Hindawi
Advances in Materials Science and Engineering
Volume 2022, Article ID 8316014, 7 pages
https://doi.org/10.1155/2022/8316014

Research Article

Nonlinear Constitutive Model of High-Temperature Viscoelastic Deformation of Gussasphalt Concrete

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Received 9 June 2022; Accepted 21 July 2022; Published 18 August 2022

Academic Editor: Wenke Huang

To accurately evaluate the high-temperature stability of cast asphalt concrete, based on the traditional viscoelastic mechanical model, this paper innovatively improves the traditional viscoelastic mechanical model considering the conditions of temperature and dynamic load and deduces the viscoelastic constitutive model of high-temperature deformation performance of cast asphalt concrete, using a dynamic penetration test (DPT) to regress improved the Burgers model parameters and verify the model's applicability and reliability. The results show that for the modified Burgers model parameters, E_1, E_2, A, and η_2 decrease with increasing temperature, while parameter B increases with the increase of temperature. The high-temperature deformation of cast asphalt concrete is mainly related to η_1, and η_1 decreases, and deformation increases with the increase in temperature. With the increase in loading times, the dynamic penetration of cast asphalt concrete (AC) gradually increases, that is, when the greater the permanent deformation is. When the specimen is loaded 3000 times, the dynamic penetration value at 60°C is about 1.237 mm, and the dynamic penetration value at 50°C is about 0.819 mm. Under other loading times, the permanent deformation of the specimen at 60°C is much greater than that at 50°C. There is a good fit between the mechanical model derived from the viscoelastic theory and the measured test data, and the correlation coefficient is greater than 0.98, indicating that the model can accurately describe the permanent deformation law of GA under periodic semivector sinusoidal pulse load at high temperatures. The research results of this paper provide a solid theoretical basis for the promotion and application of cast asphalt concrete, and the method has wide applicability in practical engineering.

1. Introduction

Gussasphalt concrete (GA) has been widely applied in pavement engineering in China due to its advanced performance in resisting low-temperature and fatigue cracking, its high bonding strength, and favorable compatible flexibility with the steel deck [1–6]. While moderate to severe rutting commonly happens during the early service life of GA pavement, this significantly compromises the long-term performance of GA in practice [7–9]. In general, the rutting is preassembly related to the GA's structure and application conditions. The recently available approaches for modeling the rutting performance, such as empirical or semimechanic empirical modeling, are not suitable for evaluating the high-temperature property of the GA material [10–13]. The literature study shows that the available modeling methodologies include Huang et al. [14] applying 3-D numerical modeling to study the deformation characterization of conventional asphalt concrete by using nonlinear simulation. Louay–Peng [15, 16] also extensively utilized the nonlinear simulation method to investigate the high-temperature deformation performance of the asphalt mixture under repeat loading conditions. However, the results of these studies indicated that the methods mentioned above are not exactly applicable to studying GA material. Reinhardt [17] and others investigated the rheological performance with GA material under high-temperature static loading, and the result was appreciable. However, this study is limited to static loading, which is different from real field situations. Hazik–Luxemburk [18] studied the mechanical properties of GA material with dynamic loading conditions, but the factor of temperature was not fully considered. According to the specific deformation character of GA material, it is necessary to develop a more suitable model for simulating the perpetual deformation performance. This study was initiated to develop a viscoelastic (VE) mechanic modeling to investigate the rutting performance. The dynamic penetration test (DPT) test was applied to verify the feasibility and reliability of the proposed modeling. The results showed that this VE modeling output had acceptable consistency with the laboratory testing results.

2. Materials and Methods

2.1. Constitutive Relationship and Viscoelastic Mechanical Model of Cast Asphalt Concrete under Periodic Half Vector Sinusoidal Pulse Load. Recently, the most recognized VE model for simulating the high-temperature deformation performance of asphalt mixtures is the "Four Elements Five Parameters" model as shown below in Figure 1.

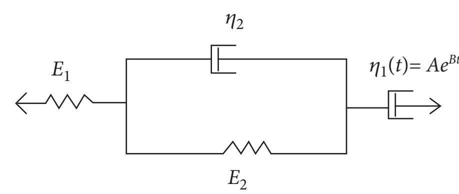

FIGURE 1: Modified Burgers model of four elements and five parameters.

This model was developed based on the existing Burgers model using the nonlinear mathematical function to adjust the deformation parameter, indicating the dynamic flow property of the GA material [19]. The modified viscosity has a function as shown below:

$$\eta_1(t) = Ae^{Bt}, \eta_1(t). \tag{1}$$

Equation (1) is the modified viscosity; A and B are both parameters; t is test time.

$J(t)$ is the parameter of creep flexibility in the modified Burgers model, which can be defined as shown below:

$$J(t) = \left[\frac{1}{E1} + \frac{1 - e^{-Bt}}{AB} + \frac{1 - e^{-(E_2/\eta_2).t}}{E_2}\right]. \tag{2}$$

The balanced equation related to the creep phenomena during the loading phase is defined as follows:

$$\epsilon(t) = \sigma.J(t). \tag{3}$$

Then, we substitute $J(t)$ by the equation (2) to get equation (4).

$$\epsilon(t) = \sigma\left[\frac{1}{E1} + \frac{1 - e^{-Bt}}{AB} + \frac{1 - e^{-(E_2/\eta_2).t}}{E_2}\right]. \tag{4}$$

In equation (4), E_1, η_2, and E_2 are the model parameters; σ is the applied stress. This modified Burgers model was developed based on the constant creep-deformation law under the experimental condition [20]. This function is commonly applied to investigate the influence of the stress level, loading duration, and loading cycles on the deformation performance of asphalt mixture materials [21]. For instance, the deformation of the asphalt mixture will increase when the loading time or the loading cycle increases within other variables being constant. In the same way, the stress level has an essential impact on the deformation performance of the asphalt mixture under the cyclic loading condition. While in the real situation, the traffic loading has a dynamic wave pattern, the dynamic response of the asphalt mixture will not be fully and accurately characterized using static creep mechanic modeling. Therefore, there is a necessity to develop a deformation model for the dynamic loading situation.

The dynamic penetration test (DPT) of GA uses dynamic semi-sine pulse loading to simulate the field traffic loading condition. For one cycle of the dynamic semi-sine wave, the loading time is defined as $T\,(T = t_1 + t_2)$, in which the time for pulse loading is $t_1 = 0.2$ s and the time of constant loading is $t_2 = 1.5$ s. Equation (5) indicates one cycle of dynamic semi-sine pulse loading as a function of time, which is divided into two parts and defined as shown below:

$$\sigma(t) = \begin{cases} (\sigma_0 - \sigma_u)\sin\dfrac{\pi}{t_1}t + \sigma_u, & 0 \le t \le T_1, \\ \\ \sigma_{u,} & T_1 \le t \le T. \end{cases} \tag{5}$$

According to the equivalent principle of stress impulse [22], it is feasible to transfer the energy generated by dynamic loading to the work provided by static loading, which can be defined as shown below:

$$\int_0^{t_1} \left(\sigma_0 - \sigma_\mu\right)\sin\frac{\pi}{t_1}t + \sigma_\mu)d_1 = \sigma_1 t_1. \tag{6}$$

The variable of σ_1 in equation (6) can be calculated as shown below:

$$\sigma_1 = \sigma_\mu + \frac{2}{\pi}\left(\sigma_0 - \sigma_\mu\right). \tag{7}$$

By this method, the effect of dynamic loading can be successfully equivalent to the output of static loading. Based on the compatibility principle, when the loading time is short enough, the deformation of the material under dynamic loading can be treated as the deformation caused by static loading. The widely applicable principle of Boltzman can be applied herein to linearly add the strains together for different loading times. For instance, it assumes that the time point of adding loading on the asphalt mixture is t_o, and the loading duration is t, which is longer than one loading cycle. The equation (8) for the creep phenomenon can be defined as shown below:

$$\epsilon(t_0+t)=\int_{t_0}^{t}\sigma_c J(t)\mathrm{d}_t. \tag{8}$$

We substitute equation (8) into equation (2) to obtain equation (9):

$$\int_{t_0}^{t}\sigma_c\left[\frac{1}{E1}+\frac{1-e^{-Bt}}{AB}+\frac{1-e^{-(E_2/\eta_2).t}}{E_2}\right]\mathrm{d}_t. \tag{9}$$

Then, we integrate equation (9) to obtain equation (11):

$$\epsilon(t_0+t)=\sigma_c\left[\frac{1}{E_1}(t-t_0)+\frac{1}{AB}(t-t_0)-\frac{1}{AB^2}e^{-B(t-t_0)}+\frac{1}{E_2}(t-t_0)+\frac{1}{AB}\frac{\eta_2}{E_2}e^{-(E_2/\eta_2)(t-t_0)}\right], \tag{10}$$

$$\epsilon(t_0+t)=\begin{cases}\sigma_{C_1}\left[\frac{1}{E_1}(t-t_0)+\frac{1}{AB}(t-t_0)-\frac{1}{AB^2}e^{-B(t-t_0)}+\frac{1}{E_2}(t-t_0)+\frac{1}{AB}\frac{\eta_2}{E_2}e^{-(E_2/\eta_2)(t-t_0)}\right],\\ \sigma_{C_2}\left[\frac{1}{E_1}(t-t_0)+\frac{1}{AB}(t-t_0)-\frac{1}{AB^2}e^{-B(t-t_0)}+\frac{1}{E_2}(t-t_0)+\frac{1}{AB}\frac{\eta_2}{E_2}e^{-(E_2/\eta_2)(t-t_0)}\right],\end{cases} \tag{11}$$

$$\begin{cases}\sigma_{C1}=\sigma_1, & t_1+nT\le t\le t_2+nT,\\ \sigma_{C2}=\sigma_0, & t_2+nT\le t\le (n+1)T.\end{cases} \tag{12}$$

Assuming that the loading is added at the time of t_o and the time of loading lasted is T ($T=t_1+t_2$), the deformation under the N times of the loading cycle can be defined as shown below:

$$\epsilon(t_0+NT)=\sigma_c\left[\frac{1}{E_1}(NT-t_0)+\frac{1}{AB}(NT-t_0)-\frac{1}{AB^2}e^{-B(NT-t_0)}+\frac{1}{E_2}(NT-t_0)+\frac{1}{AB}\frac{\eta_2}{E_2}e^{-(E_2/\eta_2)NT-t_0)}\right], \tag{13}$$

$$\begin{cases}\sigma_{C1}=\sigma_1, & t_1+nT\le t\le t_2+nT,\\ \sigma_{C2}=\sigma_0, & t_2+nT\le t\le (n+1)T.\end{cases} \tag{14}$$

The relationship between the deformation of GA concrete and the loading cycle can be determined by equation (13). This function is feasible to investigate the influence of stress level and loading time on the deformation of GA material.

2.2. Experimental Study on the High-Temperature Property of GA

2.2.1. Experimental Methodology and Testing Facility. The rutting test has been widely applied in the evaluation of the high-temperature properties of conventional asphalt concrete (AC) [23–25]. However, due to the distinct difference in component elements between the regular AC material and GA concrete, it is not applicable to use a routine rutting test to evaluate the high-temperature stability of GA concrete in the laboratory.

A dynamic penetration test (DPT) has been developed to accurately estimate the relevant deformation of GA material under high-temperature conditions [26]. The DPT is adopted in this study to simulate the response of GA concrete after deck paving construction under field traffic loading conditions. The DPT is one type of axial dynamic loading test to measure the deformation of the fabricated GA specimen within a specific dimension under a controlled environment. The laboratory-mixed and laboratory-compacted GA specimen were trimmed to be 150 mm in diameter and 60 mm in length, and the loading pattern follows the semi-sinusoid curve trend over time as shown in equation (5).

The loading head is generally even; the dynamic loading should be in the range of 0.2 to 0.875 kN. The loading level is accurately controlled at an accuracy level of ±1% when the load is larger than 0.5 kN (±5%) and when the load is less than or equal to 0.5 kN. The magnitude of loading should be maintained as a function of overloading time as defined above. Figure 2 shows the loading head of the DPT equipment, the UTM-100 machine produced by Australia's IPC Company, in our laboratory. The testing temperature is 50°C or 60°C. The penetration value is the vertical deformation of the subject specimen under specific loading cycles.

2.2.2. Materials, Properties, and Concrete Design. In this study, the raw material of asphalt used to prepare the GA mixture for the DPT test was SBS-modified asphalt provided by SK Company. The main technical indicators of SBS modified asphalt are shown in Table 1.

The aggregate used was one type of ballast aggregates, and the fine fill material was limestone dust. The aggregate gradation for the GA mixture design is indicated in Table 2.

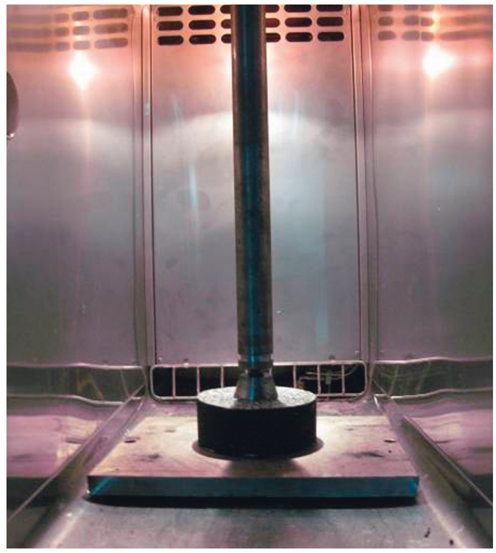

Figure 2: The dynamic penetration test equipment.

Table 1: The main technical indicators of SBS-modified asphalt.

Penetration (25°C, 100 g, 5 s), 0.1 mm	Soft point (°C)	Ductility (25°C) (cm)	Viscosity (135°C) (Pa.s)	Density (25°C) (g/cm^3)	Recovery (25°C) (%)
32	90	68	4.6	1.043	85

Table 2: The aggregate gradation for the GA mixture designs.

Sieve size (mm)	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing (%)	100	71.1	52.3	43.5	38.7	34.2	30.5	25.0

Before batching, the mixer should be preheated to a temperature in the range of 220–240°C. After mixing the mixture completely uniform, we pour the mixture into the preheated mold and then tamp the mixture using a small rod until the air void is less than 1% (specimen fabrication needs a certain level of practice experience). In this experiment, six specimens were formed and three specimens were grouped. The dynamic penetration tests at 50°C and 60°C were carried out, respectively. Demolding can be conducted when the specimen is cooled down. The specimen should be stored in a constant-temperature chamber for future testing. The UTM-100 machine (Australia IPC) is used to perform the DPT test under 50 or 60°C conditions.

3. Results and Discussion

To verify the applicability of the modified Burgers modeling in characterizing the high-temperature property of GA concrete, a comparison between the laboratory DPT results and the outputs from the modeling was evaluated. The DPT test was conducted using a UTM-100 machine and the testing temperatures were 50°C and 60°C. Figure 3 indicates the stress and strain diagram during DPT testing.

Equation (13) was applied to generate the experimental data; the Origin software was used to substitute the relevant functions to fit the parameters following the least-squares principle, and the results are presented in Table 3. The results of the modeling fit indicated that the four factors of E_1, E_2, A, and η_2 reduce with the temperature rising and the parameter B has a positive relationship with the temperature. According to the modified Burgers modeling, the high-temperature deformation is mainly affected by the parameter of η_1. As the temperature increased η_1 decreased and the deformation increased over time. In equation (1), A represents the viscosity of the element, and exponent parameter B indicates the viscosity does not have a linear function with respect to A. The variation of these parameters in the modeling indicates that the GA concrete will experience unrecovered deformation under high-temperature conditions.

Figure 4 illustrates the comparison of the laboratory experimental results and the output generated from the constitutive modeling. The coarse dot line is the measured data and the smooth line is the result of the modeling simulation. Figure 4 indicates that the dynamic penetration of the GA concrete increased with increasing the loading cycles, which means that the permanent deformation increased. In addition, the stability of GA concrete is sensitive to the ambient temperature. As shown in Figure 4, when the loading cycle was 3000 times, the average value of dynamic

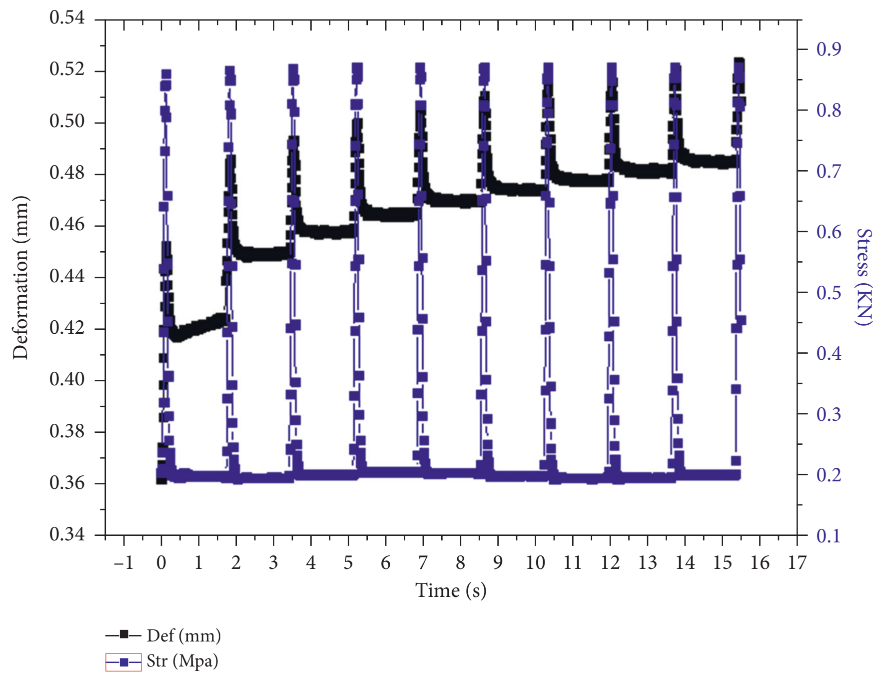

Figure 3: The measured stress-strain diagram of a periodic half-sine pulse load.

Table 3: Summary of model parameters.

Temperature (°C)	Stress	E_1 (10^3, MPa)	E_2 (10^2, MPa)	A (10^4, s)	B (10^{-6}, s^{-1})	η_2 (s)
50	σ_u	1.672	4.178	7.621	1.736	284.640
	σ_1	1.845	4.527	5.157	1.119	278.563
60	σ_u	1.289	3.354	4.897	2.973	13.445
	σ_1	1.473	3.987	3.950	1.765	27.758

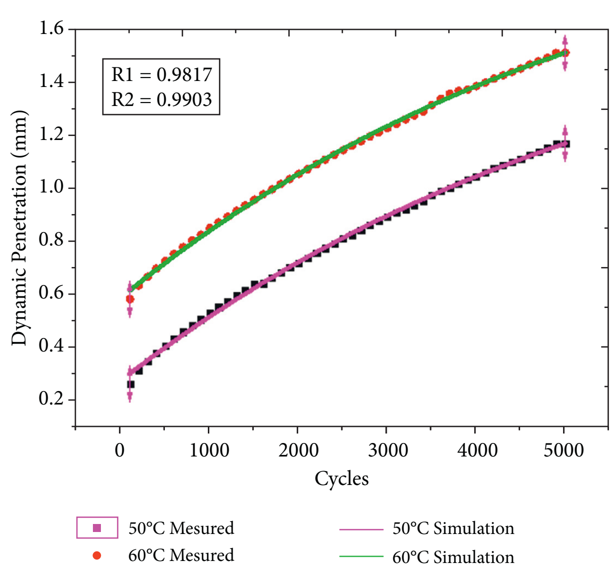

Figure 4: Measured the strain and model fit curve.

penetration at 60°C was about 1.237 mm, and the variance was 0.125. The average value of dynamic penetration at 50°C was about 0.819 mm, and the variance was 0.215. It is evident that under the same loading condition, the deformation of 60°C is greater than the deformation developed under the 50°C condition.

4. Conclusions

(1) To accurately evaluate the high-temperature stability of cast-in-place asphalt concrete based on the traditional viscoelastic mechanical model, this paper innovatively improves the traditional viscoelastic mechanical model by considering the conditions of temperature and dynamic load and deduces the viscoelastic constitutive model of high-temperature deformation performance of cast-in-place asphalt concrete. This model can obtain the relationship between the deformation of a cast-in-place asphalt mixture and the number of loadings, which can be used to analyse the influence of stress level and loading time on the deformation law of GA mixture.

(2) The dynamic penetration test was used to fit the modified Burgers model. From the fitting results, the values of four parameters E_1, E_2, A, and η_2 decreased with the increase of temperature, while the value of parameter B increased with the increase in

temperature. The high-temperature deformation of cast asphalt concrete was mainly related to η_1, and η_1 gradually decreased with the increase in temperature, and the deformation gradually increased.

(3) Ordinary asphalt concrete uses a rutting test to evaluate the high-temperature stability of the mixture, while the cast asphalt mixture in this paper uses a dynamic penetration test to evaluate its high-temperature performance. The results of the dynamic penetration test show that with the increase of loading times, the dynamic penetration of cast asphalt concrete (GA) gradually increases, that is, the permanent deformation is greater. When the specimen is loaded 3000 times, the dynamic penetration value at 60°C is about 1.237 mm, and the dynamic penetration value at 50°C is about 0.819 mm. In addition, under other loading times, the permanent deformation of the specimen at 60°C is much greater than that at 50°C.

(4) There is a good fit between the mechanical model derived by viscoelastic theory and the measured test data, and the correlation coefficient is greater than 0.98, indicating that the model can accurately describe the permanent deformation law of GA under periodic semi-vector sinusoidal pulse load at high-temperature.

In conclusion, this study was based on theoretical analyses and laboratory experimental tests. The methodology that this study developed provided a practical approach to evaluating the high-temperature stability of GA material and this also laid the basics for widely applying GA materials in bridge paving projects.

Data Availability

The data used to support the findings of this study are available upon request from the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research study was funded by the National Key Research and Development Program, grant number 2018YFB1600200.

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