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Hydromechanical Analysis of Flexible Pavement Foundations with Excess Moisture Content

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Abstract: Excess water in pavement foundations has been recognized for a long time as a principal cause of pavements failure. Few studies were conducted in the last two decades to investigate the influence of water on the stiffness of pavement foundations and account for this influence in pavements design. Such studies, however, did not explicitly model the water phase and its direct impact on the pavement distresses. In this paper, finite element analyses considering the foundations as nonlinear partially saturated porous media were carried out to examine the impact of their excess water content on the pavements rutting. The analysis results show that pavement deflection can increase by almost three times when the subgrade becomes saturated and by more than four times when both the granular base and subgrade attain saturation. The results obtained herein demonstrate the interactive behavior between the hydraulic state of the foundations and pavement mechanical response and, thus; they signify the importance of considering the Biot's coupling phenomenon in modelling the effect of the foundations excess moisture content in pavements analysis.

1. INTRODUCTION

Excess water in pavement foundations has been recognized for a long time as a principal cause of pavements deterioration (Haynes and Yoder 1963). The adverse impact of excess water on the mechanical response of pavement foundations was substantiated by a number of field and laboratory investigations. Cedergren (1987) demonstrated that if the pavement is saturated only 10 % of its life, a pavement section with a moderate stability factor will be serviceable only about 50 % of its fully drained performance period. Vuong et al. (1994) reported that a 5% increase in relative water content from optimal water content could lead to a 400 % reduction in the pavement life. Sharp et al. (1999) reported significant deterioration of the in-situ moduli values of gravel bases upon wetting (or improvement on drying) by more than a factor of 2. Christopher et al. (2006) indicated that added moisture in an unbound aggregate base and fine-grain subgrade is anticipated to result in loss of their stiffness on the order of 50 % or more. Korkiala-Tanttu and Dawson (2007) showed much faster rutting of a test pavement section having a high water table than one with a low water table.

The effects of the variation of moisture on the pavement response was often accounted for by modifying the resilient moduli of the foundations based on their moisture content; refer to the AASHTO Mechanistic-

Empirical Pavement Design Guide (M-EPDG) (ARA 2004). In some cases, the effect of the moisture content variation was simulated by introducing a constitutive law that idealizes the partially saturated porous medium of the foundation as a mechanically equivalent one phase-soil medium (Heath et al. 2004, Gupta et al. 2007, Nazzal et al. 2010). However, the current methods of modeling the excess water in pavements including the M-EPDG and constitutive theory approaches do not realistically model the water phase in the pavement nor do they explicitly quantify its effect on the pavement structural response. Also, the complexity of these methods, particularly the M-EPDG approach (Laloui et al. 2009), makes them impractical for routine pavement analyses. What is more, the seepage studies carried out on pavements to evaluate their drainage quality under different field conditions (Birgisson and Roberson 2000, Ariza and Birgisson 2002, Rabab'ah and Liang 2007) treated the pavement as a rigid structure without taking into account the traffic loading-induced water flow or pore water pressure.

Given the fact that excess water in the pavement foundations can greatly deteriorate its response, it was the goal of this paper to model the water phase and its detrimental effect more accurately by considering the foundations as deformable porous media whose behavior is governed by the coupled theory (Biot 1941). More specifically, the primary objectives of the paper were:

1- To build a finite element model that simulates the water flow-deformation coupled behavior of the partially saturated unbound foundations of conventional flexible pavements under traffic loading;
2- To quantify the detrimental impact of the foundations excess water on the structural performance of the pavement under both the porous nonlinear elastic and porous elastoplastic mechanical response of the foundations;
3- To investigate the drainability of the granular base layer under different permeability and traffic loading speed and examine its relationship to pavement stiffness against rutting.

2. COUPLED THEORY APPLIED TO PAVEMENT FOUNDATIONS

The application of the hydromechanical coupled theory (Biot 1941) to pavement structures has received little attention by the respective practitioners and researchers. Although few coupled analysis studies have been carried out on pavements in the recent years (Kettil et al. 2005, Zhong and Jian-Hua 2007, Dong et al. 2008), such studies dealt with the foundations as fully saturated media. In other words, the soil matric suction and partially saturated flow in the foundations were not accounted for in these studies. However, in order to accurately assess the effect of excess water of the foundations on the structural performance of the pavements, the coupled analysis should model the partially saturated state of the foundations. Before establishing the coupled finite element model, it is worthwhile to elaborate the underlying equations governing the coupled response of a partially saturated porous mixture, as done herein.

Generally and under the atmospheric pore air pressure, a partially saturated porous soil mixture is governed simultaneously by the linear momentum conservation equation of the mixture as well as the mass and the linear momentum conservation equations of the fluid in the mixture. However, the problem of the granular foundations of pavements under a moving traffic load can be considered a quasi-static problem in which the fluid acceleration induced by the traffic load is insignificant and, hence; it can be neglected without affecting the solution accuracy (Lewis and Schrefler 1998). Therefore, the equations governing the coupled response of the partially saturated pavement foundations can be expressed in the Cartesian coordinates system by:

[1] $\sigma_{ij} + \rho B_i = 0$

[2] $(k^{e}_{ij} \, (- p_{w,j} + \rho_w S B_j))_{,i} + \alpha \dot{\varepsilon}_{ii} + \dot{p}_w \, / Q = 0$

In the equations 1 and 2 above, σ_{ij} is the total stress tensor given by $\sigma_{ij} = \sigma'_{ij} + \delta_{ij}\chi\alpha p_w$, where σ'_{ij} is Bishop effective stress, δ_{ij} is Kronecker delta, χ is Bishop's parameter, which is considered for simplicity equal to the degree of saturation (*S*) (Lewis and Schrefler 1998), *α* is Biot's effective stress parameter which is unity for incompressible soil skeleton, *ρ* is the mass density of the mixture, B_i is the body force vector, k^e_{ij} is the effective permeability tensor given by $k^e_{ij} = k_{ij} /g\ \rho_w$, where k_{ij} (length/time) is the permeability tensor and *g* is the magnitude of the gravity acceleration, p_w is the pore water pressure, ρ_w is the mass density of the water in the mixture, ε_{ii} is the volumetric strain (first invariant of the strain tensor), Q is the storage capacity given by Q = $(1/n)(\partial p_w/\partial S)$ assuming water and soil skeleton incompressible, and n is the medium porosity. The dot overlying ε_{ii} and p_w in equation 2 implies derivative with respect to time whereas the subscripts i and j are notations used to represent the tensors in an indicial form. Given a mechanical constitutive law with the hydraulic and mechanical boundary conditions, the Galerkin method is used to develop the coupled finite element formulations from equations 1 and 2 above which formulations are then truncated in time with appropriate algorithms for the pore water pressure and displacement fields.

3. DEVELOPMENT OF THE FINITE ELEMENT MODEL

Figure 1 shows the model configuration of the pavement cross section analyzed. As shown in this figure, only one-half of the road cross section was modeled due to symmetry around the road centerline. Also, since a nonlinear coupled three dimensional analysis requires large computations time, the pavement was analyzed as a two dimensional (2D) plain strain problem. White et al. (2002) indicated that pavements can be modeled as a 2D plain strain problem without significant loss in accuracy. The materials of the pavement system analyzed represent realistic pavement layers that were adopted from the study of Rabab'ah (2007); refer to table 1 and figure 2 for the material input parameters used in the analyses. With respect to loading, the model was analyzed for a single wheel load of 40 kN (9000 Ib) with a tire contact pressure of 550 KPa (80 psi) and a rectangular contact domain having dimensions of L= 406.4 mm (16 in) and B =177.8 mm (7 in) (Yoder and Witczak 1975). This loading rectangle was applied through a triangular wave with duration of 0.1 second corresponding to an average speed of around 32.18 km/h (20 mph) (Barksdale 1971). To fulfill symmetry, the load was applied at the center of the road. The dimensions of the model (4.5 m wide and 3 m deep) are considered far away enough from the traffic-loaded area to eliminate edges error that can result from insufficient model size. In terms of the boundary conditions, the bottom edge of the model was assumed to be impermeable and fixed horizontally and vertically while the model sides were assumed to be impermeable and fixed in the horizontal direction only. On the other hand, since most AC surface layers have relatively low permeability and can often be treated as impervious (Erlingsson et al. 2009, Ariza and Birgisson 2002), the AC layer was considered impermeable and modeled as one phase medium. Consequently, no hydraulic boundary conditions were imposed on the asphalt concert (AC) layer. Regarding meshing, the AC layer was discretized with biquadratic quadrilateral plain strain element whilst the base and subgrade were truncated with biquadratic displacement, bilinear pore pressure quadrilateral plane strain element. A typical mesh used in the analyses is illustrated in figure 1.

The FE simulations, which are carried out with the general purpose code ABAQUS (HKS 2007), started with an initial step that simulated the subgrade under the in-situ loading state. In this step, the subgrade was assumed to be under the hydrostatic equilibrium (no-flow) condition. Following the initial step, a new porous medium analysis step was created to model the response of the subgrade due to the construction of the base and AC layers. Subsequently, a second porous medium analysis step simulating the transient coupled response of the pavement under the wheel load was created. In each porous medium analysis step, the coupled analysis started with an initial time increment that was assigned based on the recommendations of Vermeer and Verruijt (1981) to avoid nonphysical oscillations and, consequently, divergence of the coupled analysis.

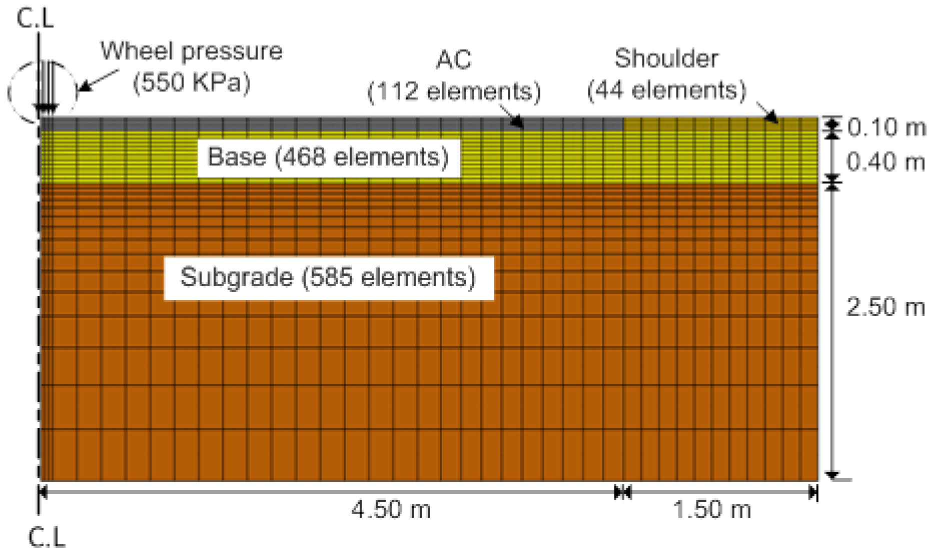
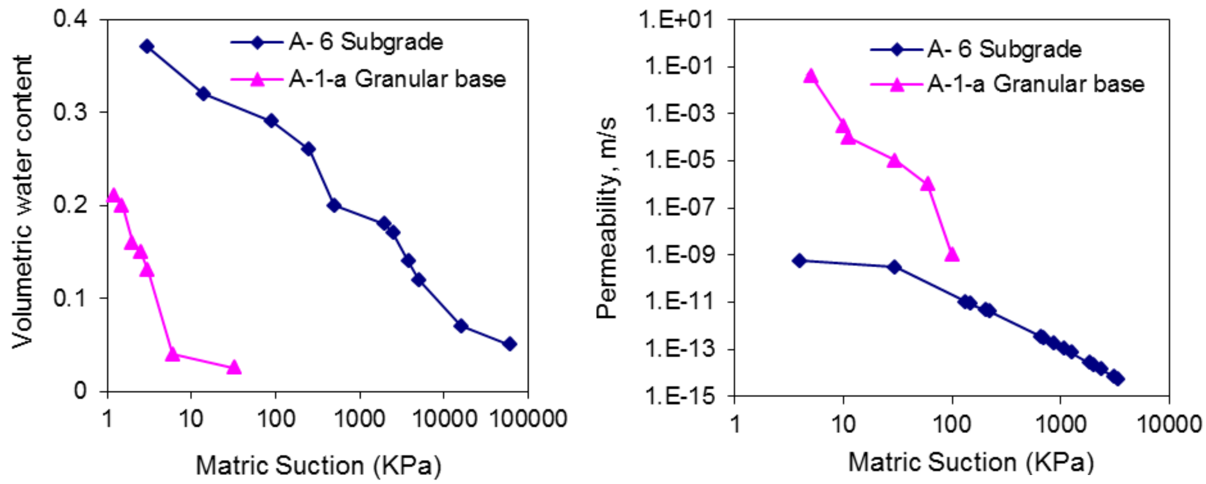


Figure 1: Configuration of the FE model of the pavement cross section analyzed

Table 1: The parameters of the pavement materials (Rabab'ah 2007) used along with the unsaturated soil properties (figure 2) in the FE modelling

Layer	AC	Base	Subgrade
Description / **Parameters**	Hot mix asphalt concert with 9 % binder content, 6.2 % voids, and reference temperature of 70 F°	A-1-a Aggregate medium course untreated granular base with no fines	A-6 Clayey subgrade soil with 69 % fines, 12.3 plasticity index, and 30 liquidity limit
Initial void ratio, e_0		0.22	0.5
Poisson's ratio, v	0.35	0.35	0.35
Logarithmic bulk modulus, κ		0.00046	0.00081
Modulus of Elasticity (KPa)	4E+07		
Cohesion (KPa), C		0	7
Friction angle, ϕ		50°	30°
Dilation angle, ψ		0°	0°
Saturated permeability (m/s), k		0.008	5.5E-10



(a) Soil water characteristic curve (b) Unsaturated permeability function

Figure 2: The unsaturated soil properties of the base and subgrade materials (Rabab'ah 2007) adopted in the FE modelling

4. ANALYSIS OF FOUNDATIONS EXCESS WATER IMPACT ON PAVEMENT RUTTING

Evaluating the impact of the foundations excess water on the pavement performance defined in this paper by surface deflection and rutting distress was done by analyzing the model under four practical scenarios, namely, (i) no excess moisture-scenario (reference scenario): this scenario represented the reference foundations condition under which both the base and subgrade of the model were assumed to be partially saturated with optimum moisture contents, (ii) high water table scenario: in this scenario the base remained unsaturated with optimum moisture content but the subgrade moisture content increased considerably as a result of increasing the water table to a shallow depth (set in this study at 1 m below the subgrade formation level), (iii) saturated subgrade scenario: under this scenario the base remained unsaturated with optimum moisture content while the subgrade became fully saturated; the saturation of pavements subgrade can be caused by an excessive increase of the water table level, lateral movement of water from adjacent locations, and/or surface water infiltration, and (iv) saturated foundations scenario: in this scenario both the base and subgrade became fully saturated which scenario might be associated with inundation condition or could occur due to excessive rise of the water table, remarkable lateral movement of water from adjacent locations, and/or extreme surface water infiltration.

4.1 Porous Nonlinear Elastic Analysis

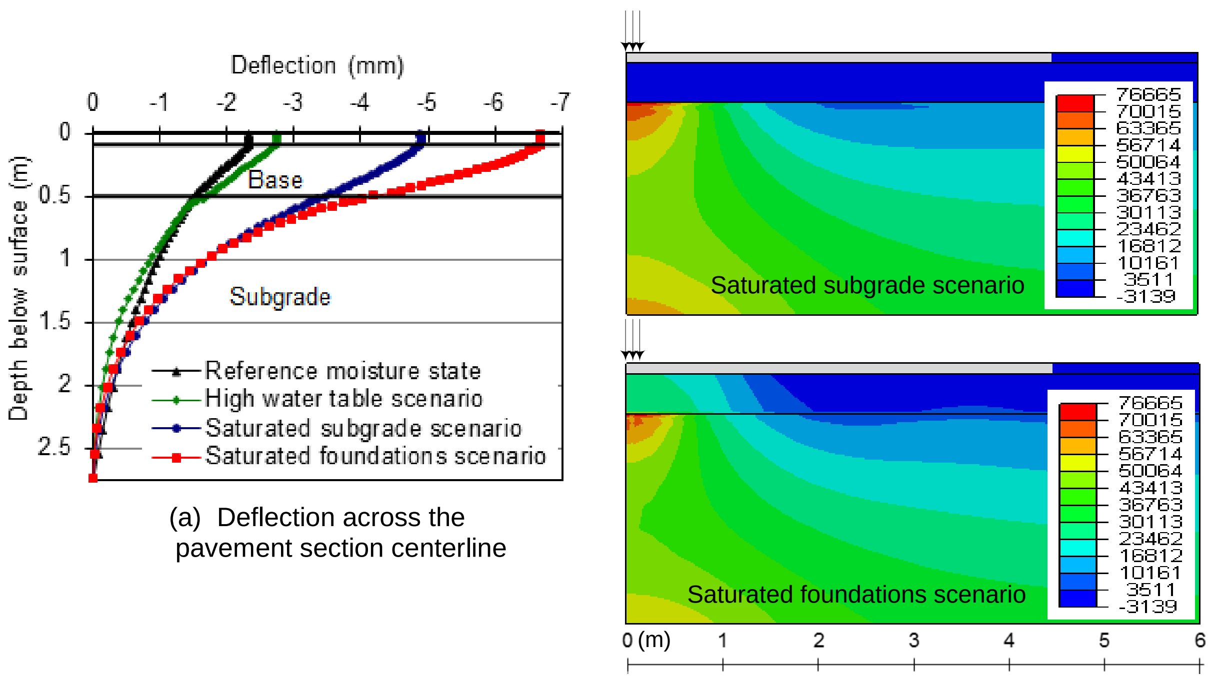
In these analyses, the AC layer was considered linear elastic; refer to Saad et al. (2005) for more details on modelling the AC layer. The granular base and subgrade, however, were idealized by the porous nonlinear elastic constitutive response which assumes that the bulk modulus (*K*) and the shear modulus (G) of the porous medium are proportional to the effective pressure (P´) based on the relationships:

[3] $P' / [\ln(P') - \ln(P_0')] = K(1+e_0)/k$

[4] $G = 3K(1-2v)/(2+2v)$

In equation 3 above, k is the logarithmic bulk modulus given by $k = (e - e_0) / [\ln (P') - \ln (P_0')]$, e is the void ratio with initial value of e_0, and P_0' is the effective pressure corresponding to e_0. The soil nonlinear elastic response expressed by equations 3 and 4 (Roscoe and Schofield 1963) was proved efficient in representing the elastic behaviour of the dense granular materials (Piccolroaz et al. 2006).

Figure 3(a) below shows the pavement deflection plotted across the across section centerline at the peak time of the wheel pulse load. The figure clearly indicates that increasing the subgrade moisture content results in significant reduction of pavement stiffness. This reduction is manifested by increasing the maximum surface deflection by almost 18 % and 110% under the high water table scenario and saturated subgrade scenario, respectively. Obviously, in the former scenario increasing the water table level eliminates the suction in the subgrade zone that becomes under water table level and decreases the suction in the subgrade portion located above the water table level. In the latter scenario, however, saturating the subgrade results in the elimination of the suction in the whole subgrade and induction of remarkable excess pore water pressure that reaches to 76 KPa; refer to figure 3(b). Figure 3(a) further reveals that the increase of the maximum surface deflection under the saturated foundations scenario reaches to 185 %. This increase is caused by generation of significant positive excess pore pressure in both the base layer and subgrade [figure 3(b)] which excess pore pressure causes tangible decrease of the foundations stiffness and, accordingly, increase of the pavement deflection. It is also observed from figure 3(a) that the AC layer contributes negligibly to surface deflection whereas the base contribution to surface deflection is almost 25 % in the pavement with reference moisture state. But the contribution of the base layer to the surface deflection increases appreciably in the presence of excess water until reaching 40 % when the foundations become saturated, as suggested by figure 3(a).



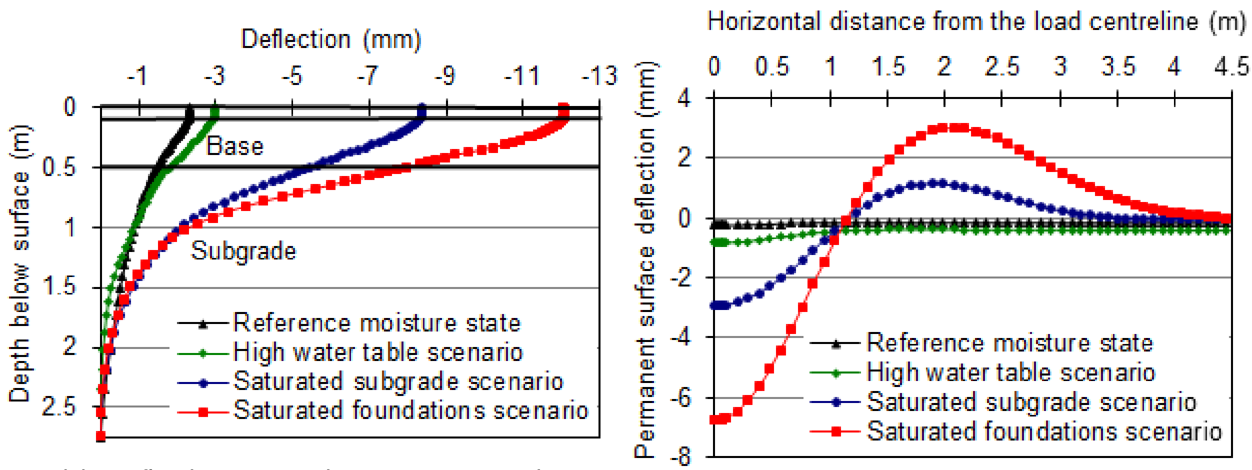
(a) Deflection across the pavement section centerline

(b) Pore water pressure (Pa)

Figure 3: Pavement hydromechanical response under nonlinear elastic foundations represented by deflection and pore water pressure at the peak time of the wheel pulse load

4.1 Porous Elastoplastic Analysis

The coupled response of the pavement system adopted in this study was also investigated considering the foundations as an elastoplastic material. The elastic response of the material was simulated by the porous elasticity constitutive equations 3 and 4 above and its yield behavior was idealized by the Drucker-Prager perfect plasticity model. Such model was employed for its simplicity and ability to model some key-features of the irrecoverable deformations of the soil materials including (i) the dependence of yield on the effective confining pressure, (ii) the non-associative rule governing the flow of the granular media, and (iii) the dependence of the yield on the effective intermediate principal stress. The analysis results indicated that the pavement section with no excess moisture scenario still respond in an elastic manner which implies that the foundations with reference moisture state actually behave elastically under traffic loading. On the other hand, upon introducing excess water in the foundations, the surface deflections obtained from the elastoplastic analyses are significantly greater than the corresponding surface deflections deduced from the elastic analyses. The elastoplastic analysis results indicate (figure 4(a)) that the maximum surface deflection increases by 285 % when the subgrade becomes saturated and by 460 % when the whole foundations attain saturation. Hence, the increase of the maximum surface deflection as a result of the existence of excess water more than doubles when the elastoplastic behavior of the foundations is accounted for. These results signify the rule of the materials constitutive mechanical behavior in the assessment of the impact of excess water on the pavement response. To examine the influence of the excess water on the pavement permanent deflection, the surface deflection profiles were plotted after the passage of the traffic loading (at the end of the pulse loading time) for the four moisture scenario analyzed; refer to figure 4(b). Figure 4(b) confirms that the pavement with no excess water content behaves elastically under traffic loading. More importantly, figure 4(b) shows that the presence of the excess water causes remarkable pavement rutting that reaches to 3 mm in the section with saturated subgrade scenario and approaches 7 mm in the section with saturated foundations scenario.



(a) Deflection across the pavement section centerline at the peak time of the wheel pulse load

(b) Permanent surface deflection profile

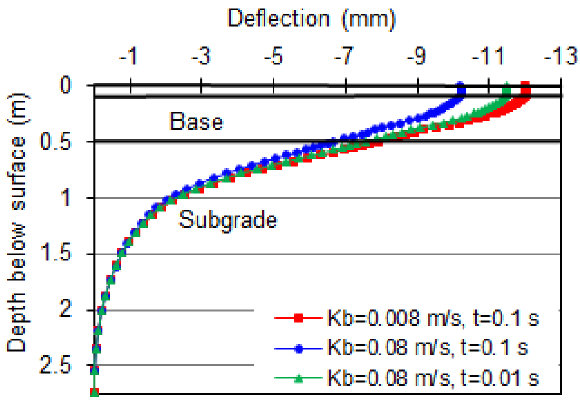
Figure 4: Pavement deflection response under elastoplastic foundations

4.3 Validation of the Model Response

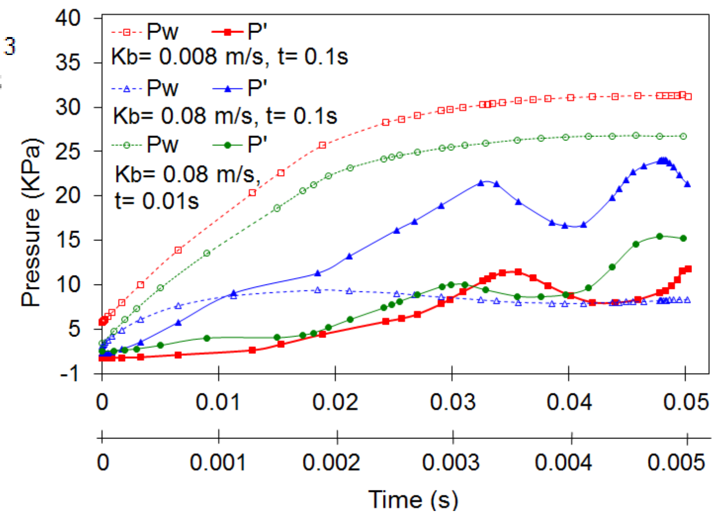
The response of the coupled FE model developed in this study is qualitatively in line with the empirical and field observations related to the impact of excess water on pavements as reported by relevant studies in literature. For example, the analysis results under the four foundation moisture scenarios analyzed by the model demonstrates the interactive response between the pavement rutting and the initial water content of the foundations which results agree with the experimental program outcomes reported by Perkins (2002). Perkins (2002) concluded that the mechanical response of the pavement is dictated by the initial moisture state and pore pressure condition in its granular foundations. Perkins (2002) further observed that the greater the excess pore pressures in the foundations, the greater the pavement rutting. This conclusion is also in line with the analysis observations deduced in this paper. Furthermore, figure 4(b) shows that under the excessive moisture scenarios of saturated subgrade and saturated foundations, the pavement surface heaves (blows-out) at a distance of around 1 m from the wheel path. The pavement heave induced in the vicinity of the wheel path was also documented in literature as one of the major failure modes caused by foundations excess water; refer for example to APRG (2003) and Dawson and Kolisoja (2004). It is also worthwhile to mention that a parametric study was carried out on the developed FE model to examine its sensitivity to some main factors dictating the hydromechanical response of the foundations, namely, the foundations permeability, traffic speeds, and base dilation angle. The results of this parametric study (which are, for brevity, not reported in this paper) were consistent with the empirical and analytical observations revealed by the relevant studies in literature. Unfortunately, no field test data for comparable pavement sections (combination of geometry, loading configuration and material types) could be found in literature for quantitative verification of the model. However, the above qualitative validation combined with the major pavement realistic features being simulated by the model should be sufficient to build a good level of confidence in the model.

5. ON THE DRAINABILITY OF THE GRANULAR BASE

To have further insight into the hydromechanical behavior of the pavement foundations, further analyses examining the effect of the drainability of the base layer on pavement deflection were carried out. More specifically, the elastoplastic model with saturated foundations scenario investigated above was re-analyzed with larger base permeability of 0.08 m/s, which represents greatly free draining base based on ASSHTO (1993), for two wheel load pulses having duration time of 0.01 second and 0.1 second. Based on Barksdale (1971), the pulse time of 0.01 second corresponds to wheel speed of around 72 Km/h (45 mph), while, as mentioned above, the pulse time of 0.1 second correspond to wheel speed of around 32 Km/h (20 mph). The pavement deflection results (figure 5(a)) suggests that under the smaller traffic loading speed, the maximum surface deflection decreases by almost 18 % as a result of increasing the base permeability from 0.008 m/s to 0.08 m/s. However, the reduction of the surface deflection as a result of such base permeability increase becomes minimal when the pavement is subjected to the greater traffic speed. To inspect the base drainability under the traffic loading, the time history of the pore and effective pressures at a representative point located in the middle of the base immediately under the wheel load was plotted during the increasing ramp of wheel load pulse; refer to figure 5(b). The figure shows that under the lower speed-traffic loading, the base responds in a drained manner; i.e., the traffic loading is carried almost completely by the effective pressure, when its permeability increases from 0.008 m/s to 0.08 m/s. Obviously, the drained response exhibited by the base in this case results in remarkable increase of the pavement stiffness. On the other hand, when subjected to the greater speed, the base with the increased permeability experiences undrained response being reflected by increasing pore pressure and negligible or slight increase in the effective pressure. In other words, even when greatly free draining materials with permeability of 0.08 m/s are used, the base continues to respond in an undrained manner under the traffic loading with the greater speed. This causes reduction of the foundations stiffness and shear strength and, consequently, significant rise of pavement deflection. The results of the analyses carried out in this section marks the importance of considering the traffic loading effect when evaluating the drainage quality of the pavement foundations and determining the impact of excess water on its structural performance.



(a) Deflection across the pavement section centerline at the peak time of the wheel pulse load



(b) Time history of the pore water pressure (P_W) and effective pressure (P´) in the middle of the base under the wheel load

Figure 5: Hydromechanical response of the pavement with saturated foundations under different granular base permeability (K_b) and wheel load pulse duration time (t)

6. ABOUT THE TIME-TO-DRAIN DRAINAGE CRITERION

The *time-to-drain* criterion has been extensively used to characterize the drainage quality of pavements (AASHTO 1993). Even so, this criterion does not take into account the mechanical behavior of the pavement materials and their interaction with water as well as the traffic loading effect, which are critical factors governing the influence of excess water on the pavement response, as substantiated in the analyses above. As such, a pavement with "*good drainage"* quality may experience more excess water-related damage than a pavement with "*fair drainage"* quality as categorized by the *time-to-drain* criterion (AASHTO 1993). As observed from the analysis results deduced in this paper, the significant rutting observed in the pavement subjected to saturated subgrade and saturated foundation media scenarios are attributed to the traffic-induced excess pore water pressure generated in these media. Therefore, an additional criterion that can reflect the drainability of pavement foundation materials under traffic loading (ability of the pavement materials to dissipate the excess pore pressure, which would be otherwise formed in the foundations leading to pavement deterioration), is needed to measures the pavement drainage quality. In this regard, the author believes that the pore pressure parameters (Skempton 1954), which are frequently used by geotechnical engineers to quantify the pore pressure build-up in soils under different loading modes, can be used in pavements for characterizing the drainage quality of their soil foundations under traffic loading.

7. **CONCLUSION**

Excess water in the pavement foundations causes remarkable reduction of pavement stiffness under traffic loading. In this paper, coupled finite element (FE) analyses were carried out to quantify the impact of excess moisture content of the foundations (which, as assumed herein, consists of free draining granular base materials over clayey subgrade soil) on the deflection of flexible pavements. The coupled analyses which considered the foundations as a porous nonlinear elastic material indicate that the pavement deflection increases by 18 % when the water table rises to a shallow depth (set in this paper at 1 m below the subgrade formation level). The increase of pavement deflection reaches to 110 % when the subgrade becomes saturated and to 185 % when the foundations (subgrade and base) attain saturation. Under the latter excess moisture scenario, the traffic loading induces significant excess pore pressure not only in the subgrade but also in the granular base which causes significant reduction of the foundations stiffness and ,consequently, drastic increase of the pavement deflection. Further, the coupled elastoplastic analysis carried out in this paper suggest that the presence of excess water in the foundations results in appreciable permanent deflection of the pavement under traffic loading. The results of these analyses reveal that the increase of the pavement deflection under the excess water scenarios analyzed above more than doubles when the yield behavior of the foundations is taken into account. Lastly, the results drawn from this study signify the importance of considering the water flow-deformation coupling behavior and traffic loading effect when defining the drainage quality of the pavements and determining the excess water impact on their structural performance.

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