

AN EFFICIENT ALGORITHM FOR DETERMINING THE HUET-SAYEGH VISCOELASTIC MODEL PARAMETERS BASED ON CREEP COMPLIANCE DATA

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Abstract. The Huet-Sayegh (HS) model is a well-known rheological model in pavement engineering for its excellence in predicting the linear viscoelastic (LVE) behavior of asphaltic materials. With the traditional approach, the model parameters are identified by minimizing the error between the predicted and experimental complex modulus data obtained in the frequency domain. However, with the advancement of testing techniques, it is beneficial to characterize the LVE behavior directly in the time domain. Consequently, there is a growing demand for determining the LVE model parameters based on time-domain data. A major challenge in applying the HS model in the time domain is the lack of an exact theoretical expression for its creep compliance function, making the parameter identification much more cumbersome with conventional trial-and-error approaches. This paper proposes an efficient algorithm to address this challenge. The obtained results show that the parameters of the HS model can be determined with high accuracy and within reasonable computational times.

Keywords: Huet-Sayegh model, parameter identification, asphalt mixtures, creep compliance, time domain.

1. INTRODUCTION

Asphalt mixtures manifest four typical types of behavior: linear viscoelasticity (LVE), nonlinearities, fatigue, and rutting (Di Benedetto et al., 2007). The behavior of asphaltic materials strongly depends on temperature and loading time (or frequency) (H. T. T. Nguyen et al., 2021). As a result, the stress/strain distribution in a pavement structure must be computed within a viscoelastic framework. However, current national design guides for the analysis and design of flexible pavements in Vietnam still rely on multi-layer elastic theory, which may give rise to significant errors in the determination of critical stress/strain conditions.

It has been demonstrated that the linear viscoelastic behavior can be characterized in the frequency domain or in the time domain (Tschoegl, 1989). Compared to the time domain, conducting tests in the frequency domain is much easier because the effects of irreversible strain can be easily eliminated (H. T. T. Nguyen et al., 2020; Tschoegl, 1989). However, characterization in the time domain is more beneficial. For instance, by conducting creep-recovery tests in the time domain, both LVE and viscoplastic (VP) behaviors can be simultaneously determined,

provided that an appropriate back-calculation algorithm is applied to separate the viscoelastic (VE) and VP strains from the total measured strain (H. T. T. Nguyen et al., 2021).

In pavement engineering, the Huet–Sayegh (HS) model is widely adopted for its efficiency in predicting the LVE behavior of asphalt mixtures. The model naturally complies with the physical causality principle; thus, it is valid both in the time and frequency domains. Although the model formula is quite simple in the frequency domain, this is not the case for its counterparts in the time domain, posing difficulties in the determination of model parameters while working in the time domain. Current techniques rely on trial-and-error parameter estimation, which is human-dependent and time-consuming. Therefore, this study aims to present a novel algorithm to overcome this limitation.

2. THEORETICAL FORMULATION

2.1. Summary of linear viscoelasticity

Let $E(t)$, $D(t)$ respectively be the relaxation modulus and creep compliance function of a linear viscoelastic material, defined as the stress and strain response of the material subjected to a unit step function of the strain (relaxation test) and stress (creep test). It has been demonstrated that $E(t)$ and $D(t)$ obey the following relationship (Tschoegl, 1989)

$$\int_0^t E(t) D(t - \tau) d\tau = \int_0^t D(t) E(t - \tau) d\tau = t. \quad (1)$$

The conjugate functions of $E(t)$, $D(t)$ in the frequency domain are the complex modulus and compliance denoted as $E^*(i\omega)$, $D^*(i\omega)$:

$$E^*(i\omega) = \mathcal{L}\{E(t)\}(s)|_{s=i\omega}, \quad D^*(i\omega) = \mathcal{L}\{D(t)\}(s)|_{s=i\omega}. \quad (2)$$

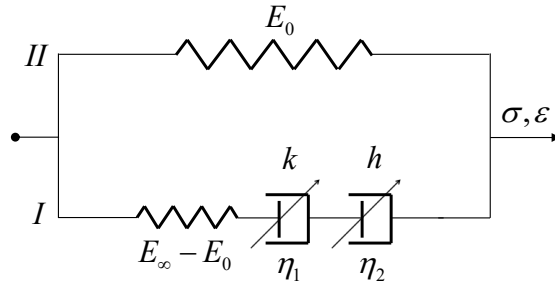


Fig. 1. Illustration of Huet–Sayegh model

For asphalt mixtures, the HS model (illustrated in Fig. 1) is widely used to predict the LVE behavior of asphalt mixtures for its excellence in fitting the experimental data. The model is quite simple, comprising a spring connected in parallel with a series of one spring and two parabolic dashpots. The complex modulus is given by Olard and Di Benedetto (2003), Pronk (2005), and Sayegh (1965) and is given in Eq. (3):

$$E^*(i\omega) = E_0 + \frac{E_\infty - E_0}{1 + \delta(i\omega\tau(T))^{-k} + (i\omega\tau(T))^{-h}}, \quad (3)$$

where ω (rad/s) is the angular frequency; δ , $0 < k < h < 1$ are model parameters; T is temperature; E_0 , E_∞ are the values of the complex modulus when $\omega\tau \rightarrow 0$ and $\omega\tau \rightarrow \infty$, respectively. It can be demonstrated that the real and imaginary components, respectively called storage and loss moduli of $E^*(i\omega)$:

$$E' = E_0 + \frac{A(E_\infty - E_0)}{A^2 + B^2}, \quad E'' = \frac{B(E_\infty - E_0)}{A^2 + B^2}, \quad (4)$$

where A, B are given as:

$$A = 1 + \delta \frac{\cos(k\frac{\pi}{2})}{(\omega\tau)^k} + \frac{\cos(h\frac{\pi}{2})}{(\omega\tau)^h}, \quad B = \delta \frac{\sin(k\frac{\pi}{2})}{(\omega\tau)^k} + \frac{\sin(h\frac{\pi}{2})}{(\omega\tau)^h}. \quad (5)$$

The LVE properties in the time domain can be interconverted from those in the frequency domain via the inverse Fourier transform (Tschoegl, 1989):

$$E(t) = \frac{2}{\pi} \int_0^{+\infty} \frac{E'(\omega) \sin(\omega t)}{\omega} d\omega = \frac{2}{\pi} \int_0^{+\infty} \frac{E''(\omega) \cos(\omega t)}{\omega} d\omega, \quad \forall t \geq 0, \quad (6)$$

$$D(t) = \frac{2}{\pi} \int_0^{+\infty} \frac{D'(\omega) \sin(\omega t)}{\omega} d\omega = \frac{2}{\pi} \int_0^{+\infty} \frac{D''(\omega) \cos(\omega t)}{\omega} d\omega, \quad \forall t \geq 0. \quad (7)$$

In general, there is no explicit formula for the relaxation modulus or creep compliance function in the time domain, which is true for the case of the HS model. According to the works of Heck (2001) and H. T. T. Nguyen et al. (2022), the exact values of the relaxation modulus and creep compliance of the Huet–Sayegh model can be numerically computed from Eq. (8) by considering a unit step function of the input stress or strain history.

$$\begin{aligned} \sigma &= \sigma^I + \sigma^{II}, \\ \varepsilon &= \varepsilon^I + \varepsilon^{II}, \\ \varepsilon^I &= \int_0^t D^I(t - \tau) \dot{\sigma}^I d\tau, \end{aligned} \quad (8)$$

where $D^I(t)$ is the creep function of the branch I of the Huet–Sayegh model given in Eq. (9) (see Heck (2001), H. T. T. Nguyen et al. (2022), and V. T. Nguyen et al. (2008)):

$$D^I(t) = \frac{1}{E_\infty - E_0} \left[1 + \delta \frac{(t/\tau)^k}{\Gamma(k+1)} + \frac{(t/\tau)^h}{\Gamma(h+1)} \right] \text{ for branch I of HS.} \quad (9)$$

It can be demonstrated that the following discrete equation for computing the creep compliance is obtained:

$$\begin{aligned} D_n &\approx \left[1 + E_0 D_I \left(\frac{\Delta t_n}{2} \right) \right]^{-1} \left\{ D_I \left(t_n - t_1 + \frac{\Delta t_1}{2} \right) \left(\frac{E_0}{E_\infty} - E_0 D_1 \right) \right. \\ &\quad \left. + \sum_{i=2}^{n-1} D_I \left(t_n - t_i + \frac{\Delta t_i}{2} \right) E_0 (D_{i-1} - D_i) + D_I \left(\frac{\Delta t_n}{2} \right) E_0 D_{n-1} + D_I(t_n) \left(1 - \frac{E_0}{E_\infty} \right) \right\} \text{ for } n \geq 2 \\ D_1 &\approx \left[1 + E_0 D_I \left(\frac{t_1}{2} \right) \right]^{-1} \cdot \left[D_I \left(\frac{t_1}{2} \right) \frac{E_0}{E_\infty} + D_I(t_1) \left(1 - \frac{E_0}{E_\infty} \right) \right]. \end{aligned} \quad (10)$$

According to the work of Phan et al. (2022), in the case that $E'(\omega)$ and $D'(\omega)$ are decomposed with high accuracy into a sum of exponential functions:

$$E'(\omega) \simeq E^*(\omega \rightarrow \infty) - \sum_{j=1}^{N_j} E'_j e^{b_j \omega}, \quad D'(\omega) \simeq D^*(\omega \rightarrow \infty) + \sum_{j=1}^{N_j} D'_j e^{c_j \omega}. \quad (11)$$

The relaxation modulus and creep compliance functions can be exactly computed:

$$E(t) = E^*(\omega \rightarrow \infty) - \frac{2}{\pi} \sum_{j=1}^{N_j} E'_j \tan^{-1} \left(\frac{t}{-b_j} \right), \quad D(t) = D^*(\omega \rightarrow \infty) + \frac{2}{\pi} \sum_{j=1}^{N_j} D'_j \tan^{-1} \left(\frac{t}{-c_j} \right). \quad (12)$$

It should be mentioned that such a decomposition into a sum of exponential functions can be achieved with high accuracy by using the modified Dombi algorithm already proposed in (H. T. T. Nguyen et al., 2022; Phan et al., 2022).

2.2. Algorithm for determining Huet–Sayegh parameters based on creep compliance data

With recent techniques, the creep compliance behavior of asphalt mixtures can be accurately measured regardless of irreversible strain perturbations (H. T. T. Nguyen et al., 2021; Tran et al., 2023). As a result, the HS parameters can be determined based on creep compliance data measured in the time domain without passing through the frequency domain. It should be mentioned that Eq. (10) is a recursive formula; thus, its calculation is time-consuming. In addition, the time discretization should be fine enough to ensure a good level of accuracy, which generally does not coincide with the set of measuring times. Therefore, using Eq. (10) to best fit the prediction with the Huet–Sayegh model is impractical, or even unfeasible in most cases.

In contrast, the analytical equation (12) can be used to determine the best-fit parameters. However, the dependence of c_j coefficients on the decomposition of storage compliance into a sum of exponential functions imposes a considerable computational burden. To address this limitation, we propose the following algorithm to improve computational efficiency (Algorithm 1).

Algorithm 1. Algorithm for determining the best-fit Huet–Sayegh parameters

Input: Measured creep compliance data; initial estimates of Huet–Sayegh parameters; tolerance ε

Output: Optimal set of Huet–Sayegh parameters

- (1) Initialize the Huet–Sayegh model parameters.
- (2) Decompose the storage compliance into a sum of exponential functions using the modified Dombi algorithm, and determine the initial set of coefficients $\{c_j\}$.
- (3) **Repeat** until convergence:
 - 3.1. Solve the linear optimization problem to determine the coefficients $\{D'_j\}$ based on the current values of $\{c_j\}$:

$$D'(\omega) \simeq D^*(\omega \rightarrow \infty) + \sum_{j=1}^{N_j} D'_j e^{c_j \omega}$$

- 3.2. Evaluate the decomposition error.
- 3.3. **If** the error exceeds ε : Update $\{c_j\}$ using the modified Dombi algorithm.
- 3.4. **Else**: Continue the optimization procedure.
- 3.5. Compute the creep compliance function:

$$D(t) = D^*(\omega \rightarrow \infty) + \frac{2}{\pi} \sum_{j=1}^{N_j} D'_j \tan^{-1} \left(\frac{t}{-c_j} \right)$$

- 3.6. Update the Huet–Sayegh parameters by minimizing the discrepancy between the predicted and measured creep compliances.
 - (4) **Return** the optimal Huet–Sayegh parameters.
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It is worth discussing the purposes of using the sum of exponential functions (SEF) in this study and those in previous studies (H. T. T. Nguyen et al., 2022; Phan et al., 2022). While the SEFs in H. T. T. Nguyen et al. (2022) and Phan et al. (2022) were mainly employed to support finite element implementation and to facilitate conversions between the time and frequency domains, the present study applies this framework to address the inverse problem of identifying the Huet-Sayegh model parameters based on experimental creep compliance data. This application extends existing approaches and constitutes the main contribution of the present work.

Using the analytical creep compliance function of the HS model (Eq. (12)), the model parameters that best fit the experimental results can be identified by solving the following optimization problem:

$$\min_{\mathbf{p}} \sum_i [D(\mathbf{p}, t_i) - D_{\text{expt.}}(t_i)]^2, \quad (13)$$

where $D_{\text{expt.}}(t_i)$ are the values of the creep compliance measured at t_i and $\mathbf{p}$ is the vector of model parameters to be determined.

3. NUMERICAL RESULTS

3.1. Model parameters identification results

Let us consider the following data set of the creep compliance of an unmodified asphalt mixture (noted as mixture #1) already determined in (Phan & Nguyen, 2025) at various temperatures, as illustrated in Fig. 2(a). The creep compliances were horizontally shifted to construct their master curve at the reference temperature of 20 °C, thanks to the time-temperature superposition principle, as illustrated in Fig. 2(c). The corresponding shift factors are all presented in Fig. 2(b).

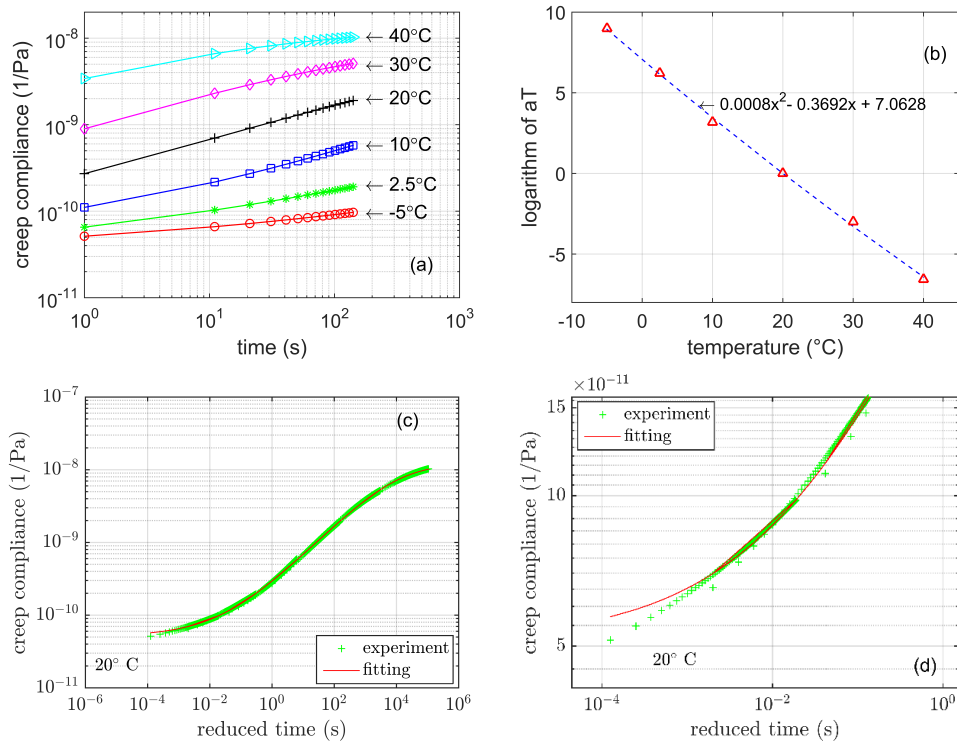


Fig. 2. (a) Creep compliances of mixture #1 at testing temperatures. (b) Shift factors used to construct the master curve. (c) Master curve of creep compliance at the reference temperature (20 °C). (d) Zoom-in of creep compliance at reduced time lower than 1 s

With the initial guess: $\{\mathbf{p}_0\} = \{E_{0,0}, E_{\infty,0}, k_0, h_0, \delta_0, \tau_0\}$ where $E_0 = 100$ MPa, $E_{\infty} = 40,000$ MPa, $k = 0.15$, $h = 0.5$, and $\delta = \tau = 1$, the optimization process finished in 382.42 s using the trust-region-reflective algorithm (predefined in the function *lsqcurvefit* of MATLAB R2015 software). The computing time was 330.22 s on an 8th Gen Core i5 computer, and the best-fit solution is displayed as the continuous line in Fig. 2(c). The corresponding HS parameters are also reported in Table 1.

Table 1. Best-fit Huet–Sayegh parameters

Material	E_0 (MPa)	E_{∞} (MPa)	k	h	δ	τ
Mixture #1	79.481	19,654.828	0.3467	0.4695	0.7511	0.1151
Mixture #2	59.741	41,521.262	0.1520	0.4469	3.2566	9.9683

It should be mentioned that non-negative constraints were set for all parameters. In addition, upper bound constraints were also set for parameters k , h such that $0 < k < h < 1$. The convergence criteria were enforced via the *step tolerance* condition: $\text{TolX} \leq 10^{-3}$, or the default maximal number of iterations of 600 was reached.

As can be observed in the figure, the fitting curve matches well with the experimental one, with the relative error (RE) defined in Eq. (14) between them being only 1.07%. Other error indicators, such as the root mean squared error (RMSE), maximal absolute error (MAE), and maximal relative error (MRE) (reported in Table 2), also confirm the good performance of the proposed algorithm in fitting the creep compliance data. Such a good level of fitting cannot be achieved through the classical trial-and-error approach. In practice, trial-and-error estimation of parameters is difficult and operator-dependent, which may take hours to reach an acceptable solution with an RE of around 5%.

$$RE = \left[\sum_j (X_j - Y_j)^2 / \sum_j Y_j^2 \right]^{1/2}, \quad (14)$$

where X_j and Y_j respectively represent the value of the predicted and the measured data at a discrete point j .

Fig. 3 also shows the evolution of storage compliance while the trial parameters are converging to their optimal values. Furthermore, in order to ensure that the decomposition of the storage moduli into sums of exponential functions was accurately performed, the relative errors at all iterations are displayed in Fig. 4. It can be observed that the relative errors at all computing times are all lower than 4×10^{-4} , confirming the good accuracy of the modified Dombi algorithm.

Similarly, the identification of the Huet–Sayegh model parameters for the creep compliance data of another asphalt mixture, previously measured by N. H. Nguyen et al. (2026), was performed using the same initial guesses as in the previous example. The results obtained are presented in Fig. 5. The corresponding optimal parameters are reported in Table 1, while the estimated fitting errors are summarized in Table 2. It can be observed that the relative error between the predicted and measured responses is comparable to that obtained for mixture #1. These results confirm the effectiveness of the proposed method in addressing the Huet–Sayegh parameter identification problem.

3.2. Sensitivity of the optimal results to the initial guess

Since the algorithm used to solve the problem posed in Eq. (13) is gradient-based, the optimal solution is local and thus dependent on the initially guessed parameters. Therefore, this subsection aims to assess the sensitivity of the optimal solutions to the chosen initial parameters. Table 3 reports the variations in fitting errors resulting from different initial guesses, namely

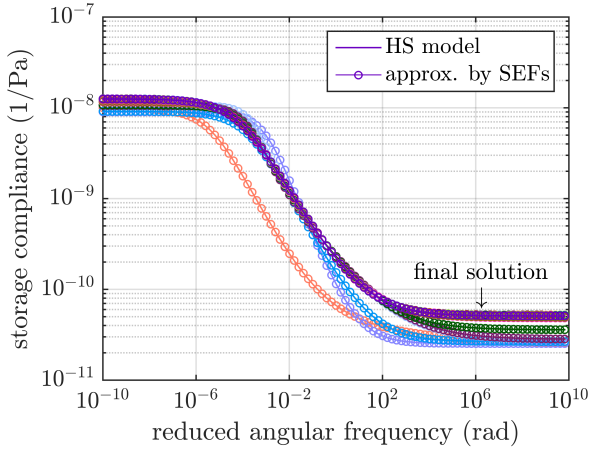


Fig. 3. Evolution of storage compliance during the optimization process

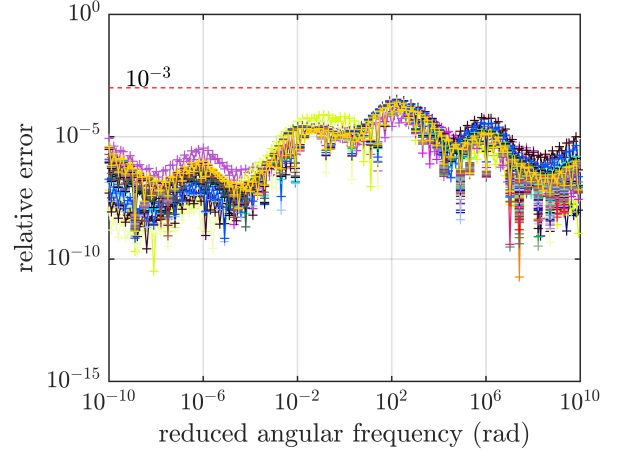


Fig. 4. Errors of the decomposition of storage compliance into sums of exponential functions during the optimization process (all errors are lower than 0.04%)

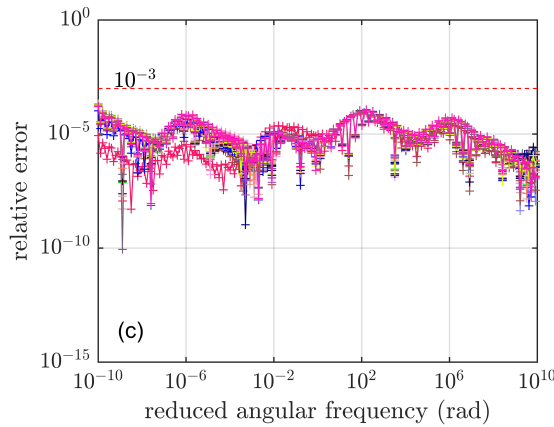
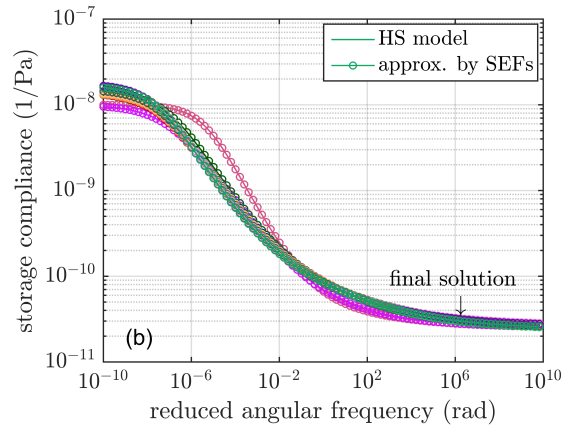
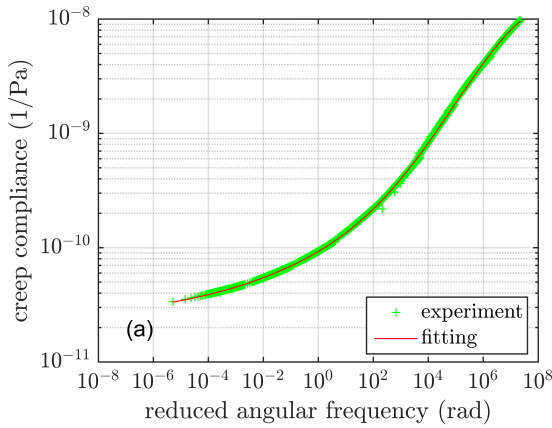


Fig. 5. (a) Fitting the master curve of creep compliance (at 20 °C) of mixture #2. (b) Evolution of storage compliance during the optimization process. (c) Errors of the decomposition of storage compliance into sums of exponential functions during the optimization process (all errors are lower than 0.04%)

0.1, 0.2, 0.5, 1, and 1.5 times the set of initial parameters (noted as $\{p_0\}$) used in the previous

Table 2. Assessment of fitting errors

Errors	Mixture #1	Mixture #2
RMSE (1/Pa)	4.4242×10^{-11}	6.1393×10^{-11}
MAE (1/Pa)	2.4376×10^{-11}	3.2049×10^{-11}
MRE	11.2977×10^{-02}	19.7178×10^{-02}
RE	1.0693×10^{-02}	1.9482×10^{-02}

subsection. With this range of initial guesses, a broad spectrum of Huet–Sayegh parameters was explored while the prescribed constraints ($0 < k < h < 1$) were strictly enforced. The results indicate that the initial parameters have a noticeable influence on the optimal solutions; however, this influence remains relatively small and can be considered negligible. Consequently, the optimal solutions obtained using the proposed algorithm may be regarded as the intrinsic parameters of the investigated materials.

Table 3. Influences of initial guess on fitting errors

Initial guess	RMSE (1/Pa)	MAE (1/Pa)	MRE	RE	Num. of iter.
Mixture #1					
0.1 $\{\mathbf{p}_0\}$	4.2706×10^{-11}	2.3447×10^{-11}	0.0833	0.0103	600
0.2 $\{\mathbf{p}_0\}$	4.2005×10^{-11}	2.3075×10^{-11}	0.0880	0.0101	600
0.5 $\{\mathbf{p}_0\}$	4.3732×10^{-11}	2.4037×10^{-11}	0.1016	0.0105	600
$\{\mathbf{p}_0\}$	4.4242×10^{-11}	2.4376×10^{-11}	0.1130	0.0107	600
1.5 $\{\mathbf{p}_0\}$	4.2661×10^{-11}	2.3777×10^{-11}	0.1187	0.0103	600
Mixture #2					
0.1 $\{\mathbf{p}_0\}$	6.1396×10^{-11}	3.2050×10^{-11}	0.1972	0.0195	189
0.2 $\{\mathbf{p}_0\}$	6.1396×10^{-11}	3.2050×10^{-11}	0.1972	0.0195	133
0.5 $\{\mathbf{p}_0\}$	6.1395×10^{-11}	3.2050×10^{-11}	0.1972	0.0195	161
$\{\mathbf{p}_0\}$	6.1393×10^{-11}	3.2049×10^{-11}	0.1972	0.0195	91
1.5 $\{\mathbf{p}_0\}$	6.1396×10^{-11}	3.2050×10^{-11}	0.1972	0.0195	364

3.3. Application in pavement analysis

In order to demonstrate the significance of this work, the obtained Huet–Sayegh parameters were subsequently used for the analysis of pavement structures with the aid of a homemade FEM (finite element method) code developed in the time domain. The following paragraph illustrates the response of a pavement structure made of two layers of mixture #1, with the total thickness being 17 cm, and a 35 cm-thick layer of graded aggregates laid on a subgrade. The equivalent stiffness modulus of the two bottom-most layers was assumed to be 150 MPa.

The pavement was subjected to a static vehicle wheel load $p(t) = 0.6$ MPa spreading over a circle with a diameter of 0.33 m according to the Vietnamese pavement design codes. In this example, the loading time was assumed to be 1 s to represent a low-speed traffic flow of 1.19 km/h, and the temperature was assumed to be homogeneously distributed and equal to 20 °C.

The pavement was modeled in axisymmetric conditions using 448 Q8 elements (Fig. 6(a)) with the total number of nodes being 1,433. The LVE properties of the material were modeled by

the Huet–Sayegh model with the determined parameters, and the Poisson’s ratio was assumed equal to 0.35. Regarding boundary conditions, all the nodes on the axisymmetric and vertical boundary lines were fixed along the horizontal direction, while nodes on the bottom of the pavement were fixed in all directions.

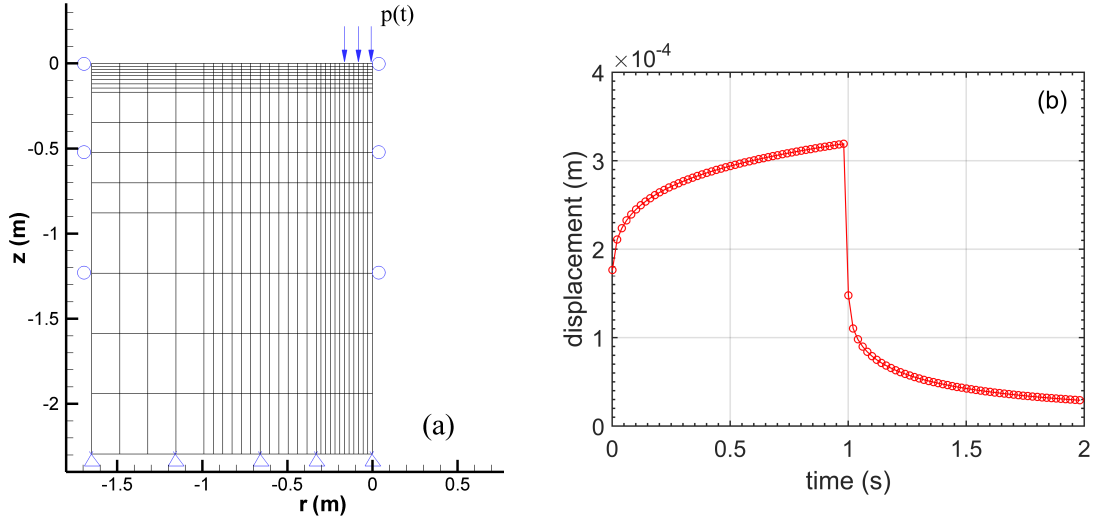


Fig. 6. (a) Discretization of the studied pavement structure. (b) Displacement response in one typical cycle of loading and recovery

The response displacement of the pavement to such a loading history is presented in Fig. 6(b). As can be observed, the displacement of the pavement surface increased from approximately 0.176 mm to reach its maximal value of 0.32 mm at the end of the loading period before starting to decline as the wheel load was removed. This typical response of asphalt pavements cannot be reproduced with an elastic approach; hence, the application of viscoelastic modeling is crucial for accurate pavement analysis and design.

4. CONCLUSIONS

The main features of the present algorithm can be summarized as follows:

- The errors of the decomposition of the storage modulus into sums of exponential functions are small, lower than 4×10^{-4} at all investigating times, thanks to the modified Dombi algorithm. This ensures the high accuracy of the creep compliance function computed.
- Owing to the explicit formula of the creep compliance function, the Huet–Sayegh parameters can be optimized to best fit the input creep compliance data with low relative error (1.95%), which cannot be reached with trial-and-error approaches.
- A noticeable sensitivity of the optimal solutions to the initially guessed parameters was observed; however, this influence is relatively small and can be considered negligible. Consequently, the Huet–Sayegh parameters identified using the proposed algorithm may be regarded as intrinsic material parameters.
- The results obtained provide critical information for the viscoelastic analysis of asphalt pavements.

Although the number of times performing the modified Dombi algorithm has been minimized, the computation time remains high compared with a classical parameter-fitting process. In future work, the influence of different tolerance levels for the sum of exponential functions on the overall fitting error will be examined to establish a well-balanced algorithm for determining the Huet–Sayegh parameters from creep compliance data.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CREDIT AUTHOR STATEMENT

H.T. Tai Nguyen: *Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Funding acquisition.* Tien Tho Do: *Conceptualization, Methodology, Validation, Writing – review & editing, Supervision, Project administration.* David Hernando: *Conceptualization, Methodology.* Thi Hang Nguyen: *Investigation, Data curation, Visualization.*

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