Finite element analysis and load tests of full-scale, variable-thickness precast, prestressed concrete pavement on granular base

Nasser M. Alwehaidah and Bruce W. Russell

- Three full-scale precast, prestressed concrete pavements with variable thicknesses were constructed on a granular base and tested under static and repeated loads and modeled using finite element methods.
- In repeated load testing and in static load testing, the pavement showed a linear relationship between load and deflection, and the deformation of the panels was calculated accurately using the finite element method.
- Some cracking did occur in the precast, prestressed concrete pavement panels when loads were applied at the edges of the panels.

Rigid pavement in the United States dates back to the first concrete pavement constructed in Bellefontaine, Ohio, in 1893.[1] Rigid pavements are built using portland cement concrete and are classified as jointed plain concrete pavement; jointed reinforced concrete pavement; continuous reinforced concrete pavement; and precast, prestressed concrete pavement.

Traditional cast-in-place concrete pavement construction causes delays because of the time required for rehabilitation of the base and subbase materials for establishing grades and other preparations for casting concrete on-site, and for the concrete to reach the prescribed maturity or specified strength. Conversely, precast, prestressed concrete pavement panels require minimal site preparation and little on-site construction time, causing far less disruption to highway users.[2] By using precast concrete, pavement surfaces can be used intermittently as construction is staged and the roads can be opened to traffic with fewer delays. Further, construction with precast concrete panels can be staged while trafficways remain open during peak periods, and construction can be done intermittently during low-traffic periods, such as nights and weekends.

The majority of the previous research on precast, prestressed concrete pavement is related to the feasibility and construction using this material. The main objectives of the present study were to determine the response of full-scale precast, prestressed concrete pavement in the field and to compare these results with finite element analysis results for specific thicknesses, prestressing forces, and loads.

Pavement design and construction

For this research, three pavement sets were built, each consisting of four precast concrete panels (three full panels and one half solid panel), for a total of 12 precast concrete panels. The full panels were 12 ft (3.7 m) wide (to match the width of one lane) and 8 ft (2.4 m) long. The length dimension of the panel is defined as the dimension in the direction of roadway travel. All panels were pretensioned in the transverse (width) direction during fabrication and were post-tensioned in the longitudinal (length) direction to form a complete pavement set.

Figure 1 shows a typical panel plan and sections and a typical plan of an assembled pavement set. Pavements I and II are nominally 8 in. (200 mm) thick, and pavement III is nominally 10 in. (250 mm) thick. The section in Fig. 1 shows variations in pavement thickness for each panel. **Table 1** gives the pavement thicknesses, the magnitude of the prestressing force, and the post-tensioning layout. The location of the thickened sections of the pavement panels correspond to the traffic wheel path or to the edges of the panels. The thickened sections serve to reduce panel stresses under the wheel path and at panel edges.[3] The voided sections are each 2 in. (50 mm) deep. These voids served as grout pockets and were filled using pressured grouting for the purposes of providing uniform load transfer from the rigid pavement to the underlying base materials.

Before placement of the pavement panels, the road bed was constructed in conformance with the Oklahoma Department of Transportation (DOT) 1999 *Standard Specifications for Highway Construction*[4] for subbase and base preparations. Base materials consisted of crushed limestone in conformance with Oklahoma DOT specifications. These materials were rolled, compacted, and leveled using laser-guided heavy equipment. Subbase soils were compacted to 95% standard density in conformance with Oklahoma DOT specifications.

During construction, a layer of polyethylene bond breaker was placed between the pavement and base, and the 2 in. void was grouted using nonshrink grout after post-tensioning. The pavements also featured two- and four-strand post-tensioning systems with 0.5 in. (13 mm) diameter strands to reduce cost and construction time.[3] Table 1 gives the pavement thicknesses, prestress magnitude, and post-tensioning layout. **Figure 2** shows the assembled pavement panels before post-tensioning and grouting.

The pavement panels were built at a precast concrete fabrication plant and then transported to the testing location. The fabrication process was completed in six days. The panels were cast on three different days. All of the casts were made in one pretensioned bed approximately 250 ft (76 m) long. The concrete compressive strength at prestress release and 28 days were specified to be 3.5 and 5 ksi (24 and 34 MPa), respectively. The strands used for this research were ½ in. (13 mm) diameter seven-wire Grade 270 (1860 MPa) low-relaxation strands. Construction on the jobsite started shortly after the panels were fabricated. The subgrade was graded and uniformly compacted at moisture content and density levels that ensured stable support.

The panels were delivered to the jobsite and assembled shortly after base preparation was completed. The panels were hauled to the jobsite by the fabricator, unloaded using a 5 ton (44 kN) rough terrain forklift, and assembled atop the base course. A layer of bond breaker was placed between the base course and the pavement panels to eliminate stresses caused by base friction.[5] A bitumen sealant was used around the perimeter of the panels to prevent grout from leaking. The same sealant was used around the ducts at the joins to prevent grout from leaking when grouting the ducts.

The strands were post-tensioned to 31 kip (140 kN) each to achieve the required prestressing force. Last, the ducts and voids were grouted. Tensioning and grouting were performed by a contractor specializing in installation of post-tensioned, grouted systems.

Concrete specimen tests

To determine the mechanical properties of the concrete mixture used in precast concrete panels, a total of 36 cylinders (4 × 8 in. [100 × 200 mm]) were cast at the same time that the panels were cast. A minimum of two specimens from each concrete placement were tested for compressive strength at 1, 7, 28, and 90 days to obtain the strengths of the batches at different ages. Furthermore, two separate specimens were tested for Young's modulus and tensile strength using the splitting cylinder test. Material properties obtained from concrete

Table 1. Test pavements I, II, and III thicknesses and prestressing details (0.5 in. diameter strands)

Pavement	Thickness, in.		Longitudinal strands		Quantity of transverse strands	Prestress magnitude, psi	
	T1	T2	Quantity	Layout (PT1-PT2-PT2-PT1)		Longitudinal	Transverse
I	8	6	8	2-2-2-2	5	213	226
II	8	6	12	2-4-4-2	7	320	316
III	10	8	12	2-4-4-2	7	247	237

Note: 1 in. = 25.4 mm; 1 psi = 6.895 kPa.

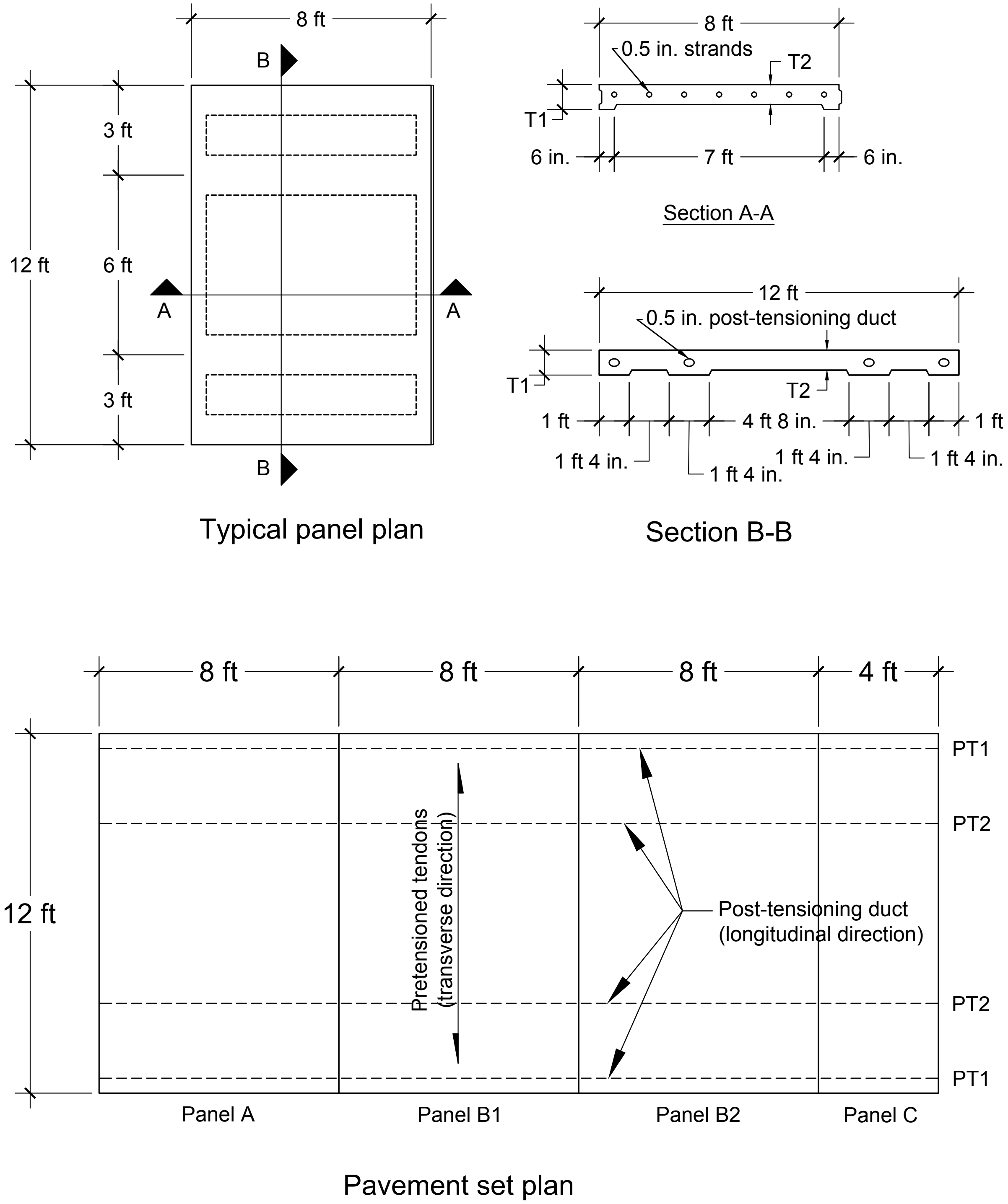


Figure 1. Typical panel plan and sections and pavement set used for the research. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

specimen tests were used in the structural analysis model to predict the pavement response to loading.

Testing procedure

The test variables for each of the panels were slab thickness and prestressing stresses in the concrete. Static and repeated load testing was performed separately on the center, wheel path, and edge of each pavement set using a loading frame designed specifically for the research. The testing frame consisted of structural tubing and was designed to support grating that held up to 80 kip (360 kN) of concrete ballast. The loading frame (Fig. 2) provided sufficient strength, stiffness, and ballast for the required testing loads to be applied at each individual load location (**Fig. 3**).

Repetitive loads of 4.5, 9, 18, and 27 kip (20, 40, 80, and 120 kN) were applied at the individual load locations at the center of the lab, the wheel path, and the edge (Fig. 3). Each location was tested independently of the other locations. The loads were repeated three times at each load cycle, and maximum loads were maintained for 5 minutes. Loading was applied at a regulated time rate and removed more quickly. After the last repeated load of 27 kip was applied, the pavement was unloaded and left unloaded for 15 minutes to eliminate any residual deformations before applying the final 30 kip (130 kN) single load. Pavement III was preloaded with a 50 kip (220 kN) load at all test locations before the repeated and static load tests. The preload was necessary to test the load frame and equipment but might have increased the stiffness of the subgrade, thereby causing inconsistent results.

Instrumentation

Linear variable differential transformers (LVDTs) and a load cell were used to measure pavement surface deflections and applied load, respectively. Figure 3 shows the layout of the LVDTs for panels A, B1, and B2. The instruments were tested and calibrated before they were used. During testing, deflections and the applied load measurements were saved to a spreadsheet using a data acquisition system running a custom virtual instrument. LVDTs were attached to a tubular

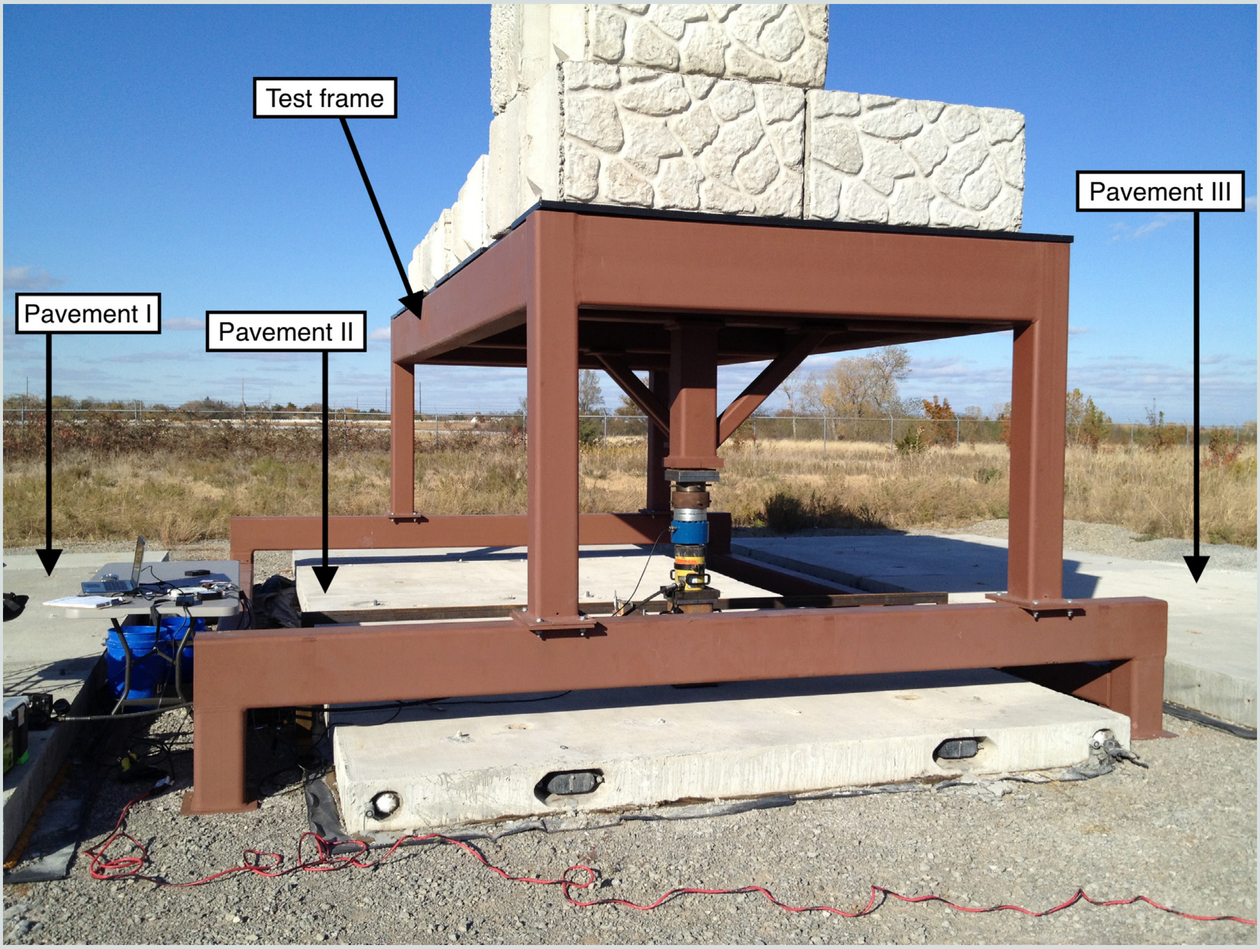


Figure 2. Completed pavement set-ups showing the test frame, post-tensioning anchors, and bond breaker between the pavement and base.

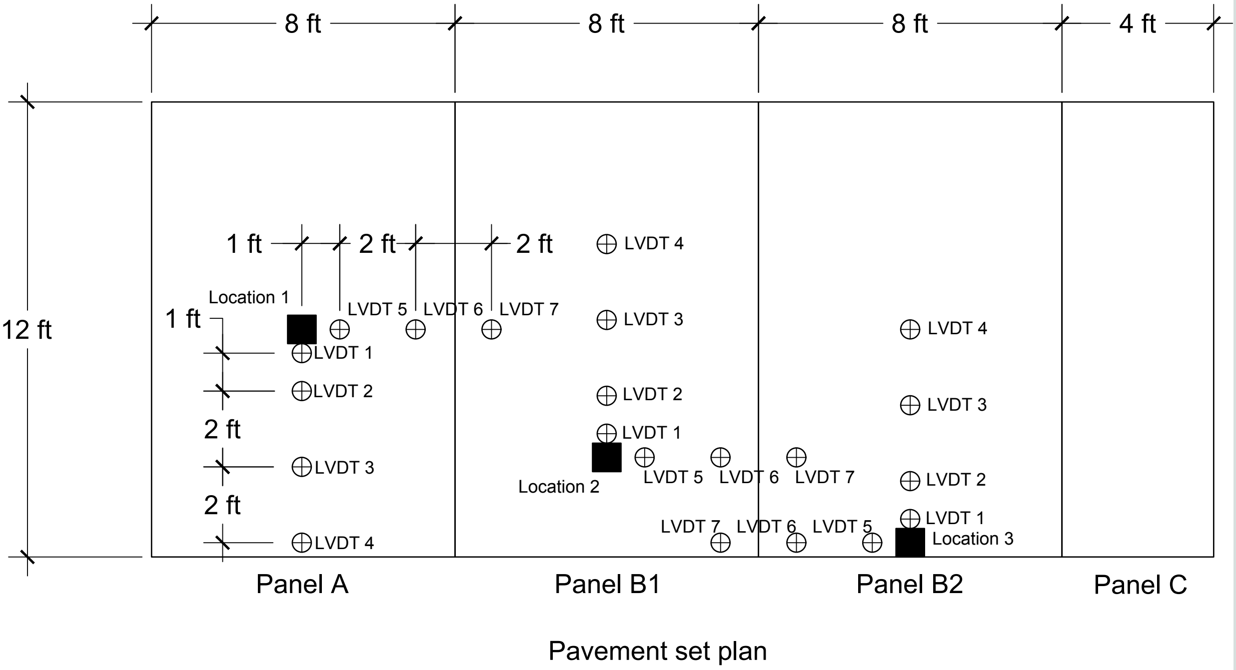


Figure 3. Load test locations and linear variable differential transformer (LVDT) locations. Note: 1 ft = 0.305 m.

steel reference frame that was isolated from the test pavement and loading frame. The load was applied using a hydraulic hand pump connected to a hydraulic actuator with a digital pressure gauge to measure pressure independently from the data acquisition system. A 9 × 9 in. (230 × 230 mm) neoprene pad was placed at the load location between the pavement and a fabricated loading column. A spherical head was used to mitigate effects from eccentricity and misalignment.

Testing results

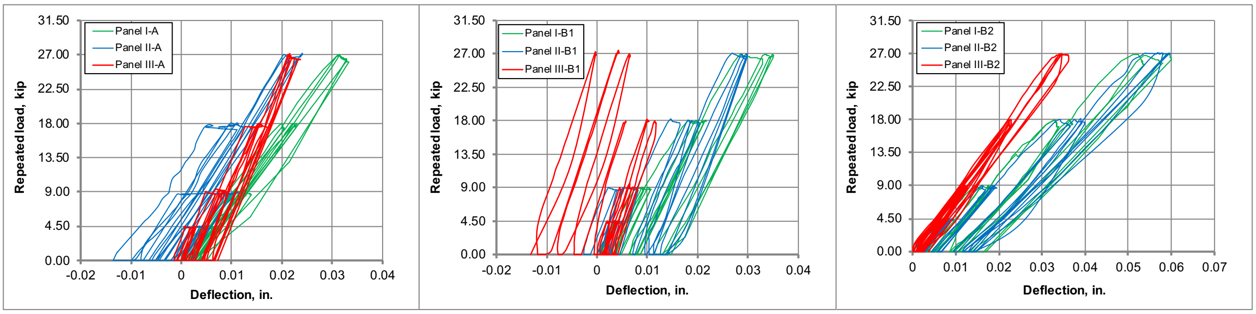
Figure 4 shows the load and deflection readings for all pavement panels at the load application locations (LVDT 1). Positive deflection values indicate downward deflection from the initial pavement level. Test pavements I and II had the same slab and beam thicknesses. As expected, the deflections between these two test panels were similar. Pavement II was subjected to higher prestressing force as per the pavement design. Test pavement III was 2 in. (50 mm) thicker than the other two test panels, and the resulting stiffness was reflected in the deflection measurements.

The repeated test load deflection measurements were not reset after each cycle (4.5, 9, 18, and 27 kip [20, 40, 80, and 120 kN]), which causes the results to look different, but in fact the results are similar if one measures the deflections as the difference when the load is zero and when the load is fully applied. Pavement-surface-level changes between zero load cycles were the result of curling caused by temperature changes during testing.

For all edge load locations (location 3), the first visible crack was observed at the bottom near the loading point. For pavements I and II, cracking started when the applied load reached 18 kip (80 kN) and increased in length as loading reached 27 kip (120 kN). Pavement III showed visible cracks when loads reached 27 kip. In all cases, cracks closed after unloading due to prestressing forces.

Figure 4 shows the maximum deflection measurements for the static load tests for panels A, B1, and B2. The data was taken from the physical measurements during the testing. The coefficient of determination was calculated to be between 0.988 and 0.999 for the static load tests. The coefficient of determination shows how well a linear regression model fits the data. Coefficient of determination values closer to 1.0 indicate a better fit.

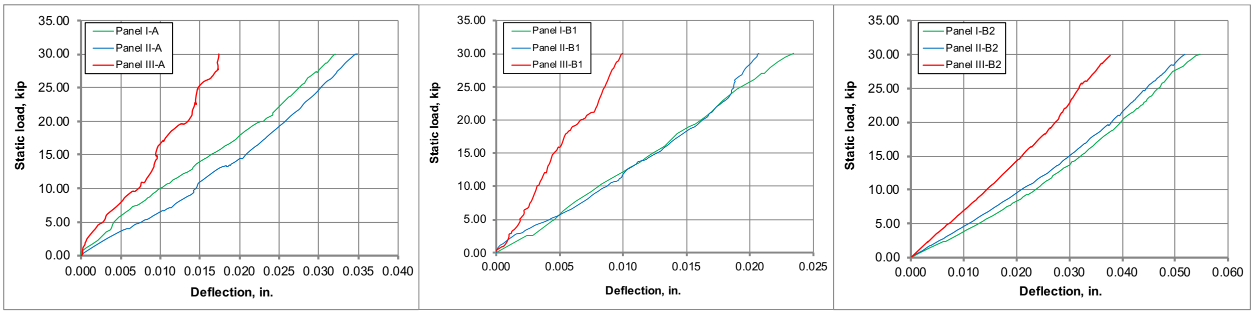
The deflection data were used to estimate the modulus of subgrade reaction *k* using methods outlined by the American Association of State Highway and Transportation Officials' (AASHTO's) *Supplement to the AASHTO Guide for Design of Pavement Structures, Part II*.[6] The method used deflection data at distances of 0, 8, 12, 18, 24, 36, and 60 in. (0, 200, 300, 460, 610, 910, and 1520 mm) from the load center to establish the deflection basin and calculate the modulus of subgrade reaction. The method requires that the deflection be measured at a location away from the edge; therefore, the deflection data for panels I-A, II-A, and III-A were used for *k*-value calculations. The test pavement deflections at 8, 18, 36, and 60 in. were not measured by instrument,



Deflection versus repeated load, panel A

Deflection versus repeated load, panel B1

Deflection versus repeated load, panel B2



Deflection versus static load, panel A

Deflection versus static load, panel B1

Deflection versus static load, panel B2

Figure 4. Linear variable differential transformer 1 deflections for repeated and static loads for pavements I, II, and III. Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN.

and interpolation was required. The calculated *k* values for pavements I, II, and II were 139, 121, and 235 psi/in. (37.7, 32.8, and 63.8 kPa/mm), respectively. A high *k* value of 235 psi/in. was reported for pavement III, which was predicted because the pavement was preloaded with 50 kip (220 kN) point loads for an extended period of time before the actual tests were performed.

Finite element analysis

Using a commercial software package, three 3-dimensional finite element models were developed to calculate deflections and stresses caused by the 30 kip (130 kN) test loads. The elements used in the finite element analysis were eight-noded solids with surface dimensions of 3 × 3 in. (75 × 75 mm)

Table 2. Test deflections and finite element analysis deflections and stresses for pavements I, II, and III at different load locations

Location (panel)	LVDT 1 test deflection, in.	Finite element analysis deflection, in.	Finite element analysis longitudinal stresses, psi	Finite element analysis transverse stresses, psi
I-A	-0.0321	-0.0311	906	966
I-B1	-0.0234	-0.0277	846	557
I-B2	-0.0547	-0.0553	1454	395
II-A	-0.0349	-0.0338	915	979
II-B1	-0.0207	-0.0304	866	560
II-B2	-0.0518	-0.0606	1485	395
III-A	-0.0174	-0.0161	531	570
III-B1	-0.0100	-0.0155	521	355
III-B2	-0.0377	-0.0351	914	238

Note: LVDT = linear variable differential transformer. 1 in. = 25.4 mm; 1 psi = 6.895 kPa.

(perpendicular to the load) and a depth of 2 in. (50 mm). In the finite element model, the panels were assumed to be continuous across the joints; effectively, the joints do not exist in the analysis. The model was loaded at three locations (Fig. 3) with a test load of 30 kip (130 kN) applied as surface pressure of 370 psi (2.55 MPa) over an area of 9 × 9 in. (225 × 225 mm). The supporting foundation system was modeled as a series of linear springs, with the spring constant based on the calculated modulus of subgrade reaction (*k* value). The properties of the concrete were based on the compressive strength and modulus of elasticity obtained from cylinder tests. Results from the analysis included stresses, base reactions, and surface deflections. **Table 2** presents the finite element analysis maximum surface deflections, test deflections, and finite element analysis stresses for pavements I, II, and III.

Conclusion

The pavement load tests showed that the pavement response to load remained linear even when the applied loads reached 30 kip (130 kN). This finding is important because it validates the use of linear springs as the support for the finite element analysis. Comparison of the measured load with deflection to a perfectly linear system indicates coefficient of determination values to be nearly 1.00.

The deflection results (Table 2) show that the deflections from the finite element model are close to those from the pavement testing. Therefore, when using an accurate modulus of subgrade reaction (*k* value), the pavement deflections and stresses can be accurately calculated using finite element analysis. Furthermore, precast, prestressed concrete pavement deflections and stresses can be accurately calculated by modeling the supporting soil as linear springs because test and finite element analysis results indicate a linear response to load.

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References

1. Snell, L. M., and B. G. Snell. 2002. "Oldest Concrete Street in the United States." *Concrete International* 24 (3): 72–74.
2. Merritt, D. K., B. F. McCullough, and N. H. Burns. 2001. "Feasibility of Using Precast Concrete Panels to Expedite Construction of Portland Cement Concrete Pavements." *Transportation Research Record* 1761: 3–9.
3. Alwehaidah, N., and B. Russell. 2013. "Refinement of Precast, Post-tensioned Concrete Pavement Technology." In *The PCI Convention and National Bridge Conference: Proceedings, September 21–24, 2013, Grapevine, Texas*. Chicago, IL: PCI. CD-ROM.
4. ODOT (Oklahoma Department of Transportation). 1999. *Standard Specifications for Highway Construction*. Oklahoma City, OK: Oklahoma Department of Transportation.
5. Chia, W. S., F. B. McCullough, and N. H. Burns. 1986. "Field Evaluation of Subbase Friction Characteristics." Research report 401-5. Austin, TX: Center for Transportation Research.
6. AASHTO (American Association of State Highway and Transportation Officials). 1998. *Supplement to the AASHTO Guide for Design of Pavement Structures. Part II, Rigid Pavement Design & Rigid Pavement Joint Design*. Washington, DC: AASHTO.

About the authors

Nasser M. Alwehaidah, PhD, PE, is a licensed professional engineer in California and lecturer at California State University–Northridge. He received his PhD in civil engineering from the School of Civil and Environmental Engineering at Oklahoma State University in Stillwater, Okla. His research interests include reinforced and prestressed concrete structures and computer applications in structural engineering.

Bruce W. Russell, PhD, PE, FACI, is director of the Bert Cooper Engineering Laboratory at Oklahoma State University. His research interests include structural and prestressed concrete, with an emphasis on the bond of prestressing reinforcement, variations in concrete mixtures and proportioning and the effects on the strength and durability of concrete structures, bridge engineering, and applications for fatigue and fracture.

Abstract

Three full-scale precast, prestressed concrete pavements with variable thicknesses were constructed on a granular base and tested under static and repeated loads. The test pavements were modeled using the finite element method, with the supporting foundation modeled as a series of linear springs and *k* values calculated using the experimental data. The pavement testing was performed using a movable testing frame designed for the research project. To monitor the response of the pavement, linear variable differential transformers and a load cell were installed and displacements were recorded to a data acquisition system during the entire testing period. The testing frame and data acquisition system that were used were found to be practical and effective tools for the testing performed for this project. In repeated load testing and in static load testing, the pavement showed a linear relationship between load and deflection and the deformation of the panels was calculated accurately using the finite element method. Furthermore, as expected, some cracking did occur in the pavement panels when loads of 30 kip (130 kN) were applied at the edges of the panels.

Keywords

Finite element method, pavement design, pavement performance, structural analysis.

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