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Evaluation of Critical Stresses in Pervious Concrete Pavement Systems Due to Partial to Full Bonding between Subgrade, Subbase, and Surface Layers

Ashraful Alam, Liv Haselbach, William F Cofer

***Abstract*— Bonding between the layers (i.e. surface, subbase, and subgrade) of a pavement system may influence its long term performance. Pervious concrete pavement systems are being considered for roadway applications, but, the mechanistic responses of a pervious concrete pavement system due to partial to full bonding between its layers is not well understood. Critical stresses in pervious concrete pavement systems were evaluated considering friction as a bonding parameter between the layers using finite element methods. The different bonding conditions between the layers of the pavement system were modeled using a surface-based contact element method, and a first order linear interpolation element was used in the material model. The range of the friction coefficients considered was 0.001 to 1000, with 0.001 representing the minimal bonding between the layers and a friction coefficient of 1000 approximating a fully bonded system. Four different bonding conditions between the layers of the pavement system were considered and it was found that the condition when all the layers are least bonded is the most critical for pavement performance. For the critical bonding condition it was found that the increase in tensile stress is approximately 15% for a de-bonded system compared to a fully bonded pavement system thus, representing a degradation of performance of the pavement system for long term load repetition.**

***Index Terms*—pervious concrete, partial bonding, full bonding, friction, finite element, tensile stress**

I. INTRODUCTION

A pavement system (rigid such as concrete or flexible such as asphalt) consists of several different layers in its structural system. Early pavement systems had two layers, the pavement surface layer and the soil layer directly beneath. As the weight and volume of the traffic on pavements increased, a layer of granular materials started to be used between the surface layer and soil layer [1]. These three layers are known as the surface layer at the top, the subbase layer at the middle, and the subgrade layer at the bottom of the pavement. These layers have a certain degree of bonding at their interface [2]. The performance of the pavement system could be dependent on the bonding condition between the pavement layers, and a redistribution of stresses and strains in the pavement system due to poor interfacial bonding could lead to the premature failure of the pavement structure [3].

Poor bonding or de-bonding in the layers of the pavement system can be attributed to many factors such as poor mix designs (materials), insufficient compaction, and age of the pavement. For design purposes, it is typically considered that there exists full bonding between the pavement layers [4]. However, under real conditions the state of bonding is unknown, ranging from full bonding to no bonding. Using two-dimensional finite element modeling, after analyzing flexible pavement systems for different interfacial bonding conditions, Kruntcheva et al. [2] concluded that a poor condition between the asphalt binder course and the base could reduce the pavement life by up to 80%. Staged construction in the upper layers of the pavement system may be another reason for poor bonding between the layers and it was reported that the stress distribution in the interface regions is highly influenced by the bonding condition at the interfaces [5, 6]. In addition, localized transverse shear stress in the layer interfaces of the pavement system due to repeated traffic loads may lead to a progressive de-bonding in the layers or even complete separation of the layers in the pavement system [7]. Bonding in the pavement system also depends on the type of subbase materials. While an untreated aggregate subbase tends to exhibit the full bonding or the maximum coefficient of friction in the pavement, a cement treated subbase typically exhibits less bonding or a minimum coefficient of friction in the pavement system [8]. However, only limited research that has been carried out to investigate the performance of the pavement system for different bonding in its layers [2].

For pervious concrete pavement systems, no previous research has been performed to investigate the mechanistic response of partially or completely de-bonded conditions. In addition, a comprehensive design guideline for pervious concrete pavement system would require evaluation of their critical stresses due to partial to no bonding between their layers. As part of the development of a preliminary structural design guideline for pervious concrete pavement system using finite element (FE) methods by Alam et al. [9-15], in this paper, the mechanistic response of a pervious concrete pavement system has been investigated for a range of bonding conditions between its layers. Previous studies include the development of a FE modeling procedure to model the porosity in pervious concrete using its unique vertical

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Ashraful Alam, Senior Structural Engineer, Structures Workshop, Inc, USA, Phone/ Mobile No. 3182433492.

Liv Haselbach, Associate Professor, Department of Civil and Environmental Engineering, Washington State University, USA, Phone/ Mobile No. 5093354874 .

William F Cofer, H Professor, Department of Civil and Environmental Engineering, Washington State University, USA, Phone/ Mobile No. 5093353232.

porosity distribution [9], field validation of the FE model in which a factor of safety of two recommended to design pervious concrete pavement systems for cyclic loads representative of five years loading on the pavement [10], analysis for a range of porosities to evaluate the stress responses [11] and also with different depths in the subbase and wheel configuration [12]. In addition, research has been performed to evaluate the mechanical properties of pervious concrete [13-15]. In the previous studies [9-12], the layers in the pavement system were considered perfectly bonded. The intention of the work summarized in this paper is to explore the impact of assuming different bonding conditions in the pavement.

II. BONDING BETWEEN THE PAVEMENT LAYERS

The inclusion of friction factors in FE modeling is complex, and different researchers have assumed different material models and approaches to include the bonding between the layers in pavement systems. To model the partial bond between the surface course and the binder course in a flexible pavement system, Kruntcheva et al. [2] inserted a soft 5 mm fully bonded layer with elastic material properties between the surface course and the binder course. However, the severity of the partial bond was not indicated and it was concluded that the bond between the layers is very important and must not be ignored in the design and evaluation process of pavement system.

Bonding in rigid and flexible pavement system can be modeled using a range of friction coefficients between the different layers [16]. Full bonding in the pavement system can be imitated by using a coefficient of friction which is close to infinity, while the no bonding condition can be achieved by specifying a coefficient of friction near to zero. The debonded condition (layers separated) in a flexible pavement system was modeled using a low friction co-efficient by Hu and Walubita [3]. The coefficient of friction used in the analyses was 0.5 between the surface and subbase layers. Hammons [8] used four different coefficients of frictions i.e. 0.1, 1, 10, and 100, to investigate the different bonding conditions in the surface layer and the subbase layer of a rigid concrete pavement system. The different coefficient of friction was used to check the load transfer efficiency between the layers of the pavement system. Based on the load transfer efficiency the gap between the layers of the pavement system was proposed for the number of repetitions of load in the pavement system.

In addition to friction coefficients and the ‘soft layer’ approach, different material models have been used to evaluate the mechanistic response of flexible and rigid pavement systems for friction. These material models have defining parameters such as the angle of internal friction and cap hardening for imitating the friction between the layers. They are included in various finite element packages and are frequently referred to as the Cam-Clay, Mohr-Coulomb, and Drucker-Prager material models. While, in some previous studies, the Mohr-Coulomb material model was used [17-20], several other researchers have used the Drucker Prager model [19, 21-24]. However, these are subsitution models, with little quantitative relationship to what might be the actual friction factors between layers. In this study, the friction coefficient between layers was chosen to be used as a direct input to analyze the mechanistic response of the pervious concrete pavement system.

III. FE FORMULATION OF BONDING BETWEEN LAYERS

In non-linear computational mechanics, finite element modeling and analysis of frictional contact between the layers of a structural system is very challenging [25]. Due to the presence of frictional bonding between the layers of a structural system, a shear stress will be present between the contacting layers. The presence of shear stress between the layers produces a highly non-linear problem and requires an iterative solution procedure that needs to be converged. Usually, the successful convergence of a frictional contact problem is much more difficult compared to a fully bonded structural system or a similar frictionless contact model and thus requiring higher computer memory and longer computational time. However, even with these difficulties and constraints, the analysis of a structural system with a frictional contact cannot be ignored because of its expected significant effect on the mechanistic response of the system analyzed.

With the ABAQUS finite element system, simulations of frictional contact between layers of a structural system can be accomplished in two ways, and those that are surface based and those that are contact element based [26]. For the surface based element method, the contact between the layers can be established on the various components in the existing model, while the contact element based method requires the creation of additional zero-thickness interfacial element, which is tedious due to these additional elements [8]. The surface based element method is much more convenient and the contact between the layers can be defined with a choice of a number of friction models. However, it should be noted that there might be convergence problems for models with very low or very high friction factor [26].

IV. SELECTION OF ELEMENTS

In ABAQUS, the element choice options for 3-D modeling are first-order linear elements and second-order quadratic element. With contact analysis, first order linear interpolation element models are recommended. To better model the bonding behavior of the layers, incompatible modes were applied, which allow for quadratic displacement of the element sides.

V. MODELING OF THE PERVIOUS CONCRETE PAVEMENT SYSTEM AND MATERIAL PROPERTIES

Usually, a pavement system has three distinct layers i.e. the subgrade soil layer, the subbase aggregate layer, and the surface pervious concrete layer. An additional challenge for modeling pervious concrete pavement systems is the need to model the inherent porosity distribution in its surface. The porosity changes along the depth of a pervious concrete section [27] and leads to a change in the mechanical properties of the pervious concrete along the depth of the section. To capture this unique vertical porosity distribution in the pervious concrete layer, Alam et al. [9] proposed to subdivide it into three sub sections i.e. bottom quarter, middle half, and top quarter by Alam et al. [9]. To be consistent, the same modeling procedure was used for the analyses reported here.

Because the main objective was to investigate the impact of varying friction factor assumptions, the mechanical properties of the different layers of the pavement system were kept similar to those of the earlier work to validate the performance of pervious concrete pavement system for a field application [10]. The material properties i.e. modulus of elasticity, Poisson's ratio, and unit weight of the surface, subbase, and subgrade used are listed in Table 1. All of the analyses performed for the sensitivity to the friction coefficient states were based on a pervious concrete system with a pavement layer of 8 inches (200 mm) and a sub-base layer of 10 inches (250 mm).

Table 1: Mechanical Properties of Pervious Concrete Used For FE Formulation for Friction Factor Sensitivity

		Unit Weight	Modulus of Elasticity	Poisson's Ratio
		kg/m^3	GPa (ksi)	
Surface	Top Quarter	1850 (115 pcf)	18.55 (2690)	0.22
	Middle Half	1850 (115 pcf)	15.70 (2277)	0.22
	Bottom Quarter	1850 (115 pcf)	12.97 (1880)	0.22
Subbase		1800 (110 pcf)	400 (58 ksi)	0.35
Subgrade		1800 (110 pcf)	50 (7 ksi)	0.40

VI. CONVERGENCE OF TENSILE STRESS

In the mechanistic-empirical design approach of pavement system, along with other considerations, tensile stress is typically the most important design parameter for determining the thickness of the concrete layer. When considering the bottom of a pavement layer, the maximum tensile stress usually occurs when a wheel is located at the edge of the pavement. Thus, that loading case was used for analyses that were performed to investigate the convergence of tensile stress in the pavement system using ABAQUS for this wheel location. The layers of the pavement system were initially fully bonded with each other. A plot of the maximum tensile stress in the pavement system with the increase in the number of element is shown in Fig. 1. The material properties used in the different layers of the pavement system were similar to those used in previous studies by Alam et al. [10].

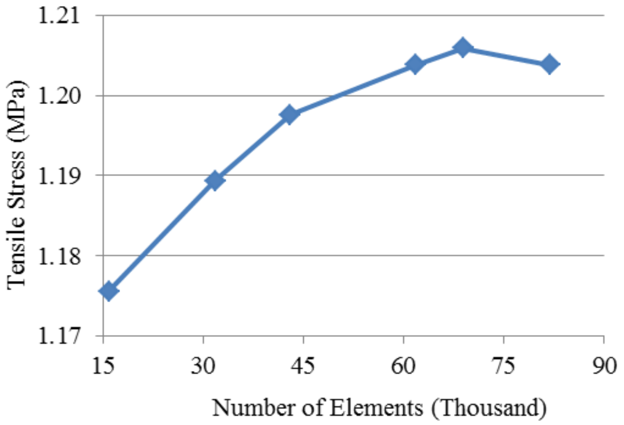

Fig. 1: Convergence of tensile stress for edge loading in the pavement system

VII. RESULTS AND DISCUSSION

The contact based method requires that surfaces de defined for contact. There are four ways to define surfaces on structural, surface, and rigid elements: single-sided surfaces, double-sided surfaces, edge-based surfaces, and node-based surfaces. The elements at the interfaces between layers are typically defined as single-sided surfaces to differentiate between the two layers.

Single-sided surfaces were used to define the contact between the surfaces, which was specified with a friction co-efficient using the ABAQUS/Standard model. Contact analysis requires at least two steps: one for establishing contact and another for the application of load.

Analyses were performed for four different contact scenarios between the three layers of the pavement system to identify the critical contact condition between them. These three conditions were:

Condition 1 – Subgrade and subbase are partially bonded with a coefficient of friction and the subbase and surface are fully bonded.

Condition 2 – Subbase and surface are partially bonded with a coefficient of friction and the subgrade and subbase are fully bonded.

Condition 3 – Subbase and surface are partially bonded with a coefficient of friction and the subgrade and subbase are partially bonded with a coefficient of friction.

Condition 4 – Fully bonded between all layers.

Prior to evaluating the system for various coefficients of friction, the extreme case of little or no bonding was first evaluated for Conditions 1, 2 and 3. A coefficient of friction equivalent to 0.001 was used to imitate this minimally partially bonded condition in the layers of the pavement system. The maximum tensile stress for the three different bonding condition was plotted (Fig. 2) to compare the bonding conditions and also to compare to Condition 4, fully bonded. As expected, when all the layers in the pavement system are minimally partially bonded the tensile stress response in the pavement system reaches its maximum. When all the layers in the pavement system are partially bonded they usually transmit shear as well as normal forces across the interface. Hence, there is then higher stress in the pavement compared to a system when only two layers in the pavement system are bonded.

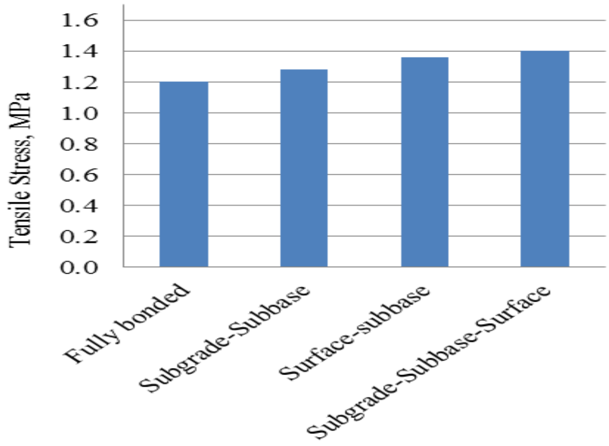

Fig. 2: Tensile stresses for the three bonding conditions in the pavement system with the coefficient of friction at 0.001 (minimally bonded) for the partially bonded case. Interfaces noted are minimally bonded while the other surfaces are fully bonded

For the critical condition of a partially bonded pavement system, analyses have been performed for a range of coefficients of friction to compare the results with a perfectly bonded pavement system. It is expected that, with the increase in the friction coefficient the stress will converge to that of a perfectly bonded system. The results of these analyses are presented in Fig. 3.

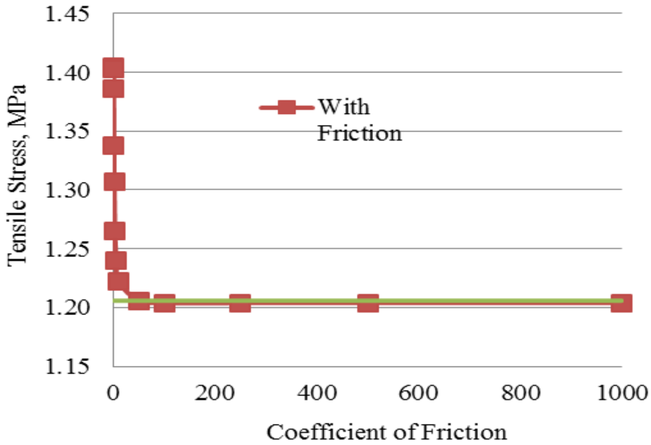

Fig. 3: Maximum tensile stress for Condition 3 (friction between all layers) versus Condition 4 (fully bonded between all layers) estimated by finite element modeling

The results for different coefficients of friction were further analyzed to develop an understanding for the partial bonding condition in the pavement system. There is little information on how traditional concrete systems are bonded and no definitive information on how it may be bonded for pervious concrete. However, it might be useful to compare these results to the friction factors used by Hammons [8] for traditional concrete pavement systems. They were 0.1, 1, 10, and 100. The objective was to investigate the load transfer efficiency for different bonding conditions for a cement-stabilized subbase. As can be seen in Fig. 3, coefficients above 100 may be considered to be fully bonded to the maximum tensile stress estimated from the finite element modeling. The results in this smaller range are depicted in Fig. 4.

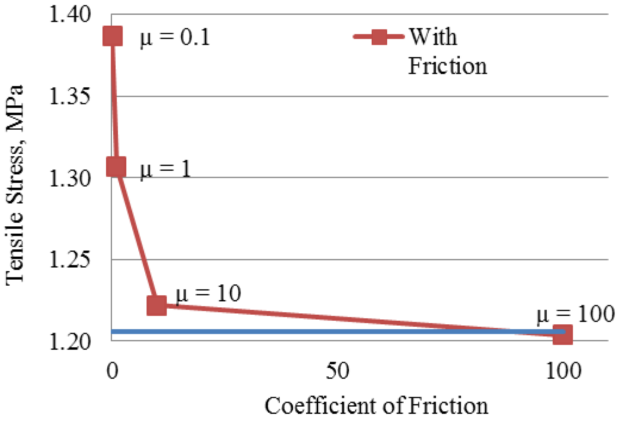

Fig. 4: Maximum tensile stress for Condition 3 (friction between all layers) for coefficient of friction 0.01, 0.1, 1, and 10 versus Condition 4 (fully bonded between all layers) estimated by finite element modeling

The results in Fig. 4 show that conditions with limited to no bonding may impact the maximum tensile stress by increases of ten percent or more. However, application to real systems is still subject to interpretation. Huang [1] gives an example of using a friction factor of 1.5 for traditional concrete systems, which gives an increase in maximum tensile stress over fully bonded of approximately seven percent. While investigating the curling stress due to temperature differential in a rigid pavement system William and Shoukry [28] used a coefficient of friction of 1.5 between the concrete and the subgrade. In addition, AASHTO [29] recommends that the range of coefficient of friction be set to 0.9 – 2.2 between the layers of the pavement system based on the type of subbase and subgrade material. While the recommended coefficient of friction for cement stabilized subbase is 1.8, for river gravel and crushed stone the recommended coefficient of friction is 1.5. With the irregular bottom surface of pervious concrete above the aggregate subbase, it would be reasonable to assume that the coefficient of friction might be higher than that of traditional concrete pavements. Also, in many traditional concrete pavement systems, with age, pumping might occur due to horizontal hydrostatic forces and bonding between the subbase and soil decrease [30]. These conditions may not be as prevalent in pervious concrete pavement systems due to the reduced development of horizontal hydrostatic forces resulting from the release of water into the interconnected pores of the pervious concrete.

VIII. CONCLUSION

A pervious concrete pavement system was analyzed to evaluate the effect on stresses in the pavement system from the consideration of friction between its layers. Among the different approaches of simulating friction between the layers of a structural system, a surface based method was used, by which the coefficient of friction was used as a direct input value. Three bonding conditions (surface-subbase, subbase-subgrade, and surface-subbase-subgrade) were considered in the analyses to determine the critical bonding condition and it was found that, the critical stress occurs when all the layers in the pavement system are partially bonded or have friction acting between the layers. In addition, analyses were performed to validate the friction model against a fully bonded system. Traditionally, with an increase of friction the mechanistic response of a structural system will converge to a rigid system. The tensile stress was found to converge to the stress obtained for a rigid structural system with the increase of friction between the layers of the pavement system. The range of coefficient of friction considered was between 0.001 and 1000.

The increase in tensile stress for a coefficient of friction above 100 is insignificant and the tensile stress in the pavement system for a smaller range of coefficient of friction (0.1 – 100) was evaluated against the tensile stress for a fully bonded system. For this range of coefficient of friction the increase in tensile stress was 15% compared to a rigid system. The typical coefficient of friction between the layers of a pavement system is 1.5 and, for this coefficient of friction the increase in tensile stress is 7% compared to a rigid system. The minimum coefficient of friction can be considered to represent the de-bonded condition in the pavement system. Beacuse the subbase in a pervious concrete system will generally be untreated aggregate, the layers are unlikely to be de-bonded. However, for a fully de-bonded system the increase in tensile stress is approximately 20% compared to a rigid pervious concrete system.

Because of its significance, friction between the layers of the pavement system needs to be considered in its design. Further research is required to determine the gap between the layers of the pavement system to evaluate its structural performance. Finally, the coefficients of friction used in this study were taken from traditional pavement system design and experimental testing needs to be performed to determine the field coefficient of friction between the layers of pervious concrete pavement system.

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