Evaluation of Precast Concrete Slabs Using a Heavy Vehicle Simulator

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ABSTRACT

Precast slabs are considered an attractive pavement option for rehabilitation or reconstruction cases where traffic closures of less than eight hours are required. Benefits include long life expectancy of concrete cast in factory-controlled conditions and that fully cured precast slabs can potentially be open to traffic almost immediately upon installation, making them attractive for use on heavily traveled highways. This paper describes an accelerated pavement testing experiment conducted in California to evaluate precast concrete slabs through the use of a Heavy Vehicle Simulator. The experiment took place between June 2005 and September 2006, in a set of specially constructed precast slabs. Two sections were loaded in dry and wet conditions, one with load levels of up to 100 kN (using dual truck tires) and the other with load levels of up to 150kN (using an aircraft tire). The results obtained indicate that: 1) The evaluated system of precast slabs can be safely opened to traffic in the un-grouted condition, so that panels can be installed in consecutive nights rather than completing the entire installation at one time. 2) The life of this system of precast slabs, when used as detailed for this test, is estimated to be between 140 and 240 million ESALs, equivalent to 25 to 37 years of service, and 3) The failure mechanism was no different than that observed in cast-in-place jointed concrete pavements.

Keywords: Heavy Vehicle Simulator, HVS, accelerated pavement testing, precast concrete pavements.

Conference Topic selected: Pavement materials

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INTRODUCTION

Precast concrete has a proven track record as a durable high-performance product for bridge and commercial building construction (1). This comes mostly as the result of the high level of quality control that can be achieved at a precast fabrication plant. For roadways, precast concrete also has an advantage in terms of how fast a facility can be re-opened to traffic. Conventional cast-in-place pavements require several days of curing time after the concrete is placed before it is strong enough to safely withstand traffic. Even fast setting concrete used for patching and hot mixed asphalt requires some time before traffic loads can be allowed. Precast pavements allow limiting construction to only off-peak travel times (at night or over a weekend), and therefore achieving significant savings in user delay costs (2).

Given the potential advantages of precast pavements, the California Department of Transportation (Caltrans), decided to evaluate the use of a system called Super-Slab® as a long-life rehabilitation strategy for concrete pavements. The accelerated pavement testing was conducted using a Mk-IV Heavy Vehicle Simulator (HVS) operated by Dynatest with technical experimental guidance from CSIR South Africa, and under the overall responsibility of the University of California Pavement Research Center (UCPRC). The UCPRC is in charge of this and another HVS machine and since 1995 has used them to evaluate various pavement technologies for Caltrans.

THE SUPER-SLAB® SYSTEM

The Super-Slab® System is a slab-on-grade precast concrete pavement system developed in the United States and used for the first time in 2001. The patented system is an assemblage of specially designed precast slabs, methods for installing them, and materials for interlocking them together to create an integrated pavement structure. The system is specifically comprised of the following (3):

1. Constant thickness precast slabs that are fabricated to length, width and thickness as required to a tolerance of +/- 3 mm.
2. Techniques for precisely grading fully-compacted bedding material, to a similar tolerance, to provide sub base support. To facilitate the grading process, the system utilizes a thin layer of finely graded bedding material placed over the existing sub base.
3. Interlocking dowels, tie bars and matching slots cast into the bottom of adjacent slabs.
4. A method of installing non-shrink structural grout from the top of the slabs into the slots below.
5. A method of positively filling voids under the slabs by means of a bedding grout distribution system cast into the bottom of each slab

Standard load transfer steel dowels are cast at one end of each slab at locations that match the location of dovetail-shaped slots as seen in Figure 1. Similarly, standard tie bars (or the female half of a standard tie bar) are cast at one side of each slab matching the location of slots cast in the adjacent slab. Figure 1 is a close up view of how dowels and slots align during the placement process.

Figure 1. Doweled joint and core showing dovetail slot/dowel bar connection

Two grout ports are cast in the slab over the top of each slot to make it accessible for grouting after the slab has been placed. Grout is pumped into one port until it exudes from the other, completing the structural load transfer connection from slab to slab. Fully grouted slabs are essentially the equivalent of cast in place pavement slabs. Dowel slots cast on the bottom of the slabs provide two benefits. First, they keep dowel grout on the bottom, protecting it from de-icing chemicals and degradation from freeze thaw activity. Secondly, they keep dowel grout out of sight maintaining a uniform-looking pavement surface.

Two distinctly different grouts are used in the installation of this precast stem. First, rapid setting high strength dowel grout, pumped into the dowel slots, completes the structural connection between individual slabs. It is important that it be installed in strict accordance with the grout manufacturer’s directions to reach specified strength before the slabs are opened to traffic. Secondly, and only after the dowel grout has been installed, a bedding grout mixture of portland cement, water and fluidifying admixture is pumped into the bedding grout distribution system described above.

CONSTRUCTION OF THE TEST SITE

A test site for the HVS experiment was constructed in San Bernardino County in southern California. It consisted of 10 slabs in a 2 by 5 arrangement. The details of the test slab installation were developed to mirror the pavement details of a potential specific project in the area (4). There were four main components of the installation:

- A 150mm cement treated base course placed on original ground.
- A thin 8mm layer of fine bedding material (stone sand)
- Precast Super-Slabs®, 225mm thick, placed upon the precisely graded sub-base and grouted as described in the foregoing and shown in Figure 2
- Diamond grinding of the top surface of the slab to meet smoothness requirements of the project.

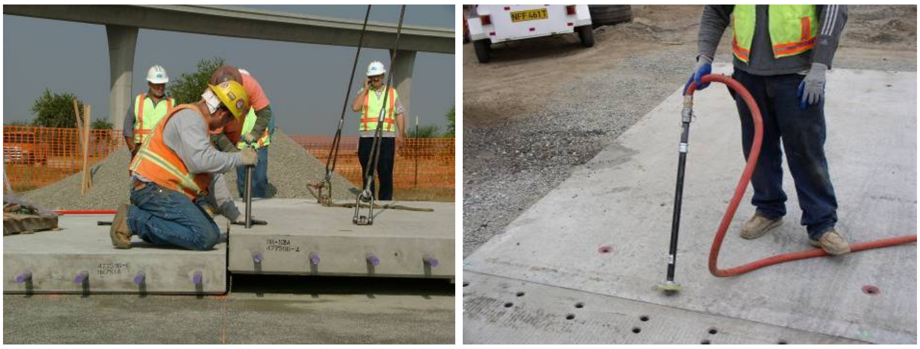


Figure 2. Precise placement of the slab on the sand bedding layer and hose with fitting for injecting grout

APT TESTING OBJECTIVES AND INSTRUMENTATION

Two test sections were evaluated as shown in Figure 3. In the evaluation of the Super-Slab® System the main test objectives were:

1- To evaluate whether traffic can be safely allowed on newly placed slabs before grouting
2- To identify how much traffic loading can the system receive, which relates to long-time performance and years of expected service
3- To determine failure mechanisms

Traffic loads were applied at the beginning of the experiment to each section to simulate the exposure to traffic from the time of placement of the slabs to the time of grouting, which would normally occur during the next nighttime closure, and aimed to fulfill objective one. The trafficking consisted of approximately 32 hours of HVS repetitions with a 60kN (13500 lbs) half axle load, equivalent to about 86500 Equivalent Single Axle Loads (ESALs).

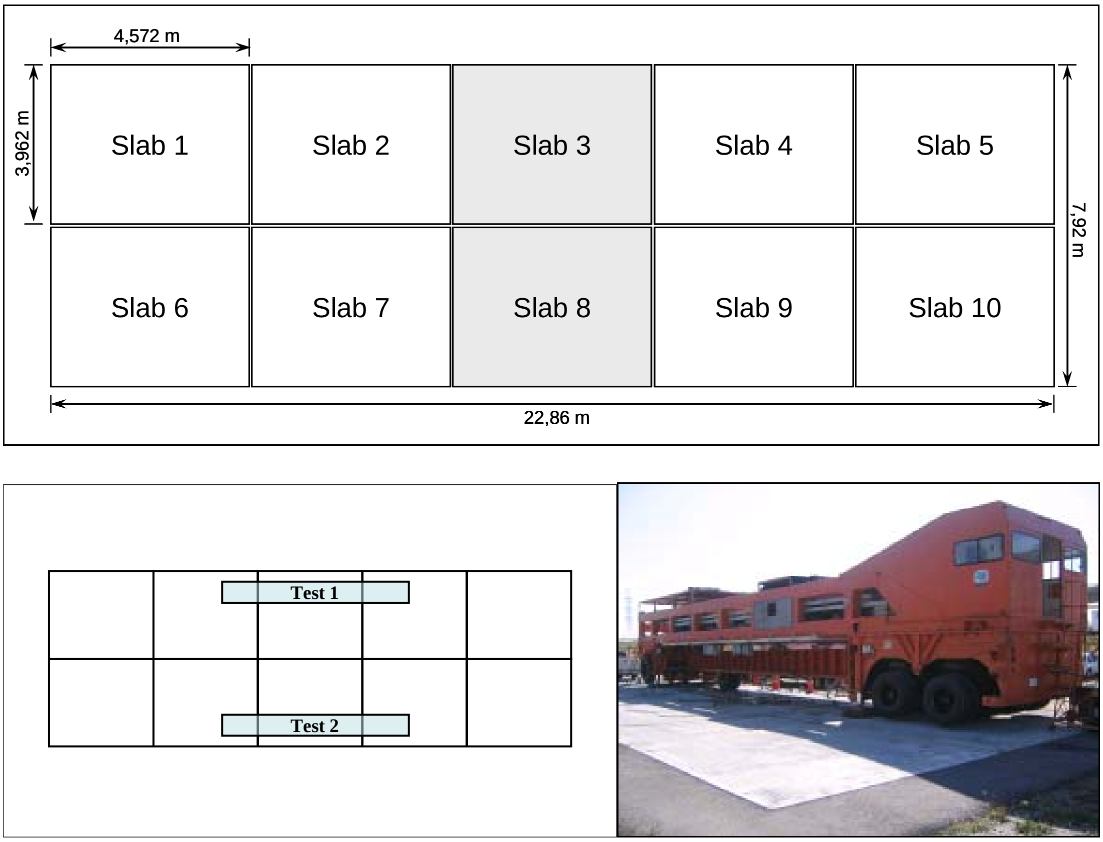


Figure 3. Dimensions, test sections layout, and HVS during load testing

To respond to the second and third objectives, the sections were loaded for extended periods under different conditions. Section 1 was heavily loaded to identify failure modes while Section 2 was utilized to determine performance under more realistic, yet accelerated, loading conditions Since climate in southern California comprises little rainfall, wet pavement conditions were simulated by pouring water directly on the slabs at the joints. The dry test on Section 1 was followed by the dry and wet test on Section 2, and once the experiment on Section 2 was finished, the HVS was returned to Section 1 to perform the wet test.

Not all the instruments were used at the same time, because some surface sensors were moved as the experiment progressed. The instrumentation concentrated mostly on slabs 3 and 8 in the five-by-two grid. Figure 4 shows the instrumentation location as it was setup for the wet test part of the testing in Section 1. Vertical (denoted by “J” or “C”) and horizontal (“H”) joint-deflection measurement devices (JDMD) were used. Vertical JDMDs have reference rods anchored away from the slabs and measure absolute vertical deformations. Horizontal JDMDs are mounted across joints and measure relative opening and closing of the joint.
In addition to the JDMDs, Multi-depth Deflectometer stacks (MDDs) were installed in close proximity to joints in the wheelpath. The MDD modules were installed in the top-cap, as close to the surface as possible, then at 230 mm depth at the top of the cement-treated base (CTB), at 380 mm depth at the bottom of the CTB, and at 680 mm depth in the subgrade. Approximate location of the MDDs is shown in Figure 5, along with a schematic view of the pavement structure. All MDDs and vertical

JDMDs were anchored at a depth of 3m. A typical joint with JDMDs and MDDs is presented in Figure 6.

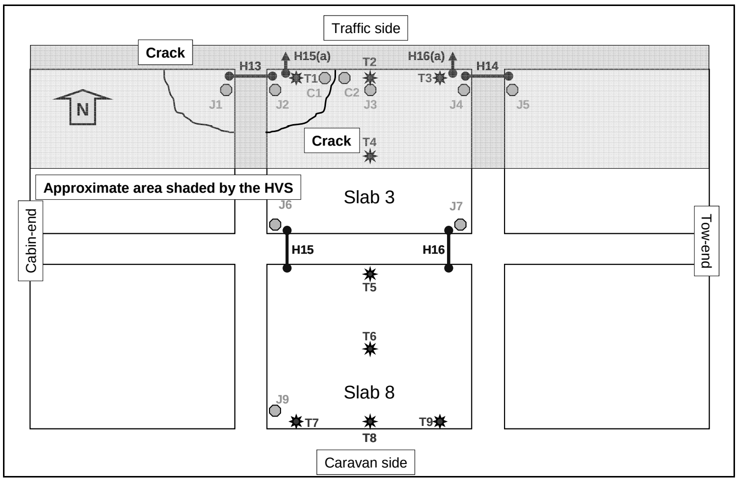


Figure 4. Example of thermocouple and JDMD locations.

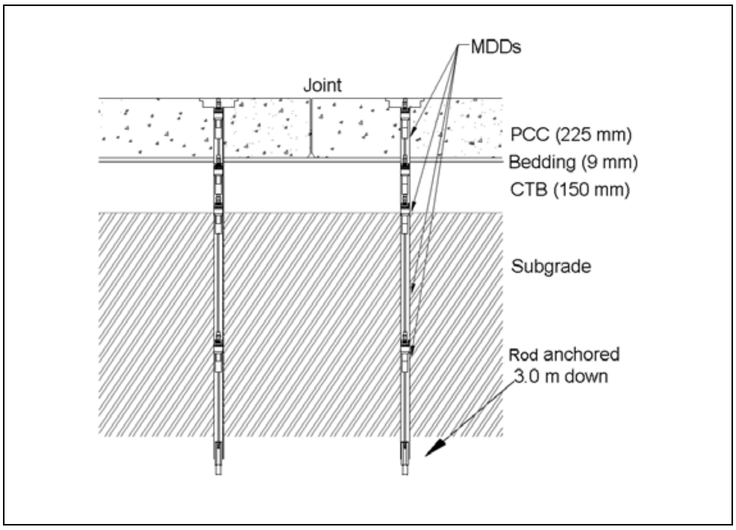


Figure 5: MDD approximate depths and pavement cross section.

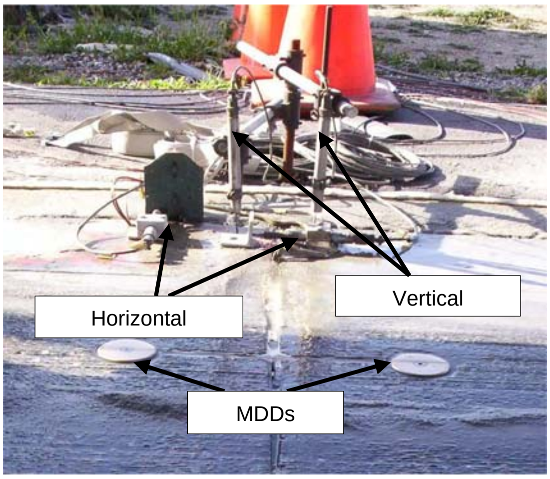
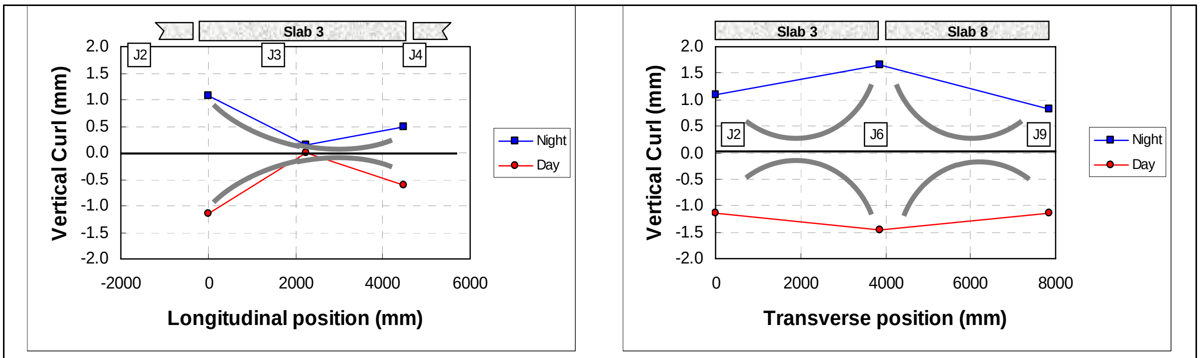


Figure 6. View of typical JDMDs and the cover of the MDDs on the precast sections.

PRELIMINARY TESTS ON UNGROUTED SLABS

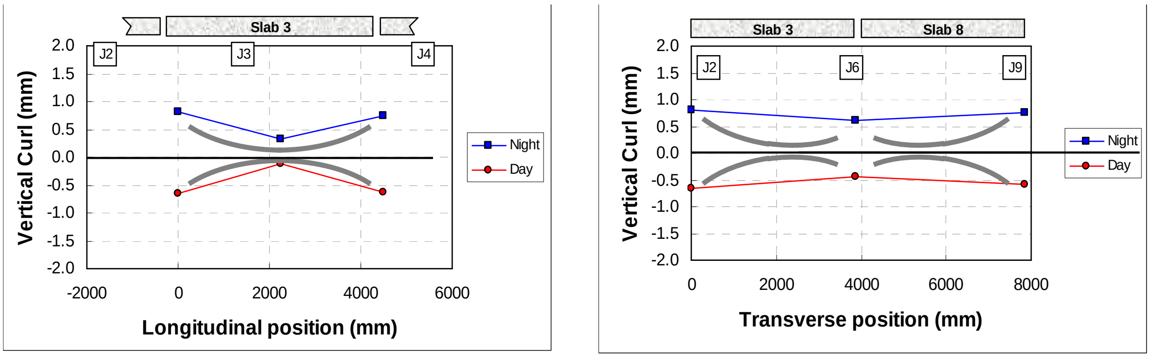
No changes in response, other than those attributable to temperature, were observed during the preliminary experiment, and therefore in terms of performance, the un-grouted Super-Slab® System was verified to withstand at least the 86500 ESALs.

The thermal deformations (with no traffic loads) were compared before and after grouting. The vertical daily displacements at an interior corner were reduced by grouting from ±1.5 to ±0.5mm as shown in Figure 7. In the un-grouted condition each slab curled separately, while after grouting the presence of tie-bars and grout in the joint (coming from the tie-bar grout slots), restrained the movement, reducing self-weight stresses and ensuring better support conditions. Along the longitudinal direction, on the exterior corners, on what would be adjacent to the shoulder, the effect of grouting was minimal (see Figure 7).



(a) Longitudinal direction before grouting

(b) Transverse direction before grouting



(c) Longitudinal direction after grouting

(d) Transverse direction after grouting

Figure 7. Comparison of the vertical deformations caused by thermal curl of the slabs before and after grouting, in the transverse and longitudinal directions

Regarding responses to wheel load, both sides of the joint moved together after grouting, while they had acted independently in the un-grouted condition. Load transfer efficiency changed from less than 10% to near 100%. The vertical deflection at the transverse joint after grouting decreased from about 1.0 to 0.25mm under the

60kN wheel load. Rocking of the slab was eliminated, as observed by the lack of vertical movement in a joint when the wheel load was on the opposite side of the slab.

TEST ON SECTION 1

The actual sequence of testing on Section 1 is summarized in Table 1. The dry part of the test was done in bi-directional (two-way) trafficking mode. Uni-directional (one-way) trafficking was initially used during the wet part of the test, as it would be inducive to the development of step-faulting. Bi-directional trafficking was reinstated later during the wet test once it was established that the dowel bars effectively prevented the development of step-faulting.

A distinction is made between the trafficking load and the deflection load. The trafficking load is the wheel load at which the load repetitions are applied to the test section, and the deflection load is the load at which deflections are recorded throughout the test. The trafficking load is the load that causes damage to the pavement during the test. As an example, the trafficking load for the most of the test on Section 1 was a 150kN, single aircraft tire load inflated to 1,440kPa inflation pressure. However, deflections were collected at three hourly intervals under the 150kN load and also at regular intervals under deflection loads of 60, 80, and 120kN.

Table 1: Load sequence and events on Section 1

Moisture Condition	Slab Condition	Traffic Mode	Portion of Section Tested	Traffic Load (kN)	Date and Repetitions at the End of the Phase	
					Date	**Repetitions**
Dry	Uncracked	Two-way	Full	60	17 June 2005	152,404
				80	24 June 2005	300,075
				120	10 August 2005	510,160
				150	25 August 2005	762,044
	Corner crack at cabin-end transverse joint			150	20 September 2005	1,239,262
Wet		One-way		60	19 May 2006	1,301,978
				100	9 June 2006	1,399,184
				150	12 July 2006	1,415,142
		Two-way		150	1 August 2006	1,446,383
	2nd corner crack			150	9 August 2006	1,605,072
			Half	150	18 August 2006	1,682,404
				150	28 August 2006	1,684,422

An example of the depth deflection bowls obtained from the MDD system is shown in Figure 8 for three consecutive load repetitions during the first day of loading. Except for the MDD module at a depth of 380 mm, there is very little noise in the data and the deflection results of the three load cycles are highly repeatable. Similar results were also obtained for the other MDD stacks. The peak deflections were extracted from the depth deflection bowls and the peak deflection from the surface deflection bowl was used for further analysis.

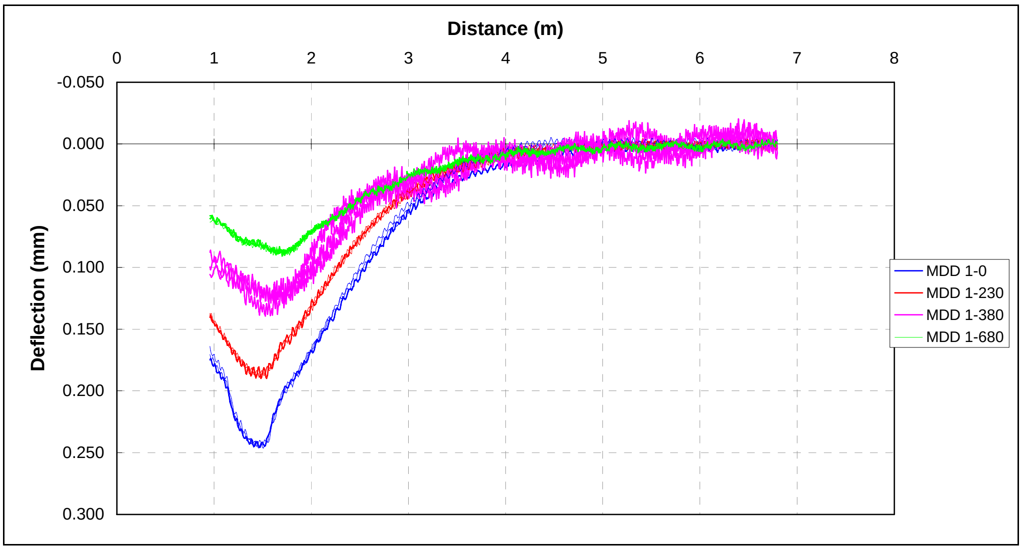


Figure 8. Typical MDD data

Probably because of the sandy soil, the signal condition from the MDDs had deteriorated to such an extent that at the time of the start of the wet test it was decided to continue with only the JDMDs. Figure 9 presents vertical deflections from the two JDMDs in one of the joints while Figure 10 shows a summary plot of the peak deflections for one of the four MDDs in Section 1 for the duration of the test. The peak deflections are shown for all the deflection loads from 60 to 150 kN, and the trafficking loads are shown at the top of each chart. The data exhibit daily cycles and three are the factors affecting the peak deflection: a) the magnitude of the deflection load, b) the daily temperature changes, and c) the amount of damage caused to the pavement.

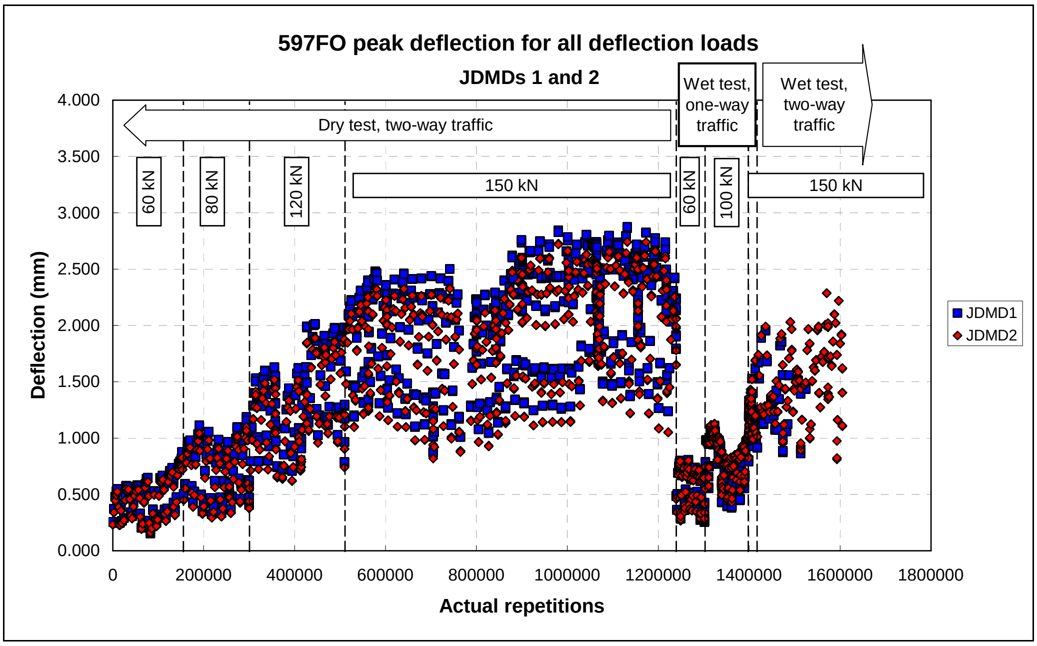


Figure 9: JDMD peak joint deflections in Section 1.

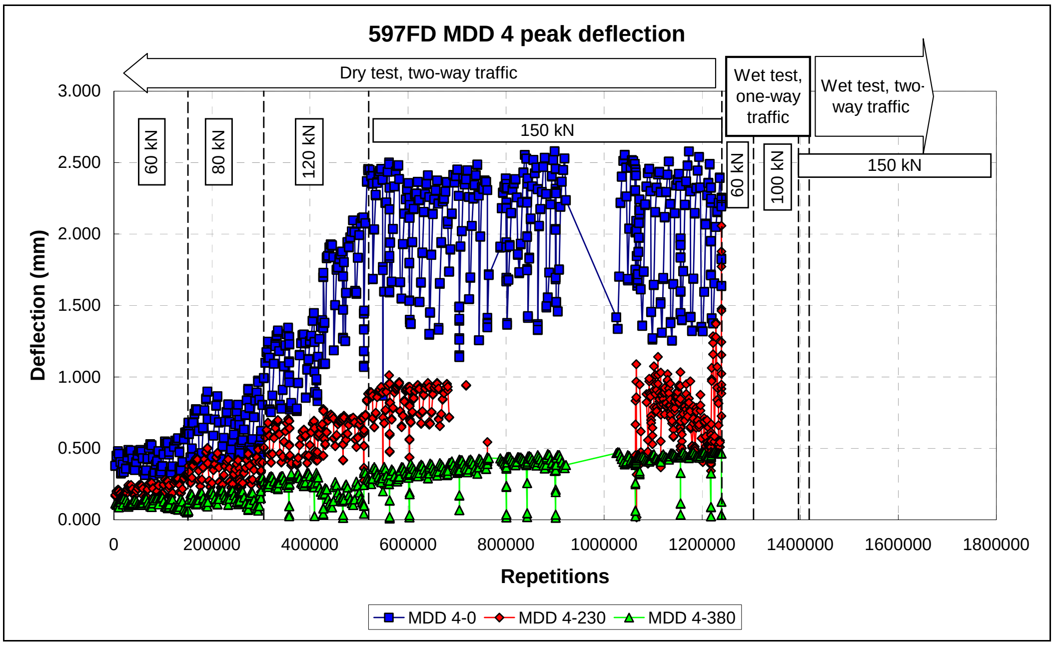


Figure 10. MDD peak joint deflections in Section 1.

Structural corner cracks were first observed at 0.76 million repetitions and were fully developed at 0.84 million repetitions. The corner cracks did, however, only develop at one of the two transverse joints during the dry part of the test. HVS trafficking in dry conditions was stopped when, after the cracks had appeared, the pavement responses were once again stable.

After the wet traffic was initiated, the slabs were able to withstand 0.76 million additional heavy load repetitions before traffic had to be stopped, which was a clear indication of a still sound structural condition of the cracked slabs at the end of the dry test. Approximately 380 liters (100 gallons) of water were poured on to the section per week for the duration of the wet test. Assuming that the water covered the 1x8m test area a total rainfall of approximately 7mm per day (0.28”) was continuously applied during the wet cycle.

Failure of the section was reached in the form of a localized collapse in one of the joints and a more extended corner crack on the other. Forensic investigation revealed that the localized failure happened in-between dowel bars, exactly where the channelized traffic loaded the pavement. Even though the failure happened at the location of one of the multi-depth deflectometer sensors, it was concluded that this had no effect. The combined observations point toward concrete fatigue under channelized traffic and the loss of support caused by pumping. The other joint presented a failure that can be considered typical of cast-in-place, with large concrete cracks. Both failed joints are shown in Figure 11 in view perpendicular and parallel to the traffic. It is important to note that pumping was major factor observed in the experiment. The use of a bound bedding material (cement treated sand) was discussed prior to the test. The decision to use unbound stone sand (not treated with cement) was made, since that was the material most commonly used on previous projects, recognizing it would likely produce “worst case” results.

Figure 11. Transverse and longitudinal view of the two failed joints at the end of pavement life in Section 1

TEST ON SECTION 2

The loading in Section 2 consisted of a total of approximately 3.46 million load repetitions applied with dual truck tires at 69kPa inflation pressure. This means more considerably more repetitions, but a lower tire pressure and lower load level compared to Section 1. No sign of any distress was observed at the end of the dry test at 2.33 million repetitions. The dry test consisted of two loading conditions, 0.24 million load repetitions at 60kN and an additional 2.09 million repetitions at a 100kN load level. The responses captured by the sensors indicated a stable condition. During the wet test the loading was applied as follows: 0.22 million repetitions at 60kN, 0. 11 million at 80kN followed by a final 0.80 million repetitions at 100kN. Section 2 was tested in bi-directional (two-way) trafficking mode, and the detailed load sequence is presented in Table 2.

Table 2: Load sequence and events on Section 2

Moisture condition	Slab condition	Traffic mode	Traffic load (kN)	Date and repetitions at the end of the phase	
				Date	Repetitions
Dry	Un-cracked	Two-way	60	3 October 2005	243 801
			100	15 February 2006	2 334 349
Wet			60	3 March 2006	2 456 357
			90	8 March 2006	2 552 935
			80	15 March 2006	2 664 929
			100	2 May 2006	3 459 387

As mentioned, no distresses were observed in Section 2 either during the dry test or during the wet test, despite the fact that considerable pumping of material from under the slab occurred during the wet trafficking. The pumping of fine sand, however, did not result in any significant rise in corner deflections. An investigation was carried out to evaluate the extent of the suspected voids under the slab caused by pumping. It revealed that the pumped material was comprised of the finer particles from the sand bedding layer and disintegrated bedding grout. There was no clearly noticeable void in the wheelpath under the joint, but there were rather widespread marks of washed fines. Drill cores obtained from various locations in both test sections indicated very good performance of the dowel grout. No sign of looseness of the dowel, which in other words means that the grout was strong enough to sustain the compressive forces of the dowel as load was transmitted across the joint. Likewise, there were no signs of bonding issues between grout and the surrounding concrete of the slot.

Figure 12. Investigation of void under the slab in Section 2

Similarly to what was presented for Section 1, Figure 13 and Figure 14 show representative JDMD and MDD joint deflections for the entire duration of the test on Section 2.

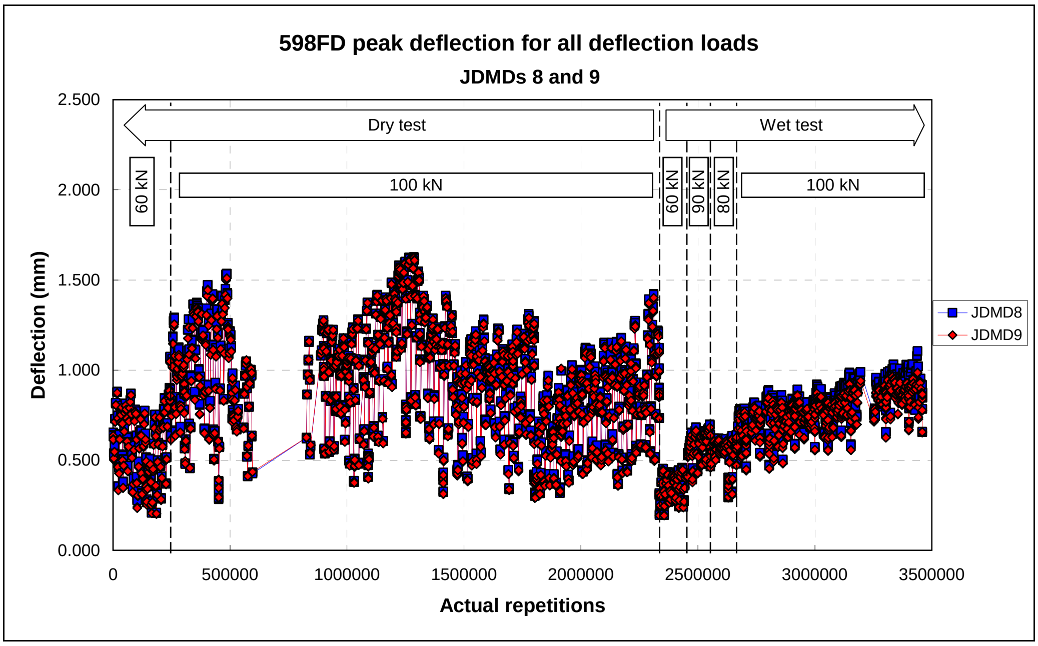


Figure 13. JDMD peak joint deflections in Section 2.

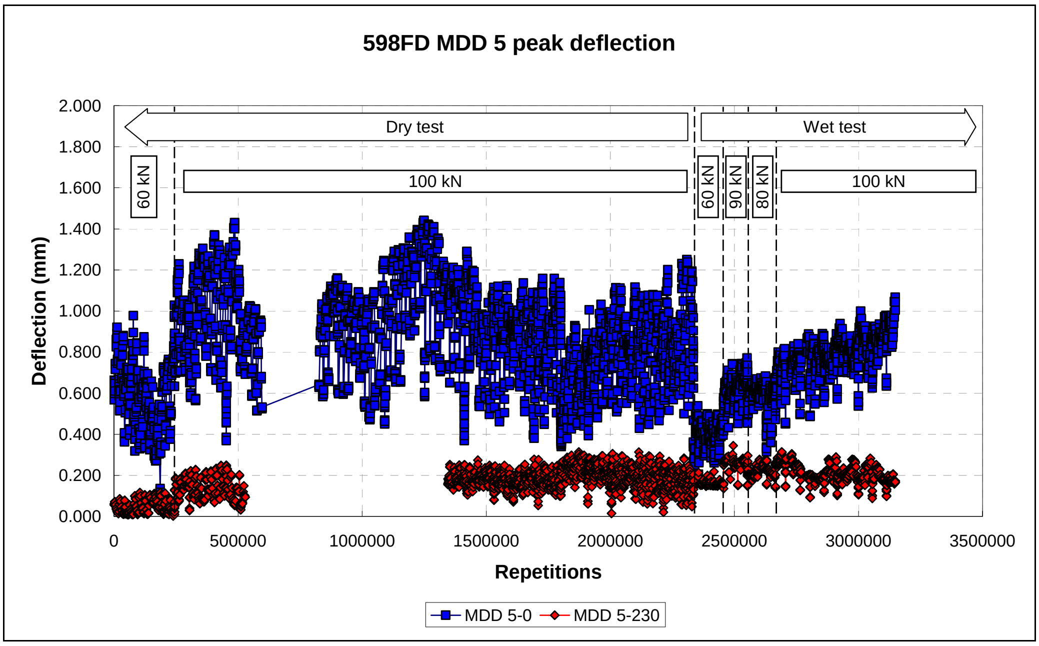


Figure 14. MDD peak joint deflections in Section 2.

SUMMARY

Table 3 presents a summary comparison of the loading conditions and results observed on the two sections of the experiment.

Table 3: Load sequence and events on Section 2

	Section 1 (Test 597FD)	**Section 2 (Test 598FD)**
Tire type and tire pressure	Aircraft tire, 209 psi	Dual Truck tire, 100 psi
Load levels	60 to 150 kN Average: 127.6 kN	60 to 100 kN Average: 94.8 kN
Test periods	7 months 8 June – 20 Sept, 2005 (dry) 11 May – 28 Aug, 2006 (wet)	7 months 21 Sept 2005- 15 Feb, 2006 (dry) 16 Feb – 2 May, 2006 (wet)
Total load repetitions	1,684,422 1,239,262 (dry) 365,810 (wet, first joint) 445,160 (wet, second joint)	3,459,387 2,334,349 (dry) 1,125,038 (wet)
Total ESALs	279 millions on first joint 299 millions on second joint	142 millions
Test result	Corner cracks at one of two transverse joints during dry test. Pumping and slab failure at the two joints during wet test.	No cracking during dry test. Pumping but no cracking or any distress during wet test.

CONCLUSIONS

Evaluation of the Super-Slab® system of precast pavement under a Heavy Vehicle Simulator provided Caltrans with answers to questions originated in the lack of performance information on this relatively new paving technique. The following conclusions were derived from the experiment:

- The Super-Slab® system of precast slabs can be safely opened to traffic in the un-grouted condition, so that the panels can be installed in consecutive nights rather than completing the entire installation at one time. This allows for the old slabs to be removed and precast slabs placed in position one night, and for completing the grouting procedure on the following night.
- The life of this system of precast slabs, when used as detailed for this test, is estimated to be between 140 and 240 million ESALs. These number results from estimated traffic applied in section 2, which did not fail, and in section 1, that failed under very high load levels. Taking as example highway I-15 in San Bernardino County, California, this number of ESALs could be assumed equivalent to more than 25 years of service, perhaps about 37 years before reaching failure.
- The failure mechanism in this system of precast slabs was no different than failure in cast-in-place jointed concrete pavements. Corner cracks, that are the result of loss of support, created conditions indicative of end of usable pavement life.

It must be taken into account that accelerated pavement testing differs in some ways from years of live traffic loading, in particular with regard to wheel load conditions with the HVS and the effect of the environment. Faster moving trucks could cause more pumping than what was observed in the experiment, especially if joint seals are not maintained and are left to deteriorate over time. Finally it should be emphasized that this test was conducted on slabs of a specific thickness, with a unique pattern of reinforcing steel and supported, by choice, upon un-bound bedding material. Use of a cement or asphalt emulsion treated concrete sand bedding material may have greatly reduced, if not eliminated, the pumping of fines that occurred under the very severe wetting conditions in the test, potentially altering the results.

ACKNOWLEDGEMENTS

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