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Effect of Dowel Bar Arrangements on Performance of Jointed Plain Concrete Pavement (JPCP)

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Abstract: A full-scale jointed plain concrete pavement (JPCP) with two different dowel bar arrangements, namely, standard and special method, was constructed and evaluated under actual traffic-environmental condition in Florida. For standard dowel bar arrangement, dowel bars spaced at 304.8 mm (12 in), while three dowel bars spaced at 304.8 mm (12 in) only within the wheel paths were installed for special dowel bar arrangement. Field performance evaluation was conducted in terms of longitudinal crack, transverse crack, corner crack, spalling, and load transfer efficiency (LTE). Also, a three-dimensional (3-D) finite element (FE) model was developed to evaluate change in structural response characteristics due to different dowel bar arrangements under the critical loading condition. The developed FE model was used to perform a parametric analysis to determine the effects of different dowel bar arrangements. Results indicated that no significant changes in pavement structural responses, including the slab stresses and deflections, were predicted between two dowel bar arrangements that may result in no significant difference in expected performance for the test slabs evaluated, and this matched well with results of field performance evaluation. Also, it was indicated that the base modulus plays an important role on the dowel-joint behavior and stiffer base condition could significantly improve the dowel-joint performance. Therefore, when the base layer is stiff enough to support the slab deflection and resist erosion (e.g., AC layer), special dowel bar arrangement could provide similar performance as compared to standard dowel bar arrangement that result in significant cost savings without any negative effects on expected pavement performance.

Keywords: dowel bar arrangement, concrete pavements, finite element analysis and long-term performance.

1. Introduction

1.1 Background

Dowel bars are commonly used in jointed plain concrete pavements (JPCP) as a load transfer device across joints, especially for pavements with heavy traffic. The primary advantage of dowel bars is to transfer load without restricting horizontal joint movements due to temperature and moisture expansion and contraction in the concrete slabs. Also, dowel bars play a role to maintain the vertical and horizontal alignment of slabs. The load transfer efficiency depends on a number of dowel-joint parameters, including modulus of dowel support, dowel bar diameter, dowel length, dowel bar spacing, dowel looseness, joint opening width, and subgrade strength (Channakeshava et al. 1993; Guo et al. 1993; Brill and Guo 2000; Kim and Hjelmstad 2003; Maitra et al. 2009).

Since the placement of dowel bars requires correct positioning, it tends to have correspondingly higher cost, including the increased construction time and construction material (i.e., dowel streel). Considering the entire project budget, the saving of even one dowel per joint will lead to significant overall cost savings. As long as these cost savings do not negatively affect the pavement performance, these cost savings could help highway agencies use their limited budgets more efficiently. In response, the Florida Department of Transportation (FDOT) implemented a pilot project on SR-5 in Volusia County in 1988 to evaluate the performance of two different dowel bar arrangements (i.e., standard and special dowel arrangements) under real traffic and environmental conditions. The special dowel bar arrangement consisted of three dowels spaced with 304.8 mm (12 in) only within each wheel path. The standard dowel bar arrangement included dowels spaced with 304.8 mm (12 in) within the entire slab width. Crack surveys, faulting measurements, and falling weight deflectometer (FWD) measurements were conducted in the years of 1989, 1992, 1998, 2005, and 2015. Based on the results analyzed, both dowel bar arrangements performed very well, and lasted longer than the design life of 28 years.

Although previous research reported that the pavement with a special dowel bar arrangement shows a good filed performance, there is a need to study how the reduced number of dowel bars achieves the appropriate load transfer

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across the joints in terms of the concrete bearing stress, dowel shear forces, and slab deflection. Also, a better understanding regarding the dowel bar load transfer mechanism may help to improve the dowel bar design and construction procedures. In this study, a three-dimensional (3-D) finite-element (FE) model was developed to simulate the dowel bar load transfer under FWD loads. Analytical FWD deflections calculated were compared with those actually measured from FWD tests to validate the FE model developed.

1.2 Objectives and Scope

The analysis conducted herein was primarily focused on evaluating the dowel bar performance using two different dowel bar arrangements under Florida conditions. The detailed objectives of this study are as follows:

- Identify the effect of different dowel bar arrangements on the bearing stresses in the surrounding concrete, shear stress in dowel bar, and deflections under the critical loading condition.
- Evaluate the effect of the base layer (i.e., base modulus) on the dowel-joint behavior for different dowel bar arrangements.
- Evaluate the effect of different dowel bar arrangements on field performance under actual traffic and environmental conditions in Florida.

2. Overview of Dowel Bar Application

The primary load transfer mechanism of a dowel bar is through transferring shear stress, especially for joint openings less than 6.4 mm (0.25 in), and bending moment transfer is considered as negligible (Guo et al. 1995). In general, the total shear load transferred by dowel bars is less than 50% of the applied wheel load. The magnitude of transferred shear load is a function of the dowel bar diameter, dowel bar length, dowel bar spacing, stiffness of the base layer, and slab dimension including thickness, length, and width (Nishizawa et al. 2001; Mackiewicz 2015). A previous study has found that the maximum load transferred by the critical dowel is typically between 41 and 43 percent of the applied load (Heinrichs et al. 1987). Dowel diameter and cross-section area are critical factors that affect the behavior and performance of the dowel-pavement system. The peak bearing stresses and deflections at a joint can be reduced by increasing the dowel stiffness. Dowel diameter may be either increased or decreased depending upon the dowel spacing, dowel bar properties including modulus of elasticity, material (e.g., mild steel or fiber-reinforced polymer) and dowel bar shapes (e.g., round or non-round dowel). Table 1 presents the recommended dowel bar diameter as a function of pavement slab thickness for several US State highway agencies.

Teller and Cashell (1959) conducted repeated load tests to determine the requirement of the length of dowel embedment for maximizing the load transfer efficiency. The results indicated that dowels could be embedded about 8 times of the dowel diameter for 19 mm (0.75 in) diameter dowels, while 25 mm (1 in) and 32 mm (1.25 in) dowels require only 6 times of the diameter (i.e., 152 mm (6 in) and 191 mm (7.5 in), respectively). Figures 1 and 2 show the effects of the length of dowel embedment on load transfer efficiency and looseness reported by Teller and Cashell (1959). The recent recommended total length of dowel is 457 mm (18 in) to achieve good pavement joint performance.

Table 1 Recommended dowel bar diameter versus pavement slab thickness.

Slab thickness	203	216	229	241	254	267	279	292	305	318
Florida	–	25	32	32	32	32	38	38	38	38
California	32	38	38	38	38	38	38	38	38	38
Iowa	32	32	32	32	38	38	38	38	38	38
Illinois	38	38	38	38	38	38	38	38	38	38
Indiana	25	25	32	32	32	32	32	32	32	38
Michigan	32	32	32	32	32	32	32	38	38	38
Minnesota	32	32	32	32	32	38	38	38	38	38
Missouri	32	32	32	32	32	38	38	38	38	38
North Dakota	32	32	32	32	32	38	38	38	38	38
Ohio	25	32	32	32	32	38	38	38	38	38
Texas	25	–	29	–	32	–	35	–	38	–
Wisconsin	32	32	32	32	38	38	38	38	38	38

Slab thickness and dowel bar diameter are in mm.

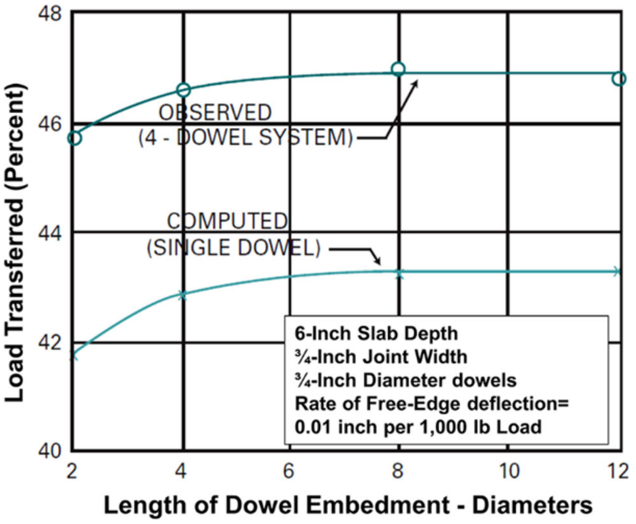


Fig. 1 Load transfer versus dowel embedment.

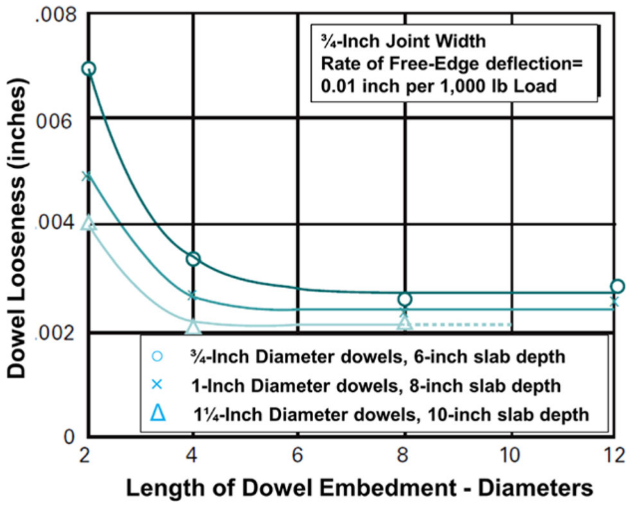


Fig. 2 Effect of dowel embedment and diameter on dowel looseness after 600,000 repetitions.

Dowel bar misalignment does not necessarily result in slab distresses. However, if a number of consecutive joints lock up, the potential for development of slab distress would increase due to the failure of stress relief at the joints. Most highway agencies have adopted the Federal Highway Administration (FHWA) recommendation limits on horizontal and vertical rotation of 6.4 mm (0.25 in) per 304.8 mm (1 ft) of dowel bar length, or 2% (FHWA 1990). It should be noted that there is no clear evidence what level of tolerance is required to achieve good joint performance. Table 2 shows the tolerance of dowel bar misalignment specified for different states.

When concrete slabs are subjected to loads, bearing stresses and deflection are mainly affected by the spacing of dowel bars. Decreased dowel bar spacing results in the reduction in bearing stresses and deflection. However, if dowel bar spacing decreases to less than 203 mm (8 in), a horizontal plane of weakness in the concrete slab at the joint face will occur. On the contrary, the increased dowel bar spacing leads to excessive bearing stresses and deflection at the joint. Currently, most highway agencies have adopted a 305 mm (12 in) spacing requirement, which also depends on the slab thickness and subgrade conditions.

3. Full-Scale Field Performance Evaluation

3.1 Project Description

The Florida Department of Transportation (FDOT) implemented a pilot project on SR-5 in Volusia County, Florida in 1988 to evaluate the performance of two different dowel bar arrangements (i.e., standard and special dowel arrangements) under real traffic and environmental conditions. It is noted that the annual daily truck traffic was reported to 15,910 in 1997. The project is composed of three sections with slab thicknesses of 152, 178, and 203 mm (6, 7, and 8 in). Each of these sections consists of six 152 m (500 ft) long subsections. The 152 mm (6 in) sections

Table 2 Specification of dowel bar misalignment tolerance.

States	Maximum rotation (mm)	Vertical translation (mm)	Longitudinal translation (mm)
Florida	13	25	50
Illinois	5	–	–
Indiana	10	–	–
Iowa	6	–	–
Kansas	10	1/10 of slab thickness	–
Minnesota	6	–	–
Nebraska	6	–	–
Georgia	14	–	–
North Carolina	10	–	–
South Carolina	14	20	76

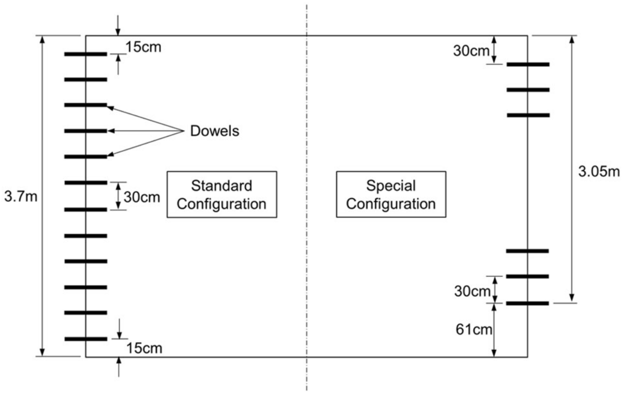


Fig. 3 Schematic layouts for project sections with different dowel arrangement.

(a) Standard dowel arrangement

(b) Special dowel arrangement

Fig. 5 Dowel arrangements used for project sections.

include slabs with 3.7, 4.3, 4.9 m (12, 14, and 16 ft) joint spacing. The 178 mm (7 in) sections include slabs with 4.3, 4.9, and 5.5 m (14, 16, and 18 ft) joint spacing. The 203 mm (8 in) sections include slabs with 4.9, 5.5, and 6.1 m (16, 18, and 20 ft) joint spacing.

The first three subsections for each of the major sections include joints with a special dowel arrangement, which consists of 3 dowels in each wheel path (i.e., right and left wheel path). The remaining three subsections for each primary section include joints with standard 12 dowels arrangement. For the case of the standard dowel arrangement, the dowel bars are spaced at 305 mm (12 in) in the centers and 152 mm (6 in) from the pavement edge. Also, the control section was composed of 178 mm (7 in) thick concrete pavement with joint spacing of 4.3 m (14 ft). All the joints for the control sections were doweled using the standard 12 dowels arrangement. Figure 3 illustrates the detailed layouts for project sections including standard and special dowel arrangements evaluated. Figure 4 shows the pavement structures used for the project sections.

3.2 Construction

The existing asphalt concrete (AC) surface was milled to an average depth of 102–114 mm (4–4.5 in) and the milled surface was then overlaid with a uniform 25 mm (1 in) of AC. Prior to the pouring of the concrete, the dowel baskets were fixed to the treated asphalt surface. Two different dowel arrangements previously mentioned were constructed as shown in Fig. 5. Fixed form paving process was used for pavement construction. The concrete was discharged from a ready mix concrete truck and was manually distributed and vibrated. A bridge deck paving machine was used to compact and finish the pavement surface. Four hours after concrete placement, all the joints were cut and were sealed with a low modulus silicon sealant. The slab surface was then cured using a white pigment curing compound and transverse tining was done to obtain a textured surface for the pavement.

3.3 Pavement Performance Evaluation

Pavement condition survey was conducted for project sections to monitor the performance in terms of longitudinal crack, transverse crack, corner crack, and spalling. Also, the FWD test was conducted to determine the structural capacity and to evaluate joint efficiency for sections with different dowel arrangements. Figures 6a–d summarize the results of four distress types analyzed using pavement images obtained by multi-purpose survey vehicle (MPSV). In general, the pavement sections with special dowel arrangement exhibited comparable performance to the one with standard dowel arrangement for four distress types evaluated. Also, the FWD test results, including maximum deflection and load

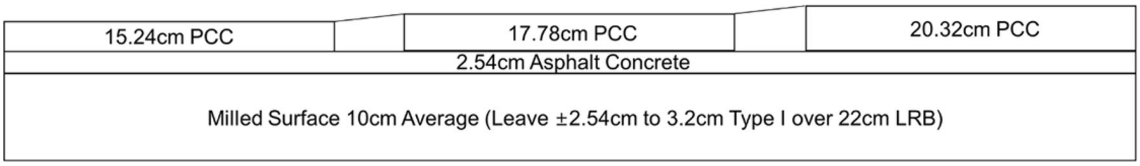
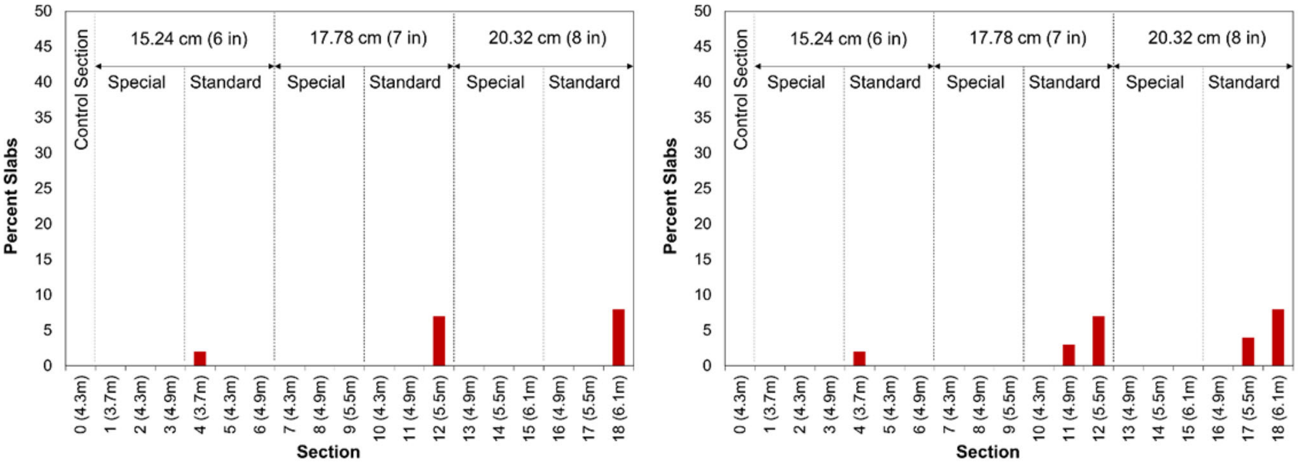
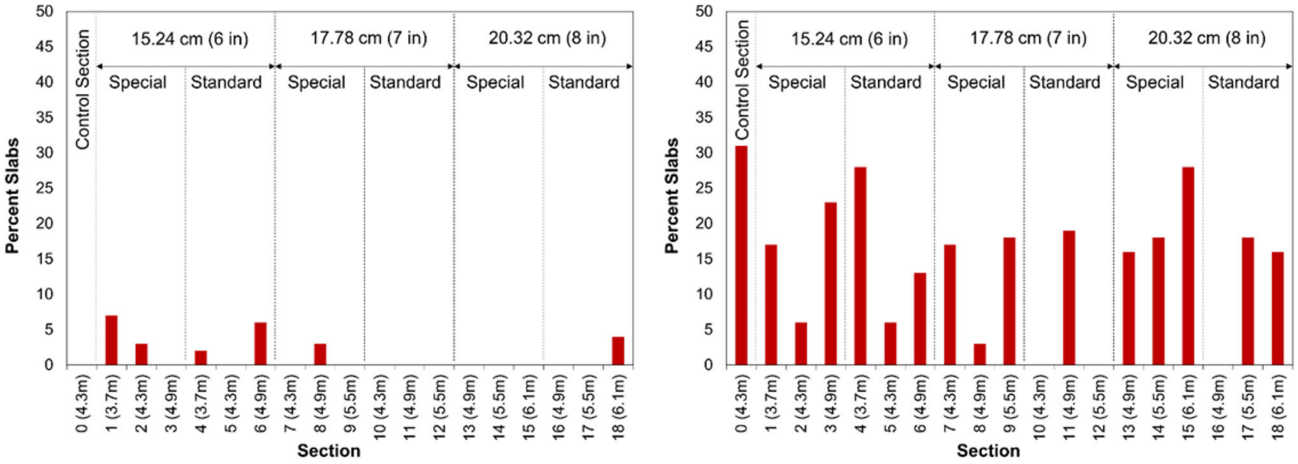


Fig. 4 Pavement structures used for project sections.



(a) Longitudinal crack **(b)** Transverse crack



(c) Corner crack **(d)** Spalling

Fig. 6 Pavement distress survey results.

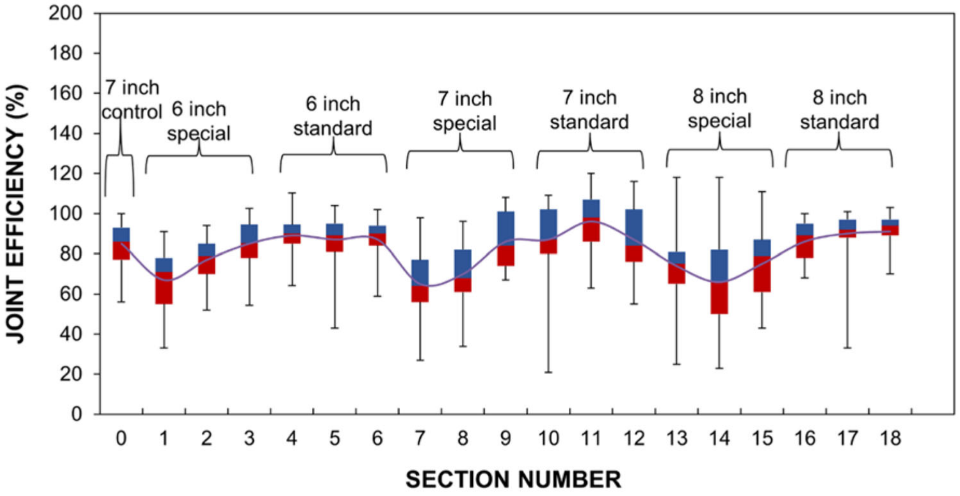


Fig. 7 Summary of load transfer efficiency (LTE) test results.

transfer efficiency (LTE), showed higher variability that potentially associated with diverse factors. These may include the number of dowels under the load, the contribution of dowel bars and aggregate interlock for LTE and differential deflection, and/or dowel bar alignment condition. However, no significant performance difference was identified between the sections with standard dowel arrangement and special dowel arrangement as shown in Fig. 7.

4. Finite Element (FE) Analysis

4.1 FE Model Development

In this study, the commercial finite element software ADINA (version 9.1.1) was used for modeling efforts. A three-dimensional finite element (FE) model of a rigid pavement was developed to study the load transfer mechanism of dowel bars. The modeled section consists of three slabs with a transverse joint width of 6.4 mm (0.25 in) supported by a 254 cm (100 in) thick subgrade layer as shown in Fig. 8. The transverse joint width was selected in order to allow expansion and contraction of the slab. A fixed boundary condition was applied for the subgrade layer in the z-direction, and symmetric boundary conditions were employed along the x- and y-directions.

No restraints were considered for the concrete slab to allow for the possible loss of contact due to temperature differentials in the slab by modeling the unbonded interface condition between the concrete slab and the subgrade layer using contact and target elements. The slab contact with the subgrade layer was only retained by the self-weight of the slab. The interface model was also capable of capturing the effect of friction, and a value of 1.5 for coefficient of friction was assumed in the FE model. Also, the surface condition between dowel bar and surrounding slab was also modeled using the contact surface with a value 0.6 for a coefficient of friction. The dowel bar was confined by the slab weight and then was allowed to slide when the force to pull the dowel bar was greater than confined force in the surface of dowel bar.

Figure 9 shows the interface modeling and contact elements between the slab and subgrade layer. The concrete slab, subgrade layer, and dowel bars were modeled by an assemblage of 8-node hexahedron elements with different sizes of mesh. To accurately capture the dowel bar behavior, a finer mesh was considered around the dowel bar and dowel sleeves. The length of the smallest element used was 9.5 mm (0.375 in) for the dowel bar.

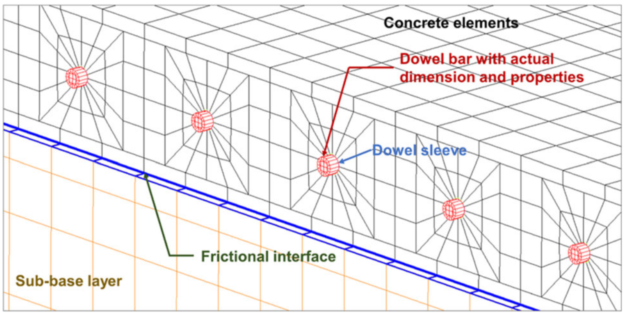


Fig. 9 Modeling of the interface condition.

The mechanical and thermal behaviors of the concrete slab are characterized by its modulus of elasticity, Poisson's ratio, coefficient of thermal expansion, and density. Also, the subgrade layer and dowel bars were considered as linear elastic materials characterized by their modulus of elasticity and Poisson's ratio. In particular, the use of a finer mesh for the 3-D dowel bar is imperative to accurately capture the dowel-sliding, shear force transfer, and bearing stresses in the concrete. In this study, the sliding interface was modeled between concrete and dowel bars in order to effectively simulate the dowel bar movement in consideration of the temperature effect.

Figure 10 exhibits slab and dowel bar mesh and contour plots for bearing stress around dowel bars. The typical size of dowel bar dimension and spacing were considered with 25 mm (1 in) in diameter, 229 mm (9 in) embedment in

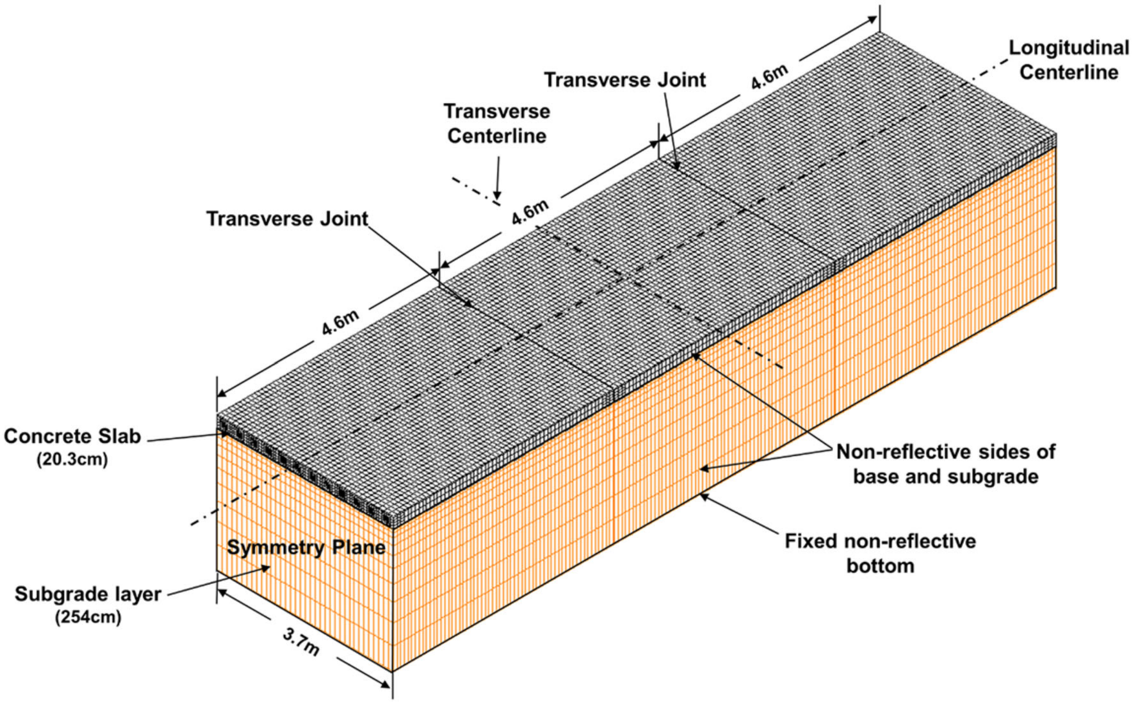
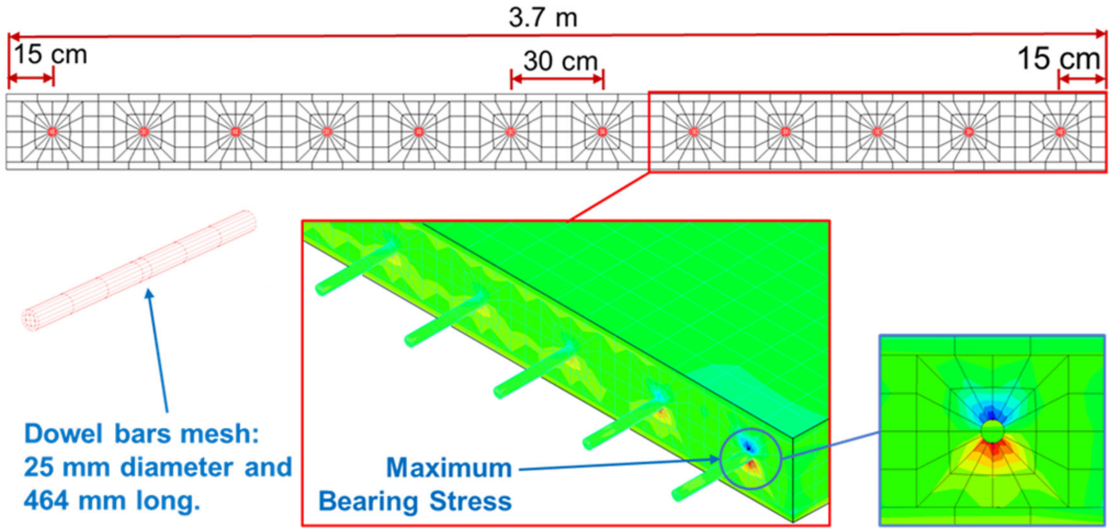
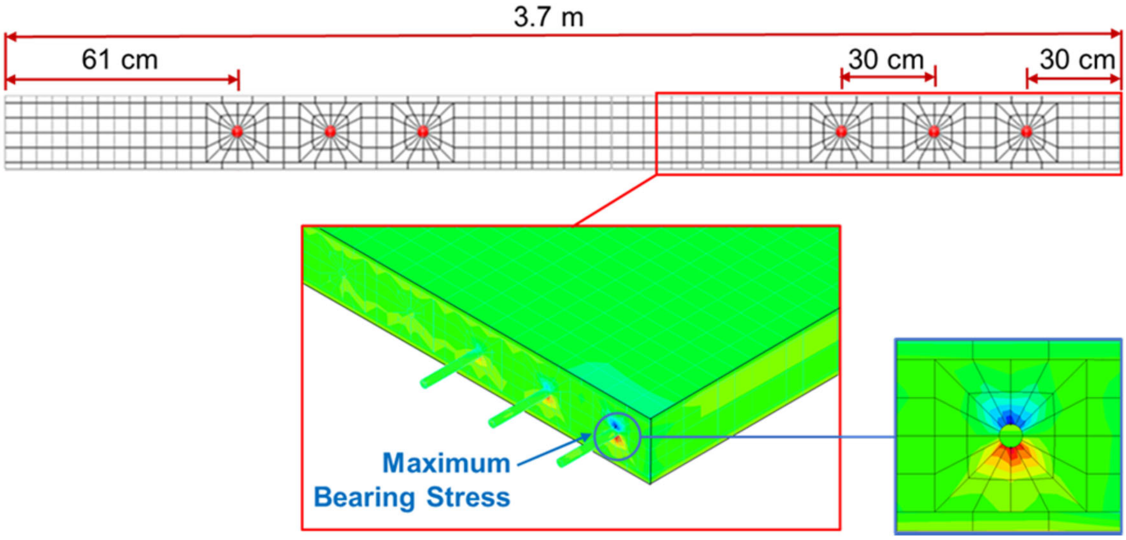


Fig. 8 Finite element modeling of JPCP with actual dowel bar dimension.



(a) Standard dowel bar configuration



(b) Special dowel bar configuration

Fig. 10 Slab and dowel bar mesh and bearing stress contour view.

both sides, and 305 mm (12 in) dowel spacing as shown in Fig. 10. Table 3 presents the material properties used in the FE model. The various types of load, including the concrete slab self-weight, wheel loads and thermal loads, are considered to determine the critical stresses in the concrete and dowel bars. Mackiewicz (2014) was found that the positive and negative temperature differentials contribute the development of the vertical stresses around dowel bars and tensile stresses in concrete slab. Therefore, In this study, a 98-kN (22-kip) axle load, which represents the maximum legal load limit for single axle loads in Florida, was used as the applied load with positive temperature differential of + 11.1 °C (+ 20 °F). To consider the most severe load condition, the axle load was placed at the corner of the slab.

4.2 Calibration of FE Model Developed and Determination of Model Parameters

In this study, the 3-D FE model developed was validated using the FWD deflection basins obtained from the JPCP field section. The FWD deflection basins induced by a 12-kip load were used and to eliminate the effect of dowel bar looseness due to the age of pavement, the FWD data obtained immediately after construction (i.e., initial condition) was used for this task. The FWD deflection basins induced by a 53-kN (12-kip) load were used to evaluate the load transfer characteristics of the doweled joints. For the analytical deflection basin, a 304.8 mm by 304.8 mm (12 in by 12 in) square loading area, instead of 304.8 mm (12 in) diameter circular loading plate, was used to model the FWD load. This set of FWD tests was performed in the daytime when the slab tends to have a positive temperature differential and to have a full contact with the subgrade at the slab corner. Figure 11 shows a comparison between the analytical FWD deflection basins predicted and those measured from the tests. As shown in Fig. 11, a good agreement between measured and predicted deflection basin was indicated within the difference of 5%.

Table 3 Material properties used in the FE model.

Layer	Property	Value
Concrete	Compressive strength (MPa)	45.5
	Flexural strength (MPa)	5.8
	Modulus of elasticity (GPa)	29.7
	Poisson's ratio	0.2
	Coefficient of thermal expansion (/ °C)	11.75×10^{-6}
	Density (kg/m^3)	2322
Dowel bar	Modulus of elasticity (GPa)	200.0
	Poisson's ratio	0.3
	Diameter of dowel bar (cm)	2.5
	Length of dowel bar (cm)	46.0
Subgrade	Modulus of elasticity (MPa)	690.0
	Poisson's ratio	0.35

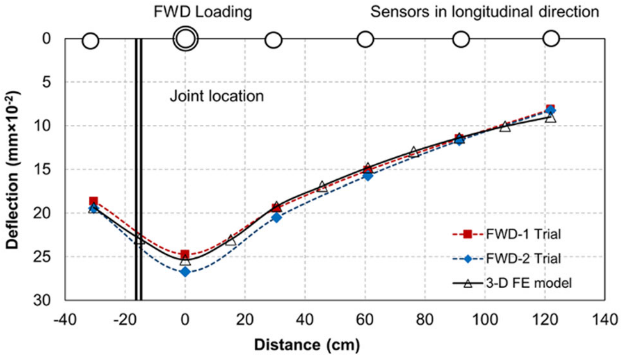


Fig. 11 Matching of deflection basin across the doweled joint.

5. FE Analysis Results

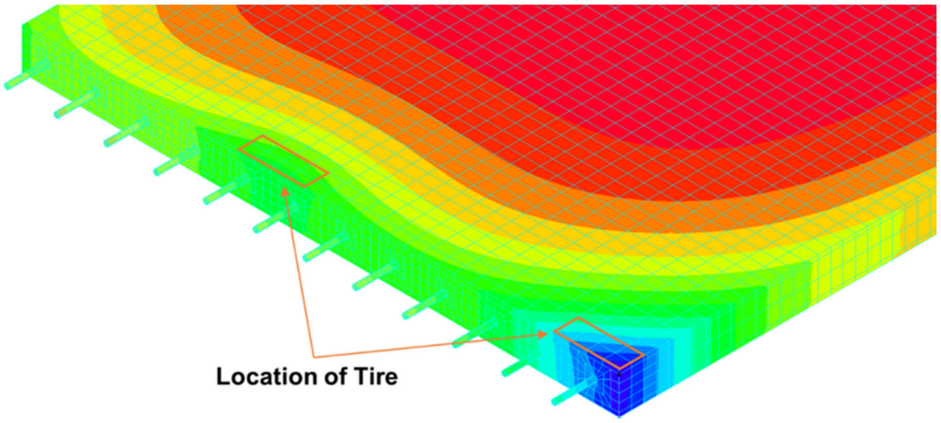
The 3-D FE model developed was used to evaluate the effects of the different dowel bar arrangements on the structural response characteristics of the JPCP. As shown in Table 4, there appeared to be little changes in the induced deflection and stresses at the joint due to the different dowel bar arrangements. The maximum corner deflection increased by 3.8% as compared to standard method. In addition, the stresses at the slab edge and bearing stresses at the dowel-concrete interface increased by 4.5 and 5.0%, respectively. However, the maximum increase in the dowel shear stresses at the critical dowel bar was found to be only 0.2%.

Figures 12a–c exhibit contour plots of deflections in concrete slab for two different dowel bar configurations under the critical traffic-environmental loads condition. Results indicated that the maximum deflection was occurred at the corner of concrete slab and the contour area of deflection seemed to be similar between special and standard dowel bar arrangement. In particular, the similar deflection response characteristics in concrete slab was identified with special dowel bar arrangement which intended more localized load transfer to the adjacent slab within the wheel path. As shown in Fig. 12, since only some limited number of dowel bars involved within the domain of load transfer (i.e., dowel bars located under the critical region) for both cases, the similar mechanical behavior was identified between standard and special dowel bar arrangement.

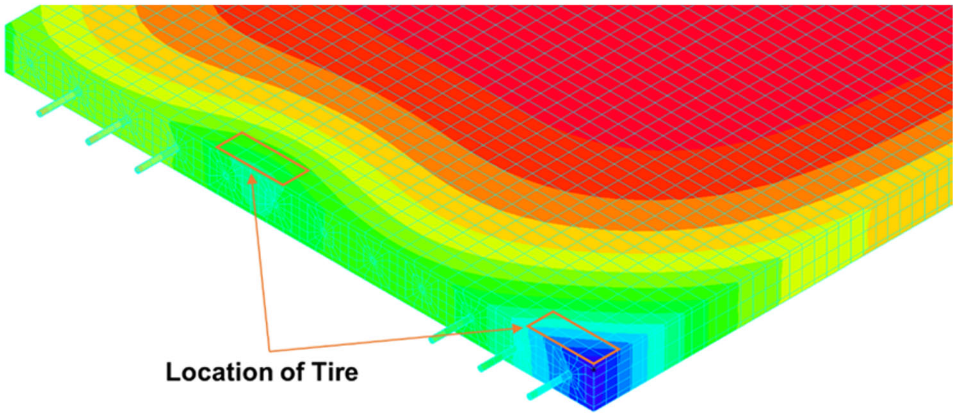
In addition, the stiff base in this pavement could possibly be the reason for the minimal effect of different dowel bar arrangements. Therefore, in order to evaluate the effects of a stiff base condition, a parametric study was conducted by varying the base modulus from 207 to 689 MPa (30 to 100

Table 4 Effects of different dowel bar arrangements on deflections and stresses.

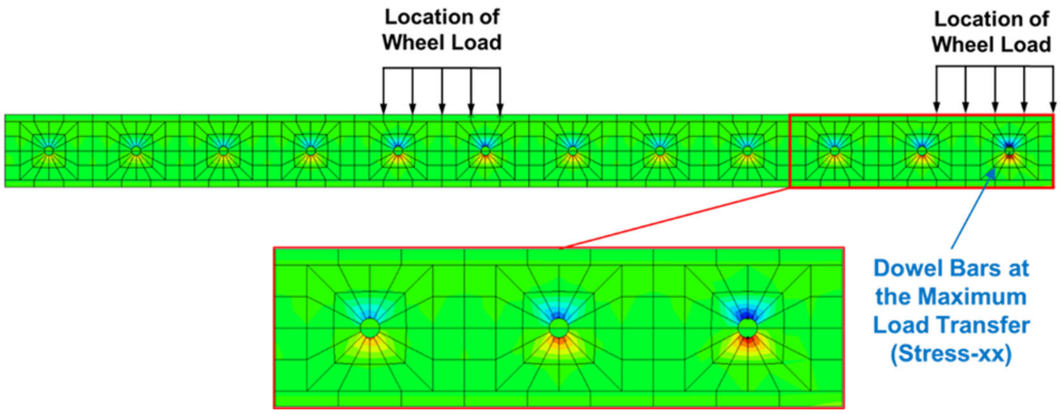
Dowel design	Standard	Special	Difference (%)
Peak corner deflection (mm $\times 10^{-2}$)	69.60	72.14	3.8
Peak edge stress (MPa)	1.97	2.06	4.5
Bearing stress in surrounding concrete (MPa)	4.53	4.75	5.0
Peak dowel shear stress (MPa)	7.73	7.74	0.2



(a) The contour view of deflection for standard dowel bar configuration



(b) The contour view of deflection for special dowel bar configuration



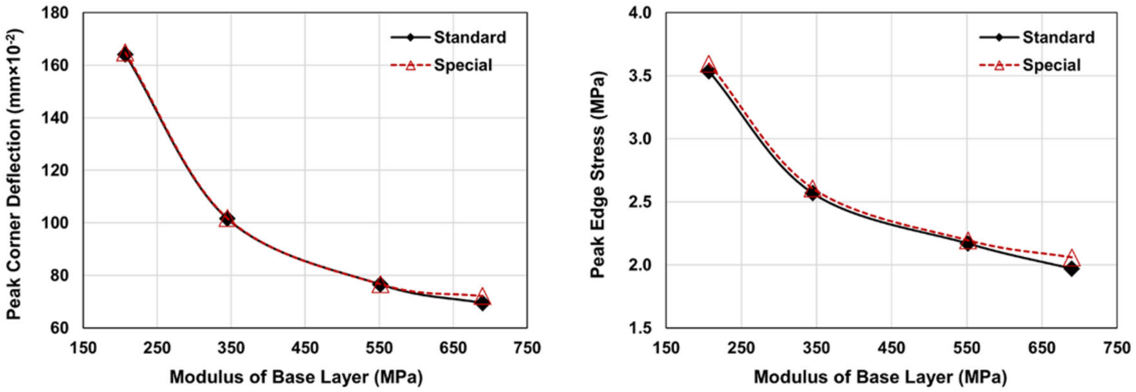
(c) The contour view of longitudinal stress (Stress-xx) for standard dowel bar configuration

Fig. 12 The contour plots of deflections in concrete slab for two different dowel bar configurations.

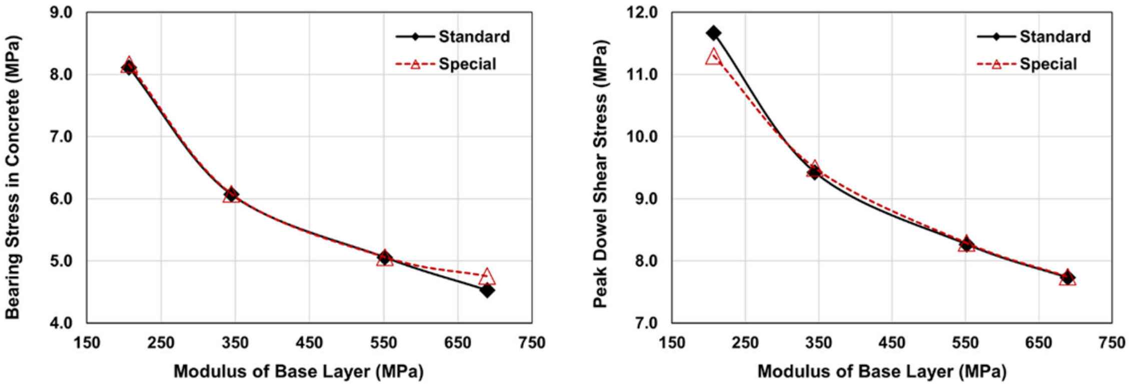
ksi). Figure 13 shows the plots of the effects of base modulus on dowel-joint behavior. The result indicates that the change in base modulus significantly affects the dowel-joint behavior of the JPCP. Based on the results of this parametric study, a stiffer base condition could significantly improve the dowel-joint performance. This further confirms the comparative results obtained between the experimental field evaluation and the analytical FE model.

6. Conclusions

In this study, the performance of two different dowel bar arrangements under real traffic and environmental conditions were evaluated using the results of FWD test, crack survey, and faulting measurement. Also, a 3-D finite element model for JCPC was developed to evaluate change in structural response characteristics due to different dowel bar



(a) Corner deflection **(b)** Peak edge stress



(c) Bearing stress in surrounding concrete **(d)** Peak dowel shear stress

Fig. 13 Effects of base modulus on the dowel-joint behavior.

arrangements under the critical loading condition. The FE model developed was calibrated using the FWD deflection data measured from the field test section. The model was then used to perform the numerical analyses to determine the effect of different dowel bar arrangements. The main findings and conclusions are summarized as follows:

- Based on the field performance evaluation results, no apparent performance difference was observed between the sections with standard dowel and special dowel arrangements. This matches well with the results obtained from the analytical FE model developed.
- No significant changes in pavement structural responses, including the slab stresses and deflections, were identified between two dowel bar arrangements evaluated. This may result in no significant difference in expected performance for the test slabs evaluated.
- It was found that the base modulus plays an important role on the dowel-joint behavior and stiffer base condition could significantly improve the dowel-joint performance.
- It was concluded that when the base layer is stiff enough to support the slab deflection and resist erosion (e.g., AC layer), the special dowel bar arrangement (i.e., reduced number of dowel bars only within the wheel paths) could provide similar performance as compared to a standard dowel bar arrangement. This may result in significant cost savings without any negative effects on expected pavement performance.
- Future research efforts are recommended to further evaluate the long-term performance of different dowel bar arrangements using dynamic fatigue tests approach.

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