HEAVY VEHICLE SIMULATOR TESTING ON PRE-CAST CONCRETE PANELS

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ABSTRACT

For heavily trafficked highways, such as those commonly found in California, pre-cast concrete slabs are considered to be a very suitable repair material for extending the service life of intermittently distressed concrete pavements. This is because of the long life expectancy of concrete slabs cast in factory-controlled conditions and because fully cured pre-cast slabs can potentially be put into use almost immediately after installation, making them attractive for use on heavily traveled highways where work windows for full-depth repairs are very short.

The foregoing benefits can only be realized if pre-cast slabs are constructed and installed with appropriate materials and adequate supervision, as there are many factors that can affect the structural and functional life of this increasingly popular type of pavement repair method.

This paper focuses on results obtained from recent accelerated loading testing in California with a Heavy Vehicle Simulator (HVS) on a particular system of pre-cast slabs, referred to as SuperSlab®.

1 INTRODUCTION

Pre-cast concrete has a proven track record as a durable high-performance product for bridge and commercial building construction. This is the result of a high degree of quality control that can be achieved at a pre-cast fabrication plant. For roadways, pre-cast concrete also has an advantage in terms of how fast a facility can be opened or re-opened to traffic. Conventional cast-in-place pavement requires several days of curing time after the concrete is placed before it is strong enough to withstand traffic loads without risking premature reduction in fatigue life. Early opening to traffic reduces the costs to drivers that are directly attributable to congestion caused by construction activities. These user delay costs consist of at least increased fuel consumption, lost work time and the social costs of increased air pollution. The savings in user delay costs realized through limiting construction to only off-peak travel times (at night or over a weekend) can be substantial.

The primary application of pre-cast concrete pavement is for the rehabilitation of high-traffic highways and urban arteries Some of the busiest highways in California carry an annual average daily traffic (AADT) of over 325 000 vehicles and, to minimize user delay costs, pre-cast concrete slab replacement is considered to be an acceptable rehabilitation option. Rehabilitation needs range from intermittent slab replacement, which is a “patching” type repair, to full-scale continuous replacement on sometimes complex geometries, such as on a curved alignment encompassing varying widths and super-elevations. While some entire roadways may be shut down for “brief” periods of time for round-the clock work, many locations are restricted to 8 hours or even 5 hour closures. In all these cases high quality materials and methods for repairing the roadway rapidly are desperately needed.

As regards high-quality material, high-strength concrete mixtures with a low water-cement ratio and uniform aggregate gradation are produced routinely by pre-cast fabrication plants. At most plants concrete batching and quality control is done on-site and the concrete is transported only a short distance from the batch plant to the forms, minimizing changes in concrete properties between the mixing and placing operations. Pre-cast fabrication plants offer tremendous flexibility over the curing operation. Pre-cast concrete elements can be fabricated indoors, they can be wet-mat cured or steam cured and curing can be maintained as long as necessary after casting. Problems that can affect cast-in-place pavement construction, such as surface strength loss, "built-in" curling, inadequate air entrainment and finishing, can all be eliminated through the use of pre-cast concrete.

2. THE SUPER-SLAB SYSTEM

The Super-Slab System is a product developed in the state of New York and was used for the first time to replace the pavement at a bridge toll plaza in 2001. The patented Super-Slab system is an assemblage of specially-designed pre-cast 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:

1. Constant thickness pre-cast 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 near complete sub-base support for the pre-cast slabs. 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; and
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 dowels are cast at one end of each slab at locations that match the location of dovetail-shaped slots cast in the bottom of each adjacent slab 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.

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Figure 1. **Precast Dowels and slots showing slot/dowel bar connection**

Two grout ports are cast in 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 and perform in the same way. 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 the dowel grout out of sight, thus maintaining a uniform-looking, high-performance pavement surface. Figure 2 shows the positioning of the slabs and a core taken from a dovetail slot/dowel bar connection.

Figure 2: Slab positioning and core showing dovetail slot/dowel bar connection

Whereas pre-cast slabs can be cast to any thickness, length and width as required, a number of factors must be considered when establishing slab dimensions. Freight costs are minimized when full legal loads are transported. Another factor to consider is that repetition of sizes help keep fabrication costs to a minimum.

The bedding grout distribution system, visible on the bottom of the slab in Figure 3, comprises a series of half-round channels cast in the bottom of the slab that extend across the slab to distribute bedding grout to the entire slab contact area. They are accessed from the top of the slab through grout ports cast in at each end of each channel (red dots in Figure 1). Also visible in Figure 3 are black foam gaskets glued to the bottom edges (and in between half-round channels) of each slab to create discrete, sealed grout chambers.

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Figure 3. Bedding grout channels and gaskets

While the SuperSlab® System has been designed to emulate un-reinforced cast-in-place concrete pavement, slabs are reinforced for handling and shipment to the job site and to resist the temperature and shrinkage stresses to which they will be subjected during curing and storage at the pre-cast facility. The reinforcement also provides the added benefits of enhancing the strength of the slabs to bridge over small voids until the slabs are fully bedded and of keeping cracks tightly closed should they occur at a later time.

Two distinctly different grouts are used in the installation of the SuperSlab® System. First, rapid-setting, high-strength dowel grout, pumped into the dowel slots, completes the structural connection between individual slabs. Since this grout must reach a minimum strength of 17 MPa before the slabs are opened to traffic, it is important that it be installed in strict accordance with the grout manufacturer's directions. Secondly, and only after the dowel grout has been pumped in, a bedding grout mixture of Portland cement, water and fluidifying admixture is pumped into the bedding grout distribution system described above. It is important that the bedding grout be fluid enough to flow into and effectively fill any small voids that may exist between the slab and the sub-base surface so as to provide complete support to the concrete slab. The strength requirement for the bedding grout is 4 MPa, since it functions as only a part of the previously placed bedding material.

3. ACCELERATED TESTING OF THE SUPERSLAB® SYSTEM

The California Department of Transportation (Caltrans), through the University of California Pavement Research Center, evaluated the use of the SuperSlab® System as a long-life rehabilitation strategy for concrete pavements. A pilot test site, consisting of 10 slabs in a 2 by 5 arrangement, was constructed at the interchange of highways I-15 and SR210 in San Bernardino County. The construction involved four main components:

- The construction of a 100mm cement treated base course;
- A thin (8mm) layer of fine bedding material (stone sand) placed on top of the base;
- Pre-cast Super-Slabs®, 225mm thick, placed upon the precisely graded sub-base and grouted as described in the foregoing and shown in Figure 4; and
- Diamond grinding of the top surface of the slab to meet the smoothness requirements of the project.

Figure 4. **Precise placement of the slab on the sand bedding layer and hose with fitting for injecting grout**

Two test sections were evaluated between June 2005 and August 2006 using a Heavy Vehicle Simulator (HVS), as shown in Figure 5. In the evaluation of the SuperSlab® System the main test objectives were:

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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; and
3. To determine failure mechanisms.

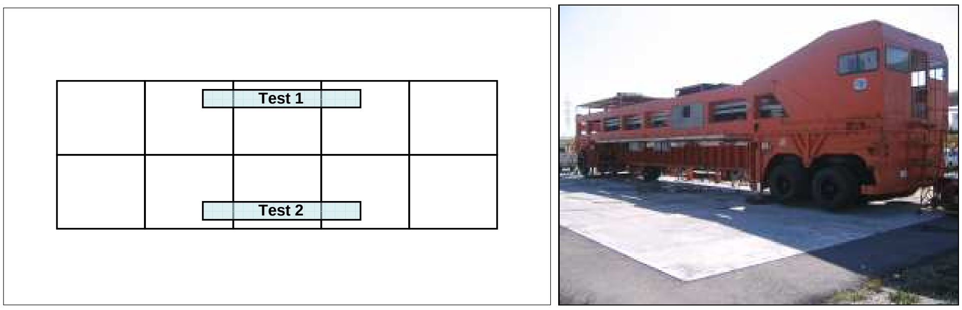

Figure 5. Layout of test sections and HVS during load testing

The instrumentation of the test sections consisted of displacement sensors mounted vertically on each section near the two trafficked joints and at mid-panel. Horizontal sensors were used to measure joint opening and multi-depth deflectometers were used to record the vertical deformation in the various layers of the system directly in the trafficked area. Thermocouple stacks were used to register temperature through the depth of the slabs.

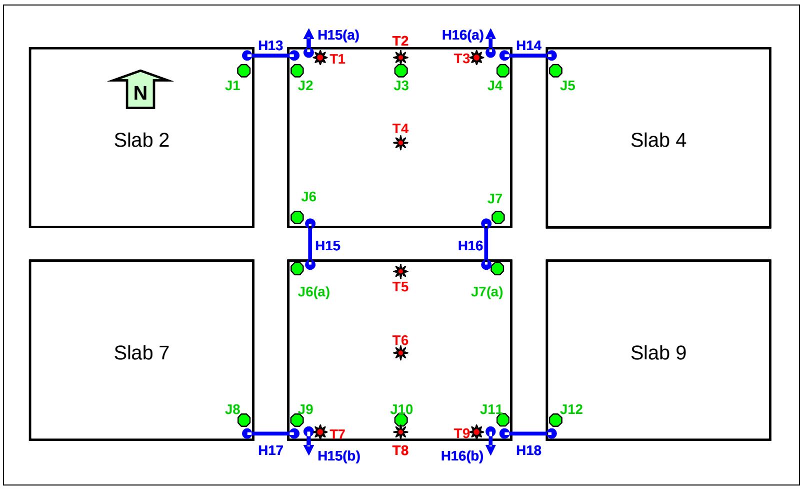

Figure 6. Location of displacement instrumentation and thermocouples

Traffic loading was applied 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. It consisted of approximately 32 hours and 32 000 HVS repetitions with a 60kN half axle load, which relates to a total axle load of 120kN. This amount of loading and repetitions were calculated to be the equivalent of about 86,500 E80s. No changes in response, other than those attributable to temperature, were observed during the experiment, and therefore in terms of performance, the un-grouted SuperSlab® System was verified to withstand at least this level of traffic for Southern California conditions. The Load Transfer efficiency during the un-grouted HVS loading test was typically below 10% and the average corner deflections under the influence of the 60kN wheel load were in the order of 1.2mm.

The thermal deformations (with no traffic loads) were compared before and after grouting. The vertical displacement at an interior corner after grouting reduced 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. This in turn should reduce self-weight stresses and ensure 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).

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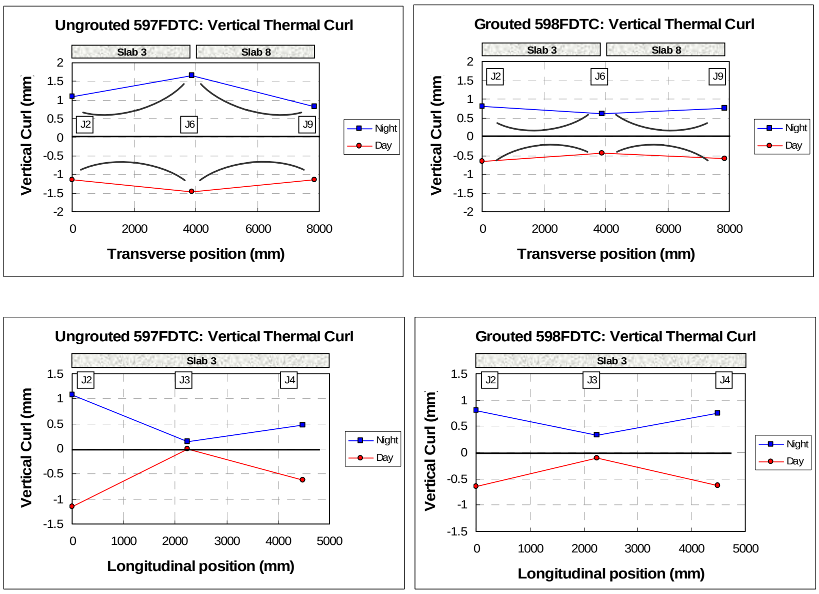

Figure 7. **Comparison of the vertical deformations caused by thermal curl of the slabs before and after grouting, in the transverse and longitudinal directions**

As regards responses to wheel load, both sides of the joint moved together after grouting, whereas they 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. 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.

To respond to the second and third objectives, the sections were loaded for extended periods under different conditions in the sequence shown in Table 1. Section 1 was heavily loaded to identify failure modes and section 2 was utilized to determine performance under more realistic, yet accelerated, loading conditions. The number of E80s shown in Table 1 was calculated using a 4.2 power of the ratio between the actual half-axle load and a standard 40kN load. The climate in southern California comprises little rainfall. Wet pavement conditions were simulated by artificially pouring water in a continuous base directly at the joints. Approximately 380 litres of water per week were poured on to the section per week for the duration of the wet test. Assuming that the water completely covered the 1x8m test area, a total rainfall of approximately 7mm per day was simulated during the wet cycle.

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Table 1. Sequence of test and loading conditions

Section	Duration (months)	Test condition (pavement/ tire type)	Load repetitions (millions)	E80s (millions)
Section 1	3 (June – Sept., 2005)	Dry / Aircraft	1.05	163
Section 2	5 (Sept. - Feb., 2006)	Dry / Truck dual	2.33	99
Section 2	2 (Feb. - May, 2006)	Wet / Truck dual	1.13	43
Section 1	5 (May – Aug., 2006)	Wet / Aircraft	0.54	79

The loading in section 2 consisted of a total of approximately 142.3 million E80s, applied with dual truck tires (690kPa). No sign of any distress was observable at the end of the dry test (99.4 million E80s). The test consisted of two loading conditions, 243 800 load repetitions at 60kN and an additional 2.1 million repetitions at a 100kN load level. The responses captured by the sensors indicated a stable condition. Water application at the joints was then initiated and loading continued. During the wet cycle loading was applied as follows: 218 600 repetitions at 60kN, 112 000 at 80kN, followed by a final 795 000 repetitions of 100kN.

After the first day of the wet cycle pumping of fine sand was visible at the joints. This, however, did not result in any significant increase in corner deflections. When the load was lifted to 80kN, the amount of pumping increased and water spouts approximately 50mm high were detected as the HVS wheel ran over the joints. Figure 8 shows the amount of pumping and water sprouting which was observed at that time.:

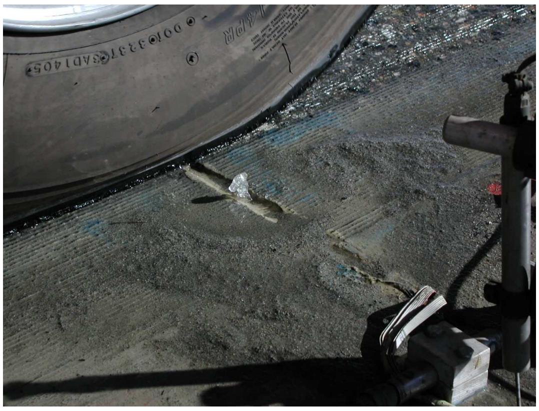

Figure 8: Water pumping from a joint during the wet cycle

Small cracks were observed at the beginning of the 100kN cycle but these did not lead to any significant increase in deflections.

Apart from this, no other forms of distress were observed, despite the fact that considerable pumping of material from under the slab occurred during wet trafficking. An investigation was carried out to evaluate the extent of the suspected voids under the slab caused by pumping (See Figure 9). It revealed that the pumped material consisted of the finer particles from the sand bedding layer and of disintegrated bedding grout. There was no clearly noticeable void in the wheelpath under the joint, but there were rather widespread marks of washed fines.

Figure 9. Investigation of void under the slab in Section 2

Assuming an AADT T (annual average daily truck traffic) of 7500 per direction, 3 E80s / heavy vehicle and 60% truck traffic in the slow lane, the total amount of E80s is currently 13,500 on a highway such as I-15 in Southern California. If it is assumed that this traffic level exists for approximately 75% of the year, the total truck traffic would amount to a total of 3.7 million E80s per year per slow lane. Assuming a growth factor of 3% it would take approximately 25 years to apply the same number of E80s as that simulated by the HVS in Section 2 during the dry and wet cycle (142 million E80s in total). It should be noted that testing in section 2 was discontinued at this traffic level and that there no distress was observed on the pavement section.

Loading in section 1 was applied with an aircraft tire (1440 KPa inflation pressure), able to take the higher load levels used in this test. The total number of E80s applied on this section was 242 millions before structural failure was observed.

Corner cracks appeared next to one of the two loaded joints. These structural corner cracks, on both sides of the joint, were first observed at 762 000 repetitions and were fully developed after 845 000 load repetitions. These can be seen in Figure 10. HVS trafficking in dry conditions was stopped when, after the cracks had appeared, the pavement responses were once again stable. After wet trafficking was initiated the slabs were able to withstand another 540 000 repetitions before traffic had to be stopped, owing to structural failure.

Figure 10. Fully developed corner cracks at one of transverse joints of Section 1, when loaded in dry pavement conditions

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 joint. Forensic investigation revealed that the localized failure happened in between the dowel bars, exactly where the channelized wheel 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 slabs, with large concrete cracks. Both failed joints are shown in Figure 11 (as an indication of their size, the brass sensor caps are 75mm in diameter).

Drill cores obtained from various locations in both test sections indicated very good performance of the dowel grout. There was no sign of looseness of the dowel, which means that the grout was strong enough to sustain the compressive forces of the dowel as the load was transmitted across the joint.

Figure 11. End of life at the two joints of section 1, loaded to failure

4. CONCLUSIONS

This paper summarizes a pilot study on the structural performance of a pre-cast concrete slab roadway rehabilitation option called SuperSlab®. The following conclusions are derived from the experiment conducted for Caltrans in which a Heavy Vehicle Simulator was used to test the structural performance of the SuperSlab® system.

- This system of pre-cast slabs can be safely opened to traffic in their un-grouted condition, so that the panels can be installed in two consecutive night-time traffic closures. During the first night the slabs are placed in position and grouting for the dowels and for filling the bedding voids is performed during the second night.
- The life of this system of pre-cast slabs is estimated to be between 142 and 242 million E80s. This number results from estimated traffic applied to section 2, which did not fail, and to section 1, which failed under very high load levels. Taking highway I-15 in San Bernardino County, California as an example, this number of E80s is equivalent to approximately 25 to 37 years of service
- The failure mechanism in this system of pre-cast slabs was no different from that of 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 should be borne in mind that accelerated pavement testing differs in some ways from years of live traffic loading, particularly with regard to wheel load conditions with the HVS and the effect of the environment. Faster moving trucks could cause pumping in excess of that which was observed in the experiment, especially if joint seals are not maintained and are left to deteriorate over time.

The second important factor which should be taken into consideration is the fact that the concrete panels were placed on top of a newly constructed CTB. Under real-life conditions slab replacement would be done on an old, well trafficked base with the base layer in probably a significantly weaker state than that of a strong, newly constructed CTB. The effect of this was not evaluated during HVS testing.

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