REFINEMENT OF PRECAST, POST-TENSIONED CONCRETE PAVEMENT TECHNOLOGY

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ABSTRACT

Precast prestressed concrete pavement can provide many advantages over other pavement alternatives. Advantages include more rapid construction, decreased traffic congestion and reduced user costs, improved pavement durability from higher quality concrete, efficient use of materials, and economy through more widespread acceptance and use The main objectives of the research were to improve current design features, evaluate pavement performance, and investigate means to make precast pavements more economical and durable.

Improvements to design features included the use of granular base material to decrease costs and construction time, and the use of pavement panels with recessed grout voids to achieve full contact with the base materials. Full-scale test pavements were built and load tests were performed. Instruments measured applied loads and deflections at multiple locations. Structural analyses models were developed to evaluate pavement response to the loads.

The research successfully demonstrated that granular base materials can be used for some applications to reduce construction times and costs, and that grouted voids on the bottom of the pavement panels were effective in providing uniform pavement support. Test results showed strong agreement with analytical results indicating that rational models based on fundamental mechanics can be used for design and successful construction precast concrete pavements.

Keywords: Post-tensioning, Precast Pavement, Prestressed Concrete, Research.

INTRODUCTION

The growing traffic counts and the deteriorating condition of nation’s infrastructure requires new, efficient and durable methods for repairing and constructing highway pavements. Most pavements in service today were not designed to handle the current traffic counts nor the level and intensity of heavy loads. Traditional cast-in-place concrete pavement construction causes construction delays due to the time required for removal of existing pavement, rehabilitation of the base and sub-base materials, for establishing grades and other preparations for casting concrete onsite, and for concrete to reach a certain maturity or specified strength. Conversely, precast prestressed concrete pavement (PPCP) panels require minimal site preparation and no on-site setting time. Therefore roads can be opened to traffic immediately after or very nearly after construction. Further, construction with precast concrete panels can be staged where highways can remain open during peak periods and construction can be done intermittently during low traffic periods like nights and weekends. For these reasons, precast post-tensioned concrete pavement can be used for the construction of new pavements or rehabilitation of older pavements in high traffic areas, for bridge underpasses to increase overhead clearance, and for existing pavement repairs.

The overall objective of this research is to improve and refine precast prestressed concrete pavement technology. The specific objectives to achieve this are to investigate and analyze the current state-of-the-art, examine and possibly improve the current design features, perform structural analysis to evaluate pavement performance and limitations, conduct laboratory tests to examine and verify proposed improvements and analysis results, and investigate means to make precast pavement more durable and economical.

LITERATURE REVIEW

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 into jointed plain concrete pavement (JPCP), jointed reinforced concrete pavement (JRCP), continuous reinforced concrete pavement (CRCP), and precast prestressed concrete pavement (PPCP).

The use of prestressed concrete pavement dates back to the 1940s in Europe where it was mainly used for airport pavement. Most of the early European airport projects used post-tensioning in both directions with pavement thickness between 5.5 in. and 8 in. [2].The first known highway applications were in France in 1945 and England in the 1950s. The first known application of prestressed pavement in the United Stated was in military airfields in 1953 at Patuxent River Naval Air Station, Maryland. The Maryland project was followed by two more airport projects in San Antonio, Texas and El Paso, Texas. The first prestressed concrete highway experimental project was in Pittsburgh, Pennsylvania in 1957 [3].

In the mid-1960s, a research program by South Dakota State University and South Dakota Highway Department initiated the development of precast concrete pavement with an asphalt concrete overlay [4]. After a favorable test results, a 1,000 ft test section was built on US 14 bypass north of Brookings, South Dakota with prestressing force of 400 psi [5]. The main problem occurred one month after opening in a form of reflective cracks in the asphalt overlay at the precast panel joints [5]. Another milestone project was one and half mile prestressed concrete pavement demonstration project built in 1973 near Harrisburg, Pennsylvania. The projects four lanes were constructed using 26 slabs resting on asphalt base [6]. Double layer polyethylene sheets were used to break the bond between the asphalt base and the panels. The project used post-tensioning in the longitudinal direction with post-tensioning of 325 psi [6]. Similar demonstration projects were also built in Brookhaven, Mississippi and Tempe, Arizona in 1977.

The projects represent early attempts to develop prestressed pavement. All of the projects featured combined slab segments with lengths between 300 to 760 ft, longitudinal prestress between 200 and 400 psi, longitudinal post-tensioning only, friction reducing layers, and semi-rigid bases. However, these projects showed transverse cracking immediately after placement and longitudinal cracking within few years. The longitudinal cracks were attributed to temperature and shrinkage and the lack of transverse prestress. Another problem was joint spalling.

Following the early full-scale pavement projects mentioned above, new prestressed concrete pavement projects were constructed in Texas, California, Iowa, and Missouri. The 1985 Waco, Texas project by the Center for Transportation Research (CTR) was constructed from cast-in-place, post-tensioned concrete. The project established several new ideas after review the successes and failures from prior projects. The project’s most important concepts were the use of central stressing, the use of a friction reducing layer, and the incorporation of transverse post-tensioning [5]. Central stressing eliminated the need to access the end anchorage by creating anchorage pockets near the middle of a prestressed concrete slab panel where jacking devices were used to post-tension strands. The project used transverse prestressing in addition to longitudinal post-tensioning [5].

A project near Georgetown, Texas focused on testing and evaluating of the precast pavement techniques and methods [4]. The project utilized full depth precast concrete pavement panels with central prestressing performed at interior panels. The panels were prestressed in the transverse direction and post-tensioned in the longitudinal direction. The base was prepared using two inches of asphalt leveling course with a single layer of polyethylene in between to reduce post-tensioning losses and friction stresses [5].

A wide range of slab lengths has been used in projects around the United States. Pavements lengths ranging from 400 to 600 ft appear to perform well with proper prestressing for longer slabs. There are newer projects completed during the last few years and available information indicate that new projects share the following features:

1) Transverse pre-tensioning & longitudinal post-tensioning.
2) Asphalt leveling base with friction reducing sheet between the asphalt & pavement.
3) Nighttime construction where lanes were closed to traffic at the evening and opened to traffic before the morning traffic.

PRECAST PRESTRESSED CONCRETE PAVEMENTS DESIGN

This projects and others are intended to broaden the reach of the technology and, through education and technology transfer, increase the use of PPCP. Typical cross sections for precast prestressed concrete pavement consists of Portland cement concrete pavement, asphalt leveling course, friction reducing layer, base or sub-base course, and subgrade as shown schematically in Figure 1.

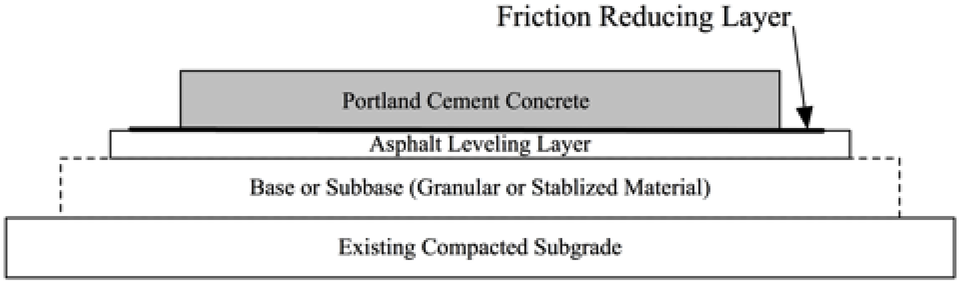

Figure 1 Typical rigid pavement cross-section

One of the objectives of this research is to improve the performance of PPCP. The designs from this research incorporate the following features:

1) The use of granular base material.
    - Reduce construction time.
    - Reduce construction costs.
2) The use of thinner pavement panel thickness.
    - Increase bridges underpass clearance.
    - Reduce panel weight for more efficient handling and transportation.
3) The use of equal magnitude of transverse prestressing and longitudinal post-tensioning.
4) The use of multi-strand tendons for faster construction.
5) The use of grouted voids underneath the panels.
    - To achieve full contact with the base.
    - Reduce the possibility of non-uniform base support.

For purposes of the experimental program, the precast panels are built with 12 ft width to match one traffic lane. The typical panel design is shown in perspective in Figure 2. Panel plan and sections are shown in Figure 3. Furthermore, the panels are constructed in eight ft lengths, the “length” of the panel being defined as the length in roadway travel. The panels are pretensioned in the transverse direction during fabrication and then post-tensioned in the longitudinal direction during panel erection and pavement construction. At the joints, the panels are to be connected with each other using shear keys to achieve high Load Transfer Efficiency (LTE). The depth of the panel at the wheel path (beams) and edges is greater than that at the center to give the pavement stronger section where needed the most.

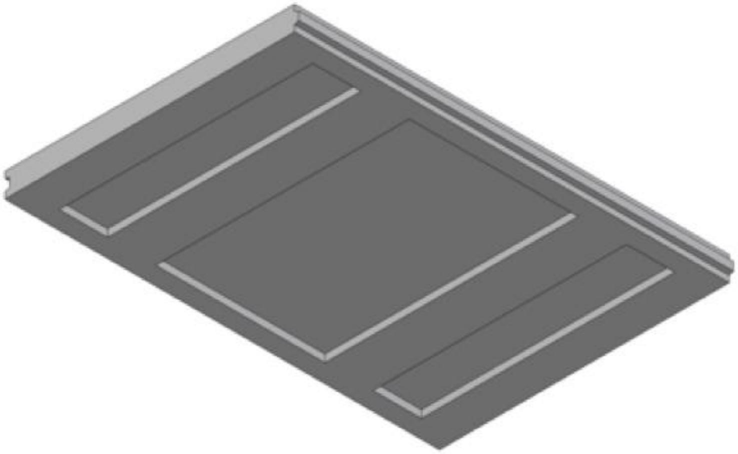

Figure 2 Perspective of the PPCP Test Panels showing under slab grout voids

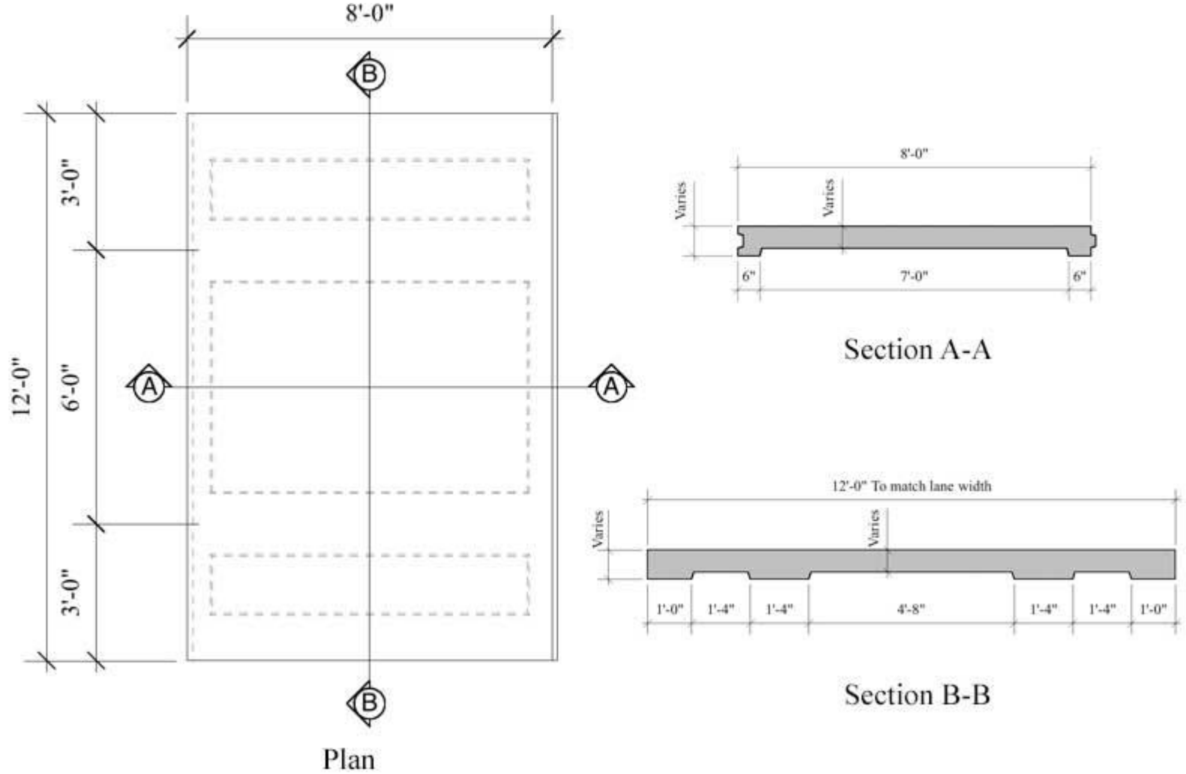

Figure 3 PPCP Panel Plan and Section

The modulus of rupture was taken as 530 psi and the elastic modulus was approximated as 4,000 ksi. The supporting subgrade was assumed to have a modulus of subgrade reaction of 150 psi/in. For comparison, the required CRCP thickness was calculated based on AASHTO Supplemental Guide for Rigid Pavement Design [7] and was found to be 13 inches. Three Test Pavements were constructed. Each Test pavement consisted of three main pavement panels and one end panel. The dimensions and thicknesses of the panels are shown in Table 1.

Pavement	Dimensions (feet)		Panel Thickness (inches)	
	Width	Length	Beam	Slab
I	12	8	8	6
II	12	8	8	6
III	12	8	10	8

Table 1 Test pavement dimensions and thicknesses

Using STAAD.Pro® software package, finite element models were developed to calculate deformations and stresses caused by an AASHTO Design load for an 18,000 lbs. single axle with tire pressure of 120 psi. In this design loading, the 18,000 lbs axle is load is distributed equally between two tire patches six ft. apart. This combination required a tire patch of 75 in^2 (two tires per axle). The tire load of 9,000 lbs. at 120 psi required a square patch 8.66 in. on each side. To account for the discreet spacing of FEM node points spaced at 3 in., an equivalent tire patch of 9 in. x 9 in. was considered with a tire patch load pressure of 111 psi. The tire pressure was applied to the entire surface of the elements that were loaded. The supporting subgrade was modeled as a series of springs (k = 150 psi/in).

FEA was performed for two load cases for each of the Test Panels. The first load case placed the axle at the middle of the panel in such a manner that each tire loading was directly above the beams precast in the panels. The second load case placed one tire load at the exterior edge and the second tire load at the center of the panel. Maximum tensile stresses found from FEA are shown in Table 2. All of the maximum stress conditions resulted from Load Case 2 where one wheel load was placed at the exterior edge of the panel.

Pavement	Panel Thickness (inches)		Maximum Transverse Stress (psi)		Maximum Longitudinal Stress (psi)	
	Beam	Slab	Compression	Tension	Compression	Tension
I & II	8	6	261 (LC2)	227 (LC2)	382 (LC2)	355 (LC2)
III	10	8	159 (LC2)	120 (LC2)	267 (LC2)	232 (LC2)

Table 2. Finite element analysis results summary

The final pavement designs were based principally on stresses obtained from the finite element analysis. The amount of prestressed was determined by calculating the effective prestress after all losses. The required prestressing magnitude was the calculated as the compression stress required to limit the tensile stresses in concrete and keep it below the fatigue limit of fifty percent of modulus of rupture [8]. In the transverse direction, 0.5 in. diameter, low relaxation prestressing strands were pre-tensioned during the fabrication of the precast panels. Longitudinal post-tensioning tendons consisted of 0.5 in. low relaxation strands in either two-strand or four-strand arrangements, depending on the required prestress.

Transverse prestressing consists of 0.5 in. diameter pretensioned strands at 28 in. spacing for Test Panels I and 14 in. spacing on Test Panel II and III. Longitudinal prestressing for Test Panel I consists of four two-strand ducts and Test Panel II and III consist of two two-strand ducts at the edges and two four-strand ducts at the wheels path. The layout and prestress for the projects Test Panels are shown in Table 3.

Pavement	Panel Thickness (inches)		Longitudinal Strands		Transverse Strands	Prestress Magnitude (psi)	
	Beam	Slab	Count	Layout	Count	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

Table 3 Pavement thicknesses and prestressing details

FABRICATION AND CONSTRUCTION OF THE EXPERIMENTAL PAVEMENTS

FABRICATION OF PANELS

The pavement panels were built at Coreslab, Oklahoma’s prestressing facility in Oklahoma City and then transported to the testing location. Fabrication started June 30, 2010 and was completed in six days, shown in the photographs, Figure 4 and Figure 5. The panels were cast in three different pours on three different days. All of the casts were made in one pretensioned bed approximately 250 ft. long. A total of 12 precast pavement panels were required for this project. The panels are intended for three sets of four panels each – each set was made to different thickness or prestressing amounts for three different and distinct tests.

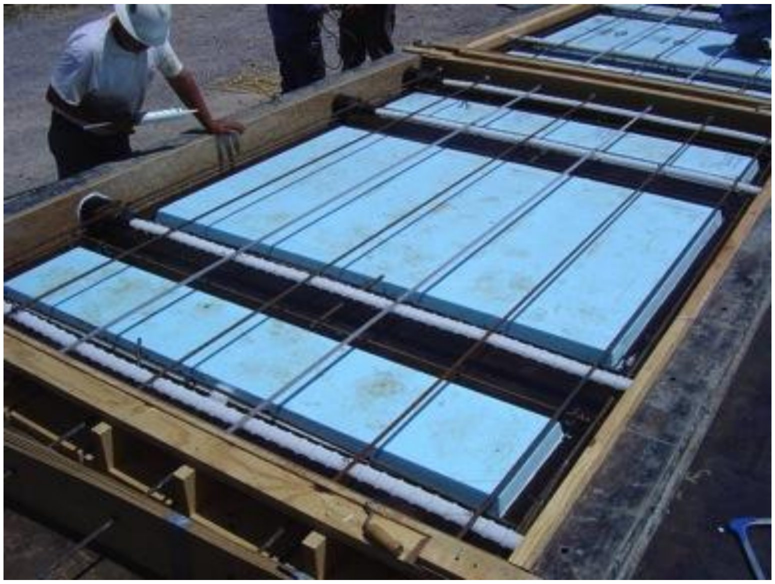

Figure 4 Formwork for Panel I-A (transverse pretensioning strands running perpendicular to PT ducts)

Figure 5 Completed panel. The shear key is visible in the panel, as are the grouting ports for grouting the under-slab voids.

SITE CONSTRUCTION

Construction on the job site started shortly after the panels were fabricated. The subgrade consisted of native soils that were suitable to support highway loadings. The subgrade was graded and uniformly compacted at a moisture content and density to conform to standards adopted by the Oklahoma Department of Transportation (ODOT). The subgrade was compacted at minimum of 95% compaction and at 100% of ASTM D 698/AASHTO T 99 [9].

Granular base materials were hauled to the site by a third party contractor. The base materials conformed to ODOT standards and originated from a pre-approved quarry for granular base materials. These materials were also compacted to in accordance with ODOT standards and were leveled using laser leveling techniques and sensors on-board grading equipment.

Figure 6 Project site subgrade preparation

Figure 7 Subgrade construction and compaction of base materials

PANEL INSTALLATION

The precast pavement panels were delivered to the jobsite and assembled shortly after base preparation was completed. The panels were hauled to the jobsite by the fabricator and were unloaded using a five-ton rough terrain forklift. After the pavement panels were unloaded, Styrofoam® liners that were used to create the voids under the panels were removed. The panels were assembled atop the base course. Two layers of bond breaker polyethylene sheets were placed between the base course and the pavement segments. A bitumen sealant was used around the perimeter of the pavement and between the panels and the bond breaker 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.

Alignment and level was checked after initial setting of the precast pavement panels. Level and alignment were suitable and no additional mechanical process was required to bring pavement elevation in line.

Figure 8 Precast Pavement Panels are assembled to form the Test Pavements I, II and III.

Figure 9 Precast Pavement Panels are assembled and readied for Post-Tensioning. The Test Panel in the foreground is Test Panel III which is 10 in. thick. It features longitudinal and transverse prestressing of approximately 240 psi. The visible ductwork in Test Panel III is fitted for two two-strand tendons and two-four strand tendons.

STRAND PLACEMENT AND POST-TENSIONING

Post-tensioning hardware including the ducts and the anchorages was supplied by V-Structural. V-Structural was also contracted to perform the post-tensioning and grouting of the tendons and under panel voids. Initially, strands and grout were delivered to the site. The post-tensioning contractor started by cleaning the ducts and anchors and cutting the strands. Next, the contractor threaded the strands through the ducts, installed anchors and anchors caps, and performed air tests to ensure the airtightness of the post-tensioning ducts. Each strand was post-tensioned to 31,000 lbs. to achieve the required prestressing force. Lastly, the ducts and voids were grouted using grout provided by the contractor.

Figure 10 Strands being threaded manually through the ducts

Figure 11 Tendons stressing for Pavement III

EXPERIMENTAL PROGRAM AND TEST RESULTS

Three test pavements were constructed as described previously. Each of the three test pavements was built from four segments, and the overall dimensions of each test pavement were 12 ft. wide by 28 ft. long. The 12 ft. width dimension matches the width of a single traffic lane. In the longitudinal direction, which corresponds to the direction of traffic, there were four pavement panels. Three of the panels were 8 ft long and the fourth panel, or the anchor panel was only four ft long. The layout of each test pavement set is shown schematically in Figure 12. The anchor panel was placed directly atop the subgrade without a bond breaker to simulate the practice of having a portion of a precast prestressed slab in direct contact with the grade to help mitigate movement of the pavement relative to the subgrade.

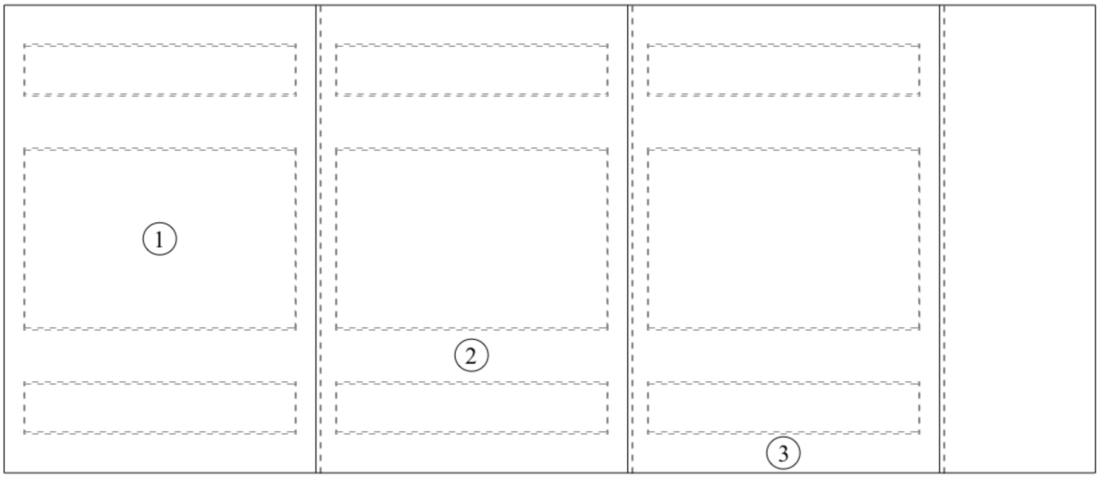

Figure 12 Locations for Static and Repeated Loads

The test variables for each of the test panels were: (a) Slab thickness, and (b) prestressing stresses in the concrete. Pavement Test Panels I and II were made with an overall thickness of 8 in. In these panels, thickened beam portions were 8 in. thick and the slabs were only 6 in. thick. In the 10 in. panels, the beams were full depth and the slab was only 8 in. thick. In accordance with the drawings and the intentions of the research, void spaces remained underneath the majority of the slab area. These voids were filled with grout after post-tensioning was completed.

Static and repeated load testing was performed on each of the Pavement Test Panels, at each of the three locations shown in Figure 12. The testing regimen is outlined in Table 4 where a combination of static load tests, with repetitions is described.

Number	Location	Initial Load (repeated 3 times)	2nd Load (repeated 3 times)	3rd Load (repeated 3 times)	4rd Load (repeated 3 times)	Final Load (Static)
1	Center of slab	4.5 kips	9 kips	18 kips	27 kips	30 kips
2	Beam at traffic wheel path	4.5 kips	9 kips	18 kips	27 kips	30 kips
3	Edge	4.5 kips	9 kips	18 kips	27 kips	30 kips

Table 4 Static and repeated tests loadings

The Pavement test panels were constructed and tested on the Stillwater campus at Oklahoma State University. A testing steel frame, shown in Figure 13, was designed and fabricated to perform the testing on the Pavement Test Panels. The testing frame consisted of structural tubing, and was designed to support grating that in turn held up to 80,000 lbs of concrete ballast. The loading frame, as shown in the photographs provided sufficient strength, stiffness and ballast to allow the required testing loads to be applied at each individual load point. The steel test frame and its fabrication was supplied by W&W Steel Co. of Oklahoma City, Oklahoma.

Figure 13 Steel frame assembled and ready for testing

INSTRUMENTATION

High accuracy Linear Variable Differential Transformers (LVDTs) were used to measure pavement surface deflections. A load cell with 100 kips (100,000 lbs) capacity was used to measure the applied load. The load cell reading was checked with a pressure gauge on the hydraulic pump. During testing, deflections and the applied load measurements were saved to a spreadsheet using a Data Acquisition system (DaQ) running a custom LabView Virtual Instrument. LVDTs were attached to a tubular steel reference frame that was isolated from the test pavement and loading frame.

All instruments were tested and calibrated at Oklahoma State University (OSU) Civil Engineering Laboratory before they were used. Loads were applied using an hydraulic hand pump connected to an hydraulic actuator. A digital pressure gauge was used to measure pressure independently from the data acquisition system. A neoprene (9 in. by 9 in.) pad was placed at the load location between the pavement and a fabricated loading column. The reference frame and LVDTs are shown in the photograph in Figure 14. The actuator was placed on top of the column with the load cell directly above it. A spherical head was used to mitigate effects from eccentricity or misalignment. The loads were applied using an hydraulic hand pump connected to an hydraulic actuator.

Figure 14 Instruments and loading at the 10 in. pavement at location 3.

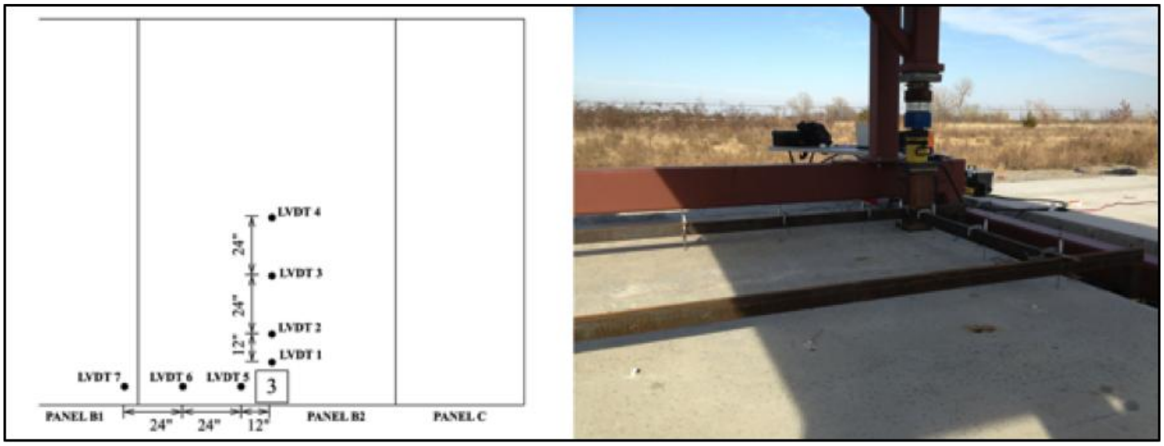

Figure 15 Instruments Layout at Test Location 1 for Test Pavement III. Test Location 3 is located at the edge of Panel B2. The instruments layout is similar to other panels.

REPEATED LOAD TESTS AND RESULTS

Repeated load tests were used to measure pavement deflections and observe behavior. Repetitive loads of 4,500 lbs., 9,000 lbs., 18,000 lbs., and 27,000 lbs were applied. The loading scheme is show in Figure 16. The loads were repeated three times at each load cycle. Maximum loads were maintained for five minutes as shown in the figure. Loading was ramped up at a regulated time rate, and removed more quickly as shown in Figure 16.

The load cell and LVDTs readings were recorded to a spreadsheet file every 10 seconds. Additionally, handwritten deflection and load measurements as well as ambient and pavement temperatures were recorded.

Figure 17 provides a visual representative of the time history of the loading and shows both the applied loads and the deflections recorded in real time. The data depicted is taken from the repeated load tests on Test Panel III, when testing at Panel B2 location 3 as indicated on Figure 12. The Applied load vs. time is depicted by the shaded area. Deflection vs. time is shown by the solid line. The loading history is obtained from the physical measurements during the testing so the loading history reflects some relaxation in the applied load within the loading intervals. The slope of the line reveals the rate of loading. Furthermore, Figure 17 illustrates the deflection history for LVDT 1, representing the pavement deformation nearest the loading point. Note that the relationship between the load and the deflection is approximately linear. This near-linear relationship is also confirmed in more rigorous analysis of the data, and is an important finding from this research indicating that the Winkler spring model is satisfactory in modeling subsurface behavior under the precast panels.

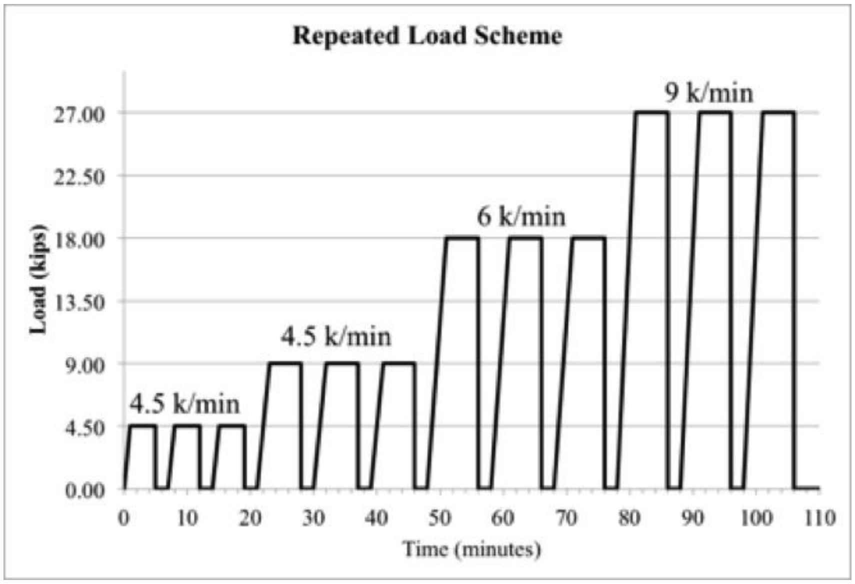

Figure 16 Repeated load test scheme

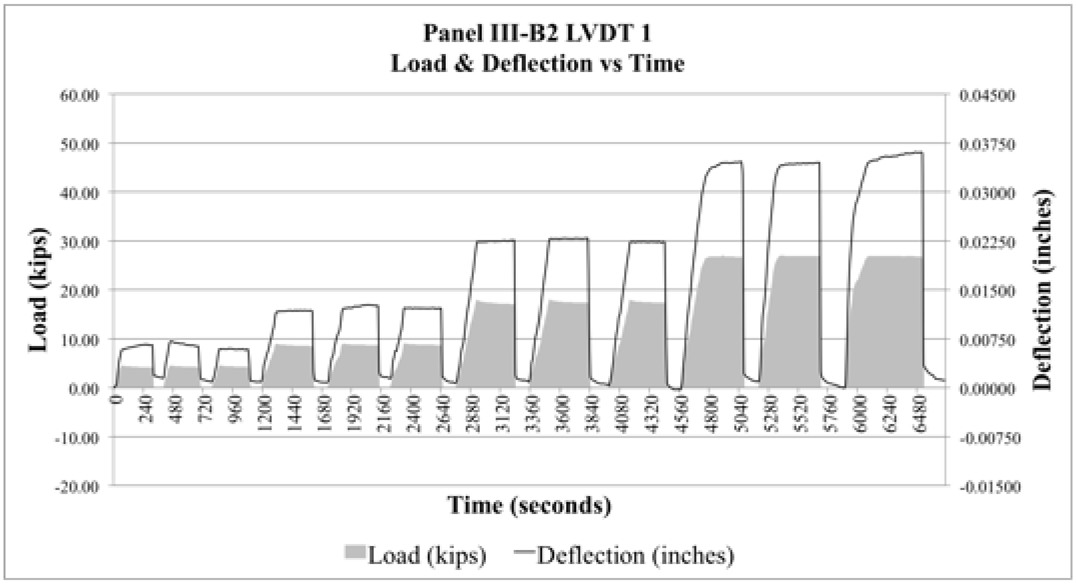

Figure 17 Repeated load & LVDT 1 deflection against time for Pavement III Panel B2

STATIC LOAD TEST

A single static load test was performed at the end of each repeated load test by applying a 30 kip load at the repeated test location. The load was applied at a rate of 2,000 lbs/min and maintained for a period of 10 minutes. Load cell readings and deflection measurements were recorded every 10 seconds during the test.

Figure 18 shows the deflection readings for all LVDTs over the duration of the test for Pavement III Panel B2. LVDT1 is the deflection reading nearest the point of loading. The response indicates that deflections increased with increases in load. LVDT 1 is the deflection nearest the load point and LVDT 2, LVDT 3 and LVDT 4 are progressively further away from the load point in the longitudinal direction. LVDT 5, LCDT 6 and LVDT 7 are progressively further away from the load point in the transverse direction, as shown in Fig. 15. The results indicate that maximum deflections occur very near the load point, and that deflection taper off with distance from the load point. The graph indicates uniform deflection in at given distances from the load in both directions. Other static load tests at the other testing locations showed similar patterns.

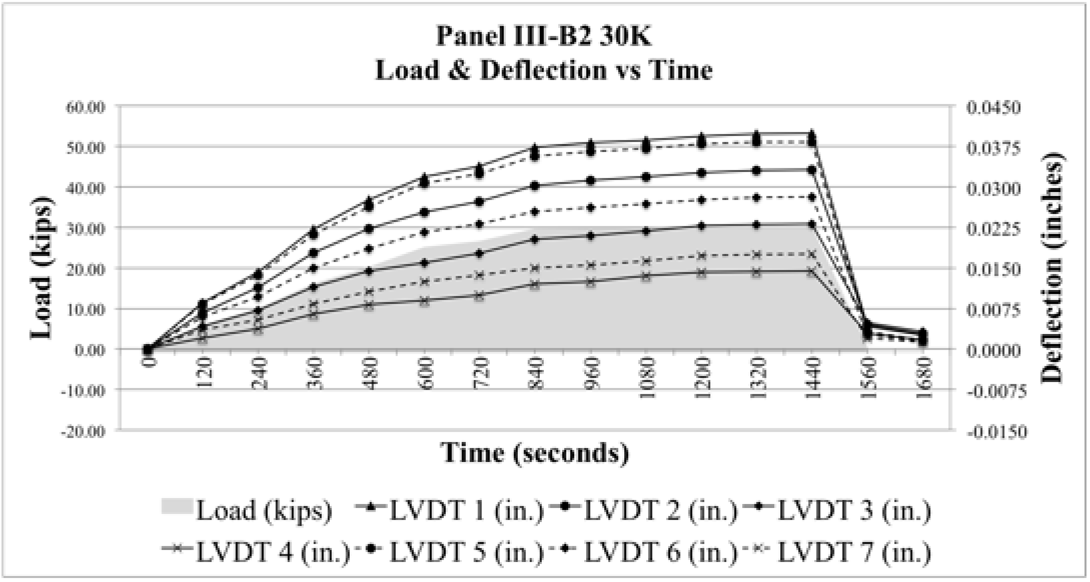

Figure 18 Static load & deflections plotted against time for Pavement III Panel B2

Deflection profiles were constructed using the deflection data collected during the static test. Figure 19 plots the measured pavement deflections in the transverse direction for the test on Pavement III Panel B2. The deflection readings were measured at transverse distances of zero, 12 in. 36 in. and 60 in. from the loading point. In the figure, the actual results are plotted vs. the results from the finite element analysis (FEA) where the subgrade reaction was assumed to be 150 psi/in.

Figure 20 plots the measurement pavement deflections in the longitudinal direction for the same panel. The test results are plotted and compared to results from the finite element analysis (FEA) and from analysis of pavement modeling as a beam on elastic foundation with an assumed modulus of subgrade reaction of 150 psi/in. Note that the joint between panel segments is located 4 ft. from the loading point, so the chart of measured deflections crosses over a post-tensioned joint. The deflection data were also used to estimate the modulus of subgrade reaction (k) using methods outlined by AASHTO [7]. These values are reported in Table 5.

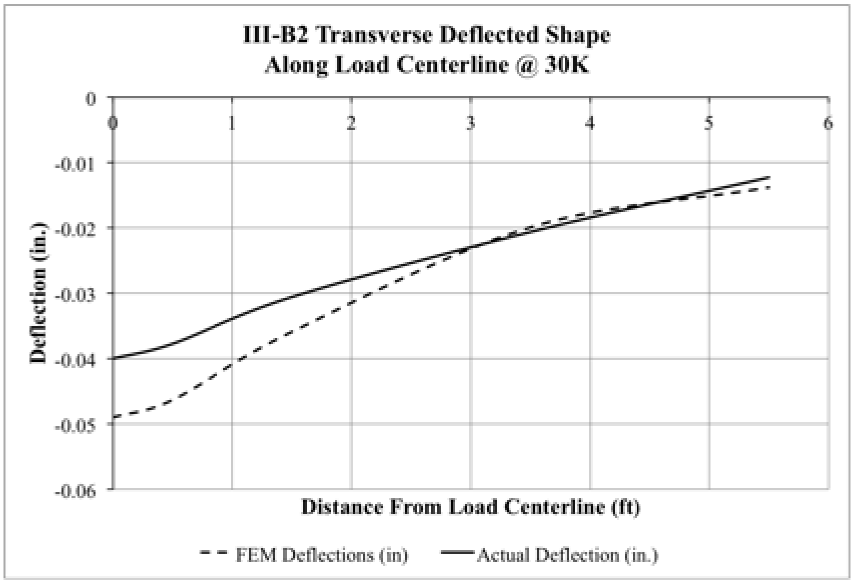

Figure 19 Pavement III Panel-B2 Transverse deflected shape at 30,000 lb.

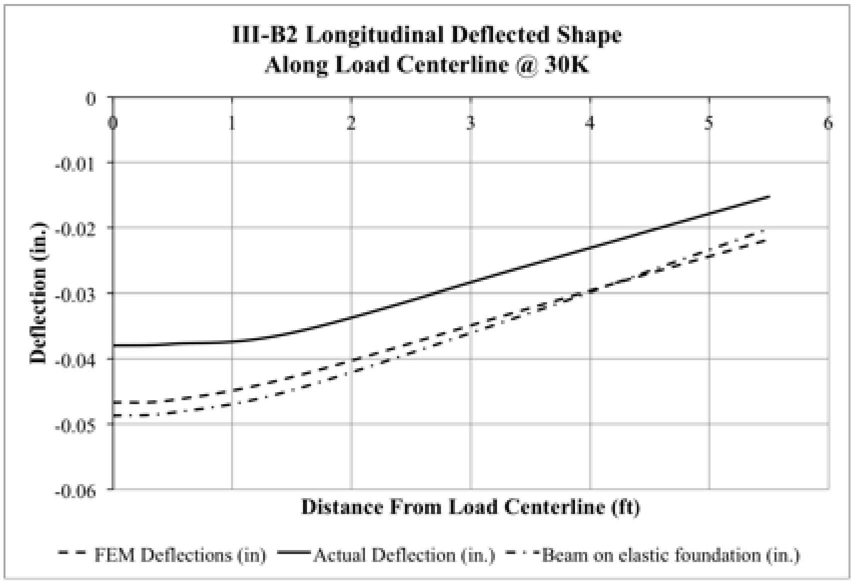

Figure 20 Pavement III Panel-B2 Longitudinal deflected shape at 30,000 lb.

	Pavement I	Pavement II	Pavement III
Calculated k-value (psi/in.)	139	177	197
Assumed k-value (psi/in)	150	150	150

Table 5 Calculated and assumed k-value

CONCLUSIONS

- The research demonstrated that precast, prestressed concrete panels can be successfully constructed on granular base materials.
- The research also demonstrated the use of voided grout pockets on the underneath side of pavement panels to help ensure more uniform load transfer between the pavement and the base materials.
- The research also shows that wheel loads are effectively transferred across panel joints and that the keyed joints with longitudinal post-tensioning effectively transferred shearing forces across precast joints. Further the research showed that the coefficient of subgrade stiffness can be discovered empirically.

As this research shows that construction of precast, prestressed pavements can occur on granular fill, and it's structural performance is not inhibited by this construction. We believe this may significantly reduce costs over the systems that require the use of flexible pavement base materials. We also see advantages in sustainability as one should expect more durable pavements as prestressed concrete should be less susceptible to cracking, and less susceptible to damage resulting from "soft" spots in the subgrade and base materials.

The technique of grouting under the precast pavement segments helps eliminate the non-uniform base supports, and should prolong the lifespan of the pavement structure. Test panels in this program demonstrated variations in spaces between panels and base materials, yet after grouting the void spaces, test results indicate similar deflection and stiffness responses to loads in both test panels.

Furthermore, the designs featured multi-strand post-tensioning systems with relatively and equal prestressing in both longitudinal and transverse directions. Panel fabrication was completed without any major setbacks.

In repeated load testing and in static load testing, the deformation of the panels was predicted accurately using fundamental principles of solid mechanics. The elastic modulus of the concrete was measured and the soil stiffness was estimated to be 150 psi/in. Furthermore, as expected, some cracking did occur in the pavement panels when the static load of 30,000 lbs was applied at the edges of the pavements.

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