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On the thermal sensitivity of unbound granular pavement layers

Eyal Levenberg and Irene Rocchi

ABSTRACT

The reversible mechanical behavior of unbound granular layers (UGLs) is commonly characterized by a stress-state dependent resilient modulus. This paper investigated the dependency of in situ resilient modulus upon a change in temperature above freezing conditions, i.e., the thermal sensitivity of UGLs in pavement systems excluding frost action. Such sensitivity is usually ignored in design and analysis because, on a material level, resilient modulus parameters are temperature independent. A model was developed to analyze this dependency by considering the stress-state changes that arise when UGLs are suppressed from thermally expanding or contracting. The formulation was incremental, based on linear thermoelasticity equations, and required as input readily available information; it assumed that changing temperature conditions are exogenous to the model and that no external loads are applied. A transcendental equation was subsequently derived, from which the sought sensitivity of UGLs could be resolved and quantified. Based on a parametric investigation of the model, covering a wide range of representative parameters, it is concluded that UGLs exhibit non-negligible thermal sensitivity. The extent of the calculated sensitivity coincides with field observations based on deflection testing, and also with seasonal factors that are traditionally applied to adjust field-measured moduli. Ultimately, the study shows that resilient modulus of UGLs is governed by an initial stress-state that is associated with a certain reference temperature level, and also by the temperature change compared to the reference.

Keywords: Unbound granular material, Resilient modulus, Thermal sensitivity, Thermoelasticity, Thermal expansion.

Introduction

The concept of resilient modulus, introduced several decades ago [1–6], is nowadays widely applied to describe the reversible constitutive behavior of well-compacted unbound granular materials (UGMs) [7–10]. In analogy with Young's modulus, resilient modulus (commonly denoted by M_R), represents a stress-state dependent elastic modulus. For UGMs in unfrozen conditions M_R is typically expressed in terms of the first stress invariant I_1 (positive in compression) and the second invariant of the stress deviator tensor J_2 [11,12]:

$$M_R = M_R(I_1, J_2) \quad (1)$$

where $I_1 = \sigma_1 + \sigma_2 + \sigma_3$, $6J_2 = (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2$, and the three σ_i 's are effective principal stresses, i.e., containing moisture suction effects [13].

The resilient Poisson's ratio ν_R is also stress-state dependent [4,14,15], formulated in a manner that is linked with M_R to guarantee stress-path independency and energy conservation [13,16–18]. Nonetheless, ν_R is frequently treated as constant, possibly because it varies within a narrow range and possibly due to experimental difficulties in obtaining reliable values.

Excluding frost action, resilient properties of UGMs have always been regarded as temperature independent due to the thermally inert nature of the individual aggregates, i.e., the mineral elastic coefficients are insensitive to temperature changes within the ranges encountered in typical engineering applications. A recent study reaffirmed this interpretation by performing resilient modulus experiments

at several temperature levels [19]. Accordingly, unbound granular layers (UGLs) are commonly treated as thermally insensitive for pavement design and analysis purposes [9,20–24].

However, UGLs must exhibit thermal sensitivity when temperature changes take place. The sensitivity is associated with changes in stress-state that originate from the material's tendency to thermally expand or contract - and the kinematic suppression to do so. This thermomechanical effect is the reason for measured variations in lateral earth pressure on structures upon variations in temperature [25–28]. This mechanism has also been reproduced in discrete element simulations of confined granular media [29,30]. For UGLs, such thermal sensitivity mechanism was noted and addressed by Chandra et al. [31,32]. The impetus for the work was the observation, based on deflection testing, that UGLs in low-volume roads exhibited M_R fluctuations in correlation to temperature (excluding frost action). The fluctuations were non-negligible in magnitude, e.g., an increase in UGL temperature from 10 °C to 40 °C was accompanied by an increase in backcalculated M_R of about 50%.

A micromechanical theory was proposed by Chandra et al. for modeling the observed thermal sensitivity. The material was viewed as a three-dimensional collection of equiradii linear elastic spheres in contact. It was further assumed that the spheres resided inside a closed rigid container preventing any bulk expansion from taking place. Subsequently, a formula was derived for quantifying the change in I_1 resulting from a temperature increment – from which a corresponding change in M_R could be calculated (after assuming the initial stress-state and M_R as a power-law of I_1). This formula considered the packing level of the spheres (i.e., porosity), the individual sphere properties - elasticity coefficients and coefficient of volumetric thermal expansion, yet it was missing a relevant input: the resilient properties prevailing prior to the temperature increment. While good reproducibility of backcalculated M_R values was noted in the study, the work has not been widely accepted in the pavement engineering community. One possible reason is the utilization of a micromechanical approach, which is perceived (predominantly) as a research tool suited for gaining insight into particle-scale interactions, and not as a geotechnical design and analysis tool [33]. Another possible reason is the unrealistic assumption of the spheres being fully confined in a rigid box, given that for pavement systems, UGLs are unrestricted to thermally expand in the vertical direction (at least).

Subsequently, it is the objective of the current contribution to develop a method for quantifying the thermal sensitivity of UGLs in pavement systems, i.e., the dependency of M_R on temperature changes. Three main attributes are sought as means of enhancing the possible acceptance and utility of the work: (i) developing a formulation within a continuum mechanics framework, (ii) considering representative in situ boundary and initial conditions, and (iii) establishing all required input parameters on readily available information or on data obtainable from standard test procedures.

The paper commences by introducing the governing thermoelastic equations for an UGM element; these are then morphed to address the situation of an UGL - for which thermal sensitivity is quantified. Then, calculation steps are demonstrated and results are generated as part of a parametric investigation. The paper terminates with a discussion about the model assumptions and limitations, followed by a short summary of the findings and some concluding remarks.

Thermoelastic analysis

Consider an isotropic and well-compacted UGM element under a certain temperature level T and a stress-state defined in terms of the three principal effective stresses. In this reference state the prevailing resilient properties are M_R and ν_R . Upon a small temperature increment dT or upon a small stress-

state increment $d\sigma_i$ (or both), a corresponding increment of principal strains $d\varepsilon_i$ will be induced. Assuming all increments are infinitesimally small, the usual linear thermoelasticity formulation applies:

$$\begin{bmatrix} d\varepsilon_1 \\ d\varepsilon_2 \\ d\varepsilon_3 \end{bmatrix} = \frac{1}{M_R} \begin{bmatrix} 1 & -\nu_r & -\nu_r \\ -\nu_r & 1 & -\nu_r \\ -\nu_r & -\nu_r & 1 \end{bmatrix} \begin{bmatrix} d\sigma_1 \\ d\sigma_2 \\ d\sigma_3 \end{bmatrix} - \alpha \begin{bmatrix} dT \\ dT \\ dT \end{bmatrix} \quad (2)$$

where α denotes the coefficient of linear thermal expansion of the UGM. Some guidance for selecting representative α values can be obtained from examining the few existing studies dealing with volume changes in sands under thermal cycles [34–36]. Excluding cases addressing loose to intermediate relative densities, it was observed that dense sand exhibits volume increase that is almost identical to the thermal expansion exhibited by individual sand particles. Accordingly, for UGMs in pavement applications the value of α can be chosen based on the aggregate rock type. It was also pointed out in these studies that the observed expansion was stress independent - confirming that α in Eq. (2) may be taken as constant.

To quantify the thermal sensitivity of an UGL, the pavement system is modeled as a stratified half-space composed of isotropic materials. Referring to Fig. 1, a Cartesian coordinate system is positioned at the half-space surface with the z -axis pointing down into the medium, while both the x and y axes are oriented parallel to the layering. No external loads are applied, and temperature conditions are assumed to be above freezing, timewise constant, spatially uniform in the xy plane, and with variability only along the depth, i.e., $T = T(z)$. In this configuration, the principal stress directions coincide with the chosen coordinate directions, i.e., σ_1 with the z -axis, σ_2 with the x -axis, and σ_3 with the y -axis. Also, due to symmetry, the two lateral effective stresses are identical, i.e., $\sigma_2 = \sigma_3$.

For any UGM element that is unsaturated (or saturated, but resides above the water table level), the effective vertical stress is defined by the depth of the element below the surface z_0 , the weighted average total unit-weight of all overlying layers γ_t , and the prevailing moisture suction S , i.e., $\sigma_1 = z_0\gamma_t - S$ where S itself is negative - representing pore water tension. The corresponding lateral effective stress is $\sigma_2 = K_0\sigma_1$, where K_0 is the coefficient of at-rest earth pressure.

Fig. 1. Assumed pavement model for thermal sensitivity analysis.

When the temperature profile slightly changes, all UGM elements located at the same depth experience an identical thermal increment. Due to the infinite lateral dimensions of the UGL, all elements are restrained from deforming laterally; also, given that the system is not externally loaded, the vertical stress-state remains unchanged. This situation can be inserted into Eq. (2) by setting $d\sigma_2 = d\sigma_3$, $d\varepsilon_2 = d\varepsilon_3 = 0$, and $d\sigma_1 = 0$; the outcome is:

$$M_R \frac{\alpha dT}{1 - \nu_R} = d\sigma_2 \quad (3)$$

For any UGM element, this expression interrelates stress-state increments, thermal increments, and prevailing resilient properties. It can be viewed as the incremental analog to Westergaard's analysis of stresses induced in concrete plates upon exposure to a uniform temperature change [37]. In case of a non-infinitesimal temperature change a nonlinear version of Eq. (3) can be written by simply replacing dT with ΔT and replacing $d\sigma_2$ with $\Delta\sigma_2$. The resulting equation is nonlinear because both M_R and ν_R depend on stress-state through the stress invariants and hence on $\Delta\sigma_2$.

Demonstrative application

The above-described formulation is demonstrated here for quantifying the thermal sensitivity of an UGL. The following resilient modulus expression was adopted for this purpose [11]:

$$M_R = (k_1 P_a) \left(\frac{I_1}{P_a} \right)^{k_2} \left(\frac{\sqrt{2J_2/3}}{P_a} + 1 \right)^{k_3} \quad (4)$$

where $P_a = 100$ kPa denotes atmospheric pressure, and the three k_i 's are unitless material parameters: k_1 and k_2 are positive while k_3 is negative. This M_R expression was inserted into Eq. (3) along with all model definitions and symbols, and after assuming a constant ν_R . Specifically, the stresses used in the invariant expressions I_1 and J_2 were: $\sigma_1 = z_0 \gamma_t - S$, $\sigma_2 = K_0 \sigma_1 + \Delta\sigma_2$, and $\sigma_3 = \sigma_2$. With some rearrangement, the following was obtained:

$$\underbrace{\left(\frac{(k_1 P_a) \left(\frac{(z_0 \gamma_t - S)(1 + 2K_0) + 2\Delta\sigma_2}{P_a} \right)^{k_2}}{\left(\frac{2(z_0 \gamma_t - S)(1 - K_0) - 2\Delta\sigma_2}{3\sqrt{2}P_a} + 1 \right)^{-k_3}} \right)}_{M_R} \frac{\alpha \Delta T}{1 - \nu_R} = \Delta\sigma_2 \quad (5)$$

This is a transcendental equation from which the sought thermal sensitivity of UGLs can be resolved. With all model parameters known, and for a given temperature increment ΔT , it requires a numerical solution for $\Delta\sigma_2$. Since the expression is of the form $f(\Delta\sigma_2) = \Delta\sigma_2$ one possible solution scheme is fixed-point iteration. This scheme works by assuming $\Delta\sigma_2$, evaluating the left-hand side, treating the outcome as a new (improved) assumption for $\Delta\sigma_2$, and repeating until convergence is attained, i.e., until the left-hand side and right-hand side of Eq. (5) are sufficiently close [38]. Once $\Delta\sigma_2$ is found it also becomes possible to evaluate the M_R (bracketed term) associated with the imposed temperature change ΔT .

The coefficient of at-rest earth pressure K_0 in Eq. (5) corresponds to the initial UGL conditions associated with $\Delta T = 0$. For any ΔT , either positive or negative (also zero), the coefficient of at-rest earth pressure is denoted by $K_0^{\Delta T}$ such that $K_0^{\Delta T} = K_0 + \Delta\sigma_2 / \sigma_1$; expressing the fact that lateral stresses increase while vertical stresses remain constant. There is no safeguard mechanism in Eq. (5) against $K_0^{\Delta T}$ exceeding the passive earth pressure coefficient or falling below the active earth pressure coefficient. These bounds must be separately checked and enforced in order to ensure that the calculation results are physically meaningful and admissible.

Eq. (5) was evaluated considering several ΔT 's covering a range of 50 °C, from $\Delta T = -25$ °C to $\Delta T = +25$ °C . Both bounds of this range are relevant for pavements under service, e.g., an UGL constructed at 30 °C that experiences a temperature of 5 °C corresponds to $\Delta T = -25$ °C , and an UGL constructed at 15 °C that experiences a temperature of 40 °C corresponds to $\Delta T = +25$ °C . Moreover, a set of representative parameter values was chosen to serve as a reference; this set is summarized in Table 1. Also investigated was the influence of varying the parameter values (one at a time) on the calculation results; the considered ranges are also listed in Table 1.

Table 1
Parameter values for method demonstration

Symbol	Parameter	units	Reference value	Range	Comments
z_0	Depth of UGM element	m	0.3	0.1 $\leftrightarrow$ 0.5	See Fig. 1
γ_t	Average total unit weight of overlying layers	kN/m ³	23	-	
S	Moisture suction	kPa	-15	-25 $\leftrightarrow$ -5	
k_1	M_R coefficient	unitless	900	700 $\leftrightarrow$ 1100	See Eq. (4)
k_2	M_R coefficient	unitless	0.7	0.5 $\leftrightarrow$ 0.9	
k_3	M_R coefficient	unitless	-0.2	-0.4 $\leftrightarrow$ 0.0	
K_0	Initial at-rest earth pressure coefficient	unitless	3.0	2.0 $\leftrightarrow$ 4.0	Refer to [39]
ν_R	Resilient Poisson's ratio	unitless	0.30	0.20 $\leftrightarrow$ 0.40	Assumed stress-independent
α	Coefficient of linear thermal expansion	1/°C	$10 \cdot 10^{-6}$	$(6 \leftrightarrow 14) \cdot 10^{-6}$	Dolomite/granite/sandstone

Thermal sensitivity calculation results are shown in Figs. 2 and 3; each figure contains four charts that depict resilient modulus versus thermal increment. Every chart contains several curves with the central curve (solid line) common to all; this central curve represents the thermal sensitivity for the reference parameter set listed in Table 1. The other curves (dashed lines) depict the outcome of varying one of the parameter values while keeping all others constant. The influence of varying the resilient modulus properties, i.e., the three k_i 's and the Poisson's ratio ν_R is shown in Fig. 2. The influence of varying parameters related to the initial stress-state, K_0 , z_0 , and S , as well as varying the thermal expansion coefficient α , is shown in Fig. 3.

Discussed first is the behavior of the reference curve. Initially, before any temperature increment is applied ($\Delta T = 0$), the M_R value is 117 MPa. This value can be simply obtained by inserting the reference parameter set into Eq. (4); it is graphically denoted across all charts by a small hollow circular marker superposed over the solid lines. As ΔT increases or decreases from zero, the reference curve exhibits a corresponding change in M_R indicating thermal sensitivity. It can be seen that for $\Delta T = +25$ °C the resilient modulus increases to $M_R = 168$ MPa, i.e., a relative change of +44%. This change was accompanied by an increase of the lateral-to-vertical effective stress ratio from $K_0 = 3.0$ to $K_0^{\Delta T} = 5.7$. When $\Delta T = -25$ °C the resilient modulus decreases to $M_R = 84$ MPa, i.e., a relative change of -28%. This change was accompanied by a drop of the lateral-to-vertical effective stress ratio from $K_0 = 3.0$ to $K_0^{\Delta T} = 1.6$. Both the low and high $K_0^{\Delta T}$'s are within an acceptable range - indicating physically admissible results [39].

Referring next to Figs. 2(a-c), it can be noticed that the thermal sensitivity is influenced when

varying the three resilient modulus parameters (the k_i 's). While the general trend of increasing M_R with increasing temperature level persists across all cases, the sensitivity increases with increasing each of the k_i 's separately (and vice versa). The effect on thermal sensitivity when varying the Poisson's ratio is plotted in Fig. 2(d); it can be seen that the effect is marginal.

Fig. 2. Thermal sensitivity plots based on Eq. (5) of an UGL with Table 1 model parameters: (a) effect of varying resilient modulus parameter k_1 , (b) effect of varying resilient modulus parameter k_2 , (c) effect of varying resilient modulus parameter k_3 , and (d) effect of varying resilient Poisson's ratio.

Fig. 3(a) deals with different K_0 values; it shows that the resulting effect on the $M_R - \Delta T$ curves is a vertical translation without shape change. This means that, in absolute terms, the thermal sensitivity is independent of the initial stress ratio. The effect of varying z_0 is plotted in Fig. 3(b); as can be seen, the effect also appears as a vertical translation of the reference M_R curve without any change in shape, i.e., M_R increases with increase in element depth. The effect of varying S is plotted in Fig. 3(c); as can be seen, changes in moisture suction result in vertical translations of the reference M_R curve without any change in shape, i.e., M_R increases with increase in $|S|$. Therefore, in absolute terms, the initial stress conditions governed by K_0 , z_0 , and S do not influence the thermal sensitivity of M_R . However, if the thermal sensitivity was assessed in relative terms - relative to the initial M_R level - then larger K_0 , z_0 , or $|S|$ (or all three), would lessen the relative thermal sensitivity. Finally, with respect to Fig. 3(d), it can be seen that varying α impacts somewhat the thermal sensitivity. A larger thermal expansion coefficient yields higher sensitivity (and vice versa). In this connection, it should be noted that the chosen reference α value is representative of silica, while the plotted range applies to a wide variety of aggregate sources: basalt, marble, granite, sandstone, limestone, and dolomite [40–41].

Fig. 3. Thermal sensitivity plots based on Eq. (5) of an UGL with Table 1 model parameters: (a) effect of varying the initial at-rest earth pressure coefficient, (b) effect of varying element depth, (c) effect of varying moisture suction, and (d) effect of varying the coefficient of linear thermal expansion.

Discussion

The model developed in this work was focused on isolating and subsequently quantifying the thermal sensitivity of UGLs resulting from temperature induced stress-state changes. The development was based on three main assumptions: (i) temperature profile changes are exogenous to the model, (ii) the mechanical behavior of UGLs is elastic, and (iii) the lateral dimensions of UGLs are infinite.

With respect to the first assumption, it should be noted that thermal conductivity, which is one of the factors determining temperature distribution with depth, is known to depend on density, initial stress conditions, and moisture content (or saturation ratio) [42–45]. Also, in actuality, there is some cross-interaction between moisture level and temperature [46–49]; particularly, an increase in temperature may be accompanied by a reduction in overall moisture content through evaporation or locally due to convective motion of the pore water - with a subsequent increase in pore water tension. On the other hand, if relative humidity increases and the moisture vapor cannot escape the pore space, then the surface tension of the pore water will reduce. All aforementioned effects are complex scenarios capable of impacting the resilient modulus. Currently these are not captured by the model, and must therefore be addressed separately if deemed important.

The second assumption, that of elastic behavior, is seminal to the applicability of Eq. (2), and therefore to the entire derivation and findings. It basically asserts that any pre-existing UGL stresses that control M_R (treating moisture-change effects as marginal) are essentially timewise constant as long as the temperature level does not change. This assumption is deemed very realistic for densely packed particulate materials, as demonstrated in discrete element models [50,51], in laboratory compaction experiments on sand [52], in laboratory thermal cycling experiments on dense sand [34], in

large-scale laboratory experiments on UGM compaction [53], in field investigations on compaction-induced stresses on retaining walls [54,55], and in application of geophysical exploration techniques to assess the in situ modulus of UGLs [56]. Finally, it is noted that there exists some experimental evidence that well-compacted UGMs under constant temperature exhibit time-dependent mechanical behavior, e.g., creep under constant level of load, and stress-relaxation under constant level of deformation [57]. Fortunately, these effects are only active over relatively short time intervals of the order of seconds and minutes. Across longer time scales of the order of hours, weeks, and months (for which temperature changes are relevant), the material behavior is essentially reversible and time-independent, supporting the applicability of Eq. (2).

The third assumption, of lateral infinity, is considered reasonable for most wide constructions such as multilane highways, airport pavements, seaport pavements, and parking lots. It may not apply to relatively narrow pavement systems such as railways, single-lane roads, bicycle paths, etc. To accommodate these situations the proposed approach can be slightly modified by considering the UGL as an infinitely long strip of finite width. Taking the y -axis to denote the strip width direction, Eq. (2) can be revisited with: $d\sigma_1 = 0$ (UGL free to expand or contract along the z -axis), $d\sigma_3 = 0$ (UGL free to expand or contract along the y -axis), and $d\varepsilon_2 = 0$ (UGL infinitely long in the x -axis direction). This set of conditions, in analogy to Eq. (3), yields: $M_R \alpha dT = d\sigma_2$ (note the absence of the Poisson's ratio). Subsequently, upon insertion of M_R (Eq. (4)) with the corresponding stress expressions, i.e., $\sigma_1 = z_0 \gamma_t - S$, $\sigma_2 = K_0 \sigma_1 + \Delta\sigma_2$, and $\sigma_3 = K_0 \sigma_1$, another transcendental equation can be formulated:

$$\left(\frac{(k_1 P_a) \left(\frac{(z_0 \gamma_t - S)(1 + 2K_0) + \Delta\sigma_2}{P_a} \right)^{k_2}}{\underbrace{\left(\frac{2\sqrt{(z_0 \gamma_t - S)^2 (1 - K_0)^2 - \Delta\sigma_2 (z_0 \gamma_t - S)(1 - K_0) + (\Delta\sigma_2)^2}}{3\sqrt{2}P_a} + 1 \right)^{-k_3}}_{M_R}} \right) \alpha \Delta T = \Delta\sigma_2 \quad (6)$$

This equation applies to the case of a UGL that is constrained from thermally expanding (or contracting) only in one (x -axis) direction. Therefore, compared to Eq. (5), it will predict reduced thermal sensitivity of about 50%. Also in this case, the coefficient of at-rest earth pressure will only change in the x -axis direction.

Conclusion

This work investigated the thermal sensitivity (excluding frost action effects) of UGMs in pavement systems. The starting point for the analysis was that the resilient modulus of UGMs is governed by the prevailing effective stress-state, with material constants (e.g. the k_i 's in Eq. (4)) that are essentially temperature independent. Subsequently, a model was developed to calculate stress-state changes in UGLs due to changes in temperature (Eq. (5)); it considered representative in situ boundary and initial conditions assuming no external loads are applied (see Fig. 1). The model was parametrically investigated, covering a wide range of characteristic input parameters (see Table 1).

The main conclusion from this investigation is that UGLs exhibit non-negligible thermal sensitivity above freezing conditions. This outcome was clearly demonstrated across all considered cases in the parametric investigation (see Figs. 2 and 3). Some validity of the findings can be derived from the fact that the extent of the calculated sensitivity matches reported field observations based on

deflection testing [31,32]. Also, the model forecasts M_R changes that coincide with seasonal factors traditionally applied to adjust field-measured moduli for subsequent design, for evaluating or reporting on structural condition, and for normalizing axle load conversion formulas [21,22,58–60]. This means that the work may be utilized to rationalize, at least in part, the selection and application of such seasonal factors.

Ultimately, the study shows that resilient modulus of UGLs is governed by an initial stress-state that is associated with a certain reference temperature level, and also a by the temperature change compared to the reference. Thus, another conclusion of practical importance that emerges from this work is that the timing of construction operations is important. UGLs compacted at the low-end of the expected temperature range will only experience increase in their resilient moduli under service, thus benefitting from the thermal sensitivity. On the other hand, UGLs compacted at the high-end of the expected temperature range will exhibit decreased resilient moduli under service.

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