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Evaluation of Viscoelastic Properties of Asphalt Mixtures by Finite Element Modeling Using Abaqus Software

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Abstract

Pavement with asphalt mixes and good quality and continuous life has been considered. The issues that lead to increased durability, quality and life of asphalt pavements have always been considered, so that pavements known as permanent pavements and high-rise pavements are introduced. Asphalt mixtures, in most cases, the lifetime of the pavement is exposed, they exhibit viscoelastic behavior. One of the methods widely used to predict viscoelastic responses of asphalt mixtures is the finite element method. ABAQUS software is one of the tools that can simulate mixed asphalt behavior based on a finite element method, taking into account all the determinant parameters. The use of the Prony series is one of the common techniques for describing the viscoelastic behavior of asphalt mixtures in ABAQUS software. For this purpose, it is necessary to determine the parameters required for this field, including proven constants, moment elastic modulus, and asphalt mixture poison ratio. On the other hand, the determination of these parameters through testing in addition to spending time and costs requires laboratory equipment. Therefore, in this thesis, a three-dimensional finite element model with ABAQUS software was constructed to analyze the persistent pavement using theoretical relations without conducting the experiment. In order to achieve this goal, in this model, 4 layers of asphaltic were defined as elastic whiskey, and the base layer and sub grid were modeled elastically, and the whiskey analysis for analysis was also used. Based on the results of this thesis, the longitudinal tensile strain model has a very good agreement with the value measured in the U.S.30 project. Also, the areas of traction and pressure are also interconnected. This correlation is also seen in the maximum vertical stresses. The effect of thickness on the finite element model is also considered, and it has been determined that thickness has a significant effect on the durability of pavement performance. By changing the thickness of the layers a little, it can be seen that the effect is on the output values. Also, viscoelastic behavior of common asphalt mixtures and time dependence of its responses at different temperatures can be modeled in ABAQUS software.
Keywords: Asphalt; Viscoelastic; Finite elements; Prony series; ABAQUS software.

1. Introduction

The theory of long-distance pavements is not a new issue; in fact, asphalt pavements were built since the 1960's. This is the name for the permanent pavement, the name of which is new [1]. More than 35 sections of pavements in the United States since 2001 have used a durable pavement, including roads, streets, highways and runways, which requires the least maintenance without complete rebuilding. The features of this kind of pavement are their high fatigue resistance [2-4]. One of the ways to increase fatigue strength is to better understand the parameters affecting the fatigue performance of asphalt mixtures. The durable pavement combines the benefits of the safety and smoothness of the asphalt with the advanced process of multi-layered pavement design and maintenance every day, so that the useful life of the road reaches half a century or more. The pavement designed and constructed will remain permanently in line with the concept of permanent pavement [5-7]. One of the important benefits of these pavements is that the overall thickness of the pavement is less than the thickness of the granular pavement. In addition, the fatigue cracking potential is reduced and the damages of the pavement are limited to the upper layer of the structure. Recent efforts in material selection, mix design, performance testing, and pavement design offer a method that achieves high-performance asphalt pavement structures (more than 50 years) until pavement work Periodically replaced [8]. Since the initial design has a significant role in the maintenance and maintenance of pavement in service life, and the quality of pavement performance is not affected by the weather conditions, load, quality of materials and mixing plan, so selecting appropriate materials and other materials Effective factors can increase the service life of the pavement and thus reduce future repair costs. Unfortunately, in our country, due to the abundance of oil resources and the overestimated prices of bitumen, in comparison with countries without these resources, there is no importance for bitumen, bitumen performance modification, mixing plan, quality control of materials used in the procedure and methods for designing not given [9-11]. So that the network of roads in the country and even airports is a concrete set of pavement breakdowns and the costs of these failures are directly or indirectly imposed on users. While it's possible to improve the durability and performance of the pavement to an acceptable level by designing and managing properly. Due to the great downtime and shortage of pavement, other countries in the world, and especially the United States, were looking to build high-rise roadside pavilions and reduce downtime as much as possible [12-14]. This research led to the invention of a new type of high-rise pavement called Sustainable pavement. This kind of pavement, in addition to its lifespan of over 50 years, benefits such as maintenance and maintenance during the useful life, the cost of life cycle is less than other pavements, and so on [15]. Despite the many downsides in asphalt pavements, annual repairs, repairs and rehabilitation of roads cost a lot. In addition to the high cost of doing this, this kind of work takes a lot of time and disrupts the traffic order [16]. Also, crashes along the way will also increase the cost for users of the way. A lot of research has been done to improve the pavement properties by improving pavement performance and survival, resulting in permanent designs [17]. Due to its high lifespan and low and superficial breakdowns, this type of pavement is a very suitable method for roads with high traffic volume, which, in addition to saving time and cost, minimizes the disruption of the traffic process for restoration, as well as It prevents the loss of unrecoverable resources due to the reconstruction of the route. Design methods and layered specifications as well as construction considerations [18, 19].

The quality and thickness of asphalt mixtures are one of the factors affecting the performance of pavement, and especially the creation of lizard skin cracks. The use of low-quality or low-density mixes results in the exorbitant cost of repairing and repairing pavements [20]. Therefore, the purpose of this research is to evaluate the materials and predict the performance of the mixture at the design stage. In the past, hot asphalt materials were considered as solid elastic in mechanistic analysis for flexural asphalt pavements, while they were in fact treated as elastic viscos-materials. Unlike elastic solids, the behavior of Asphalt materials depends essentially on the temperature and loading frequency. At low temperatures and high loading rates, they behave much like solid elastic, while at high temperatures and low loading they behave like a viscous liquid. In moderate temperature and frequency, they behave like visco-elastic materials, which have a surface of hardness of solid elastic materials, in addition to the typical properties of visco-materials [21]. The main purpose of the research is to introduce the properties of the visco-elastic materials measured in the laboratory to simulate the three dimensional finite element model of the pavement behavior so that the effects of design factors including the thickness of the layers, the modulus of the load applied layers and the velocity Check the vehicle on the longitudinal tensile strain maximum at the bottom of the asphalt layer. In this study, it has been shown that it is possible to construct this type of valuable pavement. Ultimately, the finite element modeling of an experimental path using ABAQUS software was performed to determine the effect of different parameters on the performance of this pavement.

2. Material and Methods

Common asphalt pavements in Iran consist of four layers of asphaltic, basement, subsoil and substrate, each of which has its own behavioral characteristics. Different layers of the pavement from the point of view of behavioral characteristics can be divided into two groups of elastic and viscoelastic so that the asphalt layer has viscoelastic behavior and other elastic behavioral pavement layers. In the ABAQUS software, viscoelastic properties of materials can be defined with the help of the Provence series. For this purpose, it is necessary to determine the Prony constants, moment elastic modulus and the Poisson ratio of the asphaltic mixture. In this paper, it is attempted to calculate and determine the necessary parameters using theoretical relations. To achieve these goals, this research includes the following steps:

- Calculation of dynamic modulus and Asphalt mixture phase angle at different temperature and frequencies using the Witczak relationship.
- Calculate the resting modulus of asphaltic mixtures in the proposed method by Schapery and Park
- Determination of Prony constants for the Application of Prony series.

In order to determine the dynamical modulus of the asphalt layer used in Iran's ways using Witczak relationship, we first have to determine the volume specifications of asphalt mixes and environmental conditions according to the criteria of the design. The amount of rock materials, percentage of free space, and volume percentage of effective bitumen, bitumen viscosity, temperature and loading frequencies are considered as the most important parameters in determining the dynamic modulus, the values of each of which are described below.

The aggregation of aggregate aggregates of the asphaltic mixtures studied in this study was continuous (grain No. 4 for liners and liners) and is based on the standards in the model for U.S.30 permanent pavement in Ohio, USA. This aggregate has the highest application and conformity according to the existing standards in Iran. Also, the Poisson ratio of asphalt mixture in accordance with common asphalt pavements in Iran was equal to 0.35. The percentage of free asphalt mix was 4% according to U.S.30 permanent pavement model in Ohio, USA. With regard to the type of traffic that is considered heavy, at first, the percentage of empty space filled with bitumen of U.S.30 model was determined at 70%, and then the volume percentage of effective bitumen was calculated through the ABAQUS software.

In this research, the Witczak equation (due to the actual results obtained from the dynamic modulus test) has been used to predict the dynamic modulus of asphalt mixtures. Using the Witczak equation, we can determine the asphalt mixture dynamic dynamics modulus at different loading frequencies based on the volumetric characteristics of the asphalt mixture and the type of bitumen used. These calculations are done using the ABAQUS software. Using the results of the Witczak equation, we can determine the momentum elasticity modulus of the asphaltic mixture at the desired temperature. The asphalt mixture modulus is considered at a given temperature and at a high loading frequency as the momentary elastic modulus of the asphalt mixture. In this study, the magnitude of the momentum modulus of asphalt mix at reference temperature (which is considered to be 21.1 C^0in this study) was determined to be 10693 MPas. In the ABAQUS software, viscoelastic properties of asphaltic mixtures can be described using the Prony series in the form of a shear modulus. The Prony series is an exponential series that describes the strain-strain relation for a linear viscoelastic system (represented by a spring-damper model).For modeling of asphaltic mixtures using the Prony series in ABAQUS software, Prony constants, moment elastic modulus and Poisson ratio are used for a 6-sentence Prony series. These parameters are related to common asphalt pavements in Iran (with specification and thickness provided) at reference temperature ($21.1C^0$) were calculated.

3. Findings

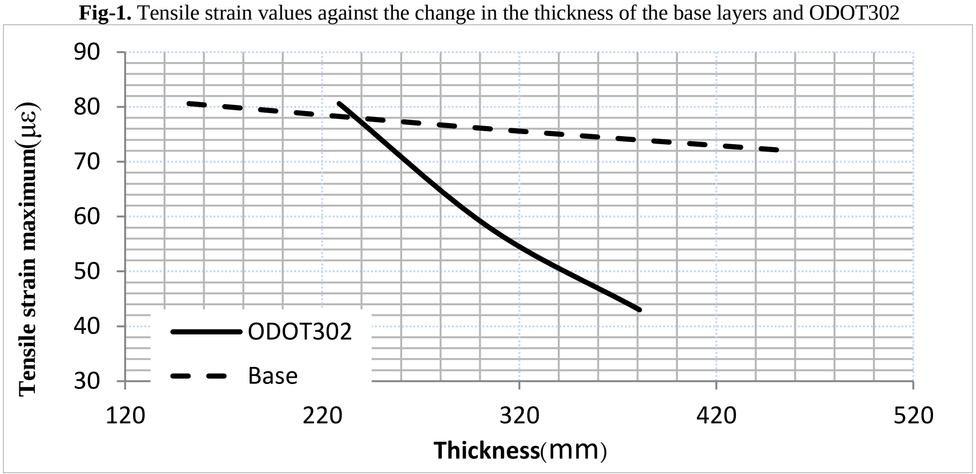
3.1. Parametric Results on the Viscoelastic Finite Element Model

The resulting viscoelastic finite element model is used to perform parametric studies to investigate the effects of design factors including layer thickness, load cell modulus and vehicle speed on the maximum longitudinal tensile strain at the bottom of the FRL asphalt layer.

3.1.1. Effect of Layer Thickness

As the pavement thickness is the most important issue in the design of the pavement, the maximum tensile strain sensitivity at the bottom of the FRL asphalt layer is studied for the thickness of the layers using the obtained viscoelastic model. In order to ensure that the fatigue crawl does not go down in the pavement, the tensile strain max must be limited to 70 microns (Fig.1).

Fig-1. Tensile strain values against the change in the thickness of the base layers and ODOT302



If this limit is met, permanent pavement will never be faded by fatigue cracks. To reduce the maximum tensile strain, a durable pavement should have a sufficient thickness. In the permanent pavement, each layer of pavement is designed to withstand a particular failure, in particular the high and low asphalt layer. Due to the fact that these two layers have the maximum recommended thickness for the permanent pavement, only the thickness of the two ODOT302 layers and the grain base is changed. For these two layers, the thickness is considered to be greater. Several different modes for the ODOT302 thickness were considered to be 228.6 mm, 304.8 mm and 381 mm, with strain values changed from 80 με to 58 με and eventually changed to 43 με. The strain was 70 micron strain in a thickness of 262 mm (Fig.2).Increasing the thickness of the base, due to its low hardness, had no significant effect on reducing the strain rate. In order to achieve an economical design, different thicknesses were considered for these two layers. Finally, a model with a thickness of 254 mm, ODOT302 and 304.8 mm were selected for finite element analysis, with a strain of 3 / 67 has a strain that is less than 70 micron strain and prevents permanent pavement damage. This value was obtained after reviewing 5 states according to Table (1).

Table-1. Different amounts of thickness intended to reach the desired cross section

Layer	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
ODOT302	9 in	10 in	10 in	10 in	10 in
Base	6 in	6 in	8 in	10 in	12 in

Fig-2. Final section after thickness change

1.5 in sma
1.8 in ODOT442
10 in ODOT302
4 in FRL
12 in Base
Sub grade

3.1.2. Effect of Layer Modulus

Layer modules are one of two important factors that play a major role in resistance to pavement failures. Theoretically, less thickness is required for pavement if asphalt materials have a higher modulus. In this section, the effect of the modulus of the layers on the longitudinal tensile strain is studied maximally. The three values for the tensile strain modulus are given in Table (2), and the effect of this change in values is shown in Table (3).

Table-2. The values of the modulus intended to examine the effect of the modulus of the layers

Layer	Layer Module (Gp)		
	-30%	measured value	+30%
SMA	3.409	4.78	6.331

ODOT442	2.55	3.65	4.745
ODOT302	5.397	7.71	10.023
FRL	5.67	8.11	10.543

Table-3. The rate of change in the strain of each of the layers due to the modulus of the layers

Layer	Maximum tensile strain variation (microstrin)	
	-30%	+30%
SMA	2.99E-02	-2.72E-02
ODOT442	2.99E-02	-2.40E-02
ODOT302	2.72E-02	-2.09E-02
FRL	1.48E-01	-1.00E-01

According to Table 3, it can be seen that the FRL layer plays the most important role on the maximum tensile strain compared to other layers. With a 30% increase in the modulus of this layer, the tensile strain decreases from 80.6 µg to 70 µm.

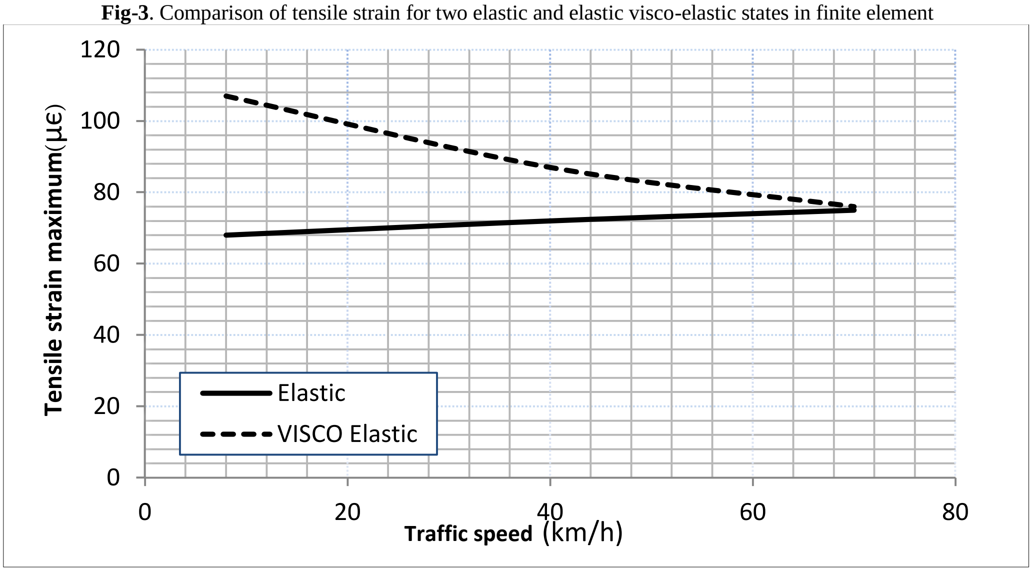
3.1.3. A Comparative Study of the Elastic Limit Element Model and the Visco-Elastic Finite Element Model in ABAQUS

In many cases, elastic analysis is used for pavement. In this analysis, materials are considered elastic for each layer, while HMA materials act as elastic only at low temperatures, and at high and average temperatures, elastic theory cannot properly show the deformation properties of asphaltic materials. In the theory of elasticity, the effect of traffic speeds cannot be considered to be more important at lower traffic speeds. In this section, a comparison between linear elastic model and viscoelastic model is performed to evaluate their relative performance. In the linear elastic model Hooke's law is used to describe the behavior of HMA materials. Although the materials are elastic and the effect of speed and time cannot be considered, the effect of temperature can be considered by measuring the modulus of resonance at different temperatures. These results were obtained from experiments designed to determine the modulus of resonance at three temperatures of 5, 25, and 40 ° C in the laboratory, and it was assumed that there is a change in temperature with temperature. Therefore, the modulus of resonance at any temperature can be obtained with this exponential model. This model is presented in the following figure and shows the relationship between the temperature and the modulus of rotation for different materials.

Comparison of the values obtained by this model with the response values from field experiments for 88.5 km/h, which also included the elastic whiskeys model, made it possible to calibrate the elastic model to reach the number obtained in the experiment. In the figure below, the tensile strain lengths at various speeds are 8, 40 and 70 km/h for both the elastic and elastic models.

As can be seen in Fig.3, the viscoelastic model is highly accurate to predict the pavement response, the viscoelastic model acts better than the elastic model. This suggests that the behavior of asphalt materials is not properly described without considering the time and input of the temperature parameter. Therefore, it is concluded that the linear elastic model cannot predict adequately the response of the pavement under different temperature and traffic velocities. Because the model is less than actual values, it is not conservative for design purposes and may lead to early damage to the pavement. It is better to replace the elastic models for the asphalt pavement analysis of the viscoelastic model.

Fig-3. Comparison of tensile strain for two elastic and elastic visco-elastic states in finite element



4. Discussion

1. The results obtained from this model for a longitudinal tensile strain are very consistent with the value measured in the U.S.30 project. Also, the areas of traction and pressure are also interconnected. This correlation is also seen in the maximum vertical stresses [22].
2. Modeling the loading wheel in the elastic whiskeys has a great effect and increases the accuracy of the finite element model.
3. Since the strain tolerance limit to prevent fatigue cracking is 70 micron strain, the results are obtained so that the cross section is not suitable. Therefore, further studies were conducted on this section to obtain a suitable dimension [23].
4. The effect of thickness on the finite element model was considered and it was found that thickness has a significant effect on the durability of pavement performance. By changing the thickness of the layers slightly, the effect can be observed on the output values [24].
5. By examining the effect of the modulus of the layers, it was found that the modulus of the layers had no significant effect on the pavement response [25, 26].
6. The fastest ratio of the strain rate is highly dependent on the speed of the vehicle and increases at a slower rate.
7. Finally, by changing the thickness of the two layers of ODOT302 and the grain base, a suitable section for permanent pavement was obtained according to the route U.S.30.
8. By making the elastic model and comparing it with the elastic visco-model, it was concluded that the elastic model is not suitable for estimating the pavement response and is not sufficiently precise [27]. Life cycle analysis was carried out for two sections of permanent pavement and ordinary asphalt pavement, resulting in a lower cost of permanent pavement during a period of 50 years.

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