PERFORMANCE EVALUATION REPORT OF THE

PAVING SLAB & PLANK FULL-SCALE TESTING

Submitted to the
ICPI Technical Committee
and the
Interlocking Concrete Pavement Institute
Foundation for Education & Research

January 28, 2022

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Background

An increasing number of ICPI members are manufacturing and installing concrete paving slabs and planks. While these products can take a modest amount of vehicular traffic, a key question for the industry and designers is *how much*?

In 2015, Applied Research Associates Ltd (ARA) pavement engineering consultants were retained by the ICPI Foundation for Education & Research to conduct computerized finite element modeling (FEM) of various shapes and thicknesses of paving slab and plank units. These were subjected to truck wheel loads modeled on three bases; dense-graded aggregate, lean concrete and concrete. The structural design tables were provided to ICPI in May 2016. These defined traffic categories and load limits for a range of the following:

- 52 square and rectangular slabs between 2 and 5 inches thick
- 96 plank sizes between 2 and 5 inches thick
- All of the above on three bases: 12 in. thick aggregate; 4 in. thick lean concrete on 6 in. aggregate base; 4 in. thick concrete on 6 in. aggregate base
- On four subgrade soil strengths: CBRs of 3%, 5%, 6.8% and 10%
- Assuming two paving unit flexural strengths of 650 and 750 psi or 4.5 and 5.2 MPa

One standard double-truck tire load (about 8,780 lbs) to the center and edges of an area of each slab and plank shape. From the applied load, the FEM calculated the resulting stresses in the slabs and base.

The structural design tables from FEM defined traffic categories suitable for the slabs and planks based on stress ratios that resulted from the applied tire load. In the design of Portland cement concrete (PCC) pavement, stress ratios are the ratio of the applied stress of one load to the flexural strength of the concrete pavement. For example, a wheel exerts 100 psi and the concrete has a flexural strength of 500 psi, that equals a stress ratio of 0.5. Stress ratios were created for PCC pavement typically jointed one slab to the next, joined together with steel dowels, or continuously reinforced. Stress ratios are used in PCC pavement design to calculate the risk of fatigue cracking and failure. A stress ratio of 0.5 is considered the maximum for PCC pavement design per AASHTO and ACPA design methods.

Logically, stress ratios required in rigid pavements decrease as wheel loads increase and that's reflected in Table 1. However, the application of stress ratios to non-jointed, non-doweled, and much smaller segmental concrete paving slabs is hypothetical. However, it's the only design rationale available in view of the absence of testing the fatigue properties of segmental concrete paving slabs. We can safely assume that the resistance to fatigue cracking in paving slabs is clearly much lower than larger PCC pavement. Indeed, one crack in a paving slab typically means failure, whereas PCC pavement is considered failed with ~15% cracks across a pavement section. In addition, stress ratios for smaller paving slabs should be decreased when considering turning and braking tires as those actions can exert forces exceeding that of a load passing over units that aren't joined together and are much smaller and thinner than PCC pavement.

Table 1 was developed from the stress ratios generated in the FEM study and assigned to various slab sizes and base assemblies. The stress ratios in Table 1 reflect a *reduction* from the original report of 0.1 for cars only, cars and light trucks, and cars and occasional heavy vehicles. These was done to add a measure of conservatism in the design tables, especially since the FEM modeled only static and not dynamic (passing) loads, nor those from turning and braking. Stress ratios were then revised to reflect slab and plank flexural strengths of 725 psi (5 MPa) rather than 750 psi (5.2 MPa) since the former is the minimum flexural strength requirement in ASTM C1782. This change had little effect on the stress ratios and traffic limits.

Table 1: Traffic Categories and limits for concrete paving slabs and planks

Traffic Limits	Category Symbol	Stress Ratio	Lifetime ESALs (TI)	Equivalent Heavy Vehicles/Day
Do Not Subject to Vehicles	No	1	0	0
Primarily Pedestrian	P	0.7	1,000 (4)	0.1
Cars only (< 4500 lbs or 2000 kg)	C	0.5	7,500 (5)	0.5
Cars and Light Trucks (< 10,000 lb or 4500 kg)	LT	0.4	30,000 (6)	2.0
Cars and Occasional Heavy Vehicles (≥ 10,000 lb or 4500 kg)	OHV	0.3	75,000 (6.6)	5.0

The objective of this project is partially validating the ARA FEM by subjecting selected paving unit/base combinations to continuous truck traffic until the paving units crack and fail. One cracked unit is considered failure, but not necessarily pavement failure defined as being an unserviceable surface. For example, a 12 x 12 x 3.125 in. thick slab installed on an aggregate base is designated in the design tables as being acceptable for cars and light truck traffic given a flexural strength of 725 psi and a range of soil subgrade strengths. This means the units should be able to withstand 30,000 ESALs or between 3,300 to 15,000 heavy truck passes before cracking from failure of the paving unit and/or base.

Validation and Testing

The ICPI Technical Committee wanted to partially validate the design tables using full-scale load testing by building a test area with slabs and planks for trafficking by 'real world' trucks. The test area was constructed at an inventory storage area at Nicolock's concrete paver plant in Frederick, Maryland. This area is regularly trafficked by trucks of various sizes and loads provided to ICPI staff. The results of this load testing are compared to the FEM results. The FEM results were included in a draft of Tech Spec 24 – *Structural Design of Segmental Concrete Paving Slab and Plank Pavement Systems.* The slab and plank products in the full-scale testing were loaded up to 75,000 ESALs.

Test Pad/Site

The test area was 13.5 by 45.5 ft and included eight, 6 x 10 ft cells separated by 6-inch wide by 12-in. deep, cast-in-place flush concrete curbs resting on compacted aggregate base. Four cells had a 12-in. thick, dense-graded aggregate base and four had a 4 in. concrete base over 6 in. of dense-graded aggregate base.

A soils report conducted by an independent engineering testing company gave the subgrade a USCS classification of SP-SC. The reddish brown, poorly-graded sand with clay and gravel has a maximum dry density is 118.0 pcf, optimum moisture content of 1.4% and average CBR of 4.68%. The subgrade was compacted to 95% of standard Proctor density per ASTM D698. Nuclear density testing of the compacted soil subgrade and aggregate bases was performed to verify density to this level.

All paving units were set on a 1-inch thick layer of bedding sand with a gradation conforming to ASTM C33. Jointing sand gradation conformed to ASTM C144. All compacted, dense-graded aggregate base materials and installation conformed to Maryland State Highway Administration CR-6 specification for use under asphalt road pavements. Cylindrical samples poured when the concrete base was placed tested at a compressive strength of 3,930 psi at 28 days per ASTM C39.

After delivery and installation of the paving slabs and planks, one specimen of each unit was sampled from the shipments and tested for flexural strength per ASTM C1782 by the research laboratory at the National Concrete Masonry Association (NCMA). Two specimens did not conform to the required minimum 725 psi flexural strength in C1782.

Unit Nominal Dimensions	NCMA Laboratory Test Results
4 x 16 x 4 in.	770 psi
4 x 12 x 4 in.	990 psi
12 x 12 x 3.125 in.	530 psi
24 x 24 x 3.125 in.	600 psi

The paver/base combinations are listed below, and the cell configuration are shown in Figure 1:

Over 4 in. thick concrete base and 6 in. thick compacted aggregate subbase:
- Cell 1. 12 x 12 x 3.125 in. thick units, flexural strength 530 psi in a running bond pattern
- Cell 2. 4 x 12 x 4 in. thick units, flexural strength 990 psi in a running bond pattern
- Cell 5. 24 x 24 x 3.125 in. thick units, flexural strength 600 psi in a running bond pattern
- Cell 6. 4 x 16 x 4 in. thick units, flexural strength 770 psi in a running bond pattern

Over a 12 in. thick compacted aggregate base:
- Cell 3. 12 x 12 x 3.125 in. thick units, flexural strength 530 psi in a running bond pattern
- Cell 4. 4 x 12 x 4 in. thick units, flexural strength 990 psi in a running bond pattern
- Cell 7. 24 x 24 x 3.125 in. thick units, flexural strength 600 psi in a running bond pattern
- Cell 8. 4 x 16 x 4 in. thick units, flexural strength 770 psi in a running bond pattern

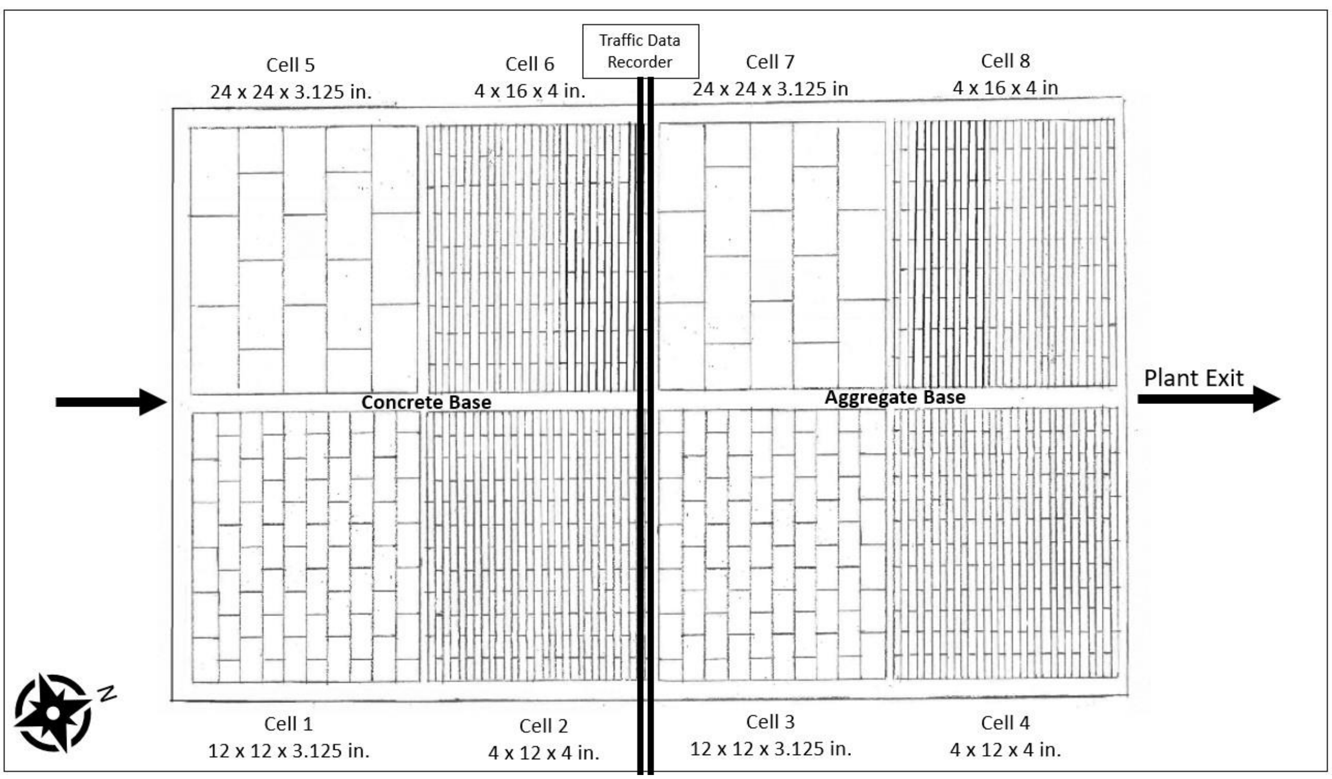

Figure 1: Slab and plank test pad cell configuration

Two groups of commercial vehicles enter the Fredrick paver plant shown in Figure 2. These two groups are flatbed vehicles of varying sizes loaded with pallets of pavers and tractor-trailers delivering aggregates to the plant. The latter unloads aggregate before crossing over the test pad, each of these tractor trailers are empty and assumed to weigh between 30,000 to 38,000 lbs. and are assigned a value of 2 ESALs. Tractor-trailers receiving pavers are loaded before crossing the test pad. While traversing the test pad some drivers braked their vehicles but none came to a complete stop, nor turned on the test pad. The weight of each loaded truck is determined by the number of pallets with paving products on it. The weight of the individual truck is determined by Table 2, the weight of the pallets is added to the weight of the truck to determine the total weight. Each pallet weighs about 3,000 lbs. The total weight of the vehicle is then divided by 18,000 lbs. to determine the number of ESALs.

Figure 2: Nicolock's Fredrick, Maryland plant - truck hauling route across test pad

Table 2: Truck weight determined by the number of pallets hauled plus its tare weight

Number of pallets hauled	Truck Classification	Estimated tare weight of the vehicle (lbs.)
1 to 3	1,2,3	14,000
4 to 9	4,5,6	26,000
9 and above	7, and above	30,000

Nicolock provided ICPI's staff with vehicle hauling logs which contain the date, time and number of pallets of each vehicle crossing the test pad. The logs are then cross-referenced with a TRAX Apollyon Road Tube Traffic Data Recorder installed on the test pad to obtain an accurate number of trucks crossing the test pad.

Final Load Test Results

The FEM evaluated stresses in evenly and fully supported paving units on bedding sand over various base materials whose strengths were characterized using typical values. As previously, noted stress ratios, or the applied stress divided by the flexural strength of the paving unit, were developed from FEM. The stress ratios provided the basis for designating traffic categories shown in Table 1. Since there is no available information on fatigue criteria i.e., applied loads as they relate to deflections and cracking, the only other method available limit failures was using stress ratios. Established for rigid concrete pavements, their validity applied to repeatedly loaded, much smaller, non-jointed concrete paving slabs and planks in Table 1 was an outcome of this research.

Table 3 shows full-scale load test data after 75,000 ESALs. These results are compared to the FEM traffic categories and limits (Table 3) recommendations for these pavers and slabs to see if these conservative (modeled) design assumptions are validated.

Table 3: Full-scale loading percent of failed paving units after 75,000 ESALs

Cell Number	Base type*	Paving Unit Dimensions, in.	Paving Units per Cell	Number Failed Paving Units	Percent Failed (%)
1	4 in. concrete	12 x 12 x 3.125	65	0	0.0
2	4 in. concrete	4 x 12 x 4	195	0	0.0
3	12 in. aggregate	12 x 12 x 3.125	65	0	0.0
4	12 in. aggregate	4 x 12 x 4	195	0	0.0
5	4 in. concrete	24 x 24 x 3.125	17	3	17.6
6	4 in. concrete	4 x 16 x 4	150	15	10
7	12 in. aggregate	24 x 24 x 3.125	17	0	0.0
8	12 in. aggregate	4 x 16 x 4	150	13	8.7

*6 in. aggregate base under concrete

- **Cell 1**: 12 x 12 x 3.125 in. thick units over a 4 in. thick concrete base and 6 inches of aggregate subbase. The recommend traffic load limit based on FEM for Cell 1 with a flexural strength 530 psi is OHV or Cars with Occasional Heavy Vehicles with a lifetime ESALs of 75,000. With zero failures after 75,000 ESALs during full-scale loading, this recommendation is accurate.

Figure 3: Cell 1. 12 x 12 x 3.125 in. thick units on a concrete base.

- **Cell 2**: 4 x 12 x 4 in. thick units over a 4 in. thick concrete base and a 6 inch thick aggregate subbase. The recommended traffic load limit based on FEM for Cell 2 with a flexural strength 990 psi is OHV or Cars with Occasional Heavy Vehicles with a lifetime ESALs of 75,000. With zero failures after 75,000 ESALs during full-scale loading this recommendation is accurate.

Figure 4: Cell 2. 4 x 12 x 4 in. thick units on a concrete base.

- **Cell 3**: 12 x 12 x 3.125 in. thick units over a 12 in. thick compacted aggregate base. The recommend traffic load limit based on FEM for Cell 3 with a flexural strength 530 psi is C or Cars Only with a lifetime ESALs of 7,500. With zero failures after 75,000 ESALs during full-scale loading this recommendation is considered to be too conservative, and a recommendation LT should be recommended.

Figure 5: Cell 3. 12 x 12 x 3.125 in. thick units on an aggregate base.

- **Cell 4**: 4 x 12 x 4 in. thick units over a 12 in. thick compacted aggregate base. The recommended traffic load limit based on finite element modeling for Cell 4 with a flexural strength 990 psi is OHV or Cars with Occasional Heavy Vehicles with a lifetime ESALs of 75,000. With zero failures after 75,000 ESALs during full-scale loading this recommendation is accurate.

Figure 6: Cell 4. 4 x 12 x 4 in. thick units on an aggregate base.

- **Cell 5**: 24 x 24 x 3.125 in. thick units over a 4 in. thick concrete base and a 6-inch-thick aggregate subbase. This cell has had some of the 24 x 24 in. x 3.125 in. thick slabs crack and fail. The first failure occurred after 708 ESALs. The broken units were replaced and then after 250 ESALs the replaced units cracked and failed *again*. It was suspected that an indention formed on the bottom of all the slabs caused additional tensile stress from the outer, thicker edges resting more firmly on the bedding sand with less support at the center of each slab. All the original slabs in this cell were removed and replaced with slabs with no indentations on the bottom supplied by a different manufacturer. These units had an average flexural strength of 910 psi per testing by the NCMA research laboratory. The recommend traffic load limit based on finite element modeling for these units is P or Primarily Pedestrian with a lifetime ESALs of 1,000. With a 17.6% cracked units after 3,662 ESALs during full-scale loading, this recommendation is accurate. The cracking in the four units shown in Figure 7, however, may be due to an uneven bedding sand layer from installation or from an uneven concrete base.

Figure 7: Cell 5. 24 x 24 x 3 in. thick units on a concrete base.
Orange paint lines indicate cracked units.

- **Cell 6**: 4 x 16 x 4 in. thick units over a 4 in. thick concrete base and a 6 inch thick aggregate subbase. The recommended traffic load limit for Cell 6 with a flexural strength 770 psi is OHV or Cars with Occasional Heavy Vehicles with a lifetime ESALs of 75,000. With 10% failure rate at 75,000 ESALs this recommendation is considered out of range, and a recommendation LT traffic limit is recommended.

Figure 8: Cell 6. 4 x 16 x 4 in. thick units on a concrete base.
Orange paint lines indicate cracks in units.

- **Cell 7**: 24 x 24 x 3.125 in. thick units over a 12 in. thick compacted aggregate base. The recommended traffic load limit based on finite element modeling for Cell 7 with a flexural strength 600 psi is LT with a lifetime ESALs of 30,000. With zero failures after 75,000 ESALs during full-scale loading this recommendation is accurate.

Figure 9: Cell 7. 24 x 24 x 3.125 in. thick units on an aggregate base.

- **Cell 8**: 4 x 16 x 4 in. thick units over a 12 in. thick compacted aggregate base. The recommended traffic load limit based on finite element modeling for Cell 8 with a flexural strength 770 psi is C with a lifetime ESALs of 7,500. With 8.7% failure rate after 75,000 ESALs during full-scale loading this recommendation is accurate.

Figure 10: Cell 8. 4 x 16 x 4 in. thick units on an aggregate base.
Orange paint lines indicate cracks in units. Picture taken around 30,000 ESALs.

Settlement and Rutting in Each Cell

After 75,000 ESALs the amount of settling/rutting of the slabs and planks was measured. To measure the settlement, A Sokkia Auto Level B40 and a 25 ft rod level capable of measuring in tenths of an inch was used. The elevation of each paving unit was checked individually except for the 24 X 24 paving slabs. Each 24 X 24 paving slabs elevation was measured at each of the 4 corners to see if one side of the paving unit settled while the other side possibly heaved. These elevations were checked against that for the concrete curb where the slab and plank surface elevations matched during construction. Figure 11 shows a "heat map" of the units settling across the entire slab. Green indicates zero settling, yellow indicates minor settling and red indicates major settling. The left side of the pad or Cells 1, 2, 5 and 6 are over a concrete base and had minor settling while the right side or cells 3,4, 7 and 8 are on the aggregate base which substantially rutted under repeated wheel loads.

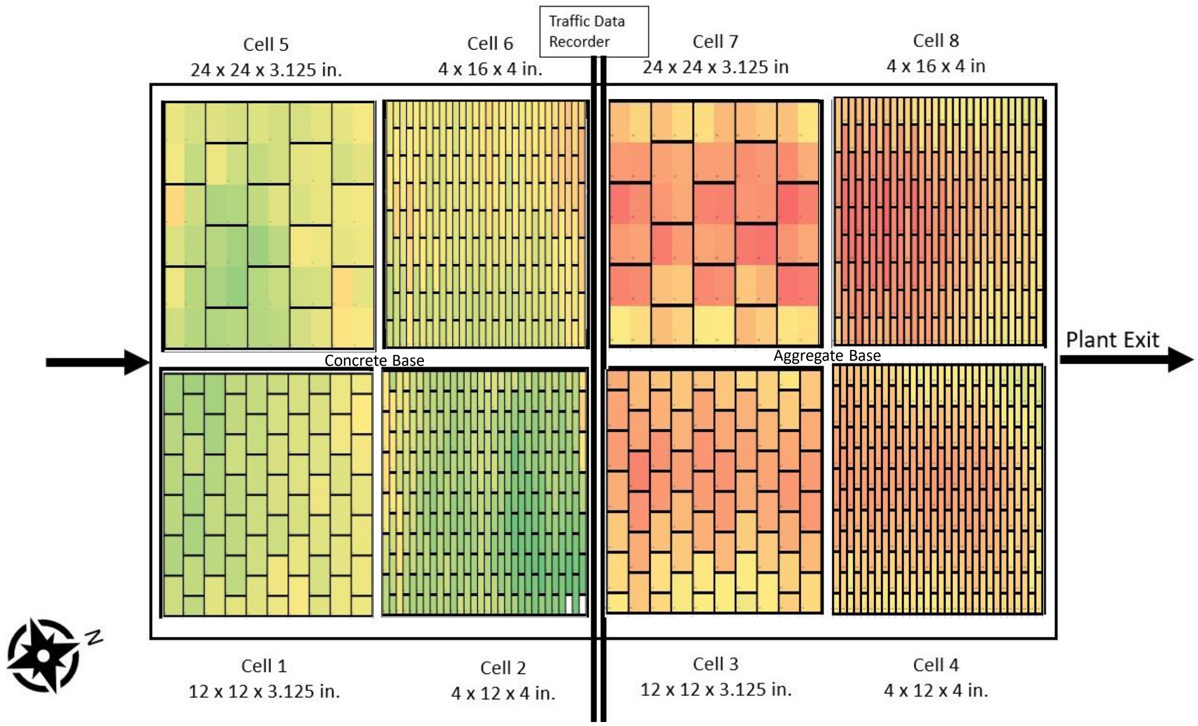

Figure 11: Slab and plank test pad settlement heat map

Pavement Condition Survey

The condition of each of cell was inspected and rated using the pavement condition index (PCI) rating system in using ASTM E2840 *Standard Practice for Pavement Condition Index Surveys for Interlocking Concrete Roads and Parking Lots*.

- **Cell 1**: 12 x 12 x 3.125 in. thick units over a 4 in. thick concrete base, had an average settlement of -0.01 of a foot or about 1/10th inch. The PCI resulted in a 12-point deduction from one slab (2%) with low severity rutting, leaving the PCI at 88 or in good condition.

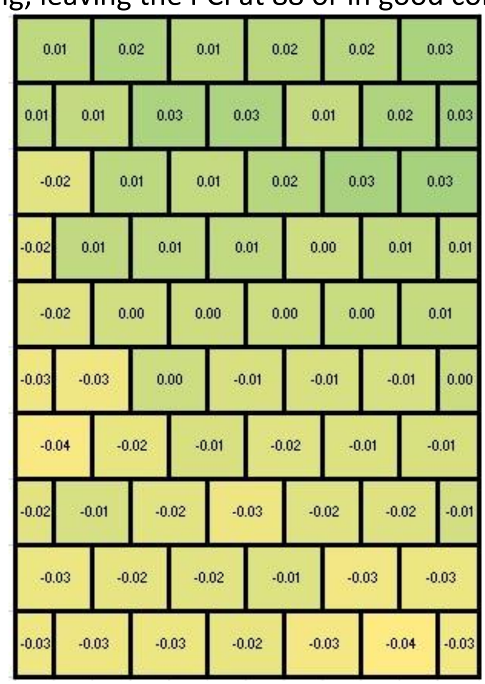

Figure 12: Cell 1. 12 x 12 x 3.125 in. thick units on a concrete base settlement heat map.

- **Cell 2**: 4 x 12 x 4 in. thick units over a 4 in. thick concrete base, had an average settlement of 0.00 feet. A PCI resulted in a 17-point deduction from 19 planks (10%) with low severity rutting The PCI was 83 or satisfactory condition.

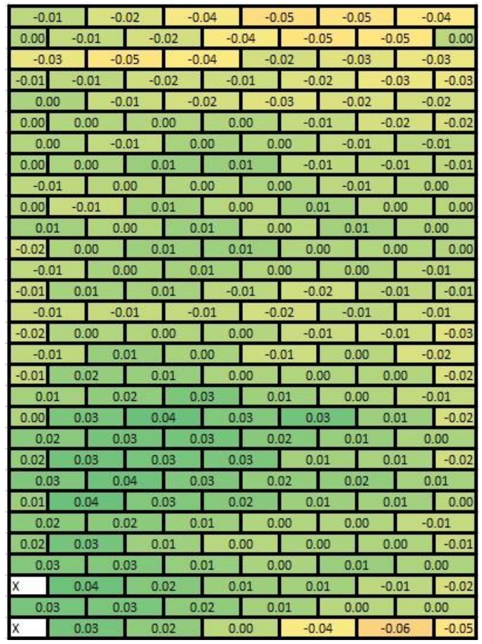

Figure 13: Cell 2. 4 x 12 x 4 in. thick units on a concrete base settlement heat map.

- **Cell 3**: 12 x 12 x 3.125 in. thick units over a 12 in. thick compacted aggregate base, had an average settlement of -0.08 of a foot or about 1 inch. The PCP resulted in a 34-point deduction due to 13 slabs (20%) with low severity rutting. This resulted in a PCI of 66 or fair condition.

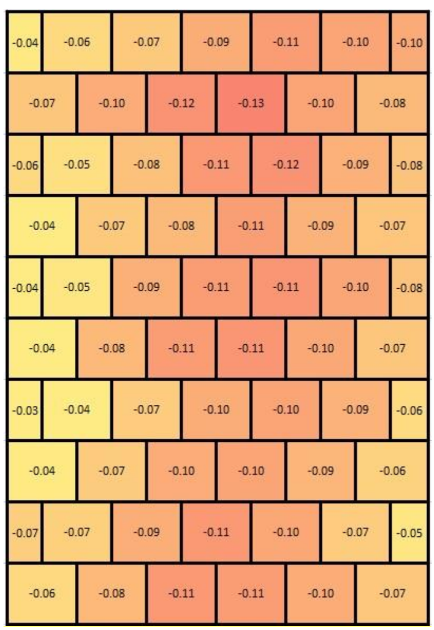

Figure 14: Cell 3. 12 x 12 x 3.125 in. thick units on an aggregate base settlement heat map.

- **Cell 4**: 4 x 12 x 4 in. thick units over a 12 in. thick compacted aggregate base, had an average settlement of -0.07 of a foot or about 7/8th inch. The PCI resulted in a 35-point deduction due to 41 planks (21%) with low severity rutting. This provided a PCI of 65 or fair condition.

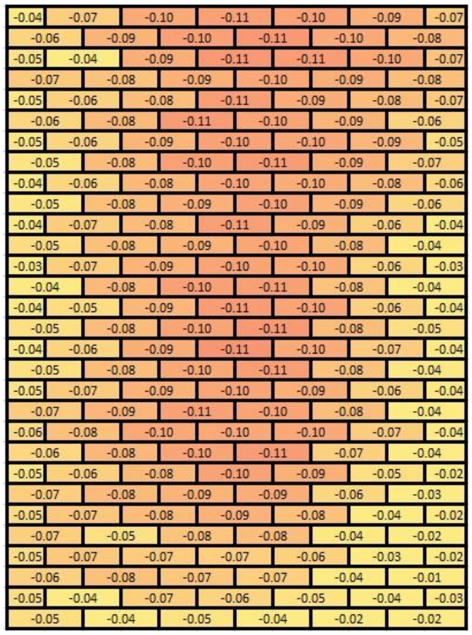

Figure 15: Cell 4. 4 x 12 x 4 in. thick units on an aggregate base settlement heat map.

- **Cell 5**: 24 x 24 x 3.125 in. thick units over a 4 in. thick concrete base, had an average settlement of -0.01 of a foot or about 1/10th inch. Inspection revealed a 25-point total deduct value from 1 slab (6%) faulting, 2 slabs (12%) with medium damage severity and 2 slabs (12%) with low damage severity. The corrected deduct value resulted in a PCI of 88 or a good condition.

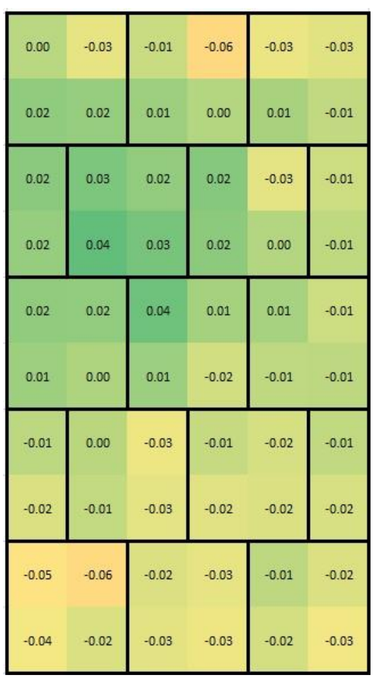

Figure 16: Cell 5. 24 x 24 x 3 in. thick units on a concrete base settlement heat map.

- **Cell 6**: 4 x 16 x 4 in. thick units over a 4 in. thick concrete base had an average settlement of -0.03 of a foot or about 3/10ths inch. This produced an 18-point total deduct value from 12 planks (10%) with low damage severity and 11 planks (9%) with low rutting severity. The corrected deduct value resulted in a PCI of 91 or a good condition.

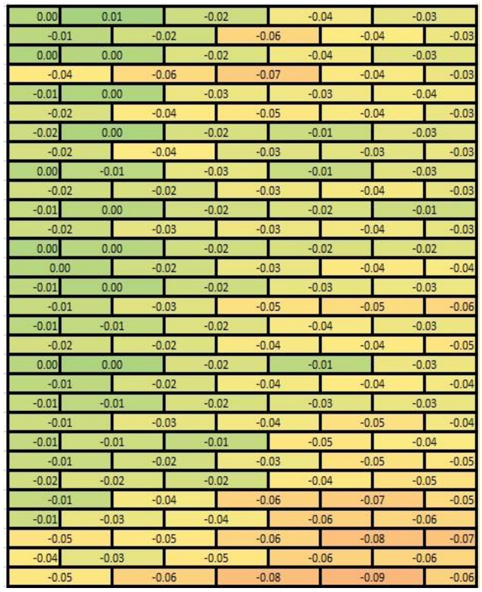

Figure 17: Cell 6. 4 x 16 x 4 in. thick units on a concrete base settlement heat map.

- **Cell 7**: 24 x 24 x 3.125 in. thick units over a 12 in. thick compacted aggregate base, had an average settlement of -0.1 of a foot or about 1 1/5th inches. The PCI produced a 46-point deduction due to 8 slabs (47%) with low rutting severity. The PCI was 64 or poor condition.

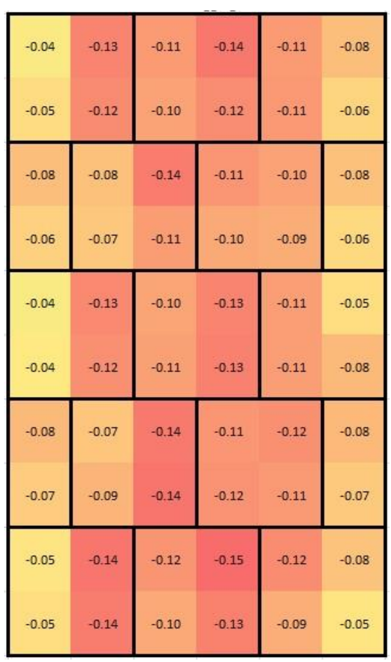

Figure 18: Cell 7. 24 x 24 x 3.125 in. thick units on an aggregate base settlement heat map.

- **Cell 8**: 4 x 16 x 4 in. thick units over a 12 in. thick compacted aggregate base, had an average settlement of -0.08 of a foot or about 1 inch. The produced an 84-point total deduct value due to 13 planks (9%) with low damage severity, 26 planks (17%) with low rutting severity, and 21 planks (14%) with medium rutting severity. The corrected deduct value resulted in a PCI of 45 or a poor condition.

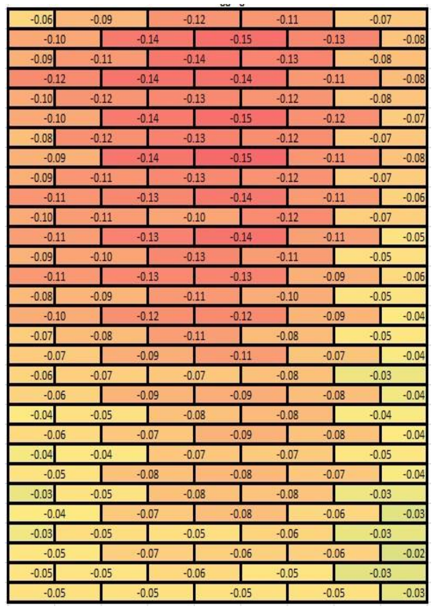

Figure 10: Cell 8. 4 x 16 x 4 in. thick units on an aggregate base settlement heat map.

Table 4: Measured settlement checks and an average settlement per cell

Cell	Average Settlement (ft)		PCI Rating scale	
1	-0.01	Concrete Base	88	Good
2	0.00	Concrete Base	82	Satisfactory
3	-0.08	Aggregate Base	66	Fair
4	-0.07	Aggregate Base	65	Fair
5	-0.01	Concrete Base	88	Good
6	-0.03	Concrete Base	91	Good
7	-0.10	Aggregate Base	64	Poor
8	-0.08	Aggregate Base	45	Poor

Conclusions

Comparing the 'real world' full scale load testing to theoretical FEM produced some promising results. Of the eight paver/base combinations, six full scale load tests cells had no cracked units, thereby meeting and likely exceeding ESAL limits recommended by the FEM defined by stress ratios.

The only recommended combination with insufficient conservatism in design is Cell 6, the 4 x 16 x 4 in. thick plank units on a minimum 4 in. concrete base and 6 in. aggregate subbase. This is designated in draft Tech Spec 24 with a traffic load limit of OHV with a lifetime ESALs of 75,000. Because several units cracked, the maximum load should be reduced to 30,000 ESALs or LT per Table 1.

The design tables in Tech Spec 24 for 12 x 12 x 3 in. thick slab units on a 12 in. thick aggregate base assign a recommend traffic load limit of C or Cars Only with a lifetime ESALs of 7,500. Since none of the paving slabs cracked after 75,000 ESALs and rutting was the only damage, this load recommendation is too conservative and can be increased to at least 30,000 ESALs. This should reduce extreme rutting while enabling additional traffic.

The three cracked 24 x 24 x 3 in. thick slabs on the concrete base are likely due to uneven bedding sand and/or an uneven concrete base, or concentrated loads since the cracked units are located at opposite edges of the cell. Uneven bedding sand and/or an uneven concrete base will need to be verified upon removing the units at the conclusion of the testing.

It is interesting to note that while there was significant rutting, none of the 24 x 24 x 3 in. thick paving slabs cracked while trafficked over an aggregate base for up to 75,000 ESALs. A load limit of 30,000 ESALs is recommended for these units to avoid unacceptable rutting. This load limit is similar to that allowed in the German slab structural design method for the same size paving slabs on 12 in. of aggregate base having a flexural strength of 725 psi (5 MPa).

Performing a pavement condition survey on each of the eight cells demonstrated that the base materials influenced the overall pavement longevity than the type of paver unit. Rutting destresses in the aggregate base ultimately lowered the average score of the cells by 27 points, leaving them with (an average) fair condition. These ratings suggest that some maintenance might be needed or with more severe rutting, the load limits need to be reduced to avoid an unacceptable rutting level. In contrast, the ratings of pavements with a concrete base remained in the average to good condition range. This difference in structural performance between a flexible and rigid concrete base is consistent with the flexible and rigid pavement design tables in Tech Spec 4 *Structural Design of Interlocking Concrete Pavement for Roads and Parking Lots.*

Finally, the 12 x 12s and the first two sets (originals and replacements) of 24 x 24 inch units did not meet the flexural strength requirements of 725 psi in ASTM C1782. These lower strengths, however, appeared to have almost no bearing on their performance over the aggregate and concrete bases.