

Design of Concrete Slabs with Optimized Geometry and Built-in Curling Effect on Performance

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ABSTRACT

A new methodology called TCP “Thin Concrete Pavements” has been developed to design the concrete slab thickness by optimizing the slab size given the geometry of the truck axles. The key principle of the design method is to configure the slab size so that not more than one set of wheels are on any given slab at any time, thereby minimizing the critical top tensile stress. Full-scale test sections were constructed and tested at Illinois under accelerated pavement loading conditions with concrete thickness of 8, 15, and 20 cm on both an aggregate (Subbase CBR 4% and 15 cm granular base) and asphalt base layer. Concrete slabs 8 cm thick on a 15 cm granular base withstood 75.000 ESALS, Slabs with 15 cm thickness showed cracks initiating at 12 million ESALs on average. The 20 cm slab thickness showed no fatigue cracking.

A Mechanistic-based software, “OptiPave”, has been developed. The new methodology designs slabs that are on average 7 cm thinner than traditional pavements, AASHTO (1993), for the same traffic, with a thickness range of 8 cm to 20 cm thick. This new solution for designing concrete pavements has been used to build roads from local streets to high traffic highways and gives an alternative to asphalt in low volume roads and competes directly in direct cost Thickness design in Chile is very sensitive to climate variables. The AASHTO 93 method doesn't consider built in curling conditions, which is especially sensitive to construction standards, making this design variable (BIC) extremely important in terms of pavement performance. Two cases are studied in this paper to show the benefits of the optimized designed slabs, in terms of thickness and sensitivity to climate conditions.

KEY WORDS

CONCRETE PAVEMENT / OPTIMIZED SLABS / THIN PAVEMENTS/
SHORTSLABS/ BUILT IN CURLING

INTRODUCTION

The typical slab dimensions for a concrete pavement is 3,6 m wide by 4,5 m long (AASHTO 93) with slab thicknesses ranging from 15 to 35 cm depending on the level of traffic. The required thickness is primarily dependent on the axle weight and number of load repetitions, concrete strength, slab length, soil type and climate conditions (curling).

This method is proposing a new methodology (Covarrubias et al. 2008) to design concrete pavements by optimizing the joint spacing, given the geometry of the trucks (truck loads). This is done by considering the way trucks load the slab. Designing the slabs sizes such that the trucks never load with more than one set of wheels on any given slab, reduces the stresses imposed by them. The reduced slab length and width also reduces curling, typical slab sizes are from 1,4 to 2,2 m in length and half a lane Width

Improvement of these factors can reduce stresses and allow the design of thinner slabs for the normal performance of concrete pavements. A slab size

optimized by this design method, can reduce the thickness by up to 10 cm for the same stresses within the slab as for 4,5 m long slabs, therefore the same performance.

Full-scale test sections of this new concrete pavement system have been constructed and tested under accelerated pavement loading conditions at The University of Illinois. The design and concrete material factors that have been subjected to repeated loading in this research are the following: concrete thickness of 8, 15, and 20 cm; aggregate base or asphalt concrete base; plain concrete or fiber reinforced concrete; and edge versus wheel path loading.

The accelerated pavement testing showed that these thinner concrete slabs with reduced slab sizes ($< 2,5$ m) could sustain a significant number of ESALs before cracking. The 20 cm concrete slabs on granular base did not experience fatigue cracking up to 51 million ESALs and the measured stresses were low. The 15 cm concrete slabs on granular base began cracking on average at 12 million ESALs. The concrete slabs, not bonded, on asphalt base resisted a significant larger number of ESALs than the same concrete thickness on granular base. The cracking performance of the 8 cm. concrete slabs varied with the stiffness of the soil. In all cases for the 9 cm slab thickness, structural fibers provided a longer fatigue life, extended service life, and high load transfer efficiency across the transverse joint relative to the plain concrete slabs. Trafficking tests indicated that the fibers may also be able to serve as a replacement for the lateral restraint pins. Finally, the shorter slab sizes, with and without fibers, maintained a medium to high load transfer efficiency over the accelerated loading period for all slab thicknesses suggesting the use of targeted dowels only on particular cases in heavy traffic.

With the use of short and optimized slab sizes and concomitantly reduced slab thickness, the pavement design concept requires several other modifications in order to achieve the intended pavement service life. The following are a list of additional adjustments that must be made to the concrete pavement system to accommodate the optimized slab design.

1. Due to the larger number of contraction joints and desire not to seal joints, thin saw blades with 2 mm joint width should be used to limit spalling by incompressibles entering the joint.
2. It is necessary to have a granular base that is insensitive to moisture and minimizes pumping due to the quantity of unsealed contraction joints. The granular base material should have less than 8 percent material finer than the 75 μ m sieve.
3. There should be a nonwoven geotextile layer between base and natural soil to act as a separation layer. This geotextile prevents subgrade intrusion into the free draining base layer as well as prevents aggregate penetration into a weaker subgrade soil.
4. Due to the large amount of saw cuts, load transfer is primarily carried by aggregate interlock and thus dowels and tie bars are not part of the standard design of this system. As the number of cracks is larger, the width of the cracks is smaller. In order to prevent the thinner slabs from moving laterally, the concrete slabs must also be restrained on the longitudinal edge with a concrete shoulder, vertical steel pins or incorporation of structural fibers. Steel pins (16 mm) spaced 50 cm have been used in previous projects successfully. Currently, a targeted load transfer system is being studied for high volume designs.

STRESSES ON SLABS:

Normally, on 3.5 to 6 meters long slabs (AASHTO recommendation), the front and rear axles apply the load simultaneously at both edges of the slab. This loading induces the traffic surface tensile stresses on the top of the pavement when it is curled upwards, inducing top down cracks. These tensile stresses at the top are due to the moment produced in the cantilever part of the slab.

If the slabs are shortened such that the slab length results in neither the front and rear axles simultaneously on the same slab (Covarrubias et al. 2008) as seen in Figure 2, the tensile stresses are significantly reduced within the slab. The stresses and deflections calculated in Figure 2 were based on a concrete thickness of 20 cm, 1500 kg load, and a -15 °C temperature differential.

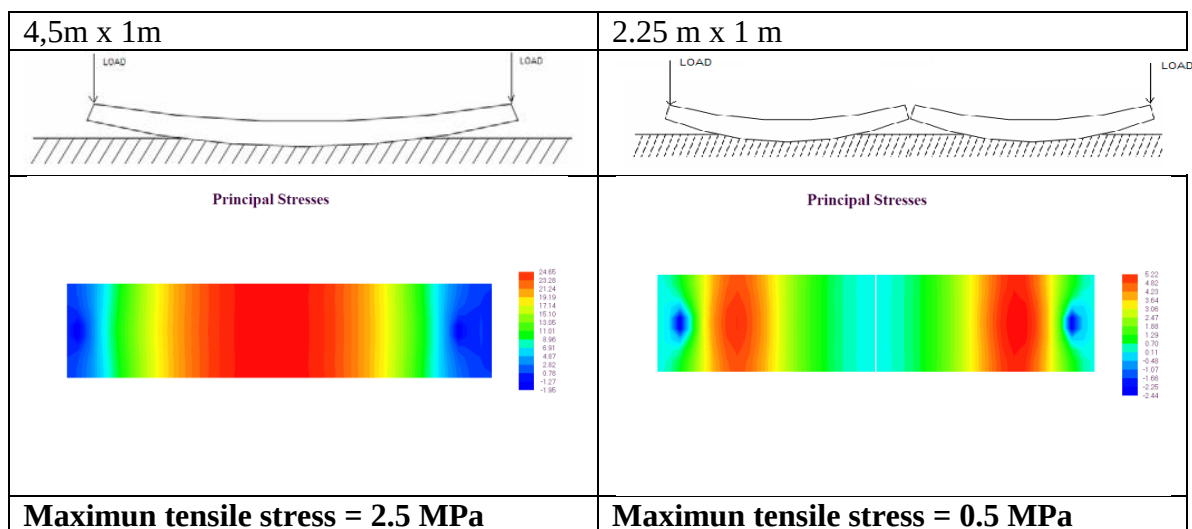


Figure 1. Comparison between long and short slabs loaded by the load configuration.

To reduce the top stress caused by the bending of the slabs when loaded by full trucks, it is necessary to dimension it such that each wheel, or a set of wheels, load a different slab at the same time (Fig 1). As different types of vehicles exist, it is designed for the most harmful, unless the traffic is known in which case it can be designed for the vehicle type that will use the road

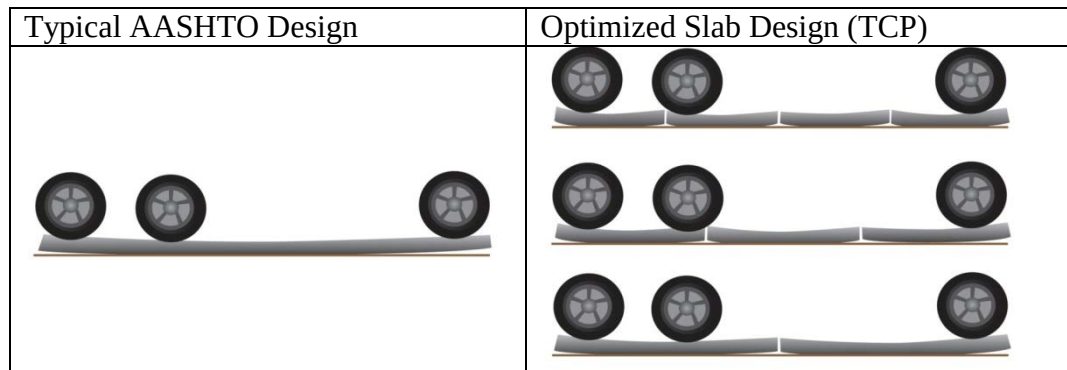


Figure 2. Lateral view of the patron vehicle load with different slab length

Reducing the stresses on the top of the slab allows for a longer service of the pavement, or seen from another point of view, it allows a reduction of the thickness to achieve the same stresses and lifespan obtained in the traditional design.

LOAD CONFIGURATION FOR STRESS ANALYSIS

The objective of developing the design software called OPTIPAVE was to be able to optimize the thickness and slab geometry for any set of climate, materials, and traffic inputs. First, the slab size is selected such that one set of wheels is on each slab, typically between 1,4 m to 2,5 m. The stresses are then calculated, top and bottom of the slab, for different conditions, i.e., curling, thickness, traffic, type of axle, etc., for different load positions as shown in Figure 2.

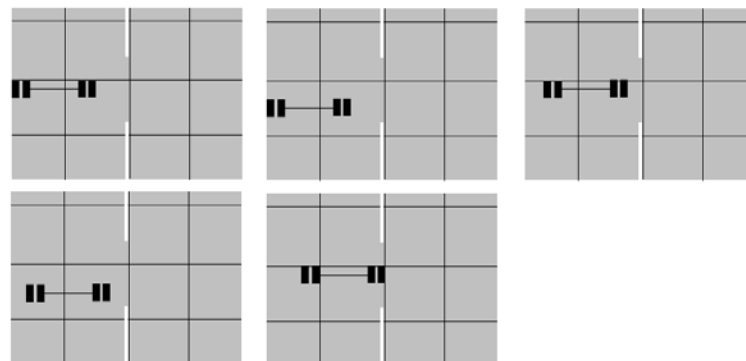


Figure 3: Loading positions considered for critical slab tensile stresses

Based on the maximum stress at each load position, the allowable passes for each condition (N_{ijk}) is calculated based on the MEPDG fatigue equation (ARA 2007)

$$\log(N_{ijkl}) = 2 \times \left(\frac{C_3 \times \sigma_{ijkl}}{MOR \times C_1 \times C_2} \right)^{-1,22} \quad (1)$$

Where

N_{ijkl} = allowable passes for axle k, curling i (as temperature) and load j, top or bottom l
 σ_{ijkl} = principal stresses calculated with ISLAB 2000 for axle k, curling i and load j, and top or bottom l

MOR = Flexural strength of concrete at 90 days

C_1 = Slab geometry and thickness correction factor

C_2 = Structural fiber correction factor

C_3 = Edge loading correction factor

Using Miner's Hypothesis the fatigue damage for every position is determined on the top and bottom of the slab based on the following formula:

$$FD_k = \sum_i \frac{n_{ijk}}{N_{ijk}} \quad (2)$$

Where:

FD= fatigue damage for a given position k

n_{ijk} = Number of real passes for point I, with axle type e for condition i,j,k

N_{ijk} = Number of admissible passes for point I, with axle type e, for condition i,j,k

The percentage of slabs cracked are then determined for 50% reliability for each position, top and bottom based on the MEPDG fatigue damage to cracking model (ARA, 2007)

$$\%Crack_{kl} = \frac{1}{1 + FD_{kl}^{-1,98}} \quad (3)$$

Where:

% Crack= Slabs crack with axle on position

FD_{kl} = fatigue damage with axle on position k, top or bottom l

Research at Illinois Full-scale test sections of this new concrete pavement system were constructed and tested under accelerated pavement loading conditions at the University of Illinois. Three 40 m test sections, 8 cm, 15 cm and 20 cm concrete over a 15 cm over granular base and an old asphalt base, were built to determine the effects of the slab thickness, base stiffness, and concrete mixture on the concrete pavement performance. Only one slab size (1.8m by 1.8m) was constructed. A total of 14 slabs and joints were tested during each loading sequence. There were no dowels or tie bars in any of the test sections and the joints were not sealed. The accelerated testing device used to load the test section, called the ATLAS (Accelerated Transportation Loading Assembly).

Accelerated pavement testing was completed on all sections until significant cracking distresses were present with medium to high severity levels. A summary of the total ESALs applied to each section and number of slabs cracked is shown in Table 1. In most cases, significant overloads were required to fail the concrete pavement sections. The approximate ESALs applied to each section were calculated based on a lateral wander magnification factor (Cervantes and Roesler 2009).

Slab Thickness	Section Location	Base Type	Load Location	Cumulative ESALs	Slabs Cracked (out of 7)	Subgrade k-value (MPa/m)
10 cm	South	Asphalt	Edge	4.4E+07	7	68
10 cm	North	Asphalt	Edge	6.4E+06	7	68
15 cm	South	Asphalt	Edge	3.7E+07	1	136
15 cm	North	Asphalt	Edge	6.9E+07	4	136
15 cm	South	Granular	Edge	2.3E+07	4	81
15 cm	North	Granular	Edge	1.7E+07	6	27
20 cm	South	Granular	Edge	2.0E+07	0	41
20 cm	North	Granular	Edge	5.1E+07	0	27
9 cm Plain	South	Granular	Edge	2.3E+05	7	41
9 cm FRC	South	Granular	Edge	2.3E+05	3	41
9 cm Plain	North	Granular	Long. Joint	4.7E+03	7	14
9 cm FRC	North	Granular	Long. Joint	6.4E+04	4	14

*FRC = fiber reinforced concrete

Plain = plain concrete

Table 1. Summary of Fatigue Data from Accelerated Pavement Tests

IRI AND FAULTING PERFORMANCE:

Serviceability is a very important factor in the design and maintenance of pavements. Existing models to predict IRI don't apply directly to this new concrete pavement design concept. The initial IRI after construction should be similar to a conventional concrete pavement and highly dependent on the contractor's equipment and skill. Furthermore, IRI can be dramatically affected by curling and warping which should be reduced with shorter slab lengths (Table 2).

One of the main concerns with this design is the possibility of faulting for heavily trafficked corridors especially without the use of dowels. Although shorter slabs will deflect more which tends to increase faulting, the design should also reduce the probability of faulting due to the following reasons:

- Higher curling can lead to faulting but optimized slab geometry has about a third of the curling deformations relative to conventional concrete design pavements
- With compacted granular base material with less than 8% fine material, pumping and erosion should be minimal and therefore faulting should be less.
- Since slab sizes are smaller, the contraction joint crack width (below the joint) is also smaller, which should improve load transfer and thus reduce the potential for faulting.

For light and medium traffic, faulting is not expected to be a problem for the aforementioned reasons. When traffic is heavy with many repetitions, a solution with 2.5 meters long slabs and targeted dowels, could be designed if there was a risk of long-term faulting.

Projects with more than 5 years of service have shown no important loss of IRI and no apparent faulting, as normally half of the IRI loss and faulting should be expected in the first 5 years, result are promising. Table 2 shows the IRI and Faulting developments in very heavy traffic in 4 projects built with this technology.

Project	Construction Year	Project Length	Thickness	Joint Spacing	Design ESALS	ESALS Up to Date	Initial IRI	IRI 2010	Faulting
Amtitlan-Palin	2006	7 Km	20 cm	180 cm	110.000.000	22.000.000	1,76 m/Km	2,01 m/Km	< 2 mm
San Cristobal-San Lucas	2006	12 Km	17 cm	180 cm	35.000.000	8.235.294	2,1 m/Km	2,34 m/Km	< 2 mm
San Lucas-Milpas	2007	6 KM	17 cm	180 cm	17.000.000	3.000.000	2,15 m/Km	2,07 m/Km	< 2 mm
Tecpan-Los Encuentros	2009	35 Km	18 cm	180 cm	20.000.000	1.111.111		1,72 m/Km	< 2 mm

* Using high speed profiling

Table 2: Measured performance of 4 projects using the new methodology

To date, there have been more than 2.500.000 square meters built with this technology, primarily in Chile, Peru, and Guatemala. Among the projects are: Highways, roads and low volume pavements, streets, exterior pavements for distribution centers and parking lots as thin as 8 cm over granular materials.

CASE STUDIES ON HEAVY LOADED ROADS:

Rout 60 Ch (Chile) This road connects Los Andes (Chile) and Mendoza (Argentina) and it is the principal route between this two countries. The pavement is a mountain pass through the Andes with an altitude of 2000m - 3500 m. The design is for 20.000.000 ESALs, with a subgrade K-value of 120 MPa/m. A nonfreezing subbase (less than 5% fines below #200 sieve) of 45 cm of crushed stone is used.

The pavement thickness with the AASHTO 93 Design was 22 cm with slabs of 4 m long by 3.5 m. wide, with a concrete flexural strength of 5 MPa, no dowels.

The pavement was opened to traffic after 21 days of constructed with more than 75 % of the concrete strength. The pavement failed in less than a week with the majority of the slabs showing a transverse crack. The opened sector was immediately closed to traffic to analyze the problem.

The contractor calculated the curling of the slabs by measuring the different height between the center and the corners of the slabs. This difference was in average 12 mm. This curling corresponds to an equivalent temperature difference (top - Bottom) of -35°C. Measured temperatures in site, taken at the same time as the profile, showed an actual temperature difference -10°C meaning that the construction curling is equivalent to -25°C

The finite element analysis using all variables measured from site and using a typical 2 axle truck with standard axle loads , shows the following stresses for the different curling equivalent temperature gradients, both construction (built in) and climatic (Variable), were figure 4 represents the stresses that the pavement would have had considering a BIC of - 6°C (MEPDG default value), figure 5 the real stresses the pavement had at that time and figure 6 using TCP size slab of 2 m x 175 m

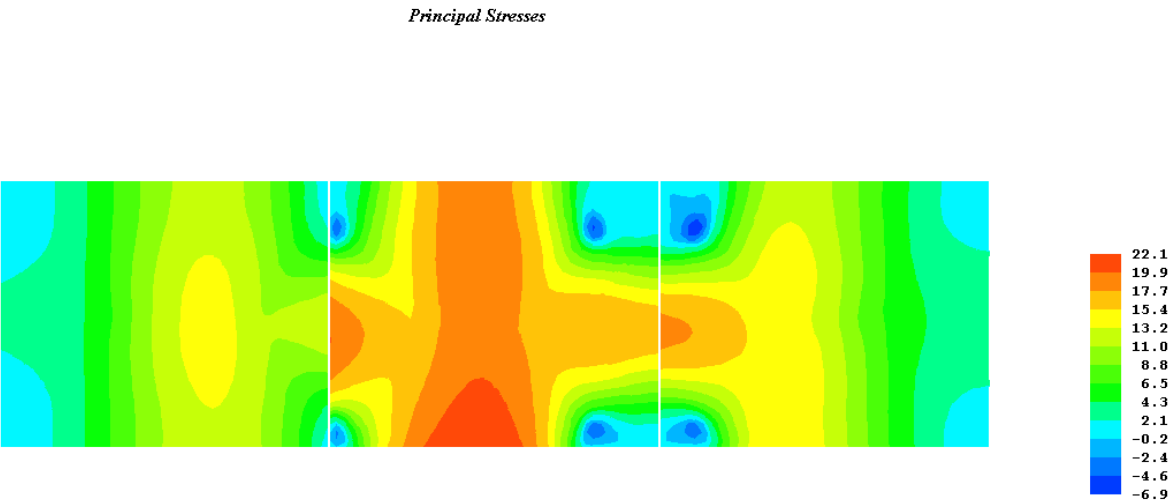


Figure 4. Tensile stress for: -6°+ -10°C curling equivalent temperature (ME-PDG default BIC) Max Top tensile Stress 2.2 MPa

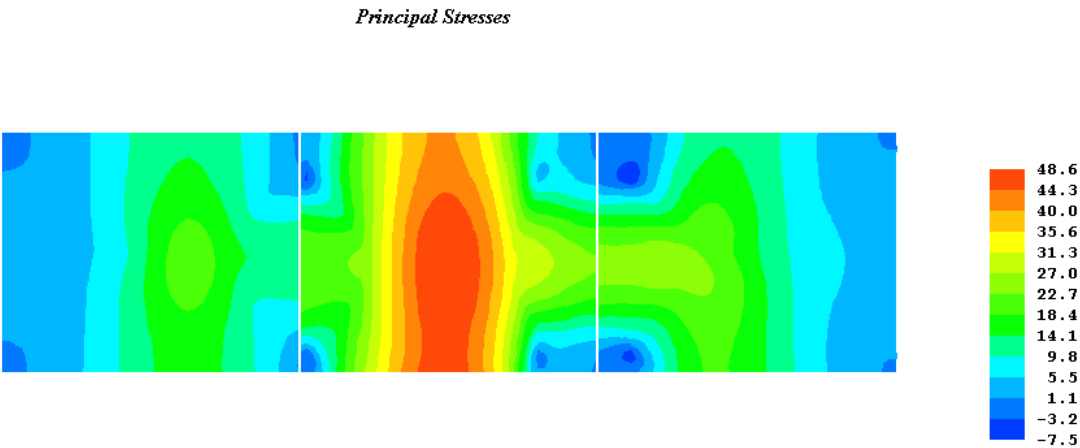


Figure 5. Real Tensile stress for: -25°+ -10°C curling equivalent temperature as measured, Max Top tensile Stress 4.9 MPa

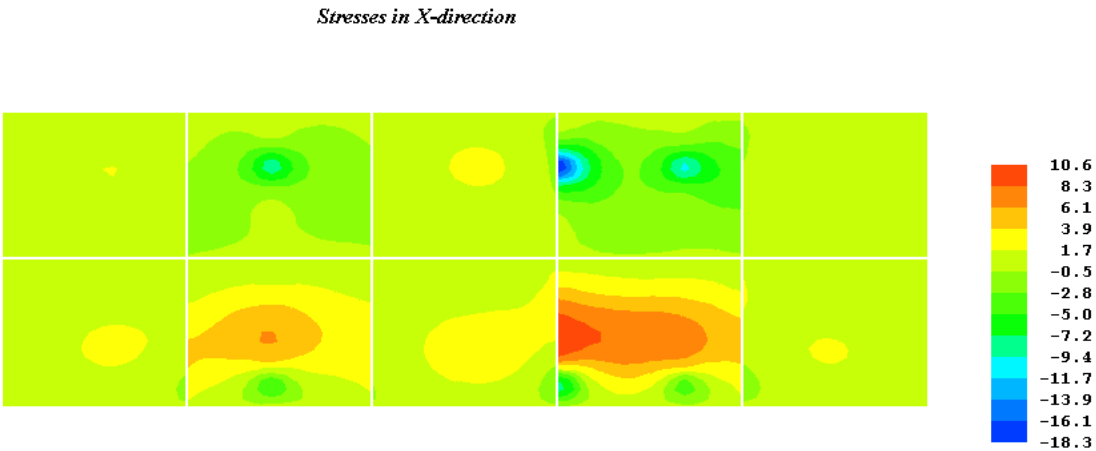


Figure 6. Tensile stress for TCP (slab size 2 x 1.75 cm): -25°+ -10°C curling equivalent temperature, Max. Top tensile stress 1.0 MPa

Using stresses calculated for different conditions, including the ones in figure 4 and 5, in the fatigue equations from ME-PDG, the table 3 was established, showing the maximum top tensile stress calculated on ISLAB 2000 and the number of load applications needed to produce a certain level of distress.

Table 3 illustrates the amount of damage in terms of load application for different slab sizes, curling and slab thickness. This table is intended only to illustrate calculated stresses for a particular condition, to be able to compare damage. It can be seen that number of application for typical AASHTO 93 design of 22 cm as curling is higher is decreased dramatically from 192,028 to 105. This of course is an extreme case but it illustrates the effect of BIC. In Chile experience shows that 3 m slabs improved cracking performance of pavements, in this case admissible load application increase from 105 to 1785 form 4,5 m to 3 m, which can be seen in table 3. The last two examples show the use of TCP technology where there is only one set of wheels per slab, it can be seen that for 22 cm fatigue life is infinite, and the thickness needed for a similar amount of admissible passes from an AASHTO 93 design (22 cm, 4,5m slabs , and -6°C BIC) an equivalent thickness using TCP concept is reduced to 17 cm, 5 cm less.

	<i>Max. top tensile stress</i>	<i>Number of load applicatio ns</i>	<i>Thicknes s</i>	<i>Slab Lengt h</i>	<i>Curling As temp Dif (Top- Bott) °C</i>	<i>Front and rear (Axle Distance</i>	<i>Kc</i>
	<i>MPa</i>	<i>18 kip Axle</i>	<i>cm</i>	<i>cm</i>	<i>°C</i>	<i>cm</i>	<i>MPa /m</i>
AASHTO 93 design, 4,5m slab Default Curling	2.2	192,028	22	450	-6	350	120
4,5 m slab design with real curling	4.9	105	22	450	-35	350	120
AASHTO 93 design 3,0 m slab with real curling	3.3	1785	22	300	-35	350	120
TCP, 22 cm, front wheel at edge of slab	1.3	infinite	22	220	-35	350	120
TCP, 17 cm Tándem at edge of slab	2.3	243,879	17	220	-35	350	120

Table 3. Performance in fatigue of the different designs and curling equivalent temperatures

The following photographs show the performance of the pavement. The left lane is the normal AASHTO 93 design and the right lane is the optimize TCP geometry. The left lane cracks occurred in the first week of traffic and the right lane is 8 months old in the photograph. Both lanes were constructed in the same summer period.



Figure 7. Slabs cracked in less than a week Figure 8. TCP design after 8 months with AASHTO design 4 m long slabs with 2 m long slabs

ME-PDG was used to compare the different scenarios calculated in table 3. For this purpose site information was used and for a climatic station, as there isn't one for Chile the US Palmdale station was used because of similar distance to the equator, elevation and climate. Time was shifted 6 months to take into account changing hemispheres

Table 4 shows different design thicknesses for all cases, showing that for 4,5 m slabs and the curling measured thickness should be increased from 22 to 37 cm and as short slabs are not influenced by curling slab thickness is reduced from 22 cm to 17 cm.

	ME-PDG	ME-PDG	AASHTO 93	TCP
K Value	120 MPa/m			
Climate	<i>Palmdale-California</i>			
BI Curling	- 6°C	-25°C	-----	-20°C*
Concrete slab size(cm)	400x350			200x175
Concrete Thickness	22	37	22	17
Serviceability	10% slabs Cracked	10% slabs Cracked	4.5–2.5 (Pf-Pi)	10% slabs Cracked
* Minimum value in software Optipave				

Table 4. Route 60 section designed with different methods

To verify the design two trial sections of 500 m each were built using the TCP design method (OptiPave) with slabs 2m x 1.75m. The first was a FRC design with a thickness of 15 cm, and the second 17 cm thick plain concrete pavement everything else is the same as the original AASHTO design. This thinner pavements are 2 years old and has no sign of structural distress at all



Figure 9. 15 cm FRC TCP design (2 m x 1.75 slab size) in Route 60 for 20.000.000 ESALs (2 year)

Rout 5 Talca (Chile) This road is the Pan-American Highway that goes north to south in Chile for more than 3000 km, the pavement was built in 1993 and the design is a 22 cm concrete pavement over a 20 cm CTB with slab size 4 m x 3.5 m with skewed joints. The built in curling in this particular area is equivalent to a thermal temperature difference of average -15°C (Poblete 1989). Historically slab cracking is very high. To maintain the pavement, slab replacement has been the main item considered, but result have been variable, with an average of slabs lasting 1 - 2 years before cracking again. Traffic is very high, the design lane is for 50.000.000 ESALS for 15 years. High built in curling and base stiffness is the explanation for this premature cracking

A TCP design was proposed to solve the problem for the heavy lane. The design was the following:

- Remove the existing slab without damaging the CTB
- 6 cm of an asphalt base to complete the 22 cm of the existing slab
- 16 cm thickness, 2 m x 1.75 slab size
- 5,3 MPa flexural strength concrete pavement
- $\text{BIC} = -15^{\circ}\text{C}$
- $E_c = 330.000 \text{ MPa}$
- No Bond (friction) was considered as it was not promoted

The finite element analysis with ISLAB2000, using all variables measured from site and a typical 2 axle truck with standard axle loads. The stress analysis for both geometries and thicknesses can be seen in the figure 10 were the 22 cm slab had a top stress of 29.9 kg/cm^2 and the TCP slab had a top stress of 22.6 kg/cm^2 . This explains the better performance, up to now, of the TCP slabs with 6 cm less of concrete thickness.

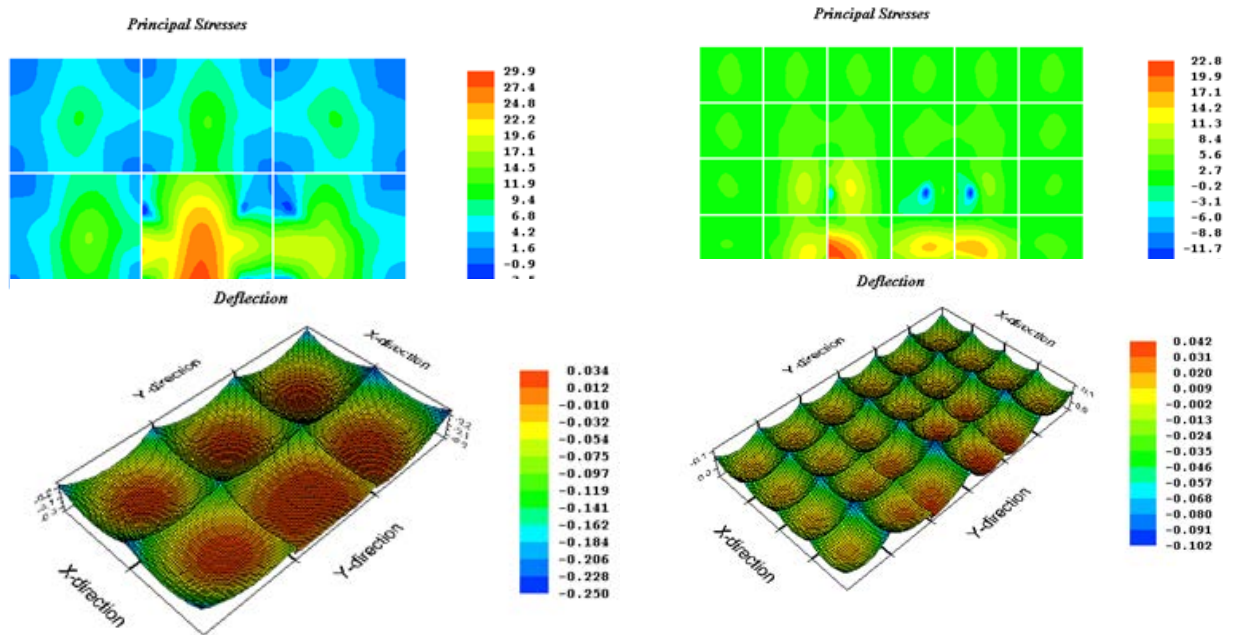


Figure 10. Stresses for 22 cm thick (3.0 MPa), 4 m long slab and TCP designed slab, 16 cm thick 2 m long (2.3 MPa)



Figure 11. Route 5, 16 cm Thick with TCP design for 50.000.000 ESALs (2,5 years)

CONCLUSIONS

A new design concept has been introduced which optimizes the concrete slab dimensions to minimize the required slab thickness. With these short slab sizes, 1.4 m to 2.5 m, top tensile stresses are reduced because only one set of wheels is loading each slab. With this new design concept, thicknesses can be designed as low as 8 cm for low traffic volumes (LVR, parking lots and subdivision roads) over granular materials. Because of the short slabs, curling stresses are also reduced and higher load transfer efficiency is maintained across the joints relative to conventional jointed concrete pavements with 4.5m slab sizes. This allows a reduction in thickness

between 4 and 10 cm compared to concrete pavements designed by the typical AASHTO method, reducing the construction cost in about 20% of the initial cost, with a similar life. When comparing with asphalt solutions, the savings are similar.

Because of the smaller slabs, climate conditions are less important as curling and the effect of it is reduced and load transfer is increased. Therefore performance of pavements with TCP design, especially in extreme conditions is much better than normal 4.5m long slabs

A M-E based software, OptiPave, was designed to be able to calculate short slab pavements with TCP design with slab sizes between 1,4m - 2,2m long and half a lane wide. The software was calibrated by the results obtained in the U. of Illinois, and has predicted the performance of 5 year old constructed pavements, for different traffics and in different climates. The software takes into account soil layers, climates, concrete properties, traffic, construction quality (Built in curl), reliability , and delivers a design thickness, IRI, and faulting. It also has a sensitivity analysis for thickness, traffic, concrete strength and soil stiffness.

In Chile, pavements from 8 cm to 20 cm thick have been built and are all performing as designed for the traffic. In Peru, there are parking lots, bus stations, distribution centers, all of them with an excellent performance, and with an overall cost lower than the original projects In Guatemala, more than 700 km lane of heavy traffic concrete pavements are performing as estimated, with no faulting and a very small increase in IRI after 4 years.

In summary More than two and a half million square meters of concrete pavements with the TCP optimized geometry design, ranging from 8 cm to 20 cm, have been built and are all performing as expected for their design traffic levels.

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