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# A model to predict creep compliance of asphalt mixtures containing recycled materials

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## HIGHLIGHTS

- Creep compliance increased with increase in temperature and time.
- High ABR results is less compliant mixes and vice versa.
- Proposed creep compliance model captures the effect of ABR not addressed in the MEPDG.
- The proposed multivariate regression model had R-squared value of 0.90 and low RMSE of 0.03.

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## ABSTRACT

Thermal cracking is one of the major distresses in flexible pavements, especially in the northern part of the U.S. and Canada. With the increasing use of recycled materials like reclaimed asphalt pavement (RAP) and recycled asphalt shingle (RAS), asphalt pavements have become more susceptible to thermal distresses. Therefore, such asphalt concrete (AC) mixtures should be carefully investigated to ensure that performance is not compromised in the pursuit of an economical solution. The Pavement ME Design uses the empirically developed model for the prediction of creep compliance as an input for Level 3 analysis, which uses the mix and binder properties. However, this prediction model cannot be applied for every climatic and mix design conditions; therefore, different researchers came up with modified models for different states within the U.S. The impact of recycled materials was not captured in the MEPDG as well as in the modified models. This research proposes a new model that captures the effect of recycled materials. It was observed that softer binder and higher asphalt content results in more compliant, while recycled materials tend to decrease the compliance. Hence, softer binder and recycled materials tend to counterbalance each other's impact. From model analysis, it was found that the existing MEPDG model significantly overestimates creep compliance compared with actual measured values. The proposed model can capture the effect of asphalt binder replacement (ABR) and has been validated with randomly selected data and found to exhibit good correlation with lab testing data.

## 1. Introduction

Asphalt concrete (AC) is the most common material used for the construction of pavements in the U.S. and many other countries in the world. To cope up with the constantly increasing demand of materials in road construction, agencies are using recycled materials as a part of sustainability and economic strategy. This preserves natural resources, including virgin binder and aggregates, and reduces landfill, thus resulting in an economical mix design. The common recycled materials being used are recycled asphalt pavement (RAP), recycled asphalt shingle (RAS), and crushed concrete. In addition to this, steel slag is also used which is a by-product from steel production. When RAP and RAS are used in AC mixture production, petroleum-based virgin binder is replaced by the recycled binder already existing in RAP and RAS. This results in cost savings during production of such recycled mixes. The strategy of Asphalt Binder Replacement (ABR) and its effectiveness on the design of mixes as well as performance have been investigated in many states.

There has been an increase in ABR usage and recently up to 60% ABR has been used, with about 8–53% RAP and 4–8% RAS content [1]. The asphalt industry has been very conscientious in incorporating recycled materials and an estimated 74.2 million tons RAP

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and 1.93 million tons RAS were used in 2015 [2]. Besides the economic advantages and a sustainable approach, the stiff nature of RAP and RAS have proven to increase some performance parameters such as permanent deformation [3–5]. However, the introduction of RAP and RAS poses some challenges at the mix design stage and performance of AC mixes with high contents of recycled materials could be compromised. Therefore, laboratory testing is often needed along with field verification to ensure well performing AC mixes.

Flexible pavements experience different distresses, such as rutting, fatigue, and thermal cracking, due to environmental and vehicular loading. Thermal cracking is a critical distress in northern parts of the U.S. and across Canada, which can be adversely affected by the addition of RAP and RAS [6]. Basically, temperature fluctuations induce tensile stress, which in turn could result in cracking if the thermally induced stresses exceed the tensile strength in the mastic phase of AC mixtures. It was found that thermal cracking could initiate and propagate faster as the AC becomes less ductile. Creep compliance and tensile strength testing are two commonly used experiments conducted to evaluate the brittleness of AC mixes [7]. Vargas [8] and You et al. [9] investigated the effect of RAP and RAS amount on AC creep compliance. A reduction in creep compliance was reported along with the resistance against the thermal cracking in flexible pavements [8,9].

Since AC material is thermo-viscoelastic in nature, its properties greatly vary with temperature. In order to characterize the resistance of AC mixes to thermal cracking, the Strategic Highway Research Program (SHRP) developed the creep compliance indirect tensile (IDT) test, where load is applied on disc shape compacted specimen through its diametral axis [10,11]. This method has been adopted as AASHTO T322 “Standard Method of Test for Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device.” Currently, IDT creep and strength are being widely used for the evaluation of low-temperature cracking in the flexible pavements. Creep compliance is one of the fundamental characteristics of the viscoelastic materials that explain the relation between an applied stress and the time-dependent strain of the AC mixtures. Due to time and the temperature dependence of AC mix, this test is conducted at different temperatures based on the binder grade, which is used to obtain the master curve.

The impact of RAP on thermal cracking in flexible pavements, especially in the colder areas were studied by several researches. In these studies, creep compliance and tensile strength of the AC mixes were obtained and utilized to estimate thermal stresses and potential cracks. Several studies reported that creep compliance increases with the increase in temperature and decreases with the increase in RAP content and use of stiffer binder, while tensile strength increases with the increase in RAP [7]. However, in some studies, it was reported that there was no significant relationship between the RAP content and the creep compliance [8]. To understand the effect of air void content on creep compliance, Richardson and Lusher [12] found that creep compliance increases with the increase in air voids (4, 6.5 and 9%) and temperature, while it decreases with the increase of RAP (0, 10 and 20%). On the other hand, the tensile strength was found to increase with the RAP amount and decrease with air voids and temperature [12]. The analysis conducted by Bonaquist [13] showed that creep compliance increases with the increase in the low temperature performance grade (PG); whereas, tensile strength was not significantly impacted by the low-temperature grade [13]. Another study conducted by Watson et al. [14] reported that the addition of RAP and RAS could bump up the low-temperature PG, which adversely affects the thermal cracking resistance properties of the AC mix [14].

Since the creep compliance testing could be complicated and time consuming, researchers introduced prediction models for Level 3 analysis of pavement design. These predictive models are built on the correlation between creep compliance, mix volumetrics, and binder fundamental properties. For Level 3 analysis, the MEPDG uses the following model for predicting creep compliance [15].

$$\mathrm{D(t)} = \mathrm{D_1 t^m} \tag{1}$$

where, m = creep coefficient; t = loading time (sec); and $D_1$ is defined as follows:

$$\begin{aligned}\log(\mathrm{D_1}) &= -8.52410 + 0.01306\mathrm{T} + 0.79570\log(\mathrm{Va}) \\ &\quad + 2.021030\log(\mathrm{VFA}) - 1.92300\log(\mathrm{A_{RTFO}})\end{aligned} \tag{2}$$

where, T = Test temperature in °F; Va = Air voids (%); VFA = Voids filled with asphalt (%); and $A_{RTFO}$ = Intercept of binder viscosity-temperature relationship for the rolling thin film oven (RTFO) condition.

The m parameter is estimated using the following model in Eq. (3).

$$\begin{aligned}\mathrm{m} &= 1.16280 - 0.00185\mathrm{T} - 0.04596\mathrm{Va} - 0.01126\mathrm{VFA} \\ &\quad + 0.00247\mathrm{Pen_{77}} + 0.00168\mathrm{Pen_{77}^{0.46050}T}\end{aligned} \tag{3}$$

where, $\mathrm{Pen_{77}}$ = Penetration at 77 °F $= 10^{290.5013-\sqrt{81177.288+257.0694\times10^{(A+2.72973\times VTS)}}}$; A = Intercept of binder viscosity-temperature relationship and VTS = Slope of binder viscosity-temperature relationship.

It has to be noted here that the Superpave$^{(R)}$ design program, which is currently a common practice in the U.S., does not require conducting the binder penetration test; therefore, A and VTS information is often missing [13], but can be obtained from literature. Asphalt binder exhibits different behaviors by source, manufacturing method, and added modifiers. Therefore, literature value may under- or over-estimate the creep compliance using the MEPDG creep compliance model. To avoid this problem, Jamrah and Kutay [16] conducted a comprehensive research on this topic and have recently reported their results in TRB [16]. Their study developed a statistically reliable creep compliance model while removing the A-VTS constraint. The complete model is presented in Eq. (4).

$$\begin{aligned}\mathrm{LogD(t)} &= 592967(-1.017\times10^{-6} + 2.412\times10^{-8}\mathrm{PG_{low}} \\ &\quad + 1.091\times10^{-8}\mathrm{PM} + 1.167\times10^{-8}\mathrm{VFA} \\ &\quad - 4.022\times10^{-7}\mathrm{FA} + 1.487\times10^{-8}\mathrm{P_{100}} + 5.132\times10^{-8}\mathrm{P_b} \\ &\quad - 7.373\times10^{-8}\mathrm{G_{mm}} + 4.274\times10^{-9}\mathrm{Time} \\ &\quad + 1.701\times10^{-8}\mathrm{Temp}) - 6.6266\end{aligned} \tag{4}$$

where, $PG_{low}$ = Magnitude of low PG grade; PM = Polymer modification factor, 1 for polymer modified and 0 for unmodified binders; VFA = voids filled with asphalt (%); FA = Fines/Asphalt ratio; $P_{100}$ = percent passing the AASHTO #100 sieve; $P_b$ = Asphalt content by weight of the mix (%); $G_{mm}$ = Maximum theoretical specific gravity of the mixture; Time = Time of interest in seconds; and Temp = Temperature of interest in °F.

Similarly, Bonaquist [13] came up with the following prediction model for different Wisconsin AC mixtures, where the creep compliance at low temperature is predominantly a function of low temperature of the binder PG, in contrast to the volumetric properties of the AC mixtures [13].

$$\mathrm{D(t)} = 3.729\times10^{-7} + 10^{-9.3552-0.0645\times\mathrm{PG_{low}}}\left[\frac{\mathrm{t}}{10^{0.0655(\mathrm{T}+4)}}\right]^{0.4705} \tag{5}$$

where, D (t) = Creep Compliance, 1/psi; T = temperature, °F; $PG_{low}$ = low-temperature continuous grade of the binder in the mixture, °C; and t = time (sec).