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Effects of Hinged Dowel System on the Performance of Concrete Pavement Joints

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Abstract: Concrete joint failure is a major distress mode in rigid pavements. Improving the joint performance in concrete pavements could yield substantial savings in terms of reduced maintenance and rehabilitation costs. The newly developed Hinged Dowel System (HDS) is a means for transferring loads across the concrete pavement joints. The HDS was patented as a new invention by the United States Patent and Trademark Office, and it is envisioned that it could significantly reduce the potential for joint failure in concrete pavements. The HDS assembly comprises a number of dowel bars and a collective hinge provided at the mid-length of the dowel bars. A finite element analysis showed that the application of HDS reduces the shear stress in concrete pavement joints by approximately 15% when compared to the conventional dowel bars. This amount of reduction in shear stress could translate into a significant reduction in shear-induced failures in concrete pavements. The HDS includes mechanisms which would allow a horizontal slip condition for the dowel bars imbedded in concrete. Moreover, these mechanisms eliminate the punching stress at the dowel tip, which is often induced by thermal expansion of the concrete slabs. The hinge in the HDS gives the concrete slab joints a degree of flexibility to reduce the stresses caused by daily curling and warping of slabs, and seasonal expansion and contraction. In addition to installation in new concrete pavements, the HDS could be utilized in retrofit of old concrete pavements. Finally, the HDS eliminates most construction-related issues associated with the installation of dowel bars, such as dowel bar misalignment and full-depth joint cut.

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***Key words**: Concrete pavement, Construction; Dowel bar; Finite element; Joint; Load transfer; Shear failure; Thermal expansion and contraction.*

Background

Plain concrete pavements are built with contraction joints between the slabs to prevent the damaging effects of thermal expansion and contraction. These joints are the weak points in a concrete pavement when it comes to transferring the traffic loads to the adjacent slabs and the subgrade. A common concrete joint problem is pumping, which leads to a loss of subgrade support. All jointed plain concrete pavements (JPCP) need a mechanism to transfer the traffic loads across the joints without causing a high deflection. Poor load transfer of the joints contributes to several distresses in concrete pavements such as faulting, pumping, and corner breaks [1].

Dowel bars are commonly used to improve the load transferring capability of the joints in the current practices of construction of jointed concrete pavements. Dowel bars are typically installed across the joints and at the mid-depth of the slabs to help transfer the traffic loads from one slab to the adjacent one. As a set of dowel bars transfer a heavy wheel load over a joint, they impose a high level of bearing and shear stresses in the joint area [2, 3]. Although the magnitude of the bearing stress under the dowel bars is not critical in most cases, the high shear stress can lead to initiation of microcracks in the concrete slabs. The fatigue effect of the traffic and environmental loads results in the propagation of the microcracks throughout the concrete and eventually joint failure. Moreover, the high level of shear stress can also exacerbate the D-cracking of the concrete slabs which is caused by freeze/thaw deterioration of aggregates [4]. Although several modifications and improvements have been proposed for using the dowel bars, the issue of shear cracking in doweled joints is yet unresolved.

Hinged Dowel System (HDS) has been introduced as a new load transfer assembly to be used in the concrete pavement joints. The introduced system and apparatus was approved by the United States Patent and trademark Office as a new invention in year 2012 [5]. It was envisioned that employment of HDS would improve the durability of the concrete pavements, and prevent some construction-related problems.

Hinged Dowel System (HDS)

Hinged Dowel System (HDS) is an apparatus which is designed to be used in concrete pavement joints in place of the conventional dowel bars. HDS is comprised of a number of dowel bars which are connected at their mid-lengths through a collective hinge. As shown in Fig. 1, the hinge itself is made of two separate tubes, whereas the inner tube can freely rotate and slide inside of the outer tube. One end of each dowel bar is attached to the outer tube and the other end is attached to the inner tube. The outer tube is notched in such a manner that the dowel bars can be attached to the inner tube (Fig. 1). Meanwhile, the outer tube notch controls the maximum amount of rotation of the collective hinge. To assure a free rotation of the

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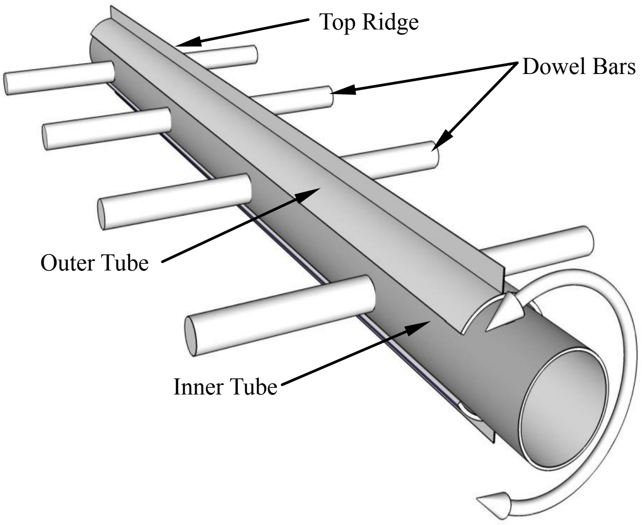

Fig. 1. Hinged Dowel System (HDS).

hinge, the surface of the tubes can be covered with a friction-reducing material.

As illustrated in Fig. 1, two ridges can be attached to the top and bottom parts of the outer tube. These ridges are utilized to place a flexible spacer in-between the joint. The flexible spacer fills the joint gap and prevents the debris from penetrating the joint. This will assure the free horizontal movement of the slabs over their design life (Fig. 2).

Another advantage of using the flexile spacers is eliminating the need for a saw cut. In concrete pavements with conventional dowel bars, the joints are cut a few days after pouring the concrete. Furthermore, it is always a cumbersome task to determine the exact location of the joints with conventional dowel bars, and the joints are normally cut within a 5-inch tolerance from the center of the dowels.

In contrast to the conventional dowel bars, HDS with flexible spacers assures a separation joint for the entire slab depth. In addition, HDS creates the joint automatically during the construction without the need for cutting the joint afterwards. In case that the flexible spacers are not used with an HDS assembly, the top and bottom ridges on the HDS will cause the joint line to be formed at the designed location after the first contraction of the slabs or load applications, and the joint would not need to be cut with a saw.

As depicted in Fig. 2, a sleeve is provided for each dowel in HDS to provide it with a free slip condition inside the concrete slab. As the slabs move due the thermal expansion and contraction, the HDS dowel bars can freely slide inside the sleeve without constraining the slabs movement. Conventional dowel bars are typically coated with an epoxy material, Tectyle® coating, or oil to weaken their bonding to the concrete; however, a free slip condition is not provided in the long term. The sleeves should be made from a high-modulus plastic material to maintain the load transfer efficiency of the joint.

As the pavement slabs move horizontally, the dowel bar tips impose a high amount of punching stress on the concrete. This punching stress is repeated after each contraction-expansion cycles and its fatigue effect may result in shattering of the concrete around the dowel tip. In order to eliminate the punching stress at the dowels tip, every dowel sleeve of the HDS is equipped with a flexible cap at its end, between the dowel tip and the concrete slab. As illustrated in Fig. 2, the flexible caps provide free space for the concrete and the dowel bar to move relative to each other. Moreover, there is only a short clearance between the end of the dowel and the inside face of the cap.

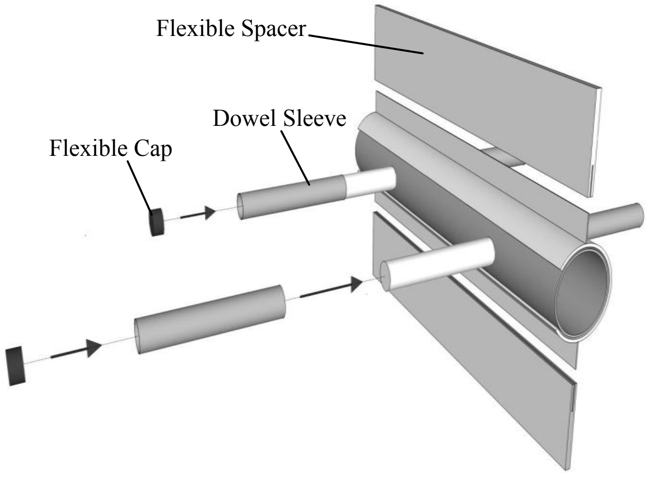

Fig. 2. Flexible Spacer, Dowel Sleeve, and Flexible Cap for the HDS

Curling of Concrete Slabs

In addition to the traffic load, environmental factors can induce various types of stresses and strains in the concrete pavements. The variations in the air temperatures during a day/night period cause different temperatures at the top and the bottom surfaces of a JPCP slab. During the day, the top surface of the slab expands with respect to the cooler bottom surface which is in contact with the subgrade. As the result of these differential thermal strains, the slab curls in a way that the joints tend to face more towards the subgrade. Conversely, during the night, the top surface contracts and consequently, the joints faces tend to curl upward (Fig. 3). This cyclic movement of the joints can impose a relatively high bending moment in the dowel bars as well as a substantially high shear stress in the concrete joint faces and along the surface of the dowel bars. Furthermore, the fatigue effect of this repeated movement contributes to the deterioration of the joint, and propagation of the microcracks.

Mahboub et al. [6] evaluated the effect of environmental factors and traffic loads on the response of concrete pavements. Field test data were collected from several points of a set of doweled slabs. The comparison between the field data and the finite element analysis results showed that the environmentally induced stresses were substantially higher than of those induced by typical highway traffic loads.

As illustrated in Fig. 3, Hinged Dowel System can mitigate the effect of thermal curling and warping of JPCP slabs. The hinge action provided by HDS allows the free rotation of the dowel bars as the adjacent slabs curl. In the meantime, the HDS provides adequate shear strength to transfer the traffic loads across the joint.

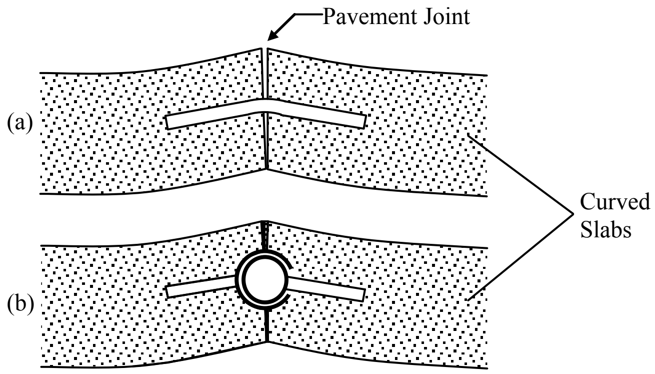

Fig. 3. Curling of the Concrete Pavement Slabs with a) Conventional Dowel Bars, and b) Hinged Dowel System.

Moreover, the flexible spacer between the slabs and the sleeve/cap mechanism provide free space for the movement of the slabs.

Construction

Several studies conducted on the jointed concrete pavements showed that the performance of the joints in concrete pavements is strongly related to the accurate installation of the dowel bars [7, 8]. A major issue which occurs frequently during the construction of jointed concrete pavements is the misalignment of the dowel bars. Misaligned dowel bars induce extra amounts of shear and bearing stresses in the joint area as they constrain the horizontal movements of the concrete slabs. It is crucial for the dowel bars to transfer the maximum possible vertical load and meanwhile, minimize the restraint on the slabs horizontal movements.

The collective hinge system acts as a spine for the dowel bars, and as a result, the bars remain at the installed direction during the construction process. HDS can be positioned at the joint location using a set of dowel baskets. The baskets are made from a light weight plastic material, and they accommodate the HDS in such a way that the dowel bars remain parallel to the pavement's longitudinal direction (Fig. 4). Two plastic caps may also be used on each end of the hinge tubes to restrain the horizontal movement of the inner tube, and prevent fresh concrete from entering the hinge. In the current practices of constructing concrete pavements with doweled joints, the dowel baskets are anchored to the pavement base to hold the dowel bars at the specified depth and alignment during the placement of concrete [9]. Similar anchoring tools may also be utilized to stabilize the dowel HDS dowel baskets during the construction. Each unit of HDS can be made with any desired number of dowel bars. The illustration in Fig. 4 shows an assembly which consists of three separate HDS unit, with four dowel bars on each unit.

Retrofit

Retrofitting the damaged joints is a major part of the maintenance and rehabilitation of jointed concrete pavements. Full-depth patch of the joint and dowel bar retrofit (DBR) are the techniques that are commonly employed to repair the damaged joints. DBR is sometimes preformed to improve the load transfer efficiency (LTE) of the non-doweled joints. Long-term monitoring of some retrofitted joints has shown that a significant number of joint failures may reoccur a few years after DBR treatment [10]. In a full-depth repair, the damaged parts in the joint area are fully removed and replaced by new concrete. The newly poured concrete slab is attached to the old concrete slab cut faces through a number of new dowel bars.

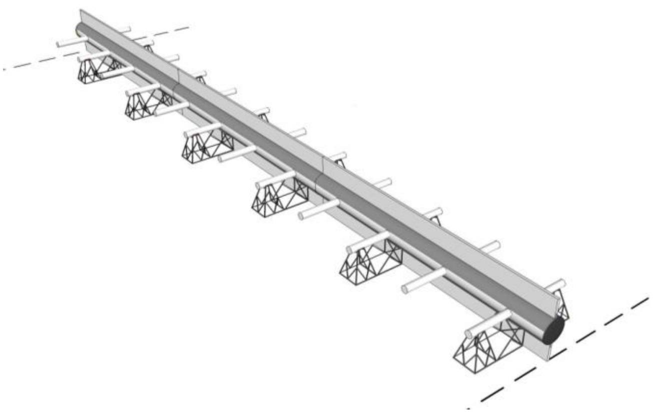

Fig. 4. Positioning of the HDS on the Road Base Using Dowel Baskets.

Hinged Dowel System can be utilized for the full-depth repair of the damaged joints. The structure of the HDS prevents dowel misalignment which commonly takes place in the joint repair operations with conventional dowel bars. To retrofit a joint with HDS, the damaged concrete around the joint must be cut and completely removed from the pavement. Then, the location of the dowel bars are accurately marked on the cut faces on the old concrete. The holes that receive the dowel bars are then drilled parallel to the longitudinal direction of the pavement. Next, the dowel sleeves are mounted inside the dowel holes using an adhesive material. Then, the entire HDS unit along with the flexible spacers can be inserted into the prepared joint faces. Dowel baskets may be utilized to stabilize the HDS unit. Finally, the concrete is poured in the repair area in accordance with the standard practices.

Finite Element Modeling

Three-dimensional finite element modeling was used to evaluate the effect of using the Hinged Dowel System on performance of the concrete pavement joints. Several models with varying traffic and structural factors were generated to compare the behavior of the joints with HDS to those with conventional dowel bars. The models were developed using ANSYS® Academic Research, Release 12.0 software [11]. The finite element models were generated based upon a typical set of properties for the concrete pavements in the United States. Table 1 presents the general properties of the finite element models.

An eight-node cuboid solid element was used to model the concrete slabs. The dowel bars were modeled using an elastic beam element which is defined by two nodes and six degrees of freedom at each node. The beam element is capable of modeling tension, compression, torsion, and bending. As for the subgrade of the pavement, a liquid foundation was assumed. The foundation was modeled using an elastic contact element which did not impose any cohesion between the concrete slab and its subgrade.

The models were generated with the combination of the

Table 1. General Properties of the Finite Element Models.

	Property	Magnitude
Concrete Slabs	Width	365.8 cm (12 ft)
	Length	457.2 cm (15 ft)
	Height	25.4 cm (10 in.)
	Density	2400 kg/m^3 (150 lb/ft^3)
	Modulus of Elasticity	27579 MPa (4×10^6 psi)
Dowel Bars	Diameter	3.175 cm (1.25 in.)
	Length	45.62 cm (18 in.)
	Distance	30.48 cm (12 in.)
	Modulus of Elasticity	199948 MPa (29×10^6 psi)

following varying factors:

- Axle load: 44.5 kN (10 kip), 80.1 kN (18 kip), 142.3 kN (32 kip)
- Axle position: joint edge, middle slab, over the joint
- Subgrade California Bearing Ratio (CBR): 2%, 4%, 8%
- Dowel material: steel, glass fiber reinforced polymer
- Dowel type: Hinged Dowel System, conventional
- Dowel-slab slip conditions: bound, unbound

The preliminary analysis showed that the effect of a single axle on a slab reaches only as far as the adjacent slabs. Consequently, all the models were generated with three slabs. To obtain a clear perspective of the effect of the load transfer systems, it was assumed that all of the loads were transferred between the slabs through the dowel bars. This implies that no friction and aggregate interlock was assumed between the joint faces.

The obtained results from the finite element models were validated by comparing to the results reported by Murison et al. [12] based upon a detailed finite element modeling of a single dowel bar. The relative deflection of the dowel bar and the resulting bearing stress beneath the dowels satisfactorily agreed for the two finite element models.

Load Transfer of the Doweled Joints

The results of the finite element modeling were used to evaluate the effect of traffic load on the stress distribution in the transverse joints. Fig. 5 illustrates the shear and the vertical compressive stresses induced in the joint face by an 80-kN axle placed on the joint edge. As seen in this figure, as the dowels transfer the axle load over the joint, a highly concentrated shear stress was induced in the vicinity of the dowel bars which were placed beneath the loading wheels. The dowel bar which was placed under the symmetry line of a dual tire wheel caused the highest amount of shear stress, and it is referred to as the *critical dowel bar* in this paper (Fig. 5).

The shear force carried by each dowel bar is an indication of the load that it transfers across the joint. It has been shown in the technical literature that for a single concentrated load, the transferred load decreases linearly as the distance from the dowel bar increases [13, 14]. The FE analysis in this paper showed that the same linear relation can be assumed with a low approximation for the case of a dual tire with distributed load; whereas, the maximum load transfer took place beneath the centroid of the loading area.

In addition to the shear stress, the variation of the vertical stress along the centerline of the joint face is depicted in Fig. 5. According to Fig. 5, the axle load did not cause any tensile stress in the joint face. As the result, the slab was at no risk in terms of the tensile failure. Moreover, the magnitude of the compressive stress (less than 0.6 MPa) implies that the concrete slabs have a high safety factor against compressive failure.

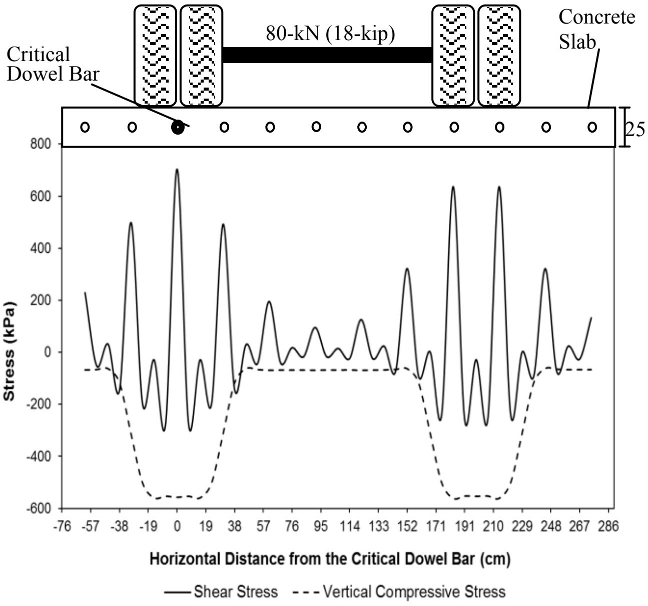

Fig. 5. Variation of Shear and Compressive Stresses in a Slab Joint with Conventional Dowel Bars.
Note: subgrade CBR= 2%, axle position: joint edge.

HDS Versus Conventional Dowel

To model the Hinged Dowel System, the rotational degree of freedom was deployed at the mid-length of each dowel bar in the FE models. Additionally, the support and stiffness of the spinal hinge system in the transverse direction was ignored. In other words, the HDS was modeled at its weakest structural state, where the collective hinge (spinal tubes) was assumed not to improve the efficiency of the load transfer assembly (a conservative assumption). The results of the finite element modeling with various axle positions on the slab revealed that positioning the axle load on the joint edge imposes the highest amount of shear stress in the doweled joint area. When the axle load was placed at the middle of the slab, it did not cause a high deflection near the slab joint. Moreover, when the axle load was applied over a joint (equally divided on adjacent slabs), the two sides of the joint showed similar deflections and the dowels did not transfer load over the joint. Consequently, the resulting shear stress was significantly lower than when the axle was placed on the joint edge.

The effect of using the Hinged Dowel System on reducing the shear stress in the concrete slab is presented in Fig. 6. This figure shows the variation of the shear stress calculated from the FE models along the critical dowel bar. The origin of the horizontal axis was assumed to be at the intersection of the dowel bar and the joint face. The analysis showed that using the HDS in place of the conventional dowel bars resulted in an approximately 15% reduced shear stress. As can be seen in Fig. 6, the reduction in the shear stress took place along the entire length of the critical dowel bar,

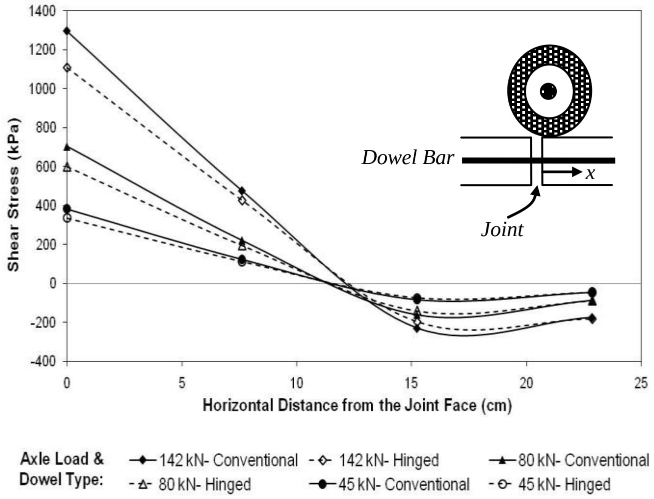

Fig. 6. Variation of the Shear Stress Along the Critical Dowel Bar. Note: subgrade CBR= 2%, dowel material: steel.

and using the HDS did not impose any risk of tensile or compressive failure on the joint system.

In addition to the critical shear stress, the load transfer efficiency of the joints was evaluated for the joints with HDS as well as the conventional dowel bars. The finite element analysis showed that the theoretical LTE of the joint did not change by replacing the conventional dowel bars by the HDS. The LTE of the joint was 99% for both dowel systems. It is worth mentioning that the effect of dowel bar looseness on the joint LTE was not considered in this FE analysis. However, the results implied that using the HDS did not reduce the load transfer efficiency of the concrete pavement joints.

Effect of HDS on Joint Durability

As the finite element analysis showed, using the HDS resulted in a 15% reduction in the shear stress when compared to the conventional dowel bars. However, the question is whether this amount of reduction in shear stress can significantly improve the durability of concrete pavement joints. In order to answer this question, the shear stress in a concrete slab should be compared to its allowable shear strength. According to the American Concrete Institute (ACI) codes [15], the shear capacity (V_c) of a non-pre-stressed concrete member which is subjected only to shear and flexural stresses is determined by the following equation:

$$V_c = 2\sqrt{f'_c}\, b_w\, d\ . \tag{1}$$

where

V_c = shear capacity of the concrete, lb

f'_c = compressive strength of the concrete, psi

b_w = width of the member, in.

d = distance from extreme compression fiber to centroid of tension reinforcement, in.

Using the Eq. (1), the allowable shear strength for a concrete slab with a rectangular cross section would be approximately:

$$v_c = 2\sqrt{f'_c}\ . \tag{2}$$

Table 2. Calculated Maximum Shear Stress for a Single Axle Load Positioned on the Joint Edge.

Subgrade CBR	Single Axle Load [kN]	Maximum Shear Stress [kPa]	
		Conventional Dowels	Hinged Dowels
2%	44.5	379.2	330.9
	80.1	703.3	599.8
	142.3	1296.2	1103.2
4%	44.5	365.4	330.9
	80.1	668.8	592.9
	142.3	1227.3	1096.3
8%	44.5	351.6	330.9
	80.1	641.2	586.1
	142.3	1172.1	1075.6

where v_c is the allowable shear strength. According to Eq. (2), the shear strength (v_c) of a typical concrete pavement slab with a compressive strength of 20 to 30 MPa would be approximately 743 to 910 kPa. The maximum shear stresses calculated from the FE models with various axle loads and subgrade CBRs are presented in Table 2.

A comparison between the shear strength and the calculated shear stresses (in Table 2) reveals that a typical concrete pavement slab is under a relatively high risk of shear failure in the joint area. Cracking of the concrete slabs beneath the dowel bars has also been observed in the laboratory simulations [16]. The high shear stress combined with the bearing stress beneath the critical dowel bar could be the cause of such failures. Furthermore, the fatigue effect of the repeated stresses caused by the traffic and environmental factors could contribute to the growth of these cracks and result in joint failure. It should be noted that the finite element models in this study were developed with a single static axle load. Taking the dynamic effect of passing wheels into account would even further increase the shear stress and consequently, the risk of shear failure in the conventional doweled joints. In such conditions of a low safety factor, decreasing the shear stress by 15% would significantly improve the joints durability and translate into substantial savings over the life of a concrete pavement.

Effect of Subgrade Stabilization

Chemical stabilization has been widely practiced to increase the stiffness of the inherently weak subgrades for concrete pavements [17]. A stiffer subgrade can potentially lower the deflection of the concrete slabs and improve the load transfer efficiency of the joints. In this study, the effect of increasing the subgrade stiffness was examined on the shear stress in doweled joints through finite element modeling. Fig. 7 presents a comparison between two methods for lowering the shear stress in a concrete pavement joint: increasing the subgrade CBR from 2% to 8%, and using the Hinged Dowel System. Although increasing the subgrade stiffness was effective on lowering the shear stress, using the HDS resulted in a higher reduction in the maximum shear stress. As seen in Fig. 7, the maximum shear stress in a joint face increases linearly with increasing the axle load. Using the HDS is more effective on decreasing the slope of this line when compared to increasing the

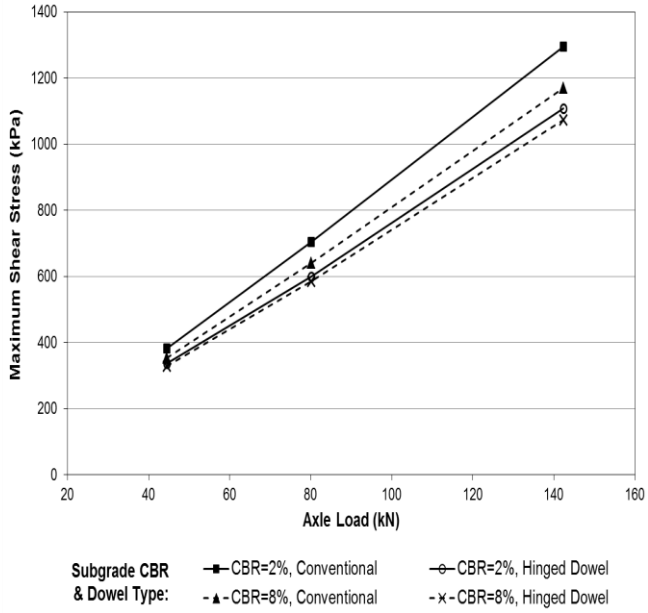

Fig. 7. Maximum Shear Stress in the Concrete Slab for Various Subgrade Supports and Dowel Types.

subgrade stiffness. This means that the advantage of using the HDS becomes more significant as the axle load increases.

Future Research

This paper introduced a new load transfer system to be used in place of the conventional dowel bars. The primary analysis showed that HDS can resolve some of the issues associated with construction and maintenance of concrete pavements. The next step of the research will be field testing of the HDS in an actual pavement. After placement and construction, the behavior of the joint and concrete slabs will be monitored, and the results will be compared to those constructed with the conventional dowel bars.

Summary

Hinged Dowel System (HDS) was introduced as a new load transfer assembly for the concrete pavement joints. HDS comprises a number of dowel bars with a collective hinge at the mid-length of the dowels. The hinge itself is fabricated with two tubes with different radii, which can freely rotate with respect to each other. The HDS provides a rotational degree of freedom around the joint longitudinal axis for the concrete slabs. Meanwhile, due to its shear load-bearing capability, the HDS transfers traffic load from one slab to another very effectively. It was envisioned that the rotational action of the HDS would diminish the stresses induced by temperature curling and warping of concrete slabs.

HDS can optionally accommodate a flexible spacer to be placed within the joint. The flexible spacer eliminates the need for a saw cut and provides adequate space for the slabs expansion. In case that the flexible spacers are not installed, the ridges on the HDS would initiate the opening and formation of the joint without the need for a saw cut.

As the JPCP slabs move due to the thermal expansion, conventional dowel bars induce a highly concentrated punching stress in the slabs. The HDS includes a sleeve and flexible cap mechanism for each dowel bar, which eliminates this punching stress. Furthermore, the sleeve and cap mechanism assures a free slip conditions for the dowel bars inside the slabs.

Three dimensional finite element analyses were conducted to evaluate the response of the concrete pavement joins with HDS under various axle loads, axle positions, subgrade CBR, and dowel types. The following conclusions were drawn from the FE modeling:

- Doweled joints are at a relatively high risk of shear cracking. Passing a heavy axle load over a joint imposes a shear stress in the joint face which is close to the estimated shear strength of the concrete slabs.
- Using the HDS in place of the conventional dowel bars resulted in a reduction of about 15% in the shear stress in the joint face. This amount of reduction in shear stress could significantly reduce the potential of shear cracking in jointed concrete pavements.
- Using the HDS instead of the conventional dowel bars was more effective on reducing the shear stress than improving the subgrade CBR from 2% to 8%.

Application of the HDS could reduce issues related to construction of concrete pavements. Attachment of the dowel bars to a single spinal hinge prevents the horizontal misalignment of dowel bars. Finally, the HDS creates the joint during the construction automatically for the full depth of the slabs, with no need for a saw cut. Future phases of this work would include field experimentation and performance studies.

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