

Investigating Viscoelastic Properties of Asphalt Mixtures

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Abstract

Today, the use of asphalt pavements in the world shows an ascending trend. Since rutting failure is among the most common failures on roads, laboratory information is required to evaluate the potential of rutting. The static creep test has been used to evaluate the rutting susceptibility of asphalt mixtures for a long time. Evaluating the strains created in asphalt mixtures at different loading times and temperatures is among the most essential methods for modeling the visco-elastic behavior of asphalt mixtures. In addition, mechanical models have been used to evaluate the nonlinear viscoelastic behavior of asphalt mixtures. Some of these models include Burgers, Maxwell, generalized, and Kelvin models. In this research, the creep behavior of asphalt mixtures is evaluated over time using static creep tests at 2, 3, 4, and 5 bar at the controlled temperature of 40°C. Next, coefficients of determination (R^2) for different mechanical models are determined to evaluate viscoelastic behavior. The experimental results and proposed mechanical models indicate that the Burgers model has the best performance ($R^2 = 0.8$) in predicting the viscoelastic behavior of asphalt mixtures at different pressures with a reliability of 95%. Finally, a logarithmic nonlinear viscoelastic model was proposed to predict the creep of asphalt mixtures by matching the experimental data.

Keywords: Viscoelastic properties; Mechanical models; Asphalt Mixture; Compressive Creep; Nonlinear viscoelastic model

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1. Introduction

Today, the use of asphalt pavements in the world shows an ascending trend. Since rutting failure is among the most common failures on roads, laboratory information is required to evaluate the potential of rutting. The static creep test has been used to evaluate the rutting susceptibility of asphalt mixtures for a long time. In this regard, it is necessary to study in the laboratory and simulate the actual conditions for asphalt mixtures to reach the best mixing design with the most significant resistance against these failures. The static creep test has been used to evaluate the rutting susceptibility of asphalt mixtures for a long time. The basis and concept of the creep test in the laboratory is to evaluate the strain under constant stress applied during the loading period.

Creep refers to the time-dependent deformation that happens under constant stress. Previous studies have identified different stages of creep, as shown in Fig. 1. The creep diagram for asphalt mixture comprises three phases: The first section, known as transient or primary creep, exhibits a high initial strain rate that diminishes over time. The second section, referred to as steady state or secondary creep, demonstrates a consistent strain rate. The third section, called tertiary creep, involves an increase in the strain rate, ultimately failing (Lain Finnie, William RH, 1959).

The static creep test is an essential component of the mix design process for a specific asphalt mixture known as coarse matrix high binder (CMHB) at the Texas Department of Transportation (TxDOT). The test results are evaluated against pass/fail standards, which include permanent strain, creep stiffness, and creep curve slope. This test, along with other similar tests, may be applied to assess the efficacy of Superpave volumetric mix design techniques. Rutting potential can be determined by conducting these creep tests at a temperature of 40°C (104°F) (Weng On Tam et al., 1999).

Van der Loo analyzed the relationship between rutting in the field and the creep test (static and dynamic) in the laboratory. Creep hardness is another commonly used criterion, which is calculated by dividing the applied stress by the resulting strain in a certain period of time (usually after one hour of loading). Permanent strain and slope are the other two criteria used for this purpose. The test temperature, applied vertical pressure, and loading time were 40°C (104°F), 2.11 kg/cm², and 1 hour, respectively. The mixture variables considered in this research included type of asphalt concrete, amount of bitumen, type of aggregate, amount of void, compaction temperature, and stress level. Investigating these data revealed compressive creep was susceptible to all these factors. In general, a creep modulus greater than 0.70 kg/cm² under real-world conditions indicates a mixture with little susceptibility to rutting. The creep modulus within the range of 0.42 to 0.70 kg/cm² shows the asphalt mixture is highly susceptible to rutting. Mayan Min et al. developed a modified time-hardening model that effectively characterizes the consolidation effect of an asphalt mixture as it undergoes viscoelastic deformation. This model integrates the Malthus model and logistic function to adjust creep strain and creep ductility (Van de Loo, 1974); (Yunming Ma, 2022).

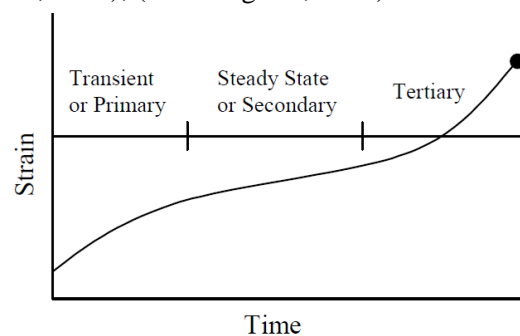


Figure 1. Creep stages

The creep properties of modified high-elasticity asphalt mixtures were investigated by conducting a single penetration creep test at various temperatures (20, 40, and 60°C) and loading levels (5.61, 7.14, 8.67, and 10.20 kg/cm²). Test results revealed that stress had a

Investigating Viscoelastic Properties of Asphalt Mixtures

more significant impact on deformation compared to temperature. Additionally, the test results were analyzed using surface fitting and compared to the time-hardening model and modified Burgers model. The analysis showed that the modified time-hardening model effectively indicated the consolidation effect and creep behavior of the asphalt mixture. Consequently, the modified time-hardening model proved to be a more efficient tool in illustrating the consolidation effect throughout the creep process.

Mejlun et al. compared Burgers and Huet-Sayegh's viscoelastic models along with Hooke's elastic model to determine pavement deflections and strains at the bottom of asphalt layers under high-temperature conditions ranging from 20-50°C (Łukasz Mejlun et al., 2017).

The present research proposes a new material model for asphalt mastic, combining the Burgers model with a viscoplastic string. Initially designed for uniaxial loading conditions, the model's creep constitutive equation was formulated. The study investigates the impact of loading stress and temperature on creep behavior and derives the model's parameters as functions of stress and

temperature. The results demonstrated that the proposed model effectively accounted for all aspects of deformation, including elastic, viscous, and viscoelastic behavior, throughout the entire creep process. Additionally, the model accurately characterized the nonlinear visco-elastoplastic properties of materials. Compared to the power model, the proposed model exhibited superior accuracy in simulating material creep under the specific stress levels and temperatures investigated in this research. Considering the literature and results obtained from the classical models, Burgers, Kelvin, modified Burgers, Maxwell, and generalized model, this study investigates the impact of different stress levels on the viscoelastic behavior of asphalt mixtures and modeled viscoelastic behavior of mixtures using the mentioned models.

2. Materials and Methods

As shown in Fig. 2, the aggregate gradation of asphalt mixtures was selected based on the binder layer granulation. The bitumen used in this experiment was of Pen60/70 type. The optimum bitumen content of asphalt mixtures was calculated as 4.5% using the Marshall mixing design method.

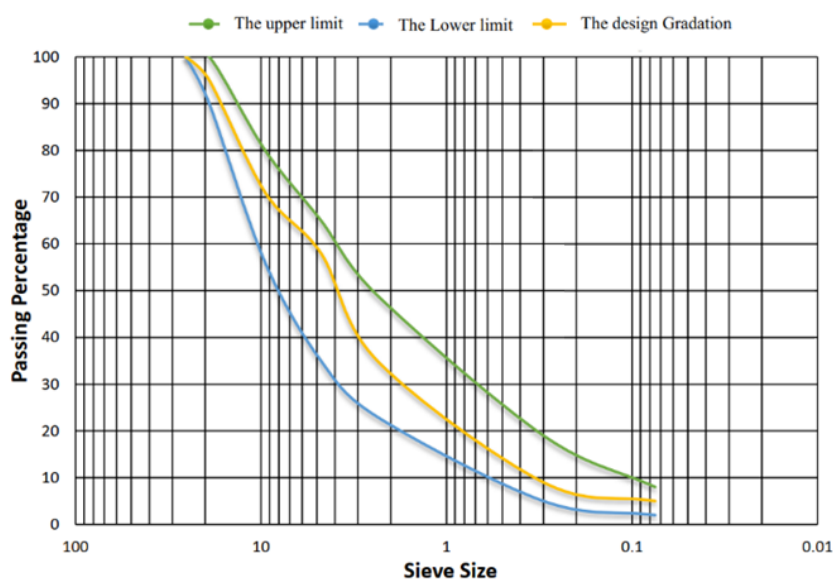


Figure 2. Aggregate gradation chart

3. Test Method

The asphalt mixture specimen in this test was subjected to the pressure at 2.04 kg/cm² (2Bar), 3.05 kg/cm² (3Bar), 4.07 kg/cm² (4Bar), and 5.09 kg/cm² (5Bar), and the mean of the results were reported after three replicates. According to the subject literature, the creep test temperature should be between 20°C and 50°C. For this reason, two temperatures of 40°C and 20°C were used in this research. In this respect, it is recommended to simulate the creep test for asphalt at high and medium temperatures. According to Fig. 3, the asphalt mixture specimen made for the isothermal process was placed into a controlled temperature chamber maintained at test temperature (20°C and 40°C) for 20 min before the start of the test to bring the specimens to the test temperature. Cylindrical specimens with a diameter of 100 mm (4-in) and a height of 150 mm were made by the ASTM D6926 and cut into a sample with a height of 62.5 mm (Fig.4). After the isothermal process, the loading process of 3,600 s (1 h) was applied to the specimen.

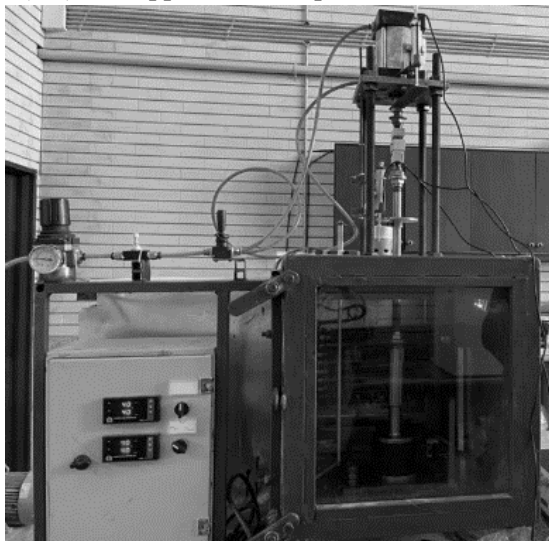


Figure 3. The invented asphalt static creep machine

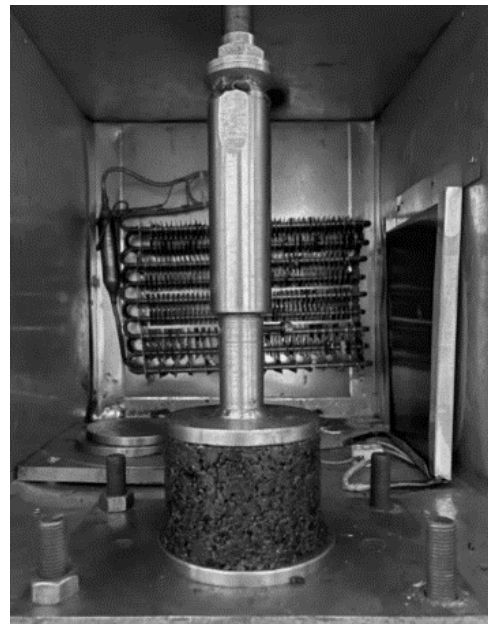


Figure 4. Asphalt specimen in the creep machine

4. Experimental and Modeling Results

As mentioned in Section 2, 12 specimens were made and subjected to the static creep test at four applied pressures. Fig. 5 presents the data of the final strain of specimens to varying pressures. As expected, increasing strain from 2 to 5 bar increased cumulative strain. Eq. (1) predicts the cumulative strain behavior of different asphalt specimens at different pressures with $R^2 = 0.9995$.

$$\varepsilon = 0.0041e^{0.4146P} \quad (1)$$

where P represents the pressure applied to the specimen (bar) and ε denotes the cumulative strain of the asphalt mixture specimen due to the applied load.

Fig. 6 illustrates the results of strain changes over time. As presented in Table 1, the length changes of the asphalt specimen increased with increasing the applied pressure at the constant temperature of 40°C.

Investigating Viscoelastic Properties of Asphalt Mixtures

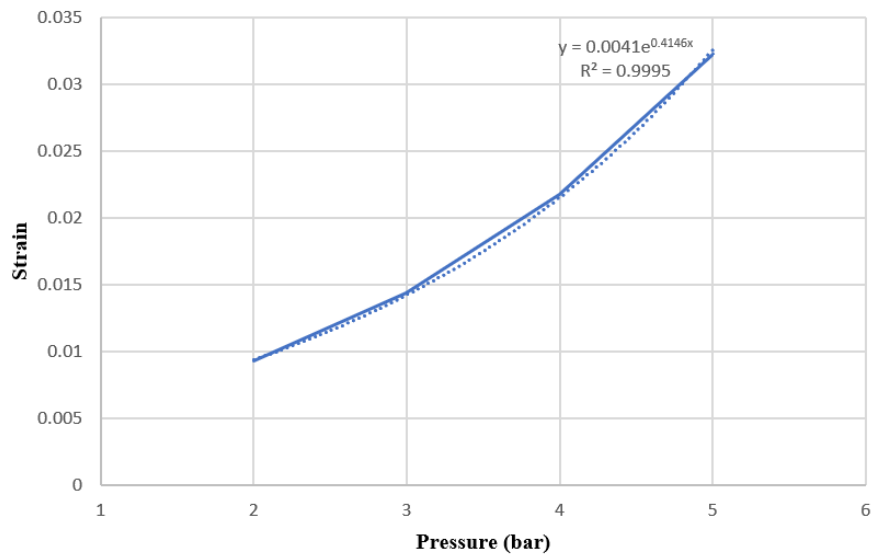


Figure 5. Diagram of stress-strain of asphalt mixture specimen

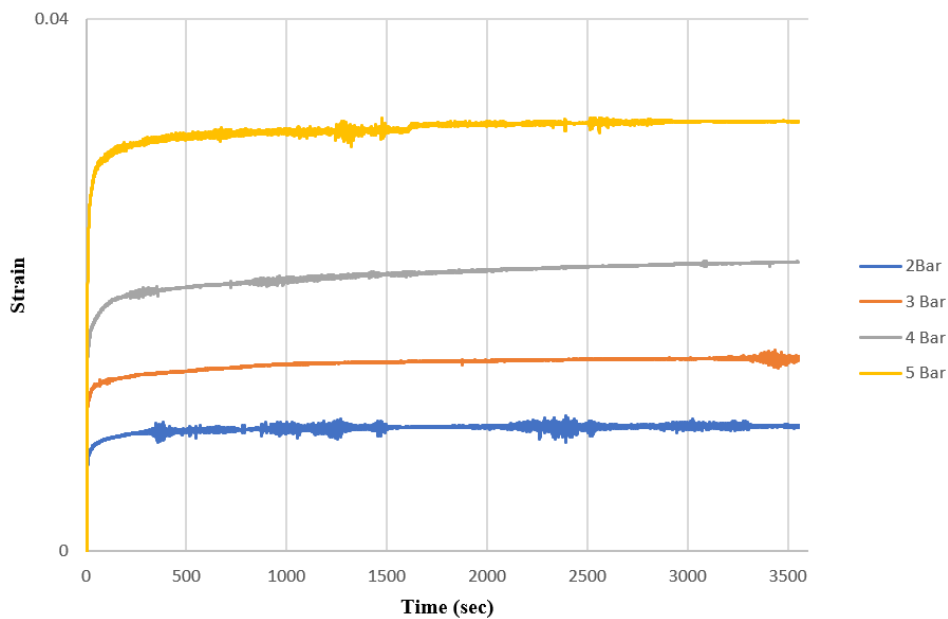


Figure 6. Diagram of strain-time of asphalt specimens

The ability of a material to withstand the deformation caused by an applied load is known as creep stiffness. This characteristic is determined by the ratio of the constant stress applied to the asphalt specimen to the resulting axial strain, and it varies with time and temperature. The hardness of the asphalt mixture is a critical mechanical property that reflects its capacity to distribute stress from the load to the layers beneath the pavement. This parameter could be obtained by Eq. (2).

Creep Compliance is among the essential features for describing the viscoelastic behavior of materials, which is calculated by the relationship between the measured strain and the applied stress. (Eq. (3)). Table 1 presents the values of creep hardness and ductility parameters.

$$S = \sigma / \varepsilon_s \quad (2)$$

$$D = \varepsilon_s / \sigma \quad (3)$$

Where ε_s is the strain at the end of the loading (3600 s) or the secondary creep section, and σ represents the stress level (MPa).

Table 1. Parameters of asphalt specimens at different stress levels

Pressure (kg/cm ²)	5.09	4.07	3.05	2.04
Length changes (mm)	2.049	1.379	0.915	0.589
Strain-ε	0.032	0.021	0.014	0.009
Creep stiffness-S (MPa)	15.492	18.412	20.814	21.530
Creep Compliance-D (MPa ⁻¹)	0.064	0.054	0.048	0.046

5. Analysis Results of Mechanical Models

The experimental data of the conventional models were compared with those of the desired models for investigating the asphalt mixture creep behavior. The model coefficients were included in the relevant tables. The models used to examine the creep characteristics of asphalt mixture over time included Burgers, Maxwell, Kelvin, and generalized, are expressed in Eqs. (4-7), respectively (Huang, 2003).

$$\epsilon = \frac{\sigma}{E_0} \left(1 + \frac{t}{T} \right) + \frac{\sigma}{E_1} \left(1 - \exp \left(-\frac{t}{T_1} \right) \right) \tag{4}$$

$$\epsilon = \frac{\sigma}{E_0} \left(1 + \frac{t}{T} \right) \tag{5}$$

$$\epsilon = \frac{\sigma}{E_1} \left(1 - \exp \left(-\frac{t}{T_1} \right) \right) \tag{6}$$

$$\epsilon = \frac{\sigma}{E_0} \left(1 + \frac{t}{T} \right) + \sum_{i=1}^n \frac{\sigma}{E_i} \left(1 - \exp \left(-\frac{t}{T_i} \right) \right) \tag{7}$$

Where T₀ represents the stress release time, and T₁ denotes the retardation time. Other standard mechanical models presented based on the development of the models mentioned above are modified Burgers, time-hardening, Huang, and logarithmic models, expressed by Eqs. (8), (9), (10), and (11), respectively.

$$\epsilon = \frac{\sigma}{E_0} \left[\frac{1}{E_1} + \frac{1}{AB} (1 - e^{-Bt}) + \frac{1}{E_2} (1 - e^{-\tau t}) \right] \tag{8}$$

In Eq. (8), A, B, and C denote dashpot coefficients of the modified Burgers model, as depicted in Fig. 7 (Wenbo Luo et al., 2020).

$$\epsilon = \frac{\sigma (C_1 \sigma^{(C_2-1)} \cdot t^{(C_3+1)})}{(C_3 + 1)} \tag{9}$$

In Eq. (9), C₁ and C₂ are more significant than 0, and C₃ is between -1 and 0 (Yunming Ma, 2022). Eq. (10) is based on the differential equations of analysis indicated in Fig. 8 in Huang’s book, adjusted using the spring-dashpot theory to simulate the asphalt viscoelastic behavior. Table 8 compares the coefficients of experimental data and this model. (Huang, 2003).

$$\epsilon = \frac{\sigma}{E_1} \left(1 - \frac{E_2}{E_1 + E_2} \exp \left(-\frac{E_1 t}{T_1 (E_1 + E_2)} \right) \right) \tag{10}$$

Eq. (11) is formulated using the logarithmic analysis of the data, where A and B are expressed based on Table 9:

$$\epsilon = A \ln t + B \tag{11}$$

The coefficients of the mentioned models were obtained after comparing them with experimental data by MATLAB 2020b and Curve Expert Professional 1.65 (Tables 2-9).

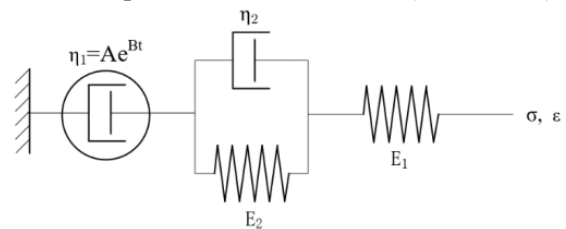


Figure 7. Modified Burgers model nomograph

Investigating Viscoelastic Properties of Asphalt Mixtures

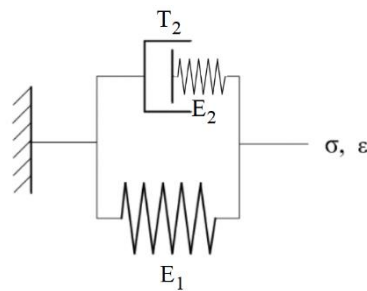


Figure 8. Spring-dashpot connection algorithm for asphalt viscoelastic behavior simulation model

Table 2. Burgers model coefficients for different loads

Pressure (kg/cm ²)	R ²	T ₁	E ₁	T ₀	E ₀
2.04	0.790	1.12 E+1	2.28 E+2	9.49 E-1	1.27 E+7
3.05	0.808	5.99E+00	2.27E+02	4.77E-01	1.63 E+07
4.07	0.791	1.12E+01	4.56E+02	9.64E-01	2.51E+07
5.09	0.892	1.07E+01	1.65E+02	7.73E-01	1.21E+07

The coefficients associated with the Burgers model are obtained by using the creep test data related to the asphalt sample and fitting its strain results with Eq. (4). These coefficients are provided in Table 2. Fitting degrees (R²) are also for Eq. (4) and the strain of the asphalt sample, which shows the quality of the Burgers model in Table 2.

Also, the fitting results of other equations to justify the creep behavior of asphalt mixture, i.e., Maxwell, Kelvin, generalized, modified

Burgers, time hardening, Huang, and logarithmic models (Eqs. 5, 6, 7, 8, 9, 10, and 11, respectively) are presented. These results are given in Tables 3-9 respectively. Fitting degrees coefficients of these equations can also be seen in the R² column of these tables. These coefficients determine the quality and ability of the model to justify the creep performance of the asphalt mixture, which is explained in the conclusion section.

Table 3. Maxwell model coefficients for different loads

Pressure (kg/cm ²)	R ²	T ₀	E ₀
2.04	0.468	4.11E+04	2.31E+02
3.05	0.475	3.13E+04	2.29E+02
4.07	0.610	2.30E+04	2.11E+02
5.09	0.230	4.35E+04	1.67E+02

Table 4. Kelvin model coefficients for different loads

Pressure (kg/cm ²)	R ²	T ₁	E ₁
2.04	0.657	1.28E+01	2.21E+02
3.05	0.420	7.51E+00	2.16E+02
4.07	0.380	1.15E+01	1.95E+02
5.09	0.756	1.20E+01	1.60E+02

Table 5. Generalized model coefficients for different loads

Pressure (kg/cm ²)	R ²	T ₄	E ₄	T ₃	E ₃	T ₂	E ₂	T ₁	E ₁	T ₀	E ₀
2.04	0.219	-1.3E10	-1.5E8	1.8E10	2.3E7	1.2E10	2.7E7	-7.1E8	1.3E7	4.1E4	2.3E2
3.05	0.473	-9.7E9	1.8E7	2.4E9	4.1E7	2.8E9	4.1E5	-9.1E8	1.7E7	3.6E4	2.1E2
4.07	0.610	4.3E8	5.2E7	1.5E7	-2.9E7	-2.8E8	3.5E5	-2.2E9	-1.4E6	2.3E4	2.1E2
5.09	0.230	5.3E10	1.7E8	-2.2E11	2.9E7	3.5E10	1.7E8	-3.9E9	1.7E9	4.3E4	1.6E2

Table 6. Coefficients of modified Burgers model for different loads

Pressure (kg/cm ²)	R ²	τ	E ₂	B	A	E ₁
2.04	0.66	100.18	6.19 E+5	0.0012	47.12	2.11 E+4
3.05	0.94	1.257	17.61	1.58 E+3	11.36	216.58
4.07	0.45	125.14	78.58	1.569	4.11 E+3	1.78 E+3
5.09	0.92	0.1278	14.38	0.00058	142.92	2.57 E+6

Table 7. Time hardening model coefficients for different loads

Pressure (kg/cm ²)	R ²	C ₃	C ₂	C ₁
2.04	0.521	-1.87E+00	-9.63E-01	9.91E-04
3.05	0.788	5.88E-01	-9.59E-01	2.21E-04
4.07	0.869	1.97E-01	-9.48E-01	5.55E-04
5.09	0.514	-2.13E+00	-9.66E-01	2.70E-02

Table 8. Coefficients of Huang's introduced model for different loads

Pressure (kg/cm ²)	R ²	T ₁	E ₁	E ₀
2.04	0.661	8.83E-03	3.21E+05	2.21E+02
3.05	0.710	3.94E+02	4.25E+01	2.11E+02
4.07	0.748	5.86E+02	4.13E+01	1.89E+02
5.09	0.751	7.12E+03	2.97E+02	2.52E+02

Table 9. Coefficients of the logarithmic model for different loads

Pressure (kg/cm ²)	R ²	B	A
2.04	0.54	0.0067	0.0003
3.05	0.80	0.0100	0.0006
4.07	0.88	0.0133	0.0010
5.09	0.53	0.0239	0.0011

Figs. 9, 10, and 11 illustrate diagrams comparing the results of the above-mentioned mechanical models with experimental data. In this section, there are graphs related to asphalt mixture loading, which show the ratio of asphalt mixture strain changes with time. These data were obtained from the static creep test of asphalt mixture under modeled loading

conditions at 40°C for each mechanical model. In this process, three replicate samples were tested at pressures of 2, 3, 4, and 5 bar. Figs. 9 to 11 are obtained by matching the laboratory data in the simulated environment with the well-known presented mechanical models. The results of this matching are summarized in Table 10.

Investigating Viscoelastic Properties of Asphalt Mixtures

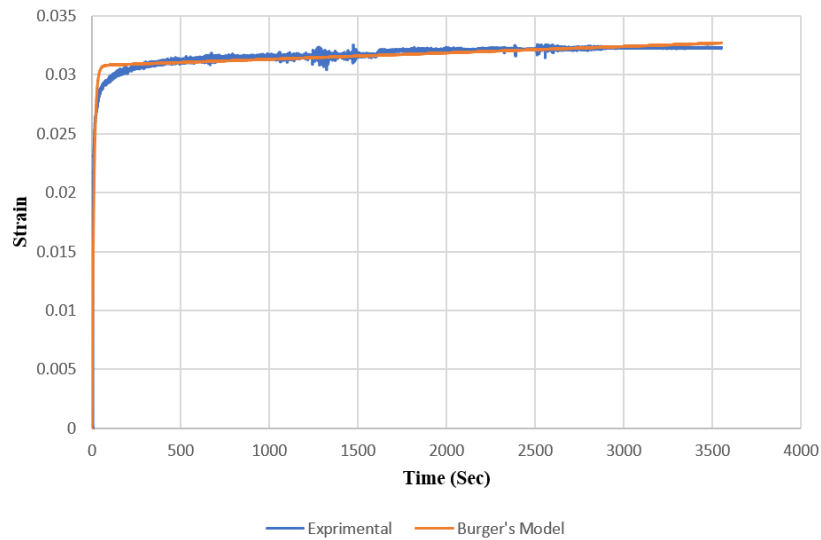


Figure 9. Diagram of fitting experimental data on the Burgers model at the stress level of 5 bar

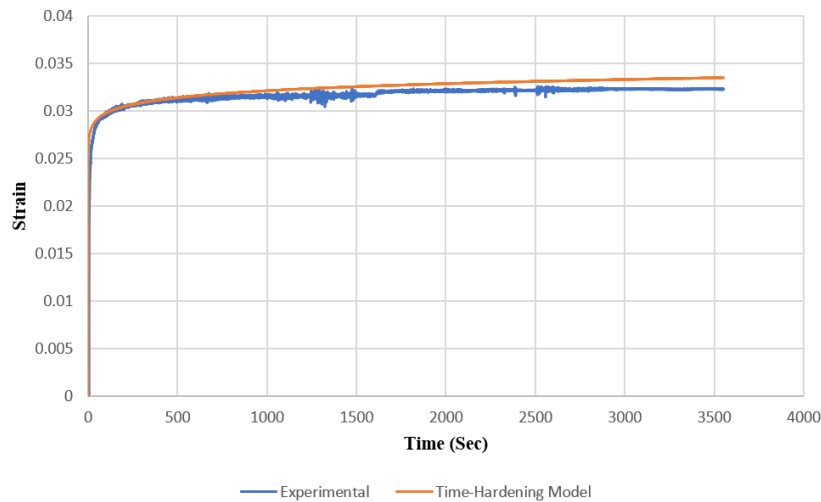


Figure 10. Diagram of fitting experimental data on the Time-Hardening model at the stress level of 5 bar

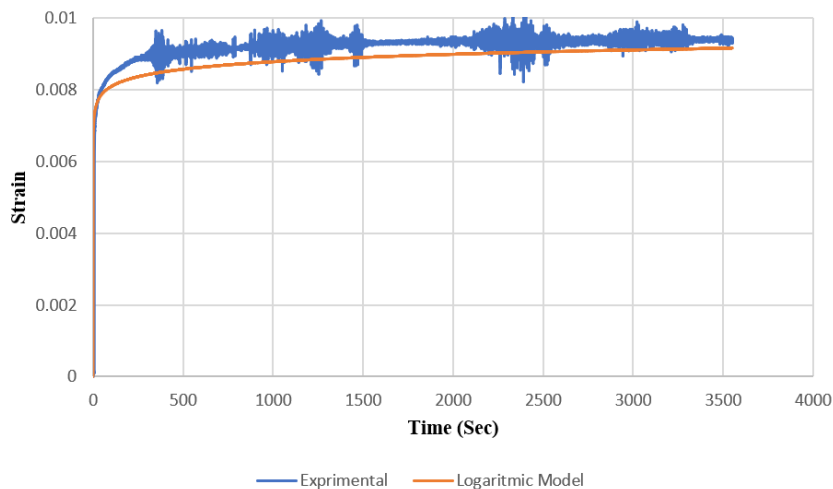


Figure 11. Diagram of fitting experimental data on the logarithmic model at the stress level of 2 bar

Table 10 presents the coefficient of determination (R^2) of the examined models. It could be stated that R^2 value shows to what

extent changes in dependent variables in a regression model are explained by the independent variable.

Table 10. Coefficients of fitting degrees (R^2) of the creep models

Pressure (kg/cm ²)	logarithmic	Huang	modified Burgers	time-hardening	generalized	Kelvin	Maxwell	Burgers
2.04	0.54	0.661	0.66	0.521	0.219	0.660	0.219	0.790
3.05	0.80	0.710	0.94	0.788	0.473	0.417	0.473	0.806
4.07	0.88	0.748	0.45	0.869	0.474	0.418	0.474	0.807
5.09	0.53	0.751	0.92	0.514	0.230	0.755	0.229	0.889

6. Conclusion

This research investigated the effect of different stress levels on the viscoelastic behavior of asphalt mixtures and modeled the viscoelastic behavior of mixtures using various models. The results revealed that the Burgers model and the models presented in this research were more accurate than other models, and the obtained values were more consistent with the experimental results.

In this research, it was found that by analyzing and using the two Burgers models and the model introduced in this article, it is possible to model the nonlinear viscoelastic behavior of asphalt mixtures. Overall, by examining the laboratory data and matching them with mechanical models, the following results were obtained:

- 1) The test conditions and the device used completely model the environmental conditions of the area. Environmental conditions include temperature and asphalt pavement loading. The range of actual load on highways is about 8.15 kg/cm² (8 bar), and the ambient temperature of asphalt in field conditions is about 50°C. Therefore, the results obtained from the device in laboratory conditions are consistent with the field results.
- 2) As the loading stress duration increased, the asphalt mixtures exhibited a continuous increase in creep strain, eventually reaching a stable state. Moreover, the strain of the asphalt mixture was found to be greater with

higher loading stress intensity and temperature.

3) Based on the results obtained from modeling the behavior of asphalt mixtures under different loadings, the Burgers model showed more accuracy in predicting the behavior of asphalt mixtures with an R^2 of about 0.8.

4) The strain of the asphalt mixture tends to increase significantly as the temperature rises. If the continuing loading process accompanies this temperature rise, it leads to the rupture of the asphalt mixture.

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8. Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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Investigating Viscoelastic Properties of Asphalt Mixtures

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