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Fracture analysis of aggregate interlock jointed slabs-on-grade

Temesgen W. Aure [a,*], Anastasios M. Ioannides [b,1]

[a] Department of Biomedical, Chemical & Environmental Engineering, College of Engineering and Applied Science, University of Cincinnati, Cincinnati, OH 45221-0071, United States
[b] Department of Civil and Architectural Engineering & Construction Management, College of Engineering and Applied Science, University of Cincinnati (ML-0071), P.O. Box 210071, Cincinnati, OH 45221-0071, United States

HIGHLIGHTS

- Load transfer efficiency decreases linearly with increasing initial joint opening.
- The effect of aggregate size is less when the initial joint opening is small.
- Daytime temperature curling results in a lower peak load and a decreased joint efficiency.
- Nighttime temperature increases the peak load and may prevent a decrease of joint efficiency.

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ABSTRACT

This paper discusses finite element analysis of crack propagation in pavement slabs-on-grade with aggregate interlock joints, using the finite element package *ABAQUS*®6.9-2. The fracture process is idealized using nonlinear fracture mechanics approach implemented through cohesive elements. Load transfer at the joint is achieved by aggregate interlock mechanism simulated in accordance with Walraven's nonlinear constitutive relations. The proposed discretization is first verified by comparing the pre-crack responses with experimental and numerical results published by independent researchers. Then the discretization is extended to post-crack analysis of slab responses. Parametric studies are conducted concerning the effects of joint opening and aggregate size on post-crack pavement responses. It is observed that load transfer efficiency with respect to load, vertical and crack mouth opening displacements decreases almost linearly with increasing joint opening. Aggregate size is found to have a negligible effect when the initial joint opening is small. On the other hand, as initial joint opening increases, larger aggregate particles result in stiffer joint behavior. A daytime temperature profile is observed to reduce both the peak load supported by the slab system and the load transfer efficiency of the joint, while a nighttime temperature distribution results in modest increases in these metrics. It is concluded that the proposed approach lays a computational basis for further exploration of fracture analysis in jointed slab-on-grade systems. The step-by-step methodology implemented in this study may contribute to the ongoing development of rational failure criteria that can replace the statistical/empirical algorithms currently used in pavement design procedures.

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1. Introduction

In jointed concrete pavement slabs, load transfer may be accomplished by two primary mechanisms: dowel bars and aggregate interlock. Dowel bars are often placed across a joint to guarantee the longevity of the load transfer mechanism, which relies almost exclusively on each bar's shear resistance. Aggregate interlock, on the other hand, results from the mechanical interaction of aggregate particles developing shear forces at the rough interfaces constituting the joint. Critical responses in jointed concrete pavements are very sensitive to the load transfer efficiency of the joint, i.e., its ability to transfer load applied on one slab to the other. Therefore, it is essential to incorporate realistic joint behavior in a fracture analysis of such pavement systems.

The present study investigates post-crack responses of a typical concrete pavement slab-on-grade under edge loading. The load transfer at the joint is assumed to be solely caused by aggregate interlock mechanism, which is idealized by Walraven's constitutive relations [34]. The fracture process in the loaded and unloaded

* Corresponding author. Tel.: +1 513 476 9906.
E-mail addresses: auretw@ucmail.uc.edu (T.W. Aure), anastasios.ioannides@uc.edu (A.M. Ioannides).
[1] Tel.: +1 513 556 3137.

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slabs is idealized using nonlinear fracture mechanics approach, particularly the fictitious crack model (FCM), first suggested by Hillerborg et al. [16], employing cohesive elements. A fixed fracture path is assumed along the center of both slabs, where principal stresses are expected, in accordance with a discrete crack approach.

The study is organized as follows. In the second section that follows, a review of aggregate interlock mechanics is presented and a suitable approach is identified. In the third section, finite element (FE) discretization of the aggregate joint, the intact slab and the fracture process is described. In the fourth section, pre-fracture analysis of aggregate interlock jointed slabs-on-grade is conducted to verify the FE simulation by comparing with numerical and experimental results available in the literature. In the fifth section, post-crack responses in jointed slabs subjected to wheel loading alone and wheel load-plus curling is examined. Parametric studies concerning joint opening, aggregate size and effects of daytime and nighttime temperature variations on the post-crack responses of the slabs are investigated.

2. Mechanics of aggregate interlock: a review

Published literature indicates that the mechanics of aggregate interlock is a complex phenomenon that depends on several parameters, including aggregate size and distribution, concrete compressive strength, friction between the aggregate particle and the cement paste, crack (or joint) opening, and crack interface sliding. According to Bažant and Gambarova [4], the normal and shear stresses at a cracked concrete interface, in a two-dimensional plane, are functions of the normal and shear displacements of the interface, as follows:

$$\sigma_n = f_n(\delta_n,\ \delta_t) \tag{1a}$$

$$\sigma_t = f_t(\delta_n,\ \delta_t) \tag{1b}$$

where: σ_n is the normal stress; σ_t is the shear (or tangential) stress; δ_n and δ_t are the normal and shear displacements, respectively, and f_n and f_t are pertinent functions to be determined.

Differentiation of Eq. (1) results in:

$$\begin{Bmatrix} d\sigma_n \\ d\sigma_t \end{Bmatrix} = \begin{bmatrix} \frac{\partial f_n}{\partial \delta_n} & \frac{\partial f_n}{\partial \delta_t} \\ \frac{\partial f_t}{\partial \delta_n} & \frac{\partial f_t}{\partial \delta_t} \end{bmatrix} \begin{Bmatrix} d\delta_n \\ d\delta_t \end{Bmatrix} = \begin{bmatrix} K_{nn} & K_{nt} \\ K_{tn} & K_{tt} \end{bmatrix} \begin{Bmatrix} d\delta_n \\ d\delta_t \end{Bmatrix} \tag{2}$$

in which: $K_{nn} = \frac{\partial f_n}{\partial \delta_n}$, $K_{nt} = \frac{\partial f_n}{\partial \delta_t}$, $K_{tn} = \frac{\partial f_t}{\partial \delta_n}$, $K_{tt} = \frac{\partial f_t}{\partial \delta_t}$ are crack stiffness coefficients that can be determined once the functions f_n and f_t are established. If the variation of functions f_n and f_t is nonlinear with respect to δ_n and δ_t, the crack stiffness coefficients may be sensitive to stress level of the cracked interface, and therefore, will change as the load is applied. This behavior is identified as nonlinear aggregate interlock mechanism. On the other hand, if crack stiffness coefficients remain constant as the load is applied, linear aggregate interlock behavior results.

Following Bažant and Gambarova [4], the majority of aggregate interlock mechanics studies have been devoted to the determination of the functions $f_{n,t}(\delta_n, \delta_t)$ using either experimental [28,11] or theoretical (also called micro-mechanical) approaches [34,10]. Notable among these is the contribution by Walraven [34], who formulated a theoretical constitutive equation assuming concrete to be a two-phase material, and implemented "a statistical analysis of the crack [or interface] structure and the associated contact areas between the crack faces [in terms] of the displacements." At the verge of sliding the critical normal (σ_{pu}) and tangential (τ_{pu}) contact stresses may be related as:

$$\tau_{pu} = \mu\sigma_{pu} \tag{3}$$

where μ is the coefficient of friction between the aggregate and the cement paste, usually taken as 0.4; τ_{pu} is the ultimate shear strength; σ_{pu} is the aggregate-paste matrix ultimate strength and depends on the uniaxial compressive strength of concrete f'_c and is given as:

$$\sigma_{pu} = 56.7 f_c'^{0.56}\,psi \tag{4}$$

Using Eq. (3) and the equilibrium conditions of the forces F_x and F_y at the aggregate-cement interface shown in Fig. 1(a) and (b), the normal and tangential stresses can be computed from the most probable projected contact areas of the aggregate particles as follows:

$$\sigma_n = \sigma_{pu}(\overline{A_x} - \mu\overline{A_y}) \tag{5a}$$

$$\sigma_t = \sigma_{pu}(\overline{A_y} + \mu\overline{A_x}) \tag{5b}$$

where: $\overline{A_x} = \sum a_x$ is the most probable projected contact area of a unit long crack area in the *x*-direction; and $\overline{A_y} = \sum a_y$ is the most probable projected contact area of a unit long crack area in the *y*-direction (see Fig. 1(b)).

Walraven [34] provides formulae for determining the contact areas $\overline{A_x}$ and $\overline{A_y}$ obtained using statistical analysis of the size distribution of the aggregate particles and of the resulting deformation modes when the aggregate bears against the cement paste. The areas are correlated to the maximum aggregate particle size, crack opening, sliding displacement and aggregate particle size distribution. Aggregate particle size distribution is described by the so-called Fuller curve [12], given by:

$$p = \sqrt{\frac{D}{D_{\max}}} \tag{6}$$

where D_{max} is the maximum aggregate particle size; D denotes a given particle size, and p gives the percent of the aggregate that is finer than D.

A few researchers have accounted for such nonlinear behavior of the aggregate interlock joint in concrete pavements [9,35], but most have adopted a simplified approach by assuming a linear pure-shear interlocking mechanism. The first such use was made by Skarlatos [30], who derived an analytical relationship between responses in the loaded and unloaded slabs, respectively, simulating the aggregate interlock mechanism using shear springs distributed over the length of the slab joint. This approach is essentially identical to that subsequently implemented in two-dimensional (2D) finite element (FE) programs, such as *KENSLABS* and *ILLI-SLAB*, commonly used in pavement engineering [17,31]. Results from *ILLI-SLAB* for different slab geometries, load sizes and joint spring stiffness values were interpreted using dimensional analysis by

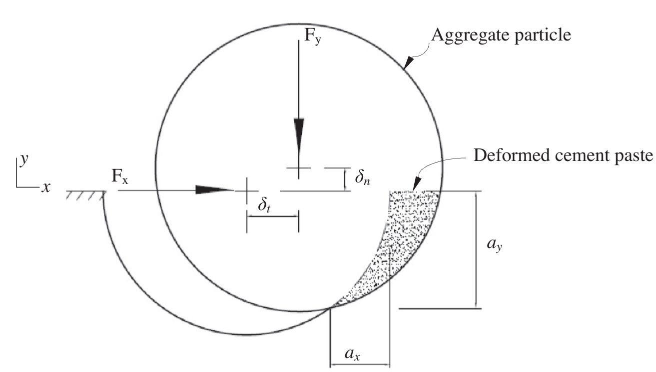

Fig. 1a. Forces on aggregate particle and contact areas between cement paste and aggregate.