THIN CONCRETE PAVEMENT (TCP): CONCEPT, DESIGN AND ON-SITE EXPERIENCE

Juan Pablo Covarrubias[1]

ABSTRACT

Since 2005, Optimized Geometry Slabs Pavements have been successfully introduced in over 10 million square meters in projects in Chile, Guatemala, Colombia and Peru. This type of pavement called TCP "Thin Concrete Pavements" uses less concrete, as they are thinner than traditional JPCP solutions. 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. To design pavements with this methodology, a mechanistic-based software, "OptiPave", has been developed and calibrated using 12 years of road performance. 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 with traditional asphalt solutions. A variation of this technology especially designed for low volume roads consists on using the TCP optimization process but adding new features to the design. Consisting in a very thin fiber reinforced concrete slabs (80 to 120 mm) placed directly over the existing granular road.

KEY WORDS

THIN CONCRETE PAVEMENTS / OPTIPAVE / HIGHWAYS / MAIN ROADS / INDUSTRIAL

Structurile rutiere rigide cu geometrie optimizată a dalelor au fost introduse cu succes, din anul 2005, pe șantiere însumând peste 10 milioane de metri pătrați, în țări precum Chile, Guatemala, Colombia sau Peru. Acest tip de structură rutieră, denumită TCP (prescurtare pentru "Thin Concrete Pavements"- Structuri rigide subțiri) necesită o cantitate mai redusă de beton, având o grosime redusă față de structurile rigide tradiționale. Principiul de bază al dimensionării îl reprezintă configurarea dimensiunilor dalei în plan orizontal astfel încât cel mult o singură roată (simplă sau dublă) să acționeze asupra oricărei dale din beton la un moment dat, minimizând astfel valoarea efortului la întindere critic. Încercări accelerate de trafic au fost efectuate pe sectoare experimentale realizate la Universitatea din Illinois (SUA), cu grosimi ale dalelor de 8, 15 și 20 cm, având drept strat de bază atât agregate naturale (strat granular cu o grosime de 15 cm și o valoare CBR de 4%) cât și straturi asfaltice.
Programul de calcul pentru dimensionarea acestui tip de structură, denumit "OptiPave", a fost dezvoltat și calibrat pe baza a 12 ani de observații asupra comportării TCP. Această abordare conduce la dimensionarea unor dale a căror grosime este redusă, în medie, cu 7 cm, față de structurile tradiționale, dimensionate cu sistemul AASHTO (1993), pentru aceleași niveluri de trafic, cu grosimi variind între 8 cm și 20 cm. Această

[1] TC Pavements, General Manager

metodă de dimensionare poate fi aplicată pentru orice valori de trafic, atât pentru drumuri locale cât și pentru autostrăzi, oferind o alternativă competitivă din punct de vedere economic cu structurile rutiere flexibile.
O evoluție a acestei metode, destinată drumurilor pietruite, cu trafic redus, o reprezintă aplicarea optimizării TCP cu introducerea unor particularități de calcul. Algoritmul aplicat conduce la realizarea unor structuri rigide cu o grosime a dalelor de 8 până la 12 cm, dalele fiind plasate direct peste împietruirea existentă.

1. INTRODUCTION

The typical slab dimensions for a concrete pavement is 3,5 m wide by 4,5 m long (12 ft wide by 15 ft long) (AASHTO 93) with slab thicknesses ranging from 15 to 35 cm (6 to 14 inches) 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).

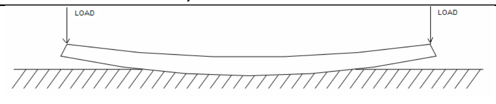
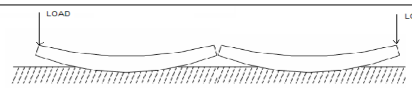
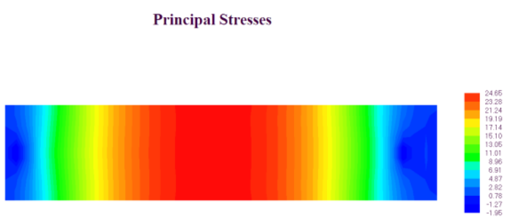
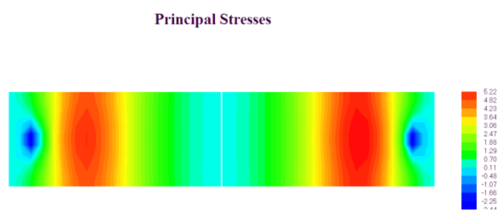
This method proposes a methodology (Covarrubias et al. 2008) to design concrete pavements by optimizing the joint spacing, given the geometry of the trucks. This is done by considering the way trucks load the slab. Designing the slabs sizes such that the trucks never load with more than one set of wheels on any given slab reduces the stresses imposed by them. The reduced slab length and width also reduces curling.

2. STRESSES ON THE CONCRETE SLAB

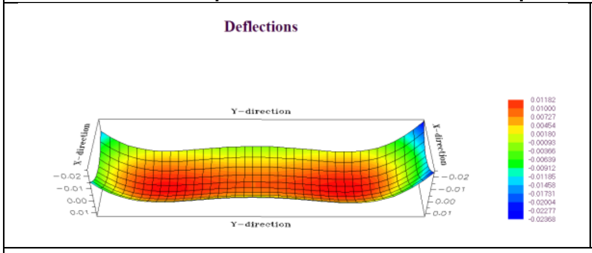
Normally, on 3.5 to 6 meters long slabs (AASHTO 93 recommendation), the front and rear axles apply the load simultaneously at both edges of the slab. This loading induces the traffic surface tensile stresses on the top of the pavement when it is curled upwards, inducing top down cracks. These tensile stresses at the top are due to the moment produced in the cantilever part of the slab.

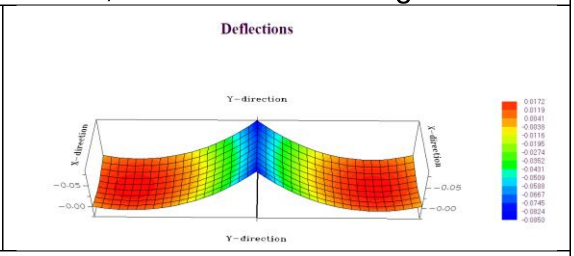
If the slabs are shortened such that the slab length results in neither the front and rear axles simultaneously on the same slab (Covarrubias et al. 2008), the tensile stresses are significantly reduced within the slab. The stresses and deflections calculated in **Eroare! Fără sursă de referință.** were based on a concrete thickness of 20 cm, 1500 kg load, and a -15 ºC temperature differential.

Table 1 - Comparison of stress between long and short slabs

4,5 m x 1 m	2.25 m x 1 m
	
	
Maximun tensile stress = 24.65 Kg/cm2	Maximun tensile stress = 5.22 Kg/cm2

Principal stresses on the top of the slab, Red is tensile strength





Deformation of the slab

Full-scale test sections of this concrete pavement system have been constructed and tested under accelerated pavement loading conditions at Illinois. The design and concrete material factors that have been subjected to repeat loading in this research are the following: concrete thickness of 8, 15, and 20 cm (4, 6 and 8 inches); 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 (8in) concrete slabs on granular base did not experience fatigue cracking up to 51 million ESALs and the measured stresses were low. The 6 inch concrete slabs on granular base began cracking on average at 12 million ESALs. The cracking performance of the 8 cm. (3.5 inch) concrete slabs varied with the stiffness of the soil. In all cases for the 3.5 inch 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.

With the use of short and optimized slab sizes and concomitantly reduced slab thickness, the pavement design concept requires several modifications in order to achieve the intended pavement service life. The following are a list of additional adjustments that are recommended to 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 μm sieve.
3. When is necessary, 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 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 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.

5. OPTIPAVE 2 DESIGN METHOD

OptiPave2® is a design software for JPCP, specially developed for joint spacing between 1.4 and 2.3 meters. This program calculates damage to the pavement, simulating different load levels, and properties of the concrete slab. It was developed from a large number of runs in finite elements, using ISLAB2000®. For greater speed and accuracy in the calculation of stress and deformation of the slab, neural networks were developed and also the concept of equivalent structure were applied in the development of the software.
The program features are:

- Calculates the percentage of cracked slabs in time, according to three failure mechanisms, transverse, longitudinal and corner cracking.
- Calculates mean joint faulting between two slabs, through an energy differential model and also IRI.
- Adds the possibility to design fiber reinforced concrete pavements.
- Allows to evaluate the performance of a certain structure or calculates the minimum thickness that meets a certain maximum damage threshold.
- It is multi-language and works on both unit systems

5.1 Cracking Model

The cracking model is based on the sum of fatigue damage (FD), through the following relationship:

$$CRK = \frac{1}{1 + a \cdot FD^{\mathrm{b}}}$$

a,b Calibration Factors.

The sum of fatigue damage is obtained by the ratio between the numbers of actual passes at certain load divided by the number of eligible passes:

$$FD = \sum \frac{n_{i,j,k,l}}{N_{i,j,k,l}}$$

Where:

FD:= Total Fatigue Damage
ni,j,k,l ,:=Number of applied loads at condition i,j,k,l,m,n
Ni,j,k,l, := Number of allowable loads at condition i,j,k,l,m,n
i:= Type of Axle
j:= Load Level
k:= Temperature Differential
l:= Load Position

Whereas the number of allowable load repetitions for each condition is obtained by the equation below:

$$\log\left(N_{i,j,k,l}\right) = 2 \cdot \left(\frac{\sigma_{i,j,k,l}}{MOR \cdot C_1 \cdot C_2}\right)^{-1,22}$$

σi,j,k,l := Applied Stress at condition i,j,k,l
MOR: Flexural Strength of Concrete

C_1:= Constant due to fracture type
C_2:= Constant of fiber reinforced Concrete

6. STRUCTURAL FIBER IN CONCRETE

Concrete is a material with high compressive strength but low tensile strength, therefore, the addition of different types of fibers (steel, glass, polypropylene, etc.) improves the concrete into a more ductile and cracking controlled material. For structural purposes, the addition of fibers is intended to increase fracture energy, this will also increase fatigue therefore the lifespan of the pavement.

The property that is intended to change in pavements is the fatigue capacity of the slabs under cyclic loading, for the 2 parameters are measured, MOR, and residual strength on a beam, with a 3mm crack opening.

7. FEATURED PROJECTS

To date, there have been more than 12.000.000 square meters built with this technology primarily in Chile, Peru, Guatemala, Colombia, EEUU and Australia. Among project are: Highways, roads and low volume pavements, streets, exterior pavements for distribution centers and parking lots as thin as 8 cm over granular materials.

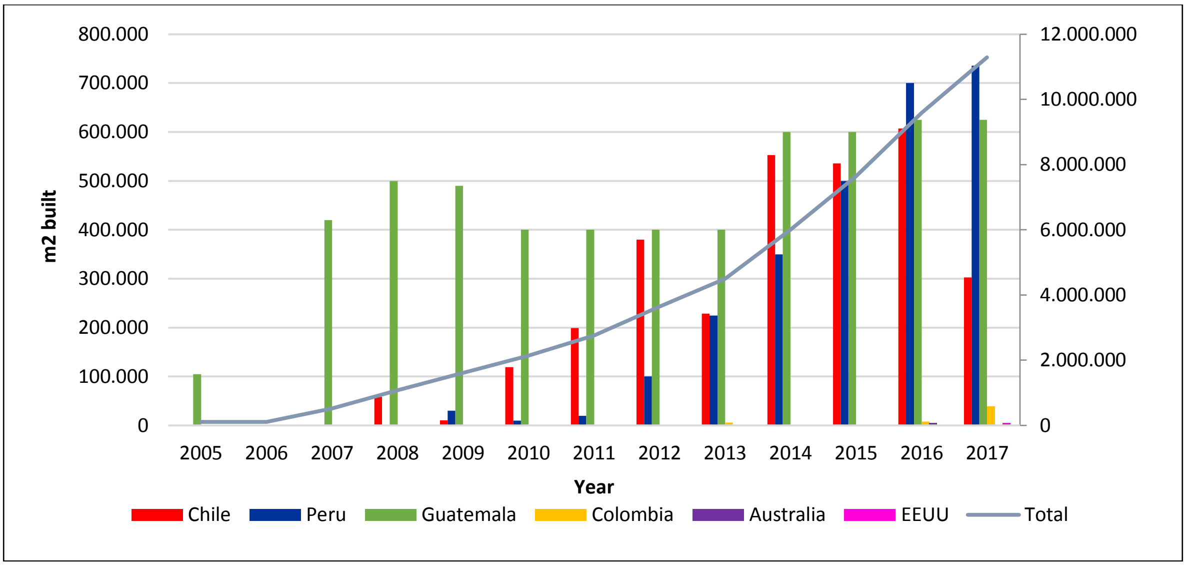


Figure 1 - Paved area with TCP

7.1 Road to Antigua (highway)

In Guatemala, Camino a Antigua is a 17 cm thick concrete pavement 12-year-old with optimized slab design. This pavement was constructed over granular base or over the old asphalt pavement used as a base. The design was for 60.000.000 ESALS with an equivalent K value of 110 MPa/m (asphalt base in bad Condition and granular material) and for 20 year.

7.2 Cerro Castillo (highway)

This pavement was the first TCP-project built by the Public Works Ministry. It is located in the southern part of Chile, where the climate is dry and freezing. The pavement was built in 2009 for 600,000 ESAL. The original project was a 18 cm concrete pavement with 3,5 m square slabs, but it was replaced with a 12 cm concrete pavement with optimized slabs. Nowadays, the pavement is working as designed, without problems. The image shows the pavement 7 years after it was built.

Figure 3 - Surface and joint performance Cerro Castillo

7.3 Camino La Pólvora (highway)

This project was paved in 2016 in 23 centimeters of fiber-reinforced concrete over the deteriorated asphalt pavement, owes its importance to the route that allows the access of heavy traffic to an important port in Chile. The section paved in concrete with optimized slabs, corresponds to a replacement of 15 km, which is currently the pavement with the highest traffic demand that has been built with this technology. It was designed for 189,000,000 ESAL in 20 years. The original solution in concrete meant a thickness of more than 30 cm in traditional slabs designed by AASHTO.

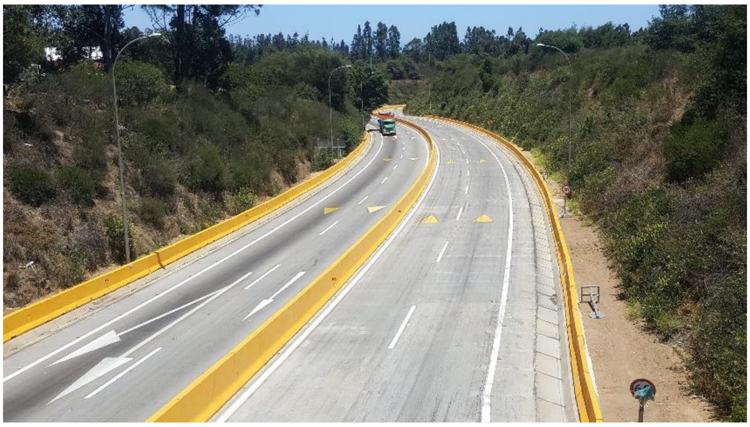


Figure 4 - Camino La Pólvora

7.4 Walmart Distribution Center (industrial)

This project is located in Santiago de Chile. It was built on 2011 with different designs according to traffic with thicknesses that go from 9 to 17 cm. The main area corresponds to the truck maneuver yard, where the pavement has 15 cm thick for 10,000,000 ESALS in 20 years. Nowadays, the pavement is working as designed, only with some problems that occurred during its construction but that do not mean structural problems.

Figure 5 - Walmart Distribution Center

8. ULTRA-THIN CONCRETE PAVEMENTS (U-TCP)

Ultra-Thin Concrete Pavements (U-TCP) are an extension of the technology. These pavements, besides being composed by short slabs, incorporate structural fiber in the concrete. This kind of pavements is placed directly over the terrain in concrete thicknesses between 8 to 12 cm, without sub-base, on roads where the subgrade is in a high level of compaction due to the traffic of cars, trucks and machinery.

To design this type of solution with software OptiPave2®, five separate tests of pavements sections were conducted on different places. The thicknesses of concrete pavements tested were between 6 and 12 cm. With the results of these tests, different conclusions were obtained about the behavior of this type of pavements, which were compared with the theoretical results delivered by the design program OptiPave2®, thus allowing the program to calibrate this type of solution.

8.1 U-TCP featured Projects

The U-TCP system has been used by private companies and by the public works ministry in the paving of low volume roads in different parts of Chile. To date there are 7 projects built with this extension that have been used for software adjustments, excluding calibration tests.

Mahuidanche Misión Inglesa

In 2012 a low volume road project using U-TCP was constructed. This pavement has a trapezoidal section of 90 mm in the center of the section and 110 mm on the edge. The concrete used was 40 MPa with fiber, a residual strength of 1 MPa, according to ASTM 1609-07. The existing road, was granular material of at least 40 cm thick. Beyond the pavement, the subgrade was estimated of average 15% CBR. Two years after it was built, no fatigue cracking, settlement or lateral displacement is observed.

Figure 6 - Contract Before and After paving

Road X-730 Access to Bahía Murta Village

This 4,4 km. section was built in 2016 and is located in a remote area at the south of Chile, with rainy and freezing weather. The pavement is 10 cm thick placed directly over the existing granular platform, without subbase. The concrete has a compressive strength of 35 MPa with 40 mm maximum aggregate size and 2,5 Kg of macro-synthetic fiber. The cost of this project was about 40% lower than the maximum allowable cost. A technical visit after the first winter showed no pavement problems of any kind, except for details originated during the construction.

Figure 7 - Road X-730 Access to Bahía Murta Village

9. CONCLUSIONS

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.

A mechanical-empirical design software (OptiPave2), that has been tested to be calibrated for very this thin concrete thicknesses, of up to 60 mm, which makes it an accurate, and adequate method for design.

The U-TCP new design approach for low volume roads is an alternative to basic asphalt solutions, with a better performance at no higher construction cost. This is confirmed in all the low volume roads constructed with this technology, in different, subgrades, climates and traffic conditions.

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