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New Model for Visco-Elastic Behavior of Asphalt Mixture with Combined Effect of Stress and Temperature

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ABSTRACT

The analysis of pavements and their ingredients has always been important due to a good understanding of their behavior under different conditions; that leads to more accurate relations. Due to the extent of asphalt mixture application in the world, the assessment of different behaviors of this mix is very important from various aspects of performance and safety. Given that the asphalt mixtures are inherently very sensitive to temperature changes due to bitumen content, identification and analysis of the viscoelastic and visco-elasto-plastic behavior of the mixture is of particular importance. The scope of present research is to provide new model of viscoelastic behavior of asphalt concrete pavements with a combined effect of stress and temperature using genetic programming techniques. For this purpose, a number of dynamic creep tests under various temperatures and different stress levels were done. Beside, in this study a comparison is made between the generalized model and proposed model in estimating the visco elastic response of asphalt samples. Performance of the genetic programming model is quite satisfactory. The new proposed model will also help further researchers willing to perform similar studies, without carrying out destructive tests.

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NOMENCLATURE

T	Temperature (ºC)	η_2	Second viscosities (MPa)
E_1	First Young's moduli (MPa)	L	Lime
E_2	Second Young's moduli (MPa)	S	siliceous
η_1	First viscosities (MPa)	t	time (s)

1. INTRODUCTION

Mechanical characteristics of asphalt mixture can be very variable because of different aggregate type and gradation used in the mixture [1-3]. Asphalt mixtures are complex materials. Given this complex behavior, lots of attention should be paid to a correct modeling of the mixture characteristics in relation to the above parameters [4]. Asphalt mixture exhibits linear viscoelasticity at small strain [5]. However, at larger strain or higher temperature, its behavior is non-linear; that cannot be adequately modeled by a linear viscoelastic approximation [6]. Non-linear viscous behaviors of asphalt mixture were investigated by many researchers [7, 8]. Their work shows that the responses of asphalt mixture to loads are very complex. As an approximation, mechanical properties of asphalt mixture were separately considered. According to whether or not deformations measured in creep and recovery tests are time dependent and recoverable during unloading [9, 10]. Kettil et al. [11] proposed an elasto-visco-plastic model for asphalt concrete to predict inelastic deformation in road structures. In his model, elastic

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strain was given by the isotropic Hooke's law, visco-plastic strain was defined by the flow potential and visco-plastic parameters.The strain hardening power law was used to describe evolution of viscoplastic strain. Gonzalez et al. [12] developed a visco-plastic model in which elastic and visco-plastic strains were individually evaluated. Young’s modulus and the viscosity parameter were strain-rate dependent. Chen et al. [13] investigated mechanical behavior of brittle rock based upon the above approaches. One of the most common viscoelastic (VE) model is the generalization of the well-known Burgers model. But this model only at small strain and low temperature can be applied, and is not general enough to estimate the behavior of temperature sensitive viscoelastic materials [14]. Thus, identifying and analyzing the viscoelastic and visco-elasto-plastic behaviors of these mixtures are of particular importance by considering temperature and stress parameters. It has been attempted to present a new model based on both stress and temperature parameters to better reflect the viscoelastic properties of asphalt concrete.

2. GENERALIZED MODEL

Asphalt creep curve is commonly has three phases. Linear viscoelastic response can be described by Burgers model, and the model can properly describe the first two phases of creep, i.e. deceleration and equi-velocity [15]. In visco-elastic phase, the whole deformation is simple addition of components including elasticity, viscosity and viscoelasticity. In Burger’s model, in uniaxial stress conditions, σ and ε are the total stress. The total strain in burger’s model are respectively associated with the three components as follows:

$$\sigma = \sigma_1 = \sigma_2 = \sigma_3 \tag{1}$$

$$\varepsilon_{VE} = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \tag{2}$$

These three stress components can be represented by their strain components stated as following:

$$\sigma_1 = E_1 \varepsilon_1 \tag{3}$$

$$\sigma_2 = \eta_1 \dot{\varepsilon}_2 \tag{4}$$

$$\sigma_3 = E_2 \varepsilon_3 + \eta_2 \dot{\varepsilon}_3 \tag{5}$$

In the above equations, Young’s moduli are represented by E_1 and E_2 while viscosities are represented by η_1 and η_2 [16]. In Equation (6), the visco-elastic constitutive relation under constant stress conditions is shown below:

$$\varepsilon(t) = \left[\frac{1}{E_1} + \frac{1}{\eta_1} t + \frac{1}{E_2} (1 - \exp(-\frac{E_2}{\eta_2} t)) \right] \sigma_0 \tag{6}$$

In addition, in a constant stress condition the strain response can be expressed as generalized model. As it is shown in Figure 1, generalized model contains a Maxwell model in series with a certain number of Kelvin-Voigt models shown in Equation (7):

$$\varepsilon(t) = \frac{\sigma_0}{E_1} (1 + \frac{t}{T_1}) + \sum_{i=1}^{n} \frac{\sigma_0}{E_i} \left[1 - \exp(-\frac{t}{T_i}) \right] \tag{7}$$

As the above equations show, only at small strain and low temperature these models can be applied. It is not general enough to estimate the behavior of temperature sensitive viscoelastic materials.

3. METHODOLOGY

3. 1. Materials The continual IV scale in ASHTOO standard [17] was used for grading the aggregates in this study. Table 1 shows aggregates gradations used in this study. Also, Aggregates specifications are given in Table 2. In producing the samples, PG 64-22 and PG 58-28 bitumen of Isfahan Refinery was used. The characteristics of bitumen are summarized in Table 3.

3. 2. Sample Preparation

3. 2. 1. Dynamic Tests Plan Table 4 shows number and type of dynamic tests. In the current article, dynamic creep tests were used to investigate the creep behavior of samples.

3. 2. 2. Marshal Test Results Considering Marshal test results, the optimum percentage of bitumen in asphalt mixtures are list out in Table 5.

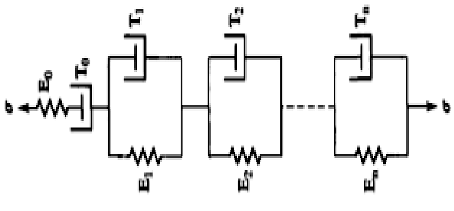

Figure 1. Generalized model [18]

TABLE 1. Gradation of aggregates used in the study

Sieve size	3/4''	1/2''	# 4	# 8	# 50	#200
Limits	100	90-100	44-74	28-58	5-21	2-10
Percent passing	100	95	59	43	13	6

TABLE 2. Specifications of aggregates used in the study

Aggregate type		**Parameter**
Lime	Silica	
2.691	2.643	Specific Gravity (gr/cm3)
21.4	26.7	Los Angeles abrasion (%)
2.2	3.5	Sodium sulfate soundness (%)

TABLE 3. Characteristics of PG 64-22 and PG 58-28 bitumen used in asphalt binder

Test	**AASHTO Method**	**Specified Limit(s)**	
		PG 64-22	**PG 58-28**
		Lab. Result	
Dynamic Shear @ Grade Temperature, °C	T 315	64	58
Absolute Viscosity at 140°F (60°C), Poises	T 202	2030	915
Specific Gravity at 60°F (15.6°C)	T 228	1.039	1.035
Penetration at 77°F (25°C), dmm	T49	70	130

TABLE 4. Number and type of dynamic test

Stress levels	**Temperature levels**	**Aggregate types**	**Bitumen Grades**	**Void (%)**
100 KPa	50°c	Silica	PG 64-22	3
200 KPa				
300 KPa	60°c	lime	PG 58-28	7

TABLE 5. Bitumen optimal percentage in asphalt containing lime and silica

Bitumen Grade	**Aggregate type**	**Optimal percentage of Bitumen**
PG 64-22	Lime	5.5
PG 64-22	Silica	5.5
PG 58-28	Lime	5
PG 58-28	Silica	5

In this research, the optimum content of bitumen is first determined based on Marshall Mix Design for all different types of bitumen and aggregate. Then, in samples preparation, different compaction energies were used to achieve the desired levels of air void content.

3. 3. Dynamic Creep Test

The dynamic creep test was conducted to evaluate the creep compliance of asphalt pavements. The test was performed using Universal Testing Machine. The test was carried out according to British Standards Institute BS 226-1996.

4. RESULTS AND DISCUSSION

4. 1. Dynamic Creep Tests Results

In Figure 2, as sample the creep curves of asphalt specimens with limestone aggregates and PG 64-22 bitumen, considering variation in the applied stress and air voids levels at 60°C are provided. The Matlab software is used to analyze and evaluate the obtained experimental results. The generalized model is used to predict the creep deformation behavior of asphalt mixture at temperature of 50 and 60°C and 3 different stress levels of 100, 200, 300 KPa. For the sake of convenience, a nonlinear fitting procedure was developed through the least square technique in SPSS software and curve fitting in Matlab. Given the rational initial values, the parameters can be determined by fitting in Equation (7) [19]. The obtained data are presented in Table 6, Figures 3 and 4. In training GP model only the viscoelastic parameters of the asphalt concrete such as E_1, E_2, η_1 and η_2 and stress level and temperature are used.

In Table 6 a part of the dataset used in GP model is presented in terms of aggregates and bitumen type in loading time of 100 s. Also, Figures 3 and 4 present as sample the changes in viscoelastic parameters of asphalt specimens containing 3% air voids of asphalt concrete in the manufacture of which PG 64-22 and PG 58-28 bitumen are used. As shown in Figures 3 and 4, asphalt specimens made with siliceous materials have higher thermal sensitivity than the asphalt specimens prepared by lime materials. This is due to the high initial modulus of elasticity in the specimens made with lime materials.

4. 2. Modeling with Genetic Programming

4. 2. 1. Genetic Programming Technique

In recent years a great number of advanced theoretical - empirical methods has been developed for design and modeling concrete pavements behaviours [20]. Genetic programming is a branch of evolutionary algorithms that solves problems without requiring the user.

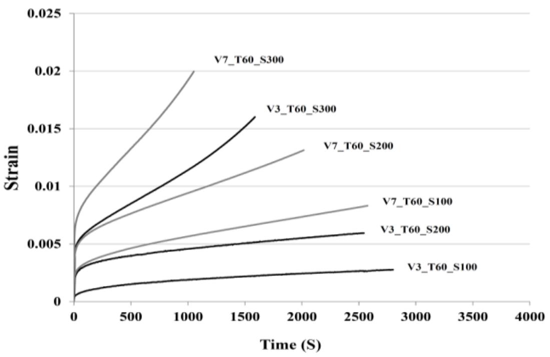

Figure 2. Creep curves of Asphalt specimens with limestone aggregates and PG 64-22 bitumen, considering variation in the applied stress and air voids levels at 60°C

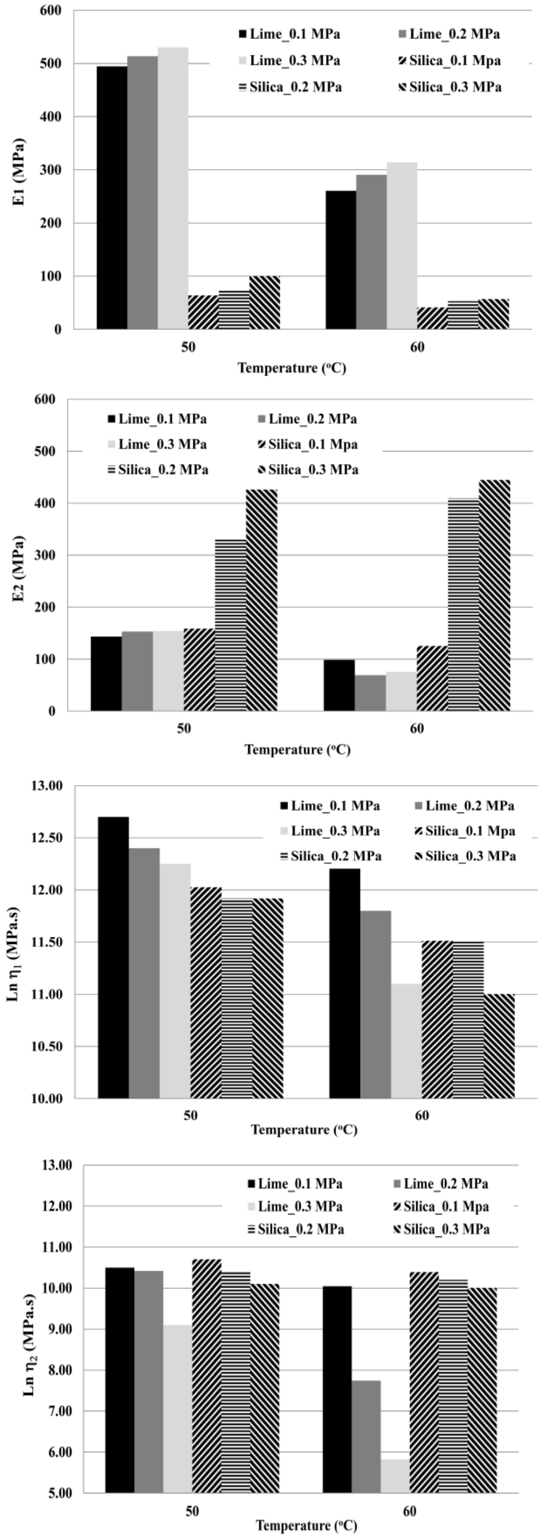

Figure 3. Changes in viscoelastic parameters of asphalt specimens containing 3 percent void manufactured by PG 64-22 bitumen

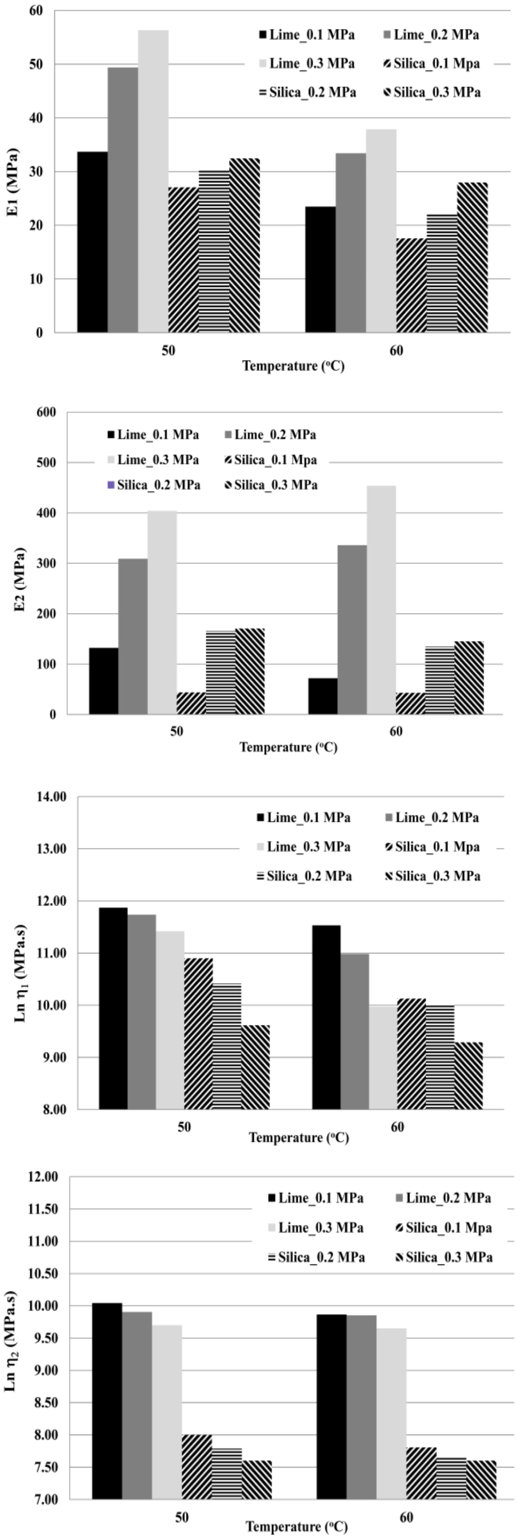

Figure 4. Changes in viscoelastic parameters of asphalt specimens containing 3 percent void manufactured by PG 58-28 bitumen

TABLE 6. Characters of asphalt specimens with 3% air void in 50 cycles and the loading time of 100s

εt	T (s)	η_2 (Mpa)	E_2 (Mpa)	E_1 (Mpa)	η_1 (Mpa)	σ_0 (Mpa)	T (ºC)	Void (%)	Bit. Types	Agg. Types	R-square of dataset (Matlab CFTool)
0.003602224	100	2.41E+04	122.6	32.44	7.69E+04	0.1	50	7	64-22	Silica	0.999
0.005132234	100	2.39E+04	401.1	44.78	6.42E+04	0.2	50	7	64-22	Silica	0.996
0.007388859	100	2.30E+04	542.8	47.43	5.06E+04	0.3	50	7	64-22	Silica	0.998
0.00465292	100	2.31E+04	866.7	23.87	3.33E+04	0.1	60	7	64-22	Silica	0.990
0.00684683	100	2.30E+04	996	33.22	3.33E+04	0.2	60	7	64-22	Silica	0.995
0.00856135	100	2.30E+04	2706	45.13	1.50E+04	0.3	60	7	64-22	Silica	0.943
0.009601842	100	1.97E+03	49.75	14.09	1.38E+04	0.1	50	7	58-28	Silica	0.999
0.014144185	100	1.95E+03	74.79	20.18	1.29E+04	0.2	50	7	58-28	Silica	0.993
0.019420719	100	1.89E+03	190.9	25.74	5.00E+03	0.3	50	7	58-28	Silica	0.995
0.01195171	100	1.92E+03	53.43	10.98	8.86E+03	0.1	60	7	58-28	Silica	0.999
0.01753778	100	1.91E+03	85.5	17.66	5.03E+03	0.2	60	7	58-28	Silica	0.990
0.03192637	100	1.80E+03	804.9	23.84	1.50E+03	0.3	60	7	58-28	Silica	0.975
0.0017844	100	9.89E+03	58.31	132.9	2.00E+05	0.1	50	7	64-22	Lime	0.985
0.004587846	100	2.04E+03	58.38	149.1	8.12E+04	0.2	50	7	64-22	Lime	0.994
0.006825367	100	1.97E+03	63.64	157.3	6.02E+04	0.3	50	7	64-22	Lime	0.990
0.00332398	100	8.89E+03	55	49	5.10E+04	0.1	60	7	64-22	Lime	0.968
0.005706607	100	5.64E+03	98	54	5.10E+04	0.2	60	7	64-22	Lime	0.977
0.00875629	100	3.31E+03	107	57	2.89E+04	0.3	60	7	64-22	Lime	0.998
0.005297196	100	1.09E+04	126.7	22.27	5.01E+04	0.1	50	7	58-28	Lime	0.982
0.007457127	100	9.99E+03	329	33.61	2.22E+04	0.2	50	7	58-28	Lime	0.998
0.011312353	100	2.61E+03	557	36.2	1.19E+04	0.3	50	7	58-28	Lime	0.996
0.007925871	100	8.97E+03	211.5	15.48	1.00E+04	0.1	60	7	58-28	Lime	0.999
0.010815454	100	8.79E+03	451.7	24.17	1.00E+04	0.2	60	7	58-28	Lime	0.997
N. A*	100	8.74E+03	608.7	30.94	4.59E+03	0.3	60	7	58-28	Lime	0.984

*N. A: lack of diagram due to reaching the maximum identified strain

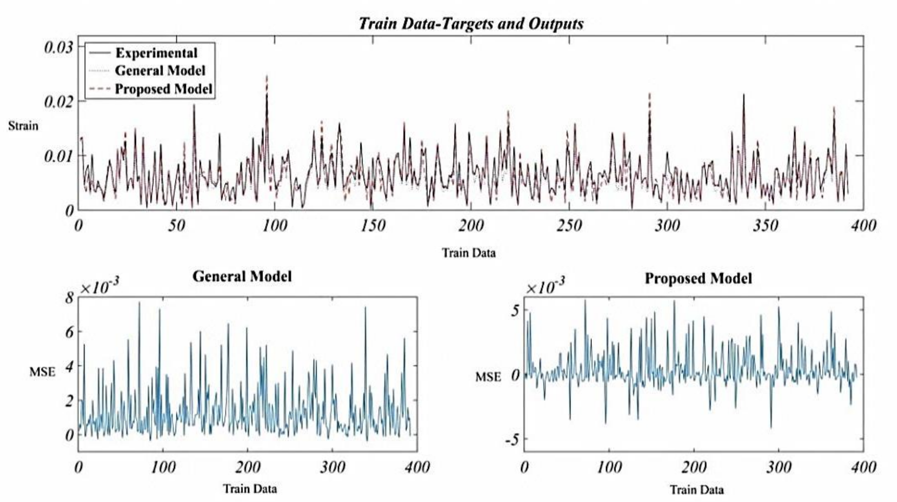

Figure 5. The results of the training data for the derived mathematical and generalized models

The history of genetic programming dates back to the early 90's and John Koza is among those who made most effort to develop this branch [21]. One article about the use of artificial intelligence in pavement management is outlined by Sundin and Braban-Ledoux [22]. Mathematical programming and heuristic approaches are used by Chan et al. [23] for pavement maintenance management with regards to networks. Tack and Chou developed genetic algorithm using a tool that optimizes the schedule for repair of multilayer pavements [24]. Triple-phase Weibull equations for describing the damage resulted in from fatigue were used by Tsai et al. [25, 26] through the stress control fatigue test that examine the strain of fatigue. Alavi et al. [27] employed a high-precision model to predict the flow number of dense asphalt mixtures using a novel hybrid method coupling genetic programming and simulated annealing, called GP/SA.

4. 2. 2. Implementation of Genetic Programming

The scope of genetic programming in this study is the automatic generation of a mathematical model that estimates the viscoelastic behavior of asphalt concrete pavement under the combined effect of stress and temperature. In implementing the GP, 70% of data are considered for training and 30% of them are for testing. Also the data related to each part are randomly selected among 560 data. Therefore, 392 data are obtained for training and 168 data were collected for testing. Figure 5 presents the results of the training data for the derived proposed model and generalized model.

Table 7 presents the results of the R-square, MSE and RMSE criteria for training data of the proposed and generalized models.

Table 8 presents the results of the R-square, MSE and RMSE criteria for test data of the proposed and generalized model. According to the results it can be observed that the proposed model has less error than generalized model. In other words, increasing the heat sensitivity of asphalt specimens, better performance was observed than the generalized model.

4. 2. 3. Genetic Programming Model Details

Mathematical model obtained by the implementation of genetic programming is defined as Equation (8):

$$\begin{aligned} y = \ln \Bigg| \Bigg[\Bigg[\Bigg[\Bigg[& [ln|x5| - \ln|[[(x5x7 - x4(x6 - x1)] \times x7 \times ln|x3|]|| \times \frac{ln|x5|}{x3 \times x2} \\ & + \frac{x7}{x5} + \frac{x2}{x1 \times ln\left|\frac{x7^2}{x4}\right|} \Bigg] \times x4 \Bigg] \Bigg] \times x4x7 \Bigg] \Bigg| \times \frac{\ln|x7|}{x3} + \frac{x2}{x1 \times \ln\left|\frac{x3}{x7}\right|} + \frac{x2}{x4} \end{aligned} \tag{8}$$

Given the conditions considered in GP to deal with division by zero, the function in t=0 is obtained according to Equation (9)

$$\frac{x2}{x1 \times \ln|x3|} + \frac{x2}{x4} \tag{9}$$

Based on Equations (8) and (9) the proposed model is written according to Equation (10).

$$\text{GP Model} = \begin{cases} \frac{x2}{x1 \times \ln|x3|} + \frac{x2}{x4} \ , & t = 0 \\ y \ , & t > 0 \end{cases} \tag{10}$$

In Table 9, the original name of the variables used in the GP model is presented.

As mentioned earlier, In training GP model only the viscoelastic parameters of the asphalt concrete such as E_1, E_2, η_1 and η_2 obtainable by the two first phases of the creep diagram and stress level and temperature are used.

4. 2. 4. Compare the proposed model and the Generalized Model

The results of R-square, MSE and RMSE criteria associated with the two specimens are presented in Tables 10 and 11.

Also Figures 6 and 7 present results of the proposed model and generalized model for two specimens prepared by silica materials at temperatures of 50 and 60ºC.

TABLE 7. Results of MSE and RMSE error criteria for training data of the proposed and generalized models

Model	MSE	RMSE	R^2
Generalized Model	3.53e-6	0.0019	0.977
Proposed Model	2.16e-6	0.0014	0.985

TABLE 8. Results of MSE and RMSE error criteria for test data of the proposed and generalized models

Model	MSE	RMSE	R^2
Generalized Model	5.01e-5	0.0022	0.973
Proposed Model	2.27e-5	0.0015	0.981

TABLE 9. The name of the variable used in GP model

Main Variable	Proposed Variable
T (°C)	X1
$\sigma\ (MPa)$	X2
$\eta_1(MPa)$	X3
$E_1(MPa)$	X4
$E_2(MPa)$	X5
$\eta_2(MPa)$	X6
$t(s)$	X7

TABLE 10. Results of the error criteria of the proposed and Generalized models for two specimens prepared by Silica materials and PG 64-22 bitumen at the temperatures of 50 and 60°C

Model	Temperature	MSE	RMSE	R^2
Generalized Model	50	2.73E-7	0.00053	0.975
Proposed Model	50	3.37E-8	0.00018	0.988
Generalized Model	60	1.41E-6	0.001	0.963
Proposed Model	60	1.85E-7	0.00043	0.979

TABLE 11. Results of the error criteria of the proposed and Generalized models for two specimens prepared by Silica materials and PG 58-28 bitumen at the temperatures of 50 and 60°C

Model	Temperature	MSE	RMSE	R^2
Generalized Model	50	2.01E-6	0.0014	0.969
Proposed Model	50	1.36E-7	0.0003	0.983
Generalized Model	60	1.06E-5	0.003	0.957
Proposed Model	60	4.14E-7	0.00064	0.976

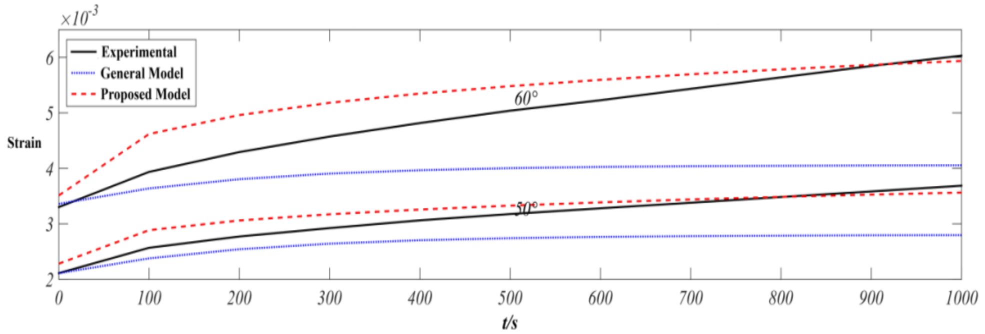

Figure 6. The output of the proposed and Generalized models for two specimens prepared by Silica materials and PG 64-22 bitumen at the temperatures of 50 and 60°C

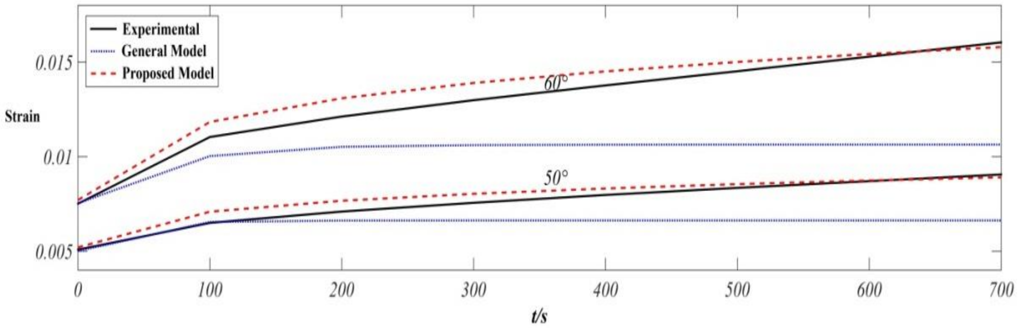

Figure 7. The output of the proposed and Generalized models for two specimens prepared by Silica materials and PG 58-28 bitumen at the temperatures of 50 and 60°C

Figure 6 is related to a specimen with the properties (Void = 3, Bitumen grade= 64-22 and Aggregate Types = S). Figure 7 is related to a specimen with the properties (Void = 3, Bitumen grade= 58-28 and Aggregate Types = S). According to the results it can be observed that the proposed model has less error than the generalized model. On the other hand it can be observed that based on the higher thermal sensitivity of the asphalt specimens prepared by siliceous materials, these specimens show higher correlation with the proposed model. In other words, by increasing the heat sensitivity of the asphalt specimens, better performance is observed than the generalized model from lime to siliceous material and PG 64-22 to PG 58-28 bitumen content.

5. CONCLUSION

The aim of this study is to provide new model of viscoelastic behavior of asphalt concrete pavements with a combined effect of stress and temperature. The most important results of the study include:

- The results indicate that compared with generalized model, the proposed model fits better with the experimental data at higher temperature.
- Based on results it can be observed that proposed model has less error than the generalized model.
- Based on results it can be observed that given the higher thermal sensitivity of the asphalt specimens prepared by siliceous materials, these specimens

have higher correlation with the proposed model. By increasing the heat sensitivity of the asphalt specimens, better performance is observed than the generalized model from lime to siliceous material and PG 64-22 to PG 58-28 bitumen content.

- For practical purposes, the most important result of this study is to underline the fact that for modeling of materials used in asphalt, GP can be used. Above all, the results of the study create a precise and effective clear formulation in pavements engineering.

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New Model for Visco-Elastic Behavior of Asphalt Mixture with Combined Effect of Stress and Temperature

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چکیده

تحلیل روسازی راه ها و مواد تشکیل دهنده آنها همواره به دلیل شناخت بهتر رفتار آنان تحت شرایط متفاوت از اهمیت بالایی برخوردار بوده و باعث درک بهتر و در نتیجه طرح روابط دقیق‌تر می‌گردد. با توجه به گستره وسیع کاربرد مخلوط های آسفالت در دنیا، ارزیابی رفتارهای مختلف این مخلوط از جنبه های مختلف عملکردی و ایمنی از اهمیت بسزایی برخوردار می باشد. با توجه به اینکه مخلوط های آسفالتی به طور ذاتی و به سبب قیر محتوی، نسبت به تغییرات دما بسیار حساس هستند، لذا شناسایی و بررسی رفتار ویسکو الاستیک و ویسکو الاستو پلاستیک این مخلوط ها و تعیین پارامترهای مؤثر در این رفتار که بسیار وابسته به تغییرات دماست، از اهمیت ویژه ای برخوردار است. هدف از این پژوهش ارائه مدل جدید رفتار ویسکو الاستیک رویه های بتن آسفالتی راه ها با تاثیر همزمان هر دو عامل تنش و دما با استفاده از تکنیک برنامه نویسی ژنتیک می باشد. برای این منظور، تعدادی آزمون خزش دینامیکی تحت دماهای مختلف و سطوح متفاوت تنش انجام گردید. علاوه بر این، در این پژوهش مقایسه ای بین مدل عمومی و مدل پیشنهادی در زمینه تخمین پاسخ ویسکو الاستیک نمونه های آسفالت انجام شده است. عملکرد مدل برنامه نویسی ژنتیکی کاملاً رضایت بخش است. همچنین مدل جدید ارائه شده، محققان بیشتری که قصد انجام تحقیقات مشابه دارند را بدون نیاز به انجام آزمونهای مخرب یاری خواهد نمود.

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