

Considerations to Improve the Aggregate Interlock Model for the Joint Load Transfer in Concrete Pavements

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ABSTRACT

The capability of a joint to transfer load from one side to the other plays a significant role in the performance of a jointed concrete pavement system. Among the available means to providing joint load transfer, the aggregate interlock mechanism is thought to have greater endurance than dowels with respect to load transfer related performance. In the current Mechanistic-Empirical Pavement Design Guide (MEPDG), the concept of joint stiffness was adopted to represent the capability of a joint to transfer load through the dowel and aggregate interlock mechanisms. The use of linear springs to represent the behavior of concrete joint stiffness may be reasonable to investigate the global response of a concrete pavement joint to different levels of load transfer, but there is little guidance available to defining a level of joint stiffness for design analysis purposes in terms of measurable material properties. Therefore, it seems that a more fundamental way of charactering the complicated behaviors of aggregate interlock mechanisms is desirable. A constitutive relationship (i.e. shear stress vs. shear displacement) that considers geometric and micromechanical behavior of a crack interface and associated laboratory testing setups to calibrate the model coefficients may be needed to address such a challenge. This paper elaborates an approach of using the shear stress vs. shear displacement response curve predicted by the application of the well-known two-phase model to calculate the shear capacity and load transfer efficiency of a joint. Although the well-known two-phase model provides good accuracy in matching experimental results, limitations still exists. Through extensive literature reviews, this paper also suggests other improvements to the micromechanics-based aggregate interlock model by taking into account the effects of boundary conditions, traffic loading and angularity of aggregate particles.

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INTRODUCTION

The overall performance of a concrete pavement system heavily relies on the capability of joints to transfer load from one slab segment to another. With joints having greater load transfer capability, specific stress concentration due to traffic loading can be greatly reduced in the vicinity of slab edges and corners and resulting in the minimization of faulting related distresses. Contribution to joint load transfer in concrete pavement can be found in multiple sources, such as aggregate interlock and dowel bars. Among these factors, research has suggested that the aggregate interlock mechanism makes a significant contribution to the overall load transfer related performance [1, 2]. In this regard, successfully modeling joint load transfer due to aggregate interlock mechanism is of great importance to the design and prediction of the performance of a concrete pavement.

By itself, the aggregate interlock transfer mechanism of a concrete joint is achieved by the shear interaction between the crack faces of two adjacent slabs at, for instance, a intentionally induced crack formed at a pavement sawcut joint. Upon loading, a series of interlocking, overriding and fracturing mechanisms can, depending on certain factors, take place along the face of the joint, which results in high shear resistance at the rough joint surface that facilitates load to be transferred at joints [3]. The effectiveness of aggregate interlock is affected by many factors, including the aggregate types, the width of the cracking, temperature variation, base/subgrade performance, concrete slab thickness, magnitude and the number of load applications, and etc. Due to the complexity of the aggregate interlock mechanism, there have been many challenges associated with characterizing and modeling such behavior towards better representing and designing the load transfer mechanism in concrete pavements.

MODELING OF AGGREGATE INTERLOCK IN MEPDG

Many researchers have attempted to model the aggregate interlock mechanism [3-9]; in MEPDG, the modeling of aggregate interlock is based on the introduction of the concept of joint stiffness [1, 6, 9]. This concept was originally introduced by Ioannides and Korovesis (1990) [6] who used a dimensionless parameter to represent the joint stiffness as $J_{AI} = AGG / k\ell$, where J_{AI} is the dimensionless joint stiffness, AGG is the joint stiffness (lb./in/in), k is the modulus of subgrade reaction (psi/in.) and ℓ is the radius of relative stiffness of the pavement (in.) [6]. Essentially, this model defines that the joint stiffness is represented by a series of discrete linear springs connecting to the cracking surface of adjacent slabs and the joint load transfer efficiency (LTE) depends on the stiffness of the springs. In addition, an “S” shape relationship was developed between the dimensionless joint stiffness and LTE, which allowed researchers to investigate the factors that influence the joint stiffness. In a later study, Zollinger and colleagues [10]

formulated a relationship between joint stiffness and shear capacity which is a function of concrete thickness and the joint/crack width . The joint width is a function of joint spacing, concrete coefficient of thermal expansion, friction coefficient between concrete slab and base, concrete temperature change and mean shrinkage strain and etc. Although the models were successfully used to predict the LTE with respect to temperature variation effects and loss of shear capacity due to abrasion of the crack surface, other factors could also be considered. Research data [11] indicates that the size of the aggregate could have significant influence on the load transfer behavior of a concrete pavement. Therefore, it seems that there is a place in the models to account for the effect of the size of aggregate on the joint stiffness. In addition, the relative strength between aggregate and the cement paste is not considered in MEPDG; when the strength of cement paste is greater than the strength of aggregates, unlike in most cases (aggregates are stronger than cement paste), the crack path will go through the aggregates, which can also significantly affect the roughness of the crack face and the joint stiffness.

The use of linear springs to represent the behavior of concrete joint stiffness has been shown to be a reasonable means to represent the response of concrete pavement joint load transfer, however the most notable limitations of the joint stiffness concept are associated with the determination of the stiffness *AGG* parameter by empirical measures.

Since there has been very little guidance available to choose joint stiffness for design analysis purposes, the approach in the MEPDG has been to predict the LT of a joint via the slab thickness and joint opening in addition to considering the characteristics of the dowel (if applicable) without directly computing *AGG*. Although it has been feasible to determine the *AGG* using back-calculation based on falling weight deflectometer (FWD) testing data obtained under field conditions, it nonetheless has not been a necessity to reveal even in forensic studies [12]; although research by Khazanovich [13] provided some useful recommended ranges for selecting the joint stiffness values based on different pavement types. The fact remains that the *AGG* parameter remains somewhat empirical and lacks definition in terms of laboratory or field testing procedures. On the surface, the joint stiffness model in MEPDG appears to adhere to a linear elastic aggregate interlock relation; in reality, the aggregate interlock model is accompanied with a joint width climatic driven dilation that indirectly accounts for loading driven dilation. Nonetheless this still results in a linear shear stress vs. shear displacement relationship. Therefore, it seems that a more fundamental way of charactering the complicated aggregate interlock mechanism with carrying out compatible laboratory experiment testing to calibrate the model would be of interest [14]. In this regard, a constitutive relationship (i.e. models characterizing shear stress and shear displacement relationship as well as considering the joint width dilation) that considers geometric and micromechanical behavior of a crack interface may be needed to better address design requirements.

MICROMECHANICS-BASED AGGREGATE INTERLOCK MODELS

In fact, the attempt to model the constitutive behavior of aggregate interlock mechanism was originally done by Bažant and Gambarova in 1980 [4] based on a total deformation theory, where they expressed a mechanism in a plane stress state as shown in Figure 1.

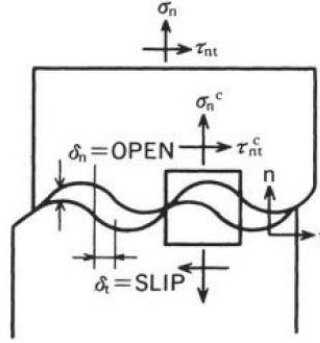


Figure 1 the rough crack model representation [15]

In this model, the relation between the normal stress at the crack face σ_n^c , the shear stress τ_{nt}^c , the relative normal displacement (crack dilation/open) δ_n and the relative shear displacement (crack slip) δ_t can be expressed as the following:

$$\begin{Bmatrix} d\tau_{nt}^c \\ d\sigma_n^c \end{Bmatrix} = \begin{bmatrix} B_{tt} & B_{tn} \\ B_{nt} & B_{nn} \end{bmatrix} \begin{Bmatrix} d\delta_t \\ d\delta_n \end{Bmatrix}, \quad (1)$$

where B_{tt} , B_{nn} are the crack stiffness coefficients and B_{tn} , B_{nt} are the off-diagonal terms; these coefficients and terms can be determined as long as the following relationships are defined:

$$\begin{aligned} \tau_{nt}^c &= f_{nt}^c(\delta_t, \delta_n) \\ \sigma_n^c &= f_n^c(\delta_n, \delta_t) \end{aligned} \quad (2)$$

On one hand, in order to determine the above relations, researchers were focusing on performing experimental testing to obtain empirical formulations between shear stress and shear displacement, such as the work done by Paulay and Loeber [16], Walraven et al. [17], Reinhardt [18, 19] and Tassios and Vintzeleou [20, 21]. In general, these experimental testing programs fell into three different test boundary conditions in terms of the way the normal forces were applied as shown in Figure 2 [2, 5]. The first boundary condition, although not commonly applied, corresponds to a constant applied normal stress which leads to a zero normal stiffness [5, 20]. In the second boundary condition, the normal stress is varied such that the crack width is maintained constant (i.e. no crack dilation); this type of boundary condition leads to an infinite normal stiffness [16]. In the third boundary condition, an external bar is installed to provide restraint

in the normal direction, such that the normal stress increases from zero to a certain level during testing, and therefore leading to constant confinement stiffness [7, 8, 22]; this types of boundary condition leads to a coupled situation in which all four parameters (i.e. σ_n^c , τ_{nt}^c , δ_n , and δ_t) are changing at the same time during testing, which makes it very difficult to model [5]. It should be noted that, although not the main focus of this study (i.e. pure aggregate interlock mechanism), the fourth boundary condition corresponds to a very practical situation where there is always a finite normal stiffness induced by the embedded dowel reinforcement.

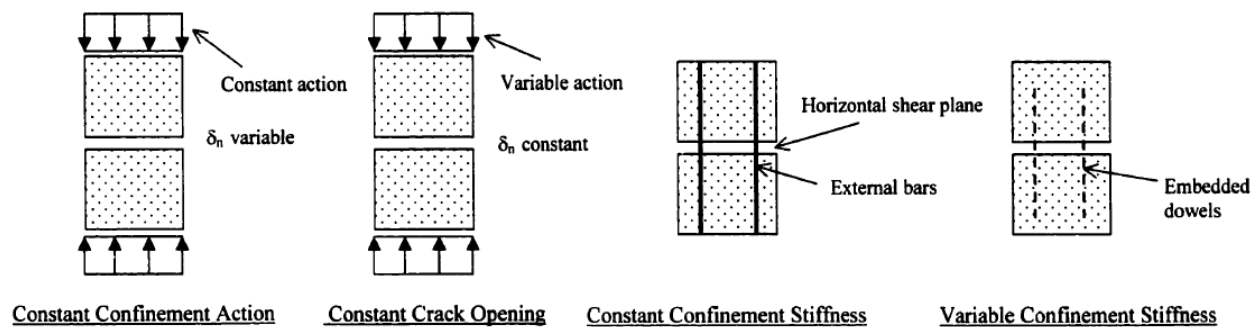


Figure 2 Four types of boundary conditions used in the experimental studies [23]

On the other hand, researchers have also made efforts to formulate the aggregate interlock mechanism based on physical mechanics after the rough crack model proposed by Bazant and Gambarova [4], such as the work done by Walraven [7, 8], Li et al. [24] and Divakar et al. [5]. Among these models, one worth noting is the two-phase model developed by Walraven [8]. An independent research by Wattar [23] conducted laboratory experiments and evaluated the existing predictive models on aggregate interlock; he concluded that the two-phase model was the most appropriate to model the aggregate interlock mechanism in concrete pavements due to the validity of the assumptions that the model was based on as well as its ease and versatility of use. In addition, several other researchers were satisfied with the accuracy of the predications made using this model and its simplicity in the application of finite element modeling [25]. Therefore, this model become one of the most recognized for the aggregate interlock mechanism.

The two-phase model was developed based on the following assumptions; the crack surface is considered as a two-phase material that consists of aggregates and cement matrix; the strength of aggregates are greater than that of the matrix (cement paste), therefore, crack path goes around aggregates along the weak link between aggregates and matrix; aggregates are modeled as rigid partials; statistical distribution is assumed for the depth of embedment of aggregate particle along the crack face. The basic formulation of this model comes from the following mechanism: when subjected to loading, the aggregate particles slide which results in a smaller area of contact with cement paste matrix causing stress concentrations; the

concentrated stress leads to the yielding and permanent plastic deformation of cement paste matrix. When equilibrium is achieved, the shear stress on the sliding surface is equal to the product of the coefficient friction of the contact surface and the normal stress on the contact area. The stress relationship can be expressed as [8]:

$$\tau_{pu} = \mu \sigma_{pu} \quad (3)$$

$$\tau = \sigma_{pu} (A_y + \mu \cdot A_x) \quad (4)$$

$$\sigma = \sigma_{pu} (A_x - \mu \cdot A_y) \quad (5)$$

where σ is the ultimate matrix compressive strength; μ is the friction coefficient between cement paste and aggregates; τ and σ are the shear stress and normal stress; A_x is the most probable projected contact area of a unit long crack for all particles of the cracking plane in x direction; A_y is the most probable projected contact area of a unit long crack for all particles of the cracking plane in y direction. Through statistical analysis and mathematical integrations, the projected contact areas can be expressed as a function of the crack width, shear displacement, maximum size of aggregates and the volume ratio of aggregate and concrete. The ultimate matrix compressive strength and the coefficient of friction were back-calculated to fit experimental results and were found to be reasonably close to the initial presumption of these values. In later research by Walraven [7], the constitutive model was extended to consider cyclic loading, in which a fracture index was introduced to predict cumulative damage. The model did well in fitting experimental data of a cracked concrete specimen subjected to high stress and low load repetitions.

MODELING OF LOAD TRANSFER CONSIDERING MICROMECHANICS-BASED AGGREGATE INTERLOCK MODEL

Modeling joint load transfer efficiency (*LTE*) is one of the key aspects in the design of concrete pavements. As aforementioned, *LTE* can be determined empirically in terms of the dimensionless joint stiffness J expressed as [26]:

$$LTE = \frac{100}{1 + \log^{-1} \left[\frac{0.214 - 0.183 \left(\frac{a}{\ell} \right) - \log(J)}{1.18} \right]} \quad (6)$$

where $J = J_D + J_{AI}$ is the total joint stiffness which considers the combined effects due to dowel stiffness J_D and aggregate interlock stiffness J_{AI} , ℓ is the radius of relative stiffness of the pavement and a is the loaded

radius. Based on previous research [27], Jeong and Zollinger [2] further modified the dimensionless aggregate interlock joint stiffness J into the following expression:

$$\log(J) = a \cdot \exp\left[-\exp\left(-\frac{J_s - b}{c}\right)\right] + d \cdot \exp\left[-\exp\left(-\frac{s_0 - e}{f}\right)\right] + g \cdot \exp\left[-\exp\left(-\frac{J_s - b}{c}\right)\right] \times \exp\left[-\exp\left(-\frac{s_0 - e}{f}\right)\right] \quad (7)$$

$$s_0 = \left\{ \frac{77.38 \cdot h^2}{9000} \right\}^{0.729} \cdot e^{-\left(0.039 \frac{cw_i}{D_N}\right)} \quad (8)$$

where $a = -4$, $b = -11.26$, $c = 7.56$, $d = -28.85$, $e = 0.35$, $f = 0.38$, $g = 56.25$, $J = \frac{AGG}{k\ell}$ = joint stiffness (dimensionless aggregate interlock factor) of transverse crack for time increment i and crack spacing k , s_0 = dimensionless shear capacity, h = thickness of combined slab, cw_i = crack width, D_N = nominal coarse aggregate size and J_s = stiffness of the shoulder/slab longitudinal joint ($J_s = 0.04$ for granular or asphalt shoulder; $J_s = 4$ for tied concrete shoulder).

The introduction of shear capacity s_0 shown in Equation (8) allows for the calculation of joint load transfer without directly considering AGG which is often troublesome. The shear capacity which represents the ability of a crack/joint to carry load through aggregate interlock was originally defined as a non-dimensional shear stress parameter [28]:

$$s_0 = \frac{\tau h^2}{P} \quad (9)$$

where τ is the shear stress on the crack face, h is the thickness of the slab and P is the wheel load. The aforementioned exponential decay function shown in Equation (8) for calculating shear capacity s_0 was formulated by relating s_0 to crack width based on non-linear regression statistics.

Instead of applying a regression model which considers only the effect of crack width, with the advancement in the modeling of aggregate interlock mechanism, it appears that the shear capacity s_0 can also be determined in a more fundamental way by directly relating it to shear stress using Equation (9) where the shear stress on a crack/joint face can be modeled using a micromechanics-based model such as the two-phase model shown in Equation (3) - (5). The use of the two-phase model does not only consider the effect of crack width, more significantly, the formulation of the model also takes into account the effects of fundamental characteristics of concrete pavement materials such as the maximum size of aggregates in

the concrete mixture, the volume ratio of aggregate and concrete, the coefficient of friction and the compressive strength of the concrete.

Table 1 Inputs for two-phase model and load transfer model [14]

Loading conditions	Traffic loading, kips	9
	Loaded radius, in	12
Material properties	Pavement thickness, in	6
	Young's modulus of concrete, ksi	4000
	Compressive strength, ksi	5
	Poisson's ratio of concrete	0.15
	Modulus of subgrade reaction, psi/in.	200
Two-phase model properties	Maximum size of aggregates, in.	0.65
	Coefficient of friction	0.4
	Aggregate volume per unit volume of concrete	0.75

The following shows an example of modeling joint load transfer due to pure aggregate interlock using the two-phase model. The demonstration uses the data from a recent paper by Aure and Ioannides [14], in which the two-phase model was incorporated into a finite element analysis of the crack propagation in the pure aggregate interlock joint of a concrete pavement. The normal and shear stresses vs. shear displacement responses at various initial joint/crack openings (shown in Figure 3) were generated based on the two-phase model using typical values of concrete pavement properties. The inputs for the two-phase model and the load transfer model are listed in **Table 1**.

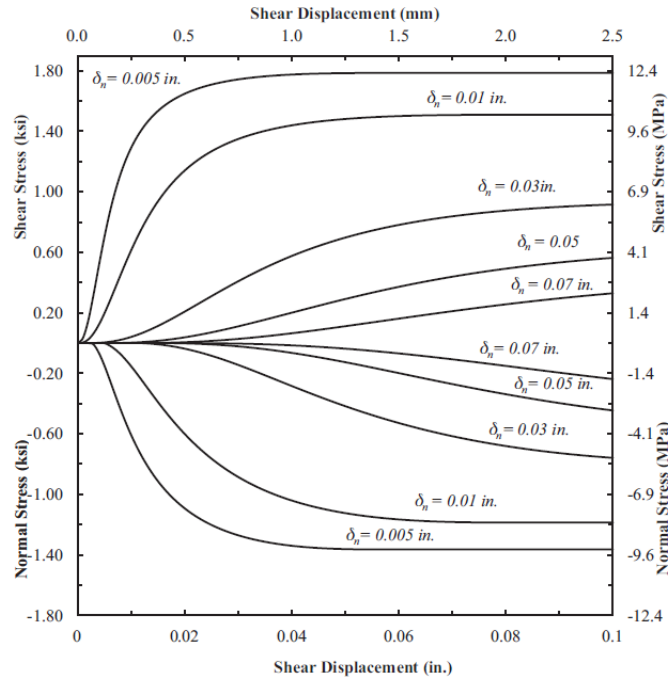


Figure 3 Shear and normal stress vs. shear displacement responses at various initial joint widths/openings [14]

To facilitate calculation of shear capacity and modeling of joint load transfer, the shear stress values shown in Figure 3 were selected at a certain shear displacement (e.g. $\delta_t = 0.02$ for the following example) for various levels of initial joint widths, then the shear capacity, aggregate interlock joint stiffness and *LTE* can be calculated using Equation (9), (7) and (6). The aggregate interlock joint stiffness and *LTE* vs. initial joint widths are shown in Figure 4, where it demonstrates that joint stiffness and *LTE* are both high at narrow initial joint width and decrease very fast as joint width is widened. As the inputs of the two-phase model vary, the stress response curves shown in Figure 3 will be changing accordingly as well as the *LTE* behavior curves shown in Figure 4. Overall, the results showed good promise regarding how the micromechanics-based aggregate interlock model can be used to directly predict the joint load transfer behavior of a concrete pavement.

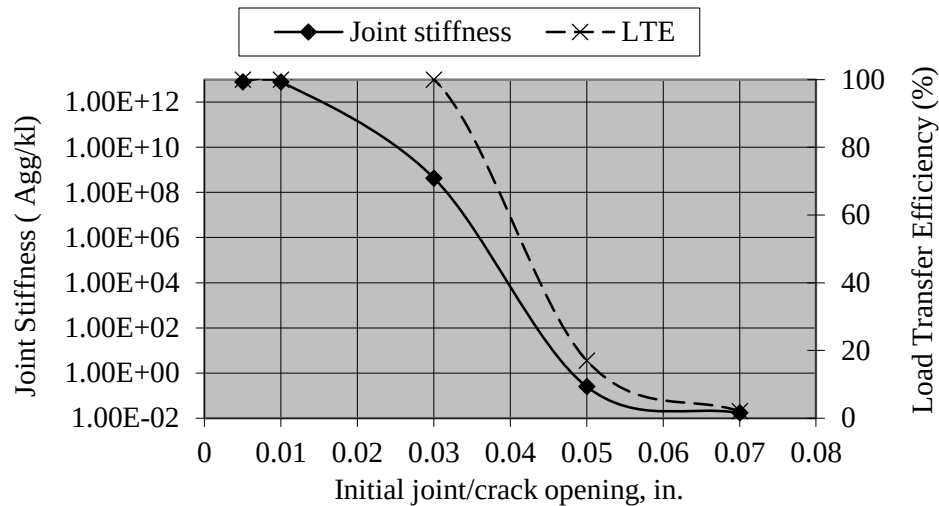


Figure 4 Aggregate interlock joint stiffness and LTE vs. initial joint width

CONSIDERATIONS FOR IMPROVING AGGREGATE INTERLOCK MODELS

Although the two-phase model was found with good accuracy to predict the shear stress vs. shear displacement relationship, however, there are still concerns regarding how accurate the model can be directly used for predicting the load transfer mechanism for a concrete pavement, especially considering the assumptions that the two-phase model was based on. The section focuses on making recommendations for improving the present aggregate interlock model.

The effect of boundary conditions

As shown in Figure 2, the laboratory experiments (push-off tests) conducted by Walraven [8] were based on the third boundary condition (i.e. constant confinement stiffness which would be difficult to accomplish). The laboratory results as shown in Figure 5 indicated that the shear stress vs. displacement response under this test boundary condition exhibited a “hardening” behavior; Walraven explained that this behavior was due to the fact that the increase in shear displacement initially led to a smaller area of contact between aggregates and cement paste causing greater stress concentration at the contact surface; then the concentrated stress resulted in crushing of cement paste and increase in the total contact area between the crack faces, which led to greater resistance to shear displacement [8]. Whether it was the case or not, this mechanism was one of the assumptions that Walraven made to formulate the two-phase model.

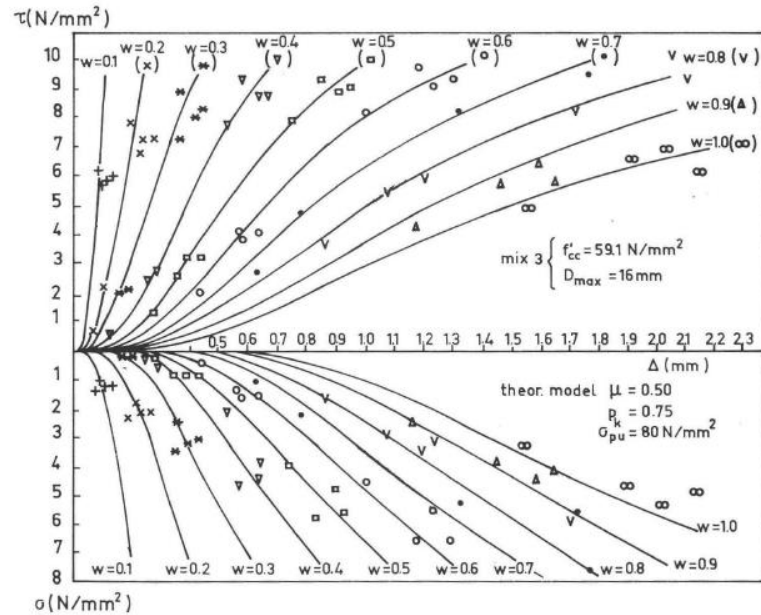


Figure 5 Comparisons between Walraven’s model prediction (curve lines) and experimental data (marker symbols) for the shear stress (τ) vs. displacement (Δ) relationship at various crack width (w) [8]

However, according to other literature, the shear stress vs. displacement responses may exhibit quite different behavior under a different boundary conditions. Divakar [29] studied extensive laboratory results and summarized shear stress vs. displacement responses of specimens applied with various levels of constant normal stress (i.e. the first boundary condition shown in Figure 2). Test results under this boundary conditions exhibited the same “hardening” behavior at a high level of constant normal stress; whereas at low and moderate level of normal stress, the behavior tends to be “softening” once a peak shear stress is achieved. The two-phase model did not seem to capture this kind of behavior but this behavior is likely the explanation behind the hysteresis observed by Colley and Humphrey [35] in their test data.



Figure 6 Shear stress vs. shear displacement at various level of constant normal stresses [29]

According to the literature, a model to describe the “softening” shear stress vs. displacement response of aggregate interlock mechanism is still non-existent. The two-phase model does not seem to be applicable for modeling this behavior since the model does not consider a constant normal stress boundary condition. Divakar [29] performed laboratory experiments under such boundary condition and formulated a constitutive model in an exponential form (however neglected the residual portion after peak shear stress) based on the laboratory data as:

$$\sigma_t = K\delta_t \left(1 + \frac{K\delta_t}{3.4077\sigma_{tp}}\right) \exp\left(\frac{-K\delta_t}{1.7039\sigma_{tp}}\right) \quad (10)$$

where K (shown in Equation (11)) is the initial shear stiffness depending on the initial crack width (W_0) and concrete compressive strength (f'_c), δ_t is the shear displacement and σ_{tp} (shown in Equation (12)) is the peak shear stress which is a function of normal stress (σ_n) and concrete compressive strength (f'_c).

$$K = 21.913 \cdot \left(\frac{1}{W_0}\right)^{1.615} \left(\frac{f'_c}{5000}\right)^{0.193} \quad (11)$$

$$\sigma_{tp} = 0.1 f'_c \left[0.5207 + 59.801 \left(\frac{\sigma_n}{f'_c}\right) - 106.55 \left(\frac{\sigma_n}{f'_c}\right)^2 + 293.62 \left(\frac{\sigma_n}{f'_c}\right)^3 - 247.37 \left(\frac{\sigma_n}{f'_c}\right)^4 \right]^{0.5} \quad (12)$$

This model is essentially an empirical function in which the parameters (K and σ_{tp}) are all determined based on empirical models which can be found elsewhere [29].

To model the “softening” part of the shear stress vs. displacement response, the residual shear stress may also be formulated as a function of normal stress and concrete compressive strength similar to the formula to determine peak shear stress; it is considered that, once the residual shear stress is determined, the “softening” portion (from peak shear stress to residual shear stress) can be modeled using a quadratic function. Due to limited experiment data given in the literature [5], the calibration of the proposed quadratic is not further elaborated unless extensive laboratory investigations can be conducted in the future.

In terms of practical meaning, modeling the aggregate interlock mechanism under constant normal stress boundary condition can be of great value to investigate the joint load transfer behavior of post-tensioned concrete pavement considering the fact that a constant normal stress is applied to this type of pavement when subjected to different levels of confinement stress with post-tensioning strands. Although the effect of post-tensioning strands can be another aspect to consider, modeling the pure aggregate interlock mechanism under constant normal stress may be the first step to study the combined effect.

Consequently, this research also considers modifying the two-phase model to account for the effects of post-tensioning stress which creates a constant normal stress boundary condition and the bending

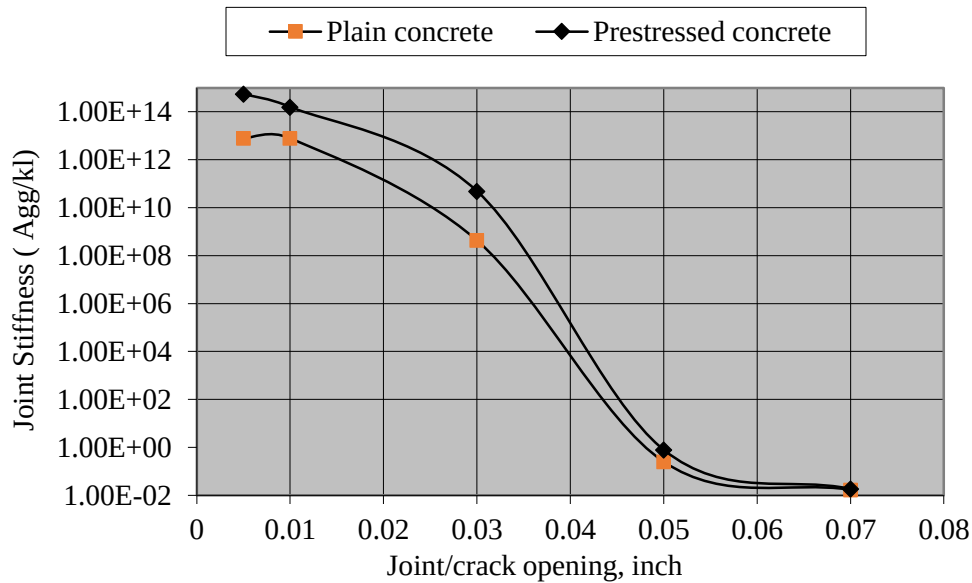
stress due to traffic loading. Following the format of Equation (4), the modified functions are expressed as follows:

$$\tau = \sigma_{pu} \cdot A_y + \sigma_N \cdot \mu \cdot A_x \quad (13)$$

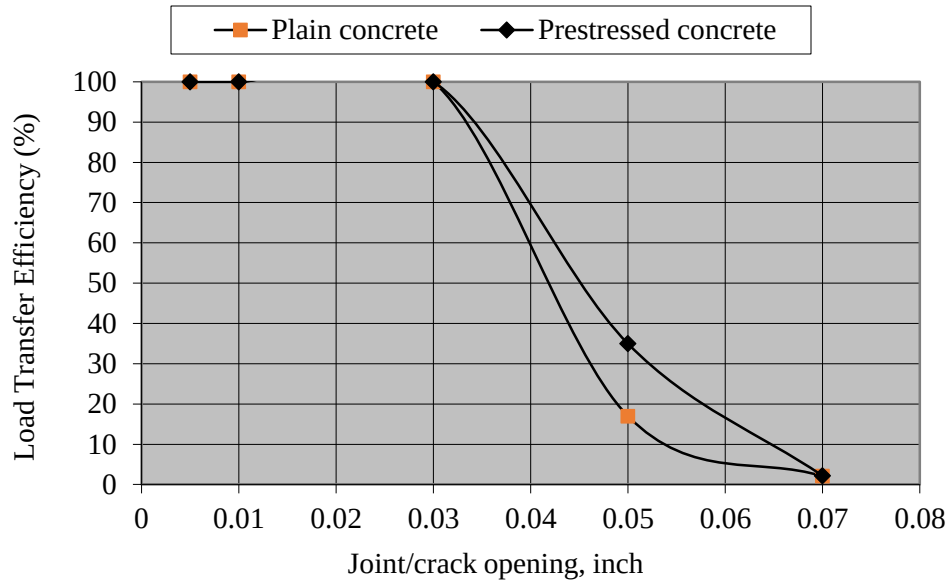
$$\sigma_N = \sigma_{ps} \pm \sigma_{bending} \quad (14)$$

where the definitions of τ , σ_{pu} , μ , A_x and A_y are the same as aforementioned; σ_N is the normal stress acting on the crack face due to the applied post-tensioning stress σ_{ps} and traffic loading induced bending stress $\sigma_{bending}$. Future studies may be focused on performing laboratory experiments to further validate the proposed model.

The following shows an example of taking into account the effect of pre or post-tensioning stress when modeling joint load transfer due to pure aggregate interlock using the modified two-phase model shown in Equation (13). The inputs and procedure are the same as the previous example in which Figure 4 was generated, the only additional input is the pre-stress σ_{ps} which is assumed to be a commonly used post-tensioning stress 150 psi [30]. The following figure shows the comparison between plain concrete and prestressed concrete with respect to their joint stiffness and *LTE*.



(a)



(b)

Figure 7 Comparison between plain concrete and prestressed concrete with respect to (a) joint stiffness and (b) load transfer efficiency.

As shown in Figure 7, both joint stiffness and *LTE* of the prestressed concrete were increased due to the effect of applied post-tensioning stress when comparing to those of the plain concrete at the same joint opening. The results of the analysis again emphasized the importance of keeping narrow joint opening in terms of maintaining a good load transfer capability of the joint.

The effect of aggregate morphologic properties

The aggregate angularity is defined by the difference between a particle radius in a certain direction and that of an equivalent ellipse [31] as shown in Figure 8 (a). The determination of aggregate angularity is usually in terms of an Angularity Index (AI) expressed as:

$$AI = \sum_{\theta=0}^{355} \frac{|R_{\theta} - R_{EE\theta}|}{R_{EE\theta}} \quad (15)$$

where R_{θ} is the radius of the particle at a directional angle θ , and $R_{EE\theta}$ is the radius of an equivalent ellipse at a directional angle θ . Research also indicated that AI has no correlation with aspect ratio, which excludes the influence from dimension effects [31].

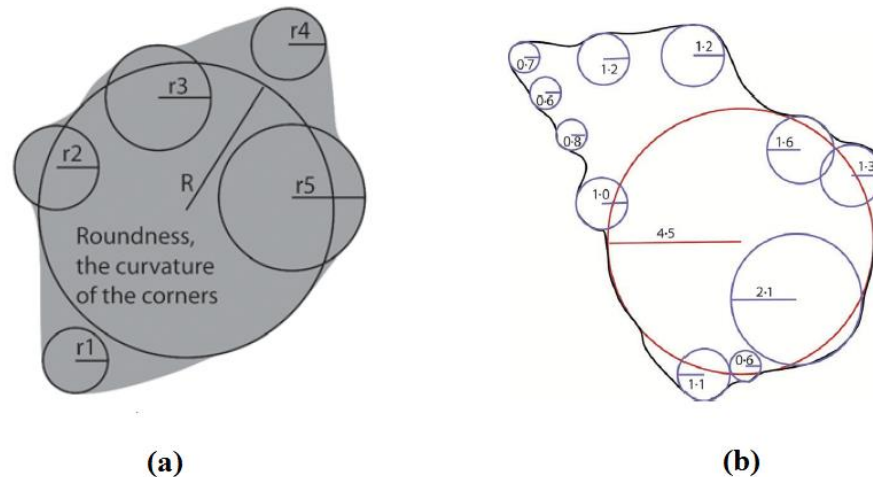


Figure 8 (a) Definition of angularity and (b) an example of angularity determination [32]

The Aggregate Image Measurement System (AIMS) has been used to analyze the morphologic properties of aggregates which consist of the angularity, shape and surface texture of aggregate particles [33, 34]. The system usually consists of a computer, image acquisition hardware, high-resolution camera, microscope, aggregate tray and lighting system and is applicable for a wide range of aggregate particle size (from 0.075 mm to 37.5 mm). In order to analyze coarse aggregates, it is required to wash and separate the aggregate particles based on various sieve sizes. Once dried, the different sizes of aggregates are placed in different trays in the system; during the process of rotating these trays, the images of the aggregate particles are taken by the camera and analyzed by the software in the computer to obtain the angularity, shape and surface texture information.

In the two-phase model, aggregates are simplified to spheres; in reality, they are irregular shapes and come with various morphologic properties. However, these factors were ignored in the two-phase model, which may affect the accuracy of the prediction of stress and displacement responses. Previous laboratory research indicated that the aggregate angularity was one of the factors that affect the effectiveness of load transfer behavior of a concrete pavement [35]. Therefore, taking into account the aggregate angularity can be another step to improve the two-phase aggregate interlock model. The significance of determining angularity of aggregates may be demonstrated as shown in Figure 9, in which both a spherical aggregate particle (assumed in the original two-phase model) and its contact area against cement paste in x and y directions are shown in the shaded area as a_x and a_y ; the figure also shows the shape of a real aggregate and its contact area against cement paste which can be quite different from that of the spherical aggregate. Therefore, it seems that the statistical analysis performed in the two-phase model to determine a_x and a_y should be modified to account for the angularity of aggregate particles.

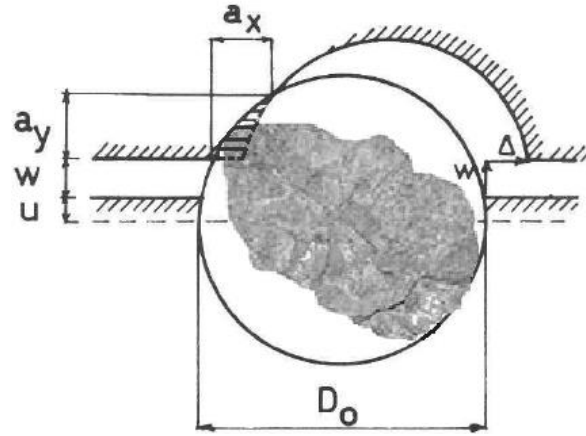


Figure 9 Representation of the two-phase model for a crack plane considering the shape of real aggregate particles, modified after [8]

The calculation of the contact area in the two-phase model relies on the maximum size of aggregate, however, it seems that the contact area is effected by the size of those equivalent ellipses that characterize the angularity of aggregates. In this regard, the angularity of the aggregates can be accounted for by modifying Equation (15):

$$R_{EE\theta} = \frac{1}{AI} \sum_{i=0}^n R_{\theta} + n \quad (16)$$

where R_{θ} , $R_{EE\theta}$ and AI were as aforementioned, and n is the number of corner positions. Statistically, the diameter of these equivalent ellipses should follow a normal distribution. Through statistical analysis, the average of the diameters can be determined and then used as an input in the statistical analysis of the two-phase model to determine the contact area and shear stress at the crack face.

CONCLUSION

- Considerable limitations exist in the model to predict joint load transfer due to aggregate interlock in MEPDG, micromechanics-based aggregate interlock models are reviewed to replace or improve the model in MEPDG;
- The two-phase model is one of the most widely known model to character aggregate interlock mechanism due to the good accuracy to match experimental results and simplicity in the application of finite element modeling;
- The two-phase model can be easily used to determine the shear capacity and load transfer behavior of a joint without conducting complicated experiments or determining the aggregate interlock factor;
- The two-phase model still needs to be improved to address the “softening” behavior of shear stress vs. displacement curve, a quadratic relationship may be used to model such behavior once a peak stress is achieved;

- High traffic load cycles and dynamical loading effects need to be addressed in the future models to characterize the aggregate interlock behavior;
- The angularity of aggregate can be incorporated into the two-phase model to improve the determination of the contact area between aggregate and cement paste, which can directly affect the shear stress vs. shear displacement response of a joint.

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