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, the use of pre-cast concrete slabs is considered to be a very suitable means of extending the service life of intermittently distressed concrete pavements. This is on account of the long life expectancy of concrete slabs cast in factory-controlled conditions and also because fully cured pre-cast slabs can potentially be trafficked almost immediately after installation, making them attractive for use on heavily trafficked highways where allowable 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 under 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 the 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 Super-Slab®.

1 INTRODUCTION

Pre-cast concrete has a proven track record as a durable high-performance product for the construction of bridges and commercial buildings. This is owing to the 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 road 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, *inter alia,* of 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 150 000 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. Whereas some entire sections of roadway may be shut down for “brief” periods of time for round-the-clock work, many locations are restricted to 8 hour or even 5 hour closures. In all these cases high-quality materials and methods for repairing the roadway rapidly are urgently needed.

As regards quality, high-strength concrete mixtures with a low water-cement ratio and uniform aggregate gradation are produced routinely by pre-cast fabrication plants. At most pre-cast 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 the properties of the concrete 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, can be wet-mat cured or steam cured and curing can be maintained for 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 significantly reduced through the use of pre-cast concrete.

This paper focuses on the performance of pre-cast concrete panels under accelerated loading. Details of the specifications and fabrication of the concrete and substructure materials are not included. Information on these can be found in the references.

2. THE SUPER-SLAB® SYSTEM

The Super-Slab® System is a product originally 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 connecting 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 placed on top of the sub-base, to a similar tolerance, to provide near complete sub-base support for the pre-cast slabs.
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.

The function of the sand bedding layer is to provide a very even support to the pre-cast slabs thereby eliminating the formation of voids between the slabs and the support to the maximum extent possible. It consists of “Stone dust”, with a maximum size of 4.8 mm and minimum stone size of 0.15 mm and a grading modulus of around 2.8. After the sand is spread on top of the sub-base, the sand is wetted, compacted and bladed repeatedly to very tight profile tolerances.

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 illustrated in Figure 1. Similarly, standard tie bars are placed at one side of each slab matching the location of slots cast in the adjacent slab.

Figure 1. **Pre-cast 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 slabs being positioned as well as a core showing the 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 illustrated in Figure 3, comprises of a series of half-round channels cast in the bottom of the slab which extend across the slab to distribute the bedding grout to the entire slab contact area. They are accessed from the top of the slab through grout ports cast into 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 between the half-round channels) of each slab to create discrete, sealed grout chambers.

Figure 3. Bedding grout channels and gaskets

Although the Super-Slab® System was 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 stage.

Two distinctly different grouts are used in the installation of the Super-Slab® 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 channels through different ports as 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.

The construction process is concluded by cutting the joints to a constant width, grinding the surface to a level plane and sealing the joints.

3. ACCELERATED TESTING OF THE SUPER-SLAB® SYSTEM

The California Department of Transportation (Caltrans), through the University of California Pavement Research Centre, evaluated the use of the Super-Slab® System as a long-life rehabilitation strategy for concrete pavements. A pilot test, 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;
- Placing of a thin layer of fine bedding material (stone sand) on top of the sub base;
- Placing of pre-cast Super-Slabs®, 5.72 m long by 3.962 m wide and 225 mm thick upon the precisely graded bedding sand and grouting of these as described above and shown in Figure 4; and
- Diamond grinding of the top surface of the slab to meet the smoothness requirements of the project.

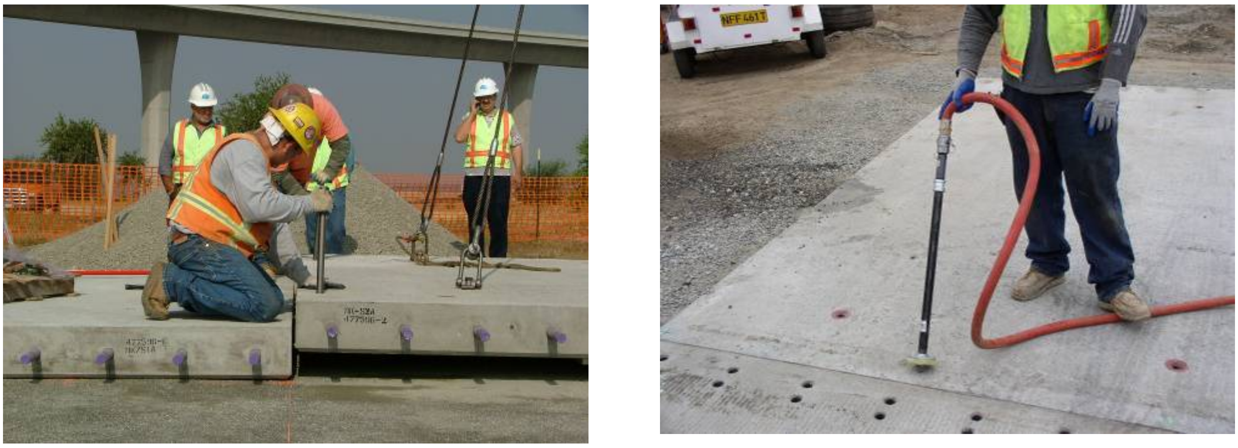

Figure 4. **Precise placement of the slab on the sand bedding layer and hose with fitting for injecting grout**

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

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

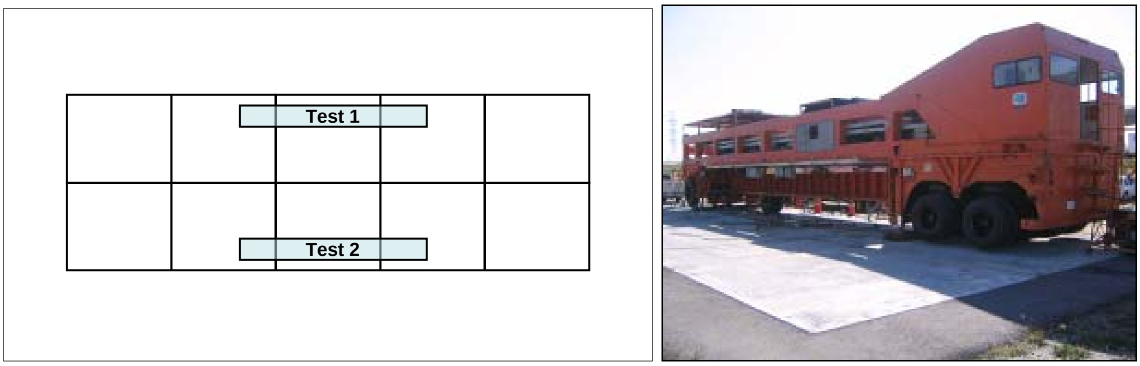

Figure 5. Layout of test sections and HVS during load testing

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 record temperatures throughout the depth of the slabs. The locations of the displacement measuring instrumentation and thermocouples are shown in Figure 6.

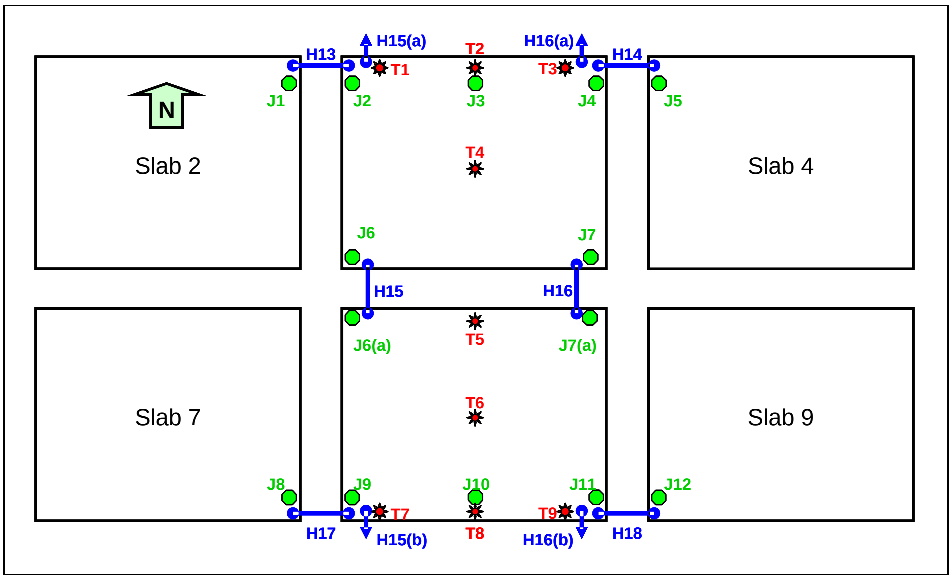

Figure 6. Location of displacement instrumentation and thermocouples

HVS loading was applied to each section to simulate the exposure to traffic from the time of placement of the slabs to the time of dowel grouting which would normally occur during the next nighttime closure. It consisted of approximately 32 hours and 16 000 Uni-directional HVS repetitions with a 60kN half axle load, which relates to a total axle load of 120kN. This amount of loading and repetitions was calculated to be the equivalent of about 87,500 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 Super-Slab® System was verified to withstand at least this level of traffic for 32 hours in 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 1.2 mm.

The thermal deformations (with no traffic loads) were compared before and after grouting. The vertical displacement at an interior corner after grouting decreased from ±1.5 to ±0.5 mm measured transversely across the slabs as shown in Figure 7. In the un-grouted condition each slab curled separately, whereas after grouting the presence of tie-bars and grout in the joint (in the tie-bar grout slots) restrained this movement. In the longitudinal direction, at the exterior corners (those that would be adjacent to the shoulder) the effect of grouting was minimal (see Figure 7).

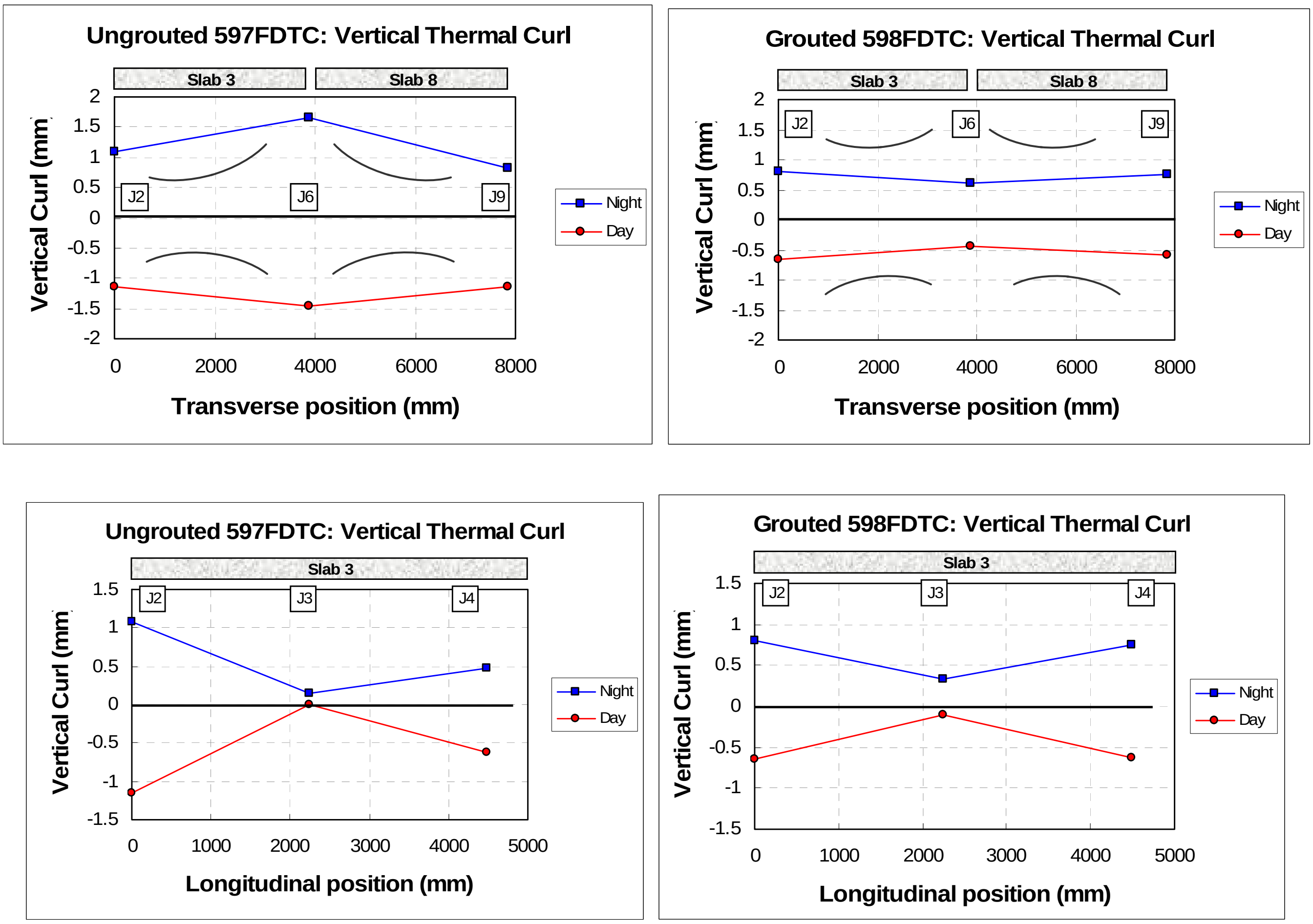

Figure 7. **Comparison of the vertical deformations caused by thermal curl of the slabs before and after grouting, in the transverse and longitudinal directions**

As regards responses to wheel load, both sides of the transverse joint moved together after grouting, whereas they acted independently in the un-grouted condition. Load transfer efficiency changed from less than 10% to almost 100%. The vertical deflection at the transverse joint after grouting decreased from about 1.0 to 0.25 mm. 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 meet the second and third objectives, the two test sections (Figure 5) were loaded for extended periods under different conditions in the sequence shown in Table 1. Test Section 1 was heavily loaded to identify failure modes and Test Section 2 was utilized to determine performance under more realistic, yet accelerated, loading conditions. The number of Equivalent 80kN axle loads (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 half-axle load. As Southern California receives very little rainfall, wet pavement conditions were artificially simulated by pouring water on a continuous basis directly onto the joints. Approximately 380 litres of water per week were poured on to the section at the joints for the duration of the wet test. Assuming that the water completely covered the 1x8 m test area, a total equivalent rainfall of approximately 7 mm per day was simulated during the wet cycle.

Table 1. Sequence of test and loading conditions

Section	Duration (months)	Test condition (pavement/ tyre 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

3.1 High Load wheel test

Loading in Section 1 was done using an aircraft tyre (1440 KPa inflation pressure), able to take the higher load levels used in this test. The section was subjected to a total of 1 590 000 repetitions mainly consisting of 150kN wheel loads. Using the 4.2 damage factor a total of 242 million E80s were applied before structural failure was observed.

Corner cracks appeared next to one of the two loaded transverse joints. These structural corner cracks, on both sides of the joint, were first observed after 762 000 repetitions (approximately 90 million E80s) and were fully developed after 845 000 repetitions (approximately 111 million E80s). These can be seen in Figure 8. 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 (78.5 million E80s) before trafficking had to be stopped, owing to structural failure.

Figure 8. Fully developed corner cracks at one of transverse joints of Section 1, when loaded in dry pavement conditions

Failure of the section took 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. 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 9. (As an indication of their size, the brass sensor caps are 75 mm in diameter.)

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

Figure 9. End of life at the two joints of section 1, loaded to failure

3.2 <u>Realistic Load wheel test</u>

Loading of Section 2 was done using normal dual truck tyres (690 KPa inflation pressure). The loading sequence consisted of 244 000 and 2.09 million wheel loads of 60kN and 100kN respectively for a total of 2.33 million load repetitions (or 99.4 million E80s) in the dry state. No signs of distress were observable at the end of the dry test. 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. Using the same damage factor the test section was subjected to a total of approximately 142.3 million E80s.

Pumping of fine sand was visible at the joints after the first day of the wet cycle. This, however, did not result in any significant increase in corner deflections. When the load was increased to 80kN, the amount of pumping increased and water spouts approximately 50 mm high were detected as the HVS wheel ran over the joints. Figure 10 shows the amount of pumping and water sprouting which was observed at that time.

Figure 10: 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 11). 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 wheel path under the joint, but there were rather widespread marks of washed fines.

Figure 11. 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 daily E80s in the slow lane 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 in the 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 no distress was observed on the pavement section.

4. CONCLUSIONS

This paper summarizes a pilot study on the structural performance of a pre-cast concrete slab rehabilitation system called Super-Slab®. 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 Super-Slab® system.

- This study showed that the system of pre-cast slabs can be safely opened to traffic in its un-grouted condition for a limited time period without the risk of early damage. This means 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.

- Based on this series of HVS testing 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

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.

An important factor which should also 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 carried out 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.

The above-mentioned estimated structural capacity should, therefore, be interpreted with caution, given the prevailing testing conditions.

- The failure mechanism in this system of pre-cast slabs was no different from that of failure in cast-in-place dowel-jointed concrete pavements. Corner cracks, that are the result of loss of support, created conditions indicative of end of usable pavement life.

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