

Zyryanov et al. [18] argued that the size of the ice-free area in the sea ice formation was dependent on different wind stresses, and the sea ice exhibited delayed-elastic recovery and viscosity. Similar to sea ice, asphalt mixes have the tendency to follow the same behavior under loading and unloading. Most numerical modeling of asphalt mixes under axial loading utilized Burger model [4, 11, 12] to simulate asphalt mixes behavior under loading, especially the time-dependency [20]. Burger model consists of Maxwell and the

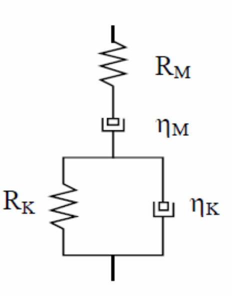


Fig. 1. Mechanistic Model Parameters of the Burger Model (After Abbas [20]).

Table 1. Mixes Properties.

Parameter	Mix 1	Mix 2
Job Mix Design Class	19.0 mm	25.4 mm
Binder Grade	PG 58-34	PG 70-28
Asphalt Content	4.6%	5.0%
G_{mm}	2.801	2.458
Sieve Size	% Passing	
25 mm	100 %	98 %
19 mm	96 %	96 %
12.5 mm	79 %	82 %
9.5 mm	70 %	73 %
4.75 mm	46 %	55 %
2.36 mm	28 %	36 %
1.18 mm	18 %	24 %
0.6 mm	12 %	13 %
0.3 mm	9 %	9 %
0.15 mm	5 %	6 %
0.07 mm	3.5 %	4.4 %

Table 2. Sea Ice Model Parameters for Asphalt Mixes.

Parameter	Mix 1	Mix 2
s	1.229378	1.229378
a_T	3.14×10^{-04} s^{-1}	3.14×10^{-04} s^{-1}
c	7.5	7.5
b	0.34	0.34
n	3	3
$\dot{e}_{vo}$	$6.59\text{x}10^{-06}$ s^{-1}	$1.78\text{x}10^{-07}$ s^{-1}

Kelvin models. The Maxwell model is a combination of a spring and dashpot in series, while the Kelvin model is a combination of a spring and dashpot in parallel, as shown in Fig. 1.

Maxwell model is most suitable for cases in which a constant strain is applied and the stress is monitored (stress relaxation), whereas Kelvin model is most suitable for cases in which a creep load is applied and the strain is monitored (strain retardation). On the contrary to the Kelvin model, the Maxwell model is capable of capturing permanent deformation due to the presence of a dashpot not connected to a spring in parallel. Any strain accumulated within that unit is entirely non-recoverable [20]. Burger model can be expressed as,

$$\dot{e} = \dot{e}_M + \dot{e}_K = \frac{\dot{\sigma}}{R_M} + \frac{\dot{\sigma}}{S\eta_M} + \frac{\dot{\sigma}}{R_K + S\eta_K} \tag{3}$$

where,

$\dot{e}_M$ is strain within the Maxwell model,
$\dot{e}_K$ is first derivative of strain within the Kelvin model,
$\dot{e}$ is the first derivative of stress carried by the mechanistic model,
R_M and R_K are Maxwell and Kelvin springs stiffnesses, respectively,
η_M and η_K are Maxwell and Kelvin dashpot damping coefficients, respectively, and
S is Laplace transformation variable.

Abbas [20] explained that the dynamic shear modulus test; AASHTO TP 62-03 [21] of asphalt binder could be used to determine the module parameters. However, this approach does not take into consideration the effect of aggregates in the mix and their interaction with the binder. Making the Sea Ice model an easier approach to use.

Experimental Verification

Test Setups

Static Creep/Flow Time (Ft) Test

Flow Time test is a triaxial static creep test, where specimens are subjected to a static axial load of 207 kPa. The test was conducted without confinement at a testing temperature of 54.4 °C. The flow time is defined as the postulated time when shear deformation, under constant volume, starts [22].

Flow Number (FN) Test

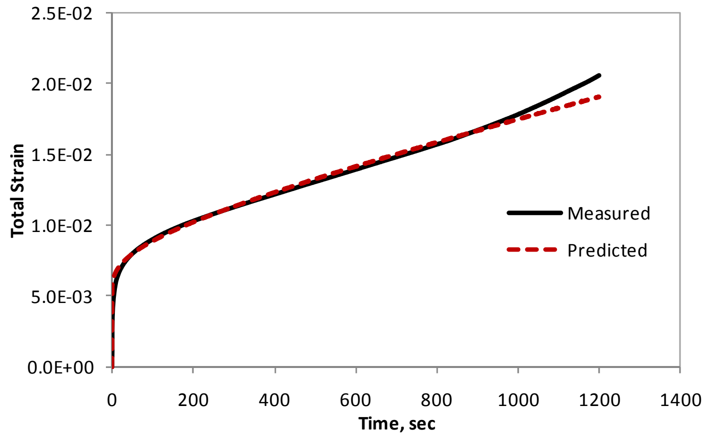
Flow Number test is a triaxial repeated load test and it was conducted using a loading cycle of 1.0 second in duration, which consists of a 0.1 second haversine load followed by a 0.9 second rest at a testing temperature of 54.4 °C. Flow Number is defined as the number of load repetitions at which shear deformation, under constant volume, starts [22].

Test Sample Preparations

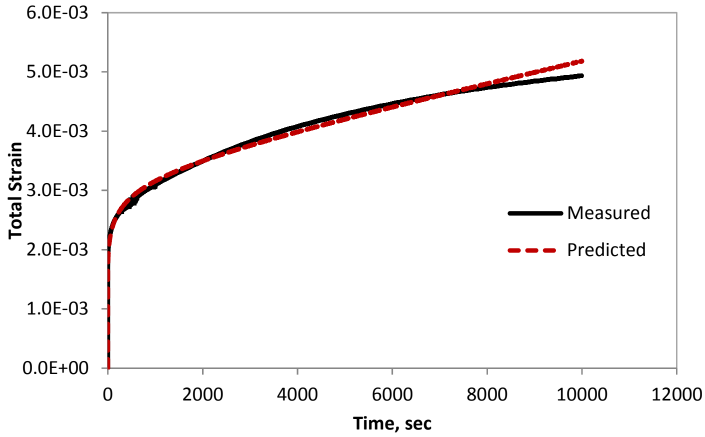
Two duplicate specimens per mix (Table 1) were used in the Static Creep/Flow Time and Flow Number tests. Samples were compacted to achieve 175 mm high specimens with a total 9% air voids. Then, specimens were cored and sawed to obtain 100 mm diameter and 150 mm high specimens with an inner 7% air voids.

Analysis of Results

Two Superpave mixes were evaluated in this study, and details of the mixes' properties are illustrated in Table 1. Test results from the Flow Time (F_t) test were used to determine the Sea Ice model parameters in Eq. (2), by using simple regression analysis (the least square method); the fitted model had an R-square of 0.9846 and 0.9815 for Mix 1 and Mix 2 respectively.



a) Mix 1



b) Mix 2

Fig. 2. Measured vs. Fitted Model Results of Total Strain determined in Flow Time Test.

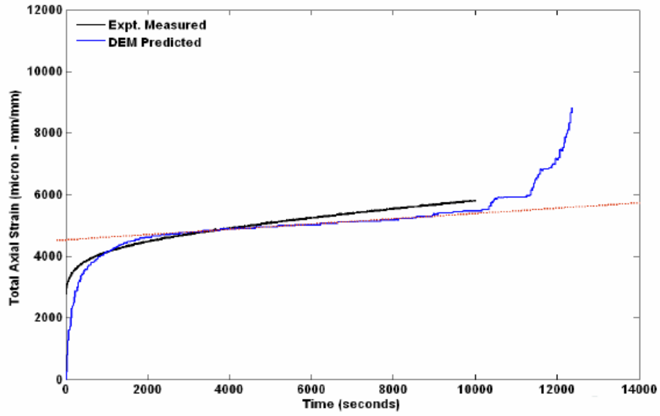


Fig. 3. Total Axial Strain Measured vs. Predicted Using Burger Model (After Zelelew and Papagiannakis [12]).

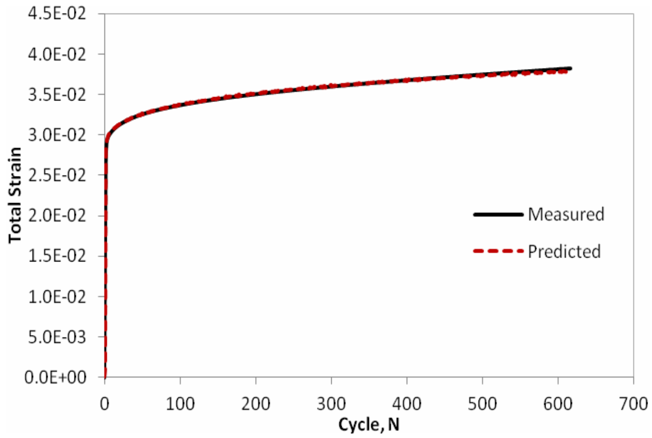


Fig. 4. Measured vs. Predicted Results of Total Strain determined in Flow Number Test (Mix 2).

Similar to previous studies [1, 4, 7, 10, 23] at which asphalt mixes were simulated as a continuum and the different particle sizes were not taken into consideration and to further simplify the Sea Ice model *d* and d_o ratio was assumed 1. The fitted parameters are shown in Table 2.

Fig. 2 illustrates the fitted model approximately matches the measured values, until Flow Time is reached, where the tested samples started to flow and shear deformation started [22]. Both mixes had the same model parameters except for the viscous strain rate (e_{vo}), as shown in Table 2.

To compare the Sea Ice model with results from the Burger model, results were obtained from the literature [12] as illustrated in Fig. 3, where Burger model was adopted. The viscoelastic properties of mastics (binder and fine materials) were characterized by fitting Burgers models to Dynamic Shear Rheometer test results. The microstructure of the asphalt mixes was captured using high-resolution X-Ray tomography. Then, an automated digital image processing was used to process the images and in input their microstructure into a discrete element method (DEM) software to predict the total stain in a Flow Time test model. The DEM creep simulation results were compared to the laboratory measured uniaxial creep tests. Their results illustrate that the measured and DEM predicted axial strain curves were similar in shape. Further, the DEM models predicted the creep compliance accurately in the secondary stage.

When comparing results from both models, it was clearly observed that the Sea Ice model had better prediction that Burger model. In addition and as shown in Table 2, for the tested asphalt mixes, most of the Sea Model parameters were the same except for the viscous strain rate (e_{vo}), making it easier to utilize than the Burger Model, which requires at least four parameters to be determined.

To validate the utilization of the model under different loading conditions, Mix 2 was tested using in Flow Number test (cyclic loading setup). The model parameters were found to be the same as shown in Table 2 for Mix 2, except for parameter *c*, which was found to be equal to 2.0 instead of 7.5 with an R-square of 0.949, as shown in Fig. 4. It is suggested that parameter *c* is a material constant that describes the behavior of material under different type of loading setups.

Summary and Conclusions

Nowadays asphalt pavements are subjected to different and harsher loading conditions, and despite the adjusting design factors, the current design methods, which based on simple yielding models that assumed that asphalt mixes behave as an elastic and isotropic material. Thus, these methods cannot predict failure accurately as before. Since Plastic deformation known as rutting is the major distress in asphalt pavements a need for a more realistic and applicable approach is required to account for the visco-plastic behavior and the anisotropic nature of asphalt mixes, to prevent failures and any undesired effect due to permanent deformations. Many numerical models were developed to predict permanent deformation in asphalt mixes; unfortunately these models have many parameters, which make them unpractical to use.

This study described the use of a simple visco-elasto-plastic model in predicting permanent deformation in asphalt mixes, which has been used successfully in determining Sea Ice distresses under different wind loads. The main reason for choosing this model was its simplicity and its ability to capture the Sea Ice behavior under different loading conditions, which was found to exhibit some of time-dependent processes namely delayed elastic recovery and creeping, further many experiments showed that sea ice strength has a dynamic value depending non-linearly upon the strain rate, thus giving this model a great advantage when used to predict asphalt mixes distresses. The model parameters were fitted using the Static Creep/Flow Time test results by simple regression analysis with an R-square of 0.9846 and 0.9815 for Mix 1 and Mix 2, respectively. Both mixes had the same model parameters except for the viscous strain rate ($\dot{e}_{vo}$).

To compare the Sea Ice model with results from Burger model, which is a widely used model to predict permanent deformation in asphalt pavement, results were obtained from the literature [12], where Burger model was adopted in discrete element method (DEM) software to predict the total stain in Flow Time test. Results showed that Burger model approximately predicted total stain. When comparing results from both models, it was observed that Sea Ice model had better prediction that Burger model.

To validate the utilization of the model, Mix 2 was tested using Flow Number test (cyclic loading setup). The model parameters were found to be the same, except for parameter *c*, which was found to be equal to 2.0 with an R-square of 0.949. It is suggested that parameter *c* is a material constant that describe the behavior of material under different type of loading setups.

Results from this study indicated that Sea Ice model could be used effectively in predicting deformation in asphalt mixes under static and cyclic loading conditions. It is easy to determine its parameters and can be utilized in any numerical method/software to predict deformation of asphalt pavements under different loading conditions.

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