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TRIAXIAL TEST OF HYDRATED LIME ON THE MECHANICAL PROPERTIES OF HOT MIX ASPHALT CONCRETE

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ABSTRACT

This paper reports on the experimental study, which conducted a series of triaxial tests for the asphalt concrete using hydrated lime as a mineral additive. Three HMA mixes, prepared by the specification for wearing, levelling and base layers, were studied under three different temperatures. The test results have demonstrated that, compared with the control mixes excluding HL, the permanent deformation resistance of the HL modified mixes has significant improvement. The deformation has been reduced at the same load repetition number, meanwhile the flow number has been considerably increased. The degree of improvement in permanent deformation resistance using HL is more pronounced at high stress deviation states and high temperature. The results have also showed that the resilient modulus strongly depends on the temperature and stress deviation while the mixes of HL addition demonstrate having higher stiffness/rigidity. Lastly, mathematical characterization models have been proposed for the measured material properties.

Keywords

Hydrated lime mineral filler, Hot mix asphalt concrete, Pavement permanent deformation, Resilient modulus

INTRODUCTION

Rutting or permanent deformation is one of the most common distresses for asphalt pavements (Zhang *et al.*, 2021). In spite of a large number of laboratory and field studies on the HL modified asphalt concrete (Sebaaly *et al.*, 2003; Bouron *et al.*, 2021), specific investigation on its rutting behavior is still limited. So far, there were few experimental data of triaxial tests reported for HL modified asphalt concrete. The situation suggests that the relevant work on material constitutive characterization, particularly, to take account the coupled thermomechanical influence is not enough to provide certain guidance for pavement design trying to use HL modified asphalt concrete (Taherkhani and Tajdini, 2019; Lagos-Varas *et al.*, 2022). To contribute more knowledge to bridge the gap, this paper reports an experimental study using uni- and tri-axial tests to compare the elastoplastic behavior of HMA concrete mixtures under coupled thermal and mechanical loads. On the obtained results, characteristic mathematical models have been proposed for the permanent deformation and resilient modulus for their variation with the composition, temperature and stress states.

EXPERIMENTATION

Asphalt concrete mixes were made following the design standard (ASTM D 3494) for three pavement course layers, i.e., Wearing, Levelling and Base courses. At first, three control mixes which use limestone dust only for the mineral filler (MF) were made. The particle size of the limestone duct was less than 0.075 mm (passing US sieve No. 200). The MF contents are 7, 6, and 5% by total weight of the mix for the Wearing, Levelling and Base mixes, respectively. Thereafter, three other counterpart modified mixes were made to use hydrated lime to replace the limestone dust by 2.5% of the total weight of the aggregates of each control mix.

Figure 1 displays the experimental setup for triaxial tests. The prepared six mixes were cast into cylindrical specimens in triplicate. The specimens have a size of 101.6 mm (4 inch) in diameter and 152.4 mm (6 inch) in height. Specimens were put into an airtight pressure cell, in which a peripheral confining pressure on the cylindrical side surface was applied, meanwhile a vertical axial compressive load exists on the top of the sample. The surface of the specimens was airproofed. The pressure cell and the specimen together were put into an environmental chamber at a controlled temperature and left for at least two hours to reach a thermal equilibrium state.

(a) Airtight pressure cell

(b) Triaxial test under controlled temperature

Figure 1. Triaxial experiment setup.

Triaxial tests were performed by applying a repetitive axial compressive loading (load stress) in the form of a rectangular wave with a frequency of 1Hz, i.e., loaded for 0.1 seconds followed by unloaded for 0.9 seconds. The triaxial tests were conducted under 3 controlled temperatures, were 20, 40 and 60°C. Each test had the total load repetition number up to 10,000. The deformation in the axial direction of the specimen was recorded using two LVDTs. The confining pressure (confining stress) was applied by the controlled static air pressure in the pressure cell. Using air pressure instead of traditional hydraulic pressure to provide confining pressure for triaxial tests has been employed to study the effects of loading speed, raw material types, and asphalt content on the shear strength, permanent deformation of asphalt mixtures (Goetz and Schaub, 1959; Orosa *et al.*, 2022). Table 1 lists the total four loading conditions used conducted in this work, which includes a uniaxial test conducted in another study by the same serial research.

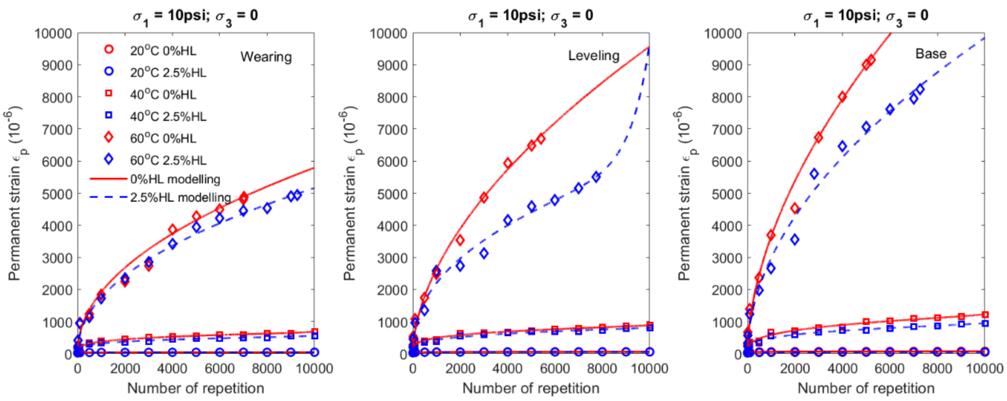
Table 1. The triaxial test load conditions

Deviatoric Stress psi (kPa)	Confining Stress psi (kPa)	Axial load Stress psi (kPa)
10 (68.9)	0 (0)	10 (68.9)
20 (137.9) *	0 (0) *	20 (137.9) *
20 (137.9)	10 (68.9)	30 (206.8)
30 (206.9)	10 (68.9)	40 (275.8)

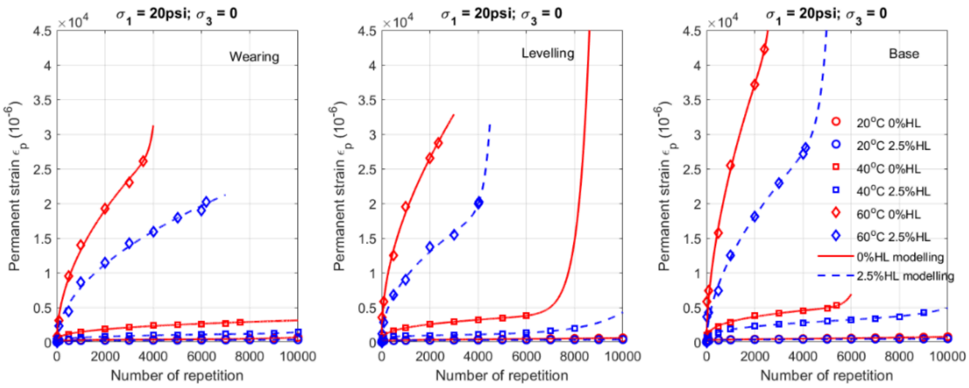
* *Work conducted by Al-Tameemi et al (2016).*

EXPERIMENTAL RESULTS

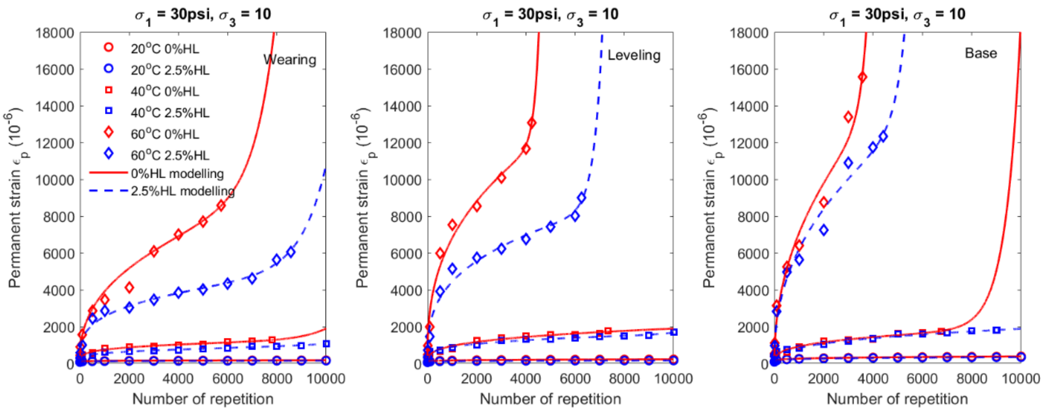
Both the permanent and elastic deformation have been recorded for the number load repetition at 1, 2, 10, 100, 500, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000 and 10000. Fig. 2 shows the measured axial permanent strain (ε_p) under the four load conditions. Temperature shows distinctive influence on permanent deformation, the higher the temperature the larger the permanent deformation. The results in Fig. 2 demonstrate that, in general under the four loading conditions, increasing mineral filler (MF) content improves the rutting resistance since the permanent deformation of the wearing layer mix (7% MF) < levelling layer mix (6% MF) < base layer mix (5% MF). For all the mixes under the four loading conditions, the HL modification shows the greatest effect on stability improvement when exposed to high temperature.



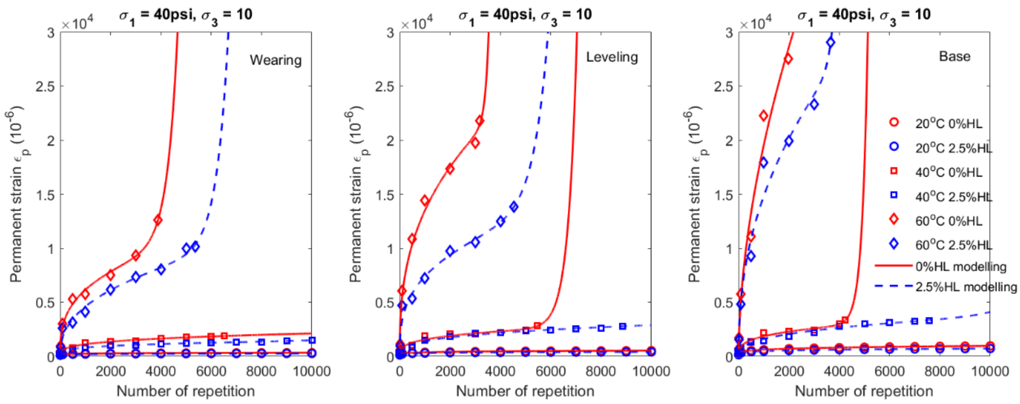
(a) Axial stress (σ_1) is 10 psi (68.9 kPa), confining stress (σ_3) is 0



(b) Axial stress (σ_1) is 20 psi (137.9 kPa), confining stress (σ_3) is 0



(c) Axial stress (σ_1) is 30 psi (206.9 kPa), confining stress (σ_3) is 10 psi (68.9 kPa)



(d) Axial stress (σ_1) is 40 psi (275.8 kPa), confining stress (σ_3) is 10 psi (68.9 kPa)

Figure 2. Permanent strain, ε_p variation with repetition

The curve of permanent strain vs the number of the load repetition (ε_p-N) in general presents three distinctive stages (Xu and Sun, 2013; Ji *et al.*, 2021), they are 1) an initial stage of consolidation; 2) a secondary stage of slow and stable rate of deformation accumulation, where the curve presents a linear trend; 3) a tertiary stage dominated by shear deformation. The number of cyclic load repetition, which corresponds the start of the tertiary stage, is called the flow number (*Fn*), when the slope of the curve begins to sharply increase. The Francken model, Eq. (1), has commonly been adopted to represent the ε_p-N curve as it can represent the three stage characteristics and clarify the *Fn* (Bonaquist, 2012).

$$_p = aN^b + c(e^{dN} - 1)$$
(1)

where ε_p is the permanent strain, *N* is the number of repetitions, *a*, *b*, *c* and *d* are four constant parameters. The modelling curves using Eq. (1) in Fig. 2 shows that the Francken model well represents all of the measured ε_p-N relationship. The model has clearly identified the tertiary stage and *Fn* for the measured curves which fail before the maximum load repetition number, 10,000. The modelling curves have shown that the HL modification largely increases the *Fn* when compared to that of the control counterpart mixes, particularly at high temperature.

Fig. 3 shows the calculated average axial resilient modulus, $M_r = \frac{\sigma_1}{\bar{\varepsilon}_r}$, where $\bar{\varepsilon}_r$ is the average of the axial resilient strain measurement. The results in Fig. 3 show that for all the mixes the resilient modulus is considerably influenced by temperature, the higher the temperature the lower the modulus. The HL modification improves the stiffness/rigidity of the asphalt concrete, enhancing the resilient modulus value at all three temperatures.

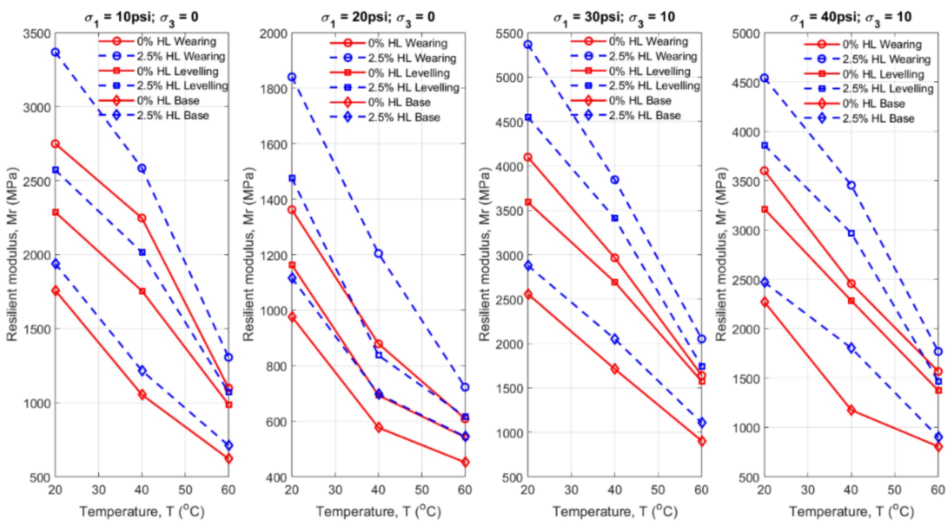


Figure 3. Resilient modulus variation with temperature.

TRIAXIAL RESULTS CHARACTERIZATION

Permanent Deformation

For the sake of pavement design and structural analysis, a fully integrated thermomechanical characteristic model to predict the permanent deformation is a necessary tool required for numerical modelling and simulation. For this purpose, the parameters obtained from the Francken modelling shown in Fig. 2 for permanent deformation and resilient modulus results in Fig. 3 need further investigation to characterise the effects of temperature and the stress states on the two mechanical properties. To be inclusive for both uniaxial and triaxial stress states, for the permanent deformation, this paper proposes the model, Eq. (2), to characterize the effect of the temperature and stress state on the Francken parameters, i.e.:

$$p_{fk} = \exp exp\,(\alpha T)\ \exp exp\,(\beta I)\ + mTI + n \qquad (2)$$

where, p_{fk} represents the four individual parameters, a, b, c, d, of the Francken model for permanent deformation, T is temperature in °C, $I = \sqrt{\sigma_1^2 + \sigma_3^2 + (\sigma_1 - \sigma_3)^2}$ is for the stress state, α, β, m and n are four constants. I is defined by referring to the von Mises stress as asphalt mixes are von Mises material(Deshpande and Cebon, 1999). As asphalt concrete is weak to sustain tensile stress, for both uni- and tri-axial tests, the σ_2 in circumferential direction is neglected in this paper.

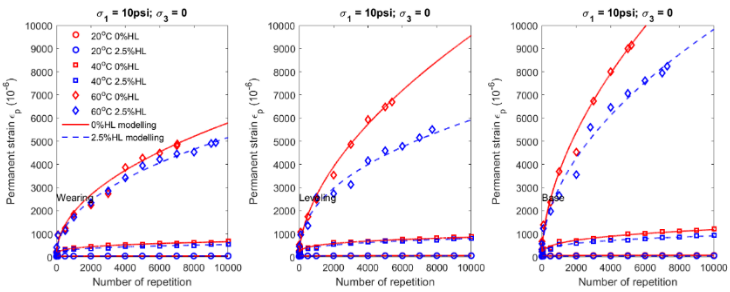


Figure 4. The represented permanent deformation by the 1st term of the Franken model.

For permanent deformation, the Francken model for the ε_p-N curve contains four parameters. Using Eq. (2) to characterise the four parameters will consider temperature and types of mix individually, resulting in a complex and inconvenient characterisation; therefore, for simplification purposes, this paper will adopt the first power function term of the determined Francken model to represent the ε_p-N curve. Fig. 4 shows the results of the term $\varepsilon_p = a\,N^{\,b}$ of the Francken modelling in Fig. 2. It can be seen that although the power function term alone does not clearly reflect the flow number, Fn, it presents a good representation for the ε_p-N curve in the effective range before the load repetition reaches the flow number or the mixes start to fail. The power function model will be accurate enough for permanent deformation or rutting prediction for the sake of pavement design and structural analysis.

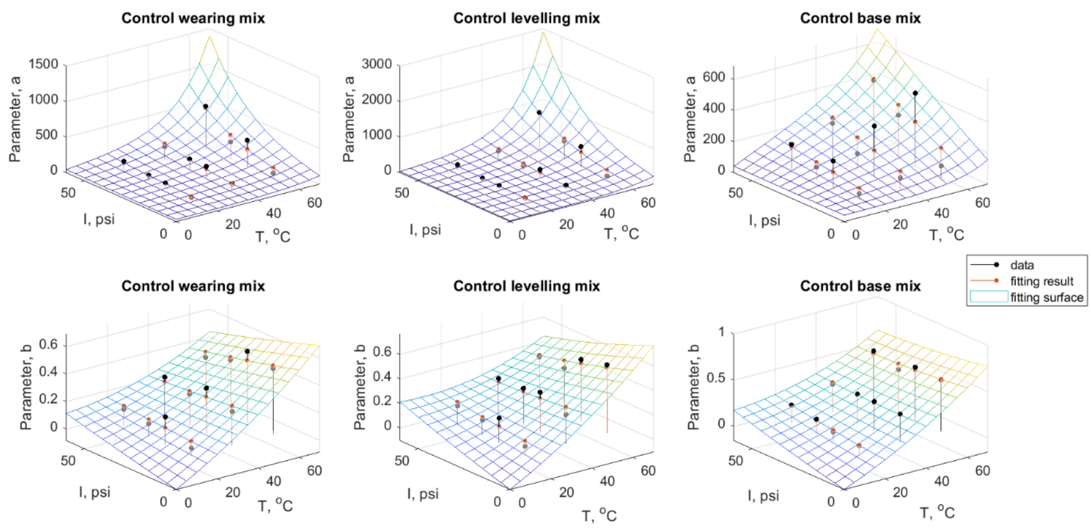


Figure 5. Francken model, Eq. (1), parametric surface for the control mixes

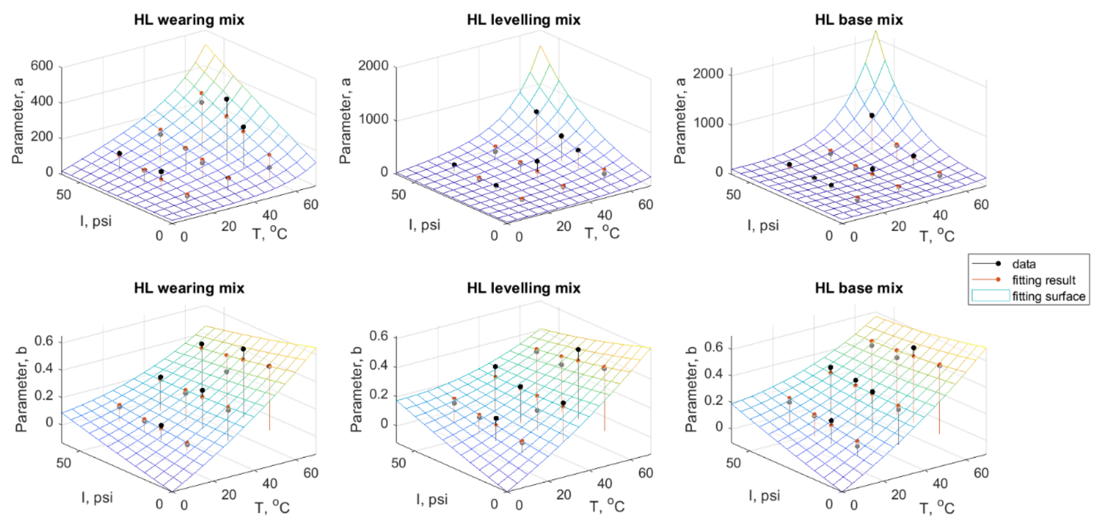


Figure 6. Francken model, Eq. (1), parametric surface for the 2.5% HL mixes.

Figs. 5 and 6 show the represented parametric surfaces of the two determined parameters, *a* and *b*, of the Francken model fitting to the ε_p-N curves for the control and HL mixes. The markers of 'data' and 'fitting result' compare the determined parameters, *a* and *b*, from the fitting results in Fig. 2 with the values of that on the parametric fitting surfaces. The comparison demonstrates that the parametric model, Eq. (2), well represents the permanent deformation of all these mixes under triaxial stress states when exposed to different temperature conditions.

Resilient Modulus

A mathematical expression for granular material resilient modulus under the triaxial stress conditions has been suggested (Zeng and Shao, 2016) , which can be simplified as:

$$M_r = K\sigma_1^m\sigma_3^n$$
(3)

where, M_r is the resilient modulus, K is a material parameter relevant to the atmospheric pressure and void ratio, m and n are two material parameters. σ_1 is the axial stress, σ_3 is the confining pressure. The Eq. (3) has also been adopted for asphalt concrete(Sağlik and Gungor, 2012). However, Eq. (3) has a limitation as it is unable to represent a uniaxial condition when confining pressure is zero. No temperature effect has been explicitly included. This paper proposes a revision to Eq. (3), to make it practical for application to complex stress conditions from uniaxial to triaxial states. The revised model has the form shown in Eq. (4):

$$M_r = \sigma_1^m(\sigma_3 + b)^n$$
(4)

where b is a newly introduced stress constant for the confining stress, σ_3.

Figs. 7 and 8 show the represented M_r surfaces under the axial stress, σ_1, and confining stress, σ_3, states. The markers of 'data' and 'fitting' provide a visual comparison for the accuracy of the representation for the Mr using the Eq. (3) at the four stress states in Fig 5. It can be seen that Eq. (3) well represents the resilient modulus of all these mixes under complex stress and the three temperature conditions. As an example, Fig. 9 displays the parametric values of Eq. (3) at three temperatures for the control wearing mix.

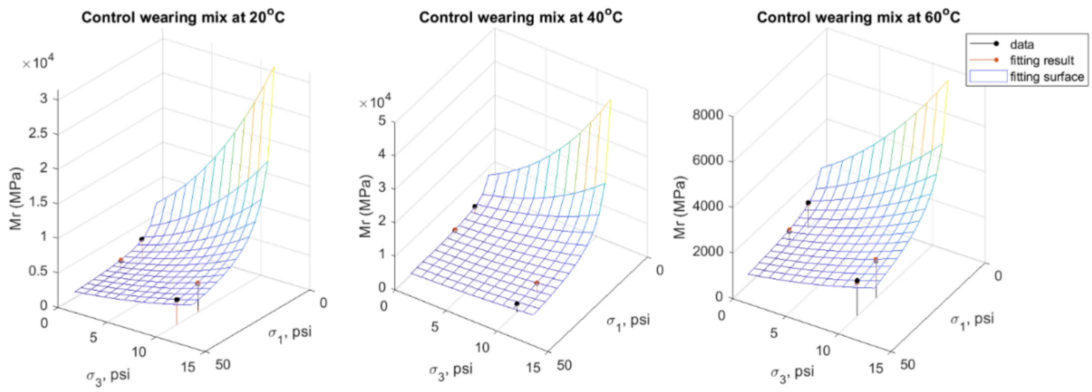


Figure 7. ε_r model, Eq. (3), parametric surface for the control mixes

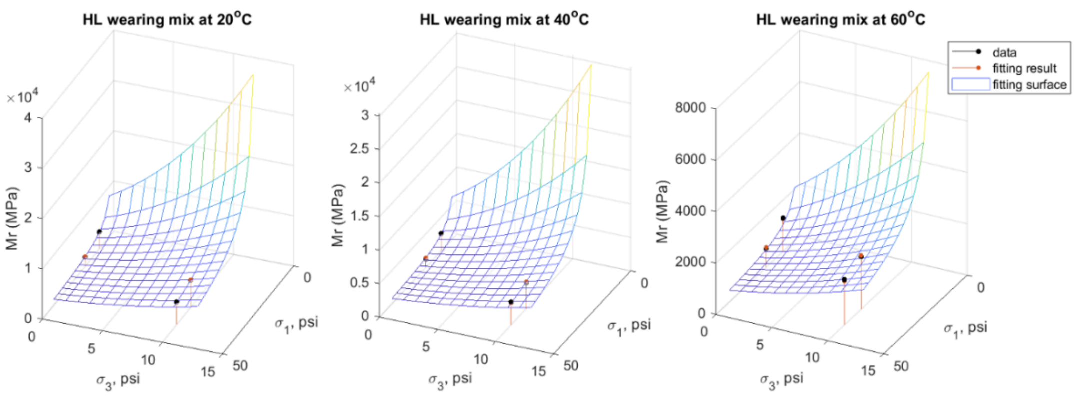


Figure 8. ε_r model, Eq. (3), parametric surface for the 2.5% HL mixes

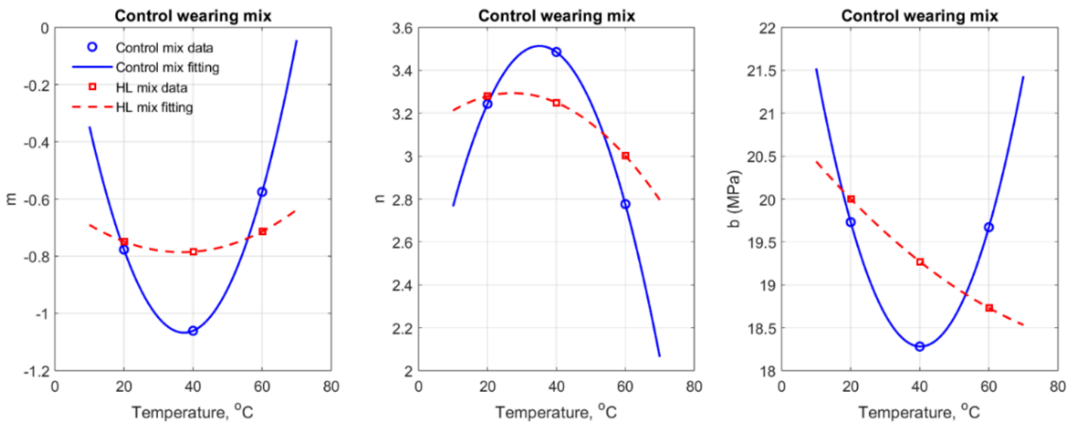


Figure 9. Parameter value, Eq. (4) variation with temperature.

CONCLUSIONS

This paper reports the triaxial tests and modelling characterization for the permanent deformation and resilient modulus of hydrated lime modified. The following conclusions can be drawn from this study.

- HL helps the permanent resistance of the HMA concrete. Its effect is particularly pronounced at high content of mineral filler, and accordingly HL additive.
- The elastic resilient modulus for fresh HMA displays initial increase when exposed to repetitive loads. This is probably due to aggregate re-arrangement in the asphalt matrix which improves the mix of asphalt paste and aggregates. This explanation is in line with the results that the HL addition reduces the resilient strain of mixes, particularly at higher temperature because HL improves the stiffness of the asphalt paste.
- The proposed integrated thermomechanical characteristic model for the parameters of the Francken model for the relationship of the permanent deformation vs load repetition number presents a reasonable representation for the ε_p-N curves from uniaxial to triaxial stress states under different temperatures.
- The modified resilient modulus model also works for wide stress states from

uniaxial to triaxial. Its parameter can be further characterized for the influence of temperature by the second degree of polynomial functions.

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REFERENCES

Bonaquist, R. F. (2012) '*Evaluation of Flow Number (FN) as a discriminating HMA mixture property*'. Wisconsin Highway Research Program.

Bouron, S. *et al.* (2021) 'Improving the durability of asphalt mixtures with hydrated lime: Field results from highway A84', *Case Studies in Construction Materials*. Elsevier, 14, p. e00551.

Deshpande, V. S. and Cebon, D. (1999) 'Steady-state constitutive relationship for idealised asphalt mixes', *Mechanics of materials*. Elsevier, 31(4), pp. 271–287.

Goetz, W. H. and Schaub, J. H. (1959) 'Triaxial Testing of Bituminous Mixtures: Technical Report'. Purdue University.

Ji, J. *et al.* (2021) 'Rutting prediction model of asphalt mixture based on the triaxial repeated load test', *Advances in Civil Engineering*. Hindawi Limited, 2021, pp. 1–9.

Lagos-Varas, M. *et al.* (2022) 'Viscoelasticity modelling of asphalt mastics under permanent deformation through the use of fractional calculus', *Construction and Building Materials*. Elsevier, 329, p. 127102.

Orosa, P., Pérez, I. and Pasandín, A. R. (2022) 'Evaluation of the shear and permanent deformation properties of cold in-place recycled mixtures with bitumen emulsion using triaxial tests', *Construction and Building Materials*. Elsevier, 328, p. 127054.

Sağlik, A. and Gungor, A. G. (2012) 'Resilient modulus of unbound and bituminous bound road materials', in *5th Eurasphalt & Eurobitume congress*, pp. 455–463.

Sebaaly, P. E., Hitti, E. and Weitzel, D. (2003) 'Effectiveness of lime in hot-mix asphalt pavements', *Transportation Research Record*. SAGE Publications Sage CA: Los Angeles, CA, 1832(1), pp. 34–41.

Taherkhani, H. and Tajdini, M. (2019) 'Comparing the effects of nano-silica and hydrated lime on the properties of asphalt concrete', *Construction and Building Materials*. Elsevier, 218, pp. 308–315.

Xu, Y. and Sun, L. (2013) 'Study on permanent deformation of asphalt mixtures by single penetration repeated shear test', *Procedia-Social and Behavioral Sciences*. Elsevier, 96, pp. 886–893.

Zeng, F. and Shao, L. (2016) 'Unloading elastic behavior of sand in cyclic triaxial tests', *Geotechnical Testing Journal*. ASTM International, 39(3), pp. 462–475.

Zhang, K., Xie, W. and Zhao, Y. (2021) 'Permanent deformation characteristic of asphalt mixture under coupling effect of moisture, overload and loading frequency', *Construction and Building Materials*. Elsevier, 272, p. 121985.