“TCP Design” for Thin Concrete Pavement

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Abstract

Measurements made in Chile, in different climates (dry, wet, hot and cold) reveal that slabs are always curled with the borders in the air and never warped (Larrain, 1986). This curling is mostly influenced by thermal and hydraulic gradients during construction. This type of curling can be so large that positive gradients given by daily and season cycle of temperature and humidity gradients will most of the time not be enough to warp (edges downwards) the slab, so warping will only occur on some condition and in very short period of time during the day (Larraín 1986). Because of this, the maximum tensile stresses are on the top of the slab and are produced by the loads of the truck flattening the slab. The sum of all the stresses is the cause of fatigue life and affects the performance of the pavement (Jane Jang, Shiraz Tayabji 1998)

Introduction

TCPavements is proposing a new methodology to design concrete pavements 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, this reduces the stresses imposed by them. The reduced slab length also reduces curling.

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 TCP design method, , can reduce the thickness by up to than 10 cm (4 inches) for the same stresses within the slab as for 4,5 m long slabs, therefore the same performance.

A summary on how concrete slabs deform, a discussion on the cause of the stresses and an analysis made with finite elements with ISLAB2000 for new TCP design system of concrete pavements are presented in the paper.

As a conclusion, it can be said: TCP design has lower stresses for a given thickness allowing higher axle loads or slabs can be thinner for a given stress with actual axle loads.

Development

A) ***Effect of the Rigidity of the Base.***-The pavement slabs are supported by the base. When the slab curls with the edges upward, if the base is stiff, the slab will not sink in it and the central area of support will be small and the cantilever long (Figs. 1). With the loads at the edges, this will produce high tensile stresses on the surface of the slab and top down cracks. If the base has the appropriate stiffness, the slab will sink on it leaving a shorter cantilever and lower stresses with the same loading. For this case, the ideal support rigidity is with a stiffness between k value of 8 kg/cm^3 to 14 kg/cm^3 (Fig 2)

If the base is too soft with the load at the center, tensile stresses at the bottom of the slab and bottom up cracks will be produced. This is explained because the slab will be wholly supported and the stresses will be induced by the deformation of the slab over a deformable support (Fig 2). This same effect is induced if the slabs are curled downward. This is the original thought on calculating the stresses with the design methods, before the curling up phenomena was acknowledged

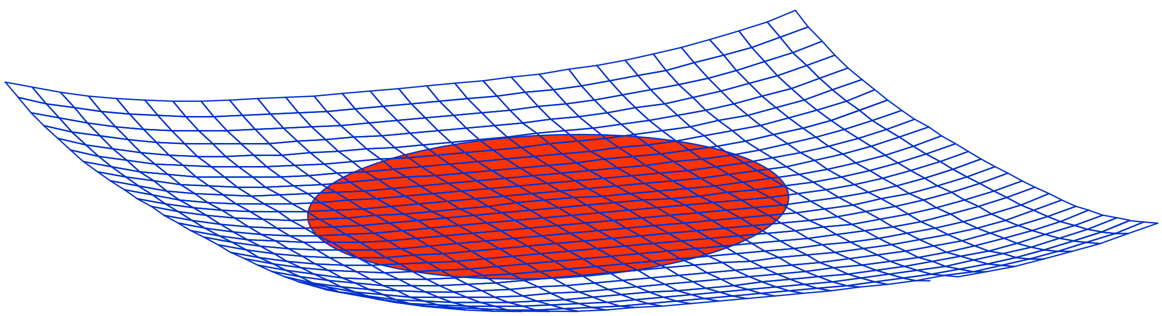

Fig. 1 .-Measured curling on an industrial floor slab 150 mm thick, 4 meters long. The slab is supported on the central circle, the edges are in cantilever. The corners are four times more deformed than the center of the edges.

B) ***Construction curling:*** The construction curling is produced by a force on the surface of the slab. This force is due to drying and thermal differential shrinkage on the surface of the concrete. Being at the surface and not at the neutral axis of the slab, produces the curling. The magnitude of this force is dependent on the length of the surface, therefore is smaller on shorter slabs, which means that shorter slabs have reduced curling.

Also, if the slab curls upward leaving a cantilever of a given fraction of its length, then a shorter slab will have a shorter cantilever (Fig 2). These two effects mean that shorter slabs will have reduced curling and shorter cantilevers, it will so, reduced tensile stresses on the top than longer slabs.

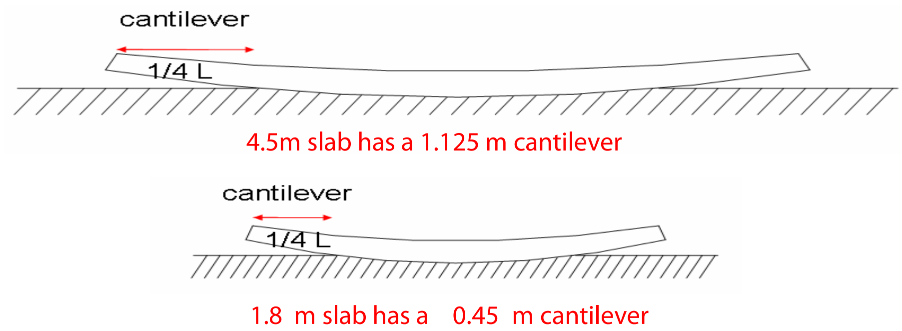

Fig 2.- Shorter slabs have shorter cantilevers than longer slabs, and therefore smaller tensile stresses on the top(Covarrubias, 2006).

The drying shrinkage curling is due to the moisture difference between the top and the bottom of the slab. The slab is always wet at the bottom, as the humidity of the soil condenses under the pavement, and it is most of the time dry on the surface. The residual upward curling for the slab with zero temperature gradient was measured in Chile on real pavements, and was equivalent to a total temperature diference of -17.5 °C. The maximum positive total temperature difference measured at midday, when the slab is hottest at the surface, was 19 °C. This means that the slab got flat on the ground just for a short period of the day (HDM4 1997). In most of the time presented an upward curling, being maximum at night, when the built in and the negative temperature gradient, with the top colder, are added.

The main thermal shrinkage is produced during construction. When the concrete is placed during the day, the concrete on the surface of the slab will be hotter and will harden with a longer surface because of its higher temperature than the bottom surface. It will also harden first. When the temperature comes down to normal working temperature, the top of the slab will reduce its length more than the bottom part, and induce a superficial force that produces the upward curling.

These forces induced by drying and temperature shrinkage of the surface are dependent on the slab length. For longer slabs, the curling force will be larger, and so the curling and the cantilever (Table 3).

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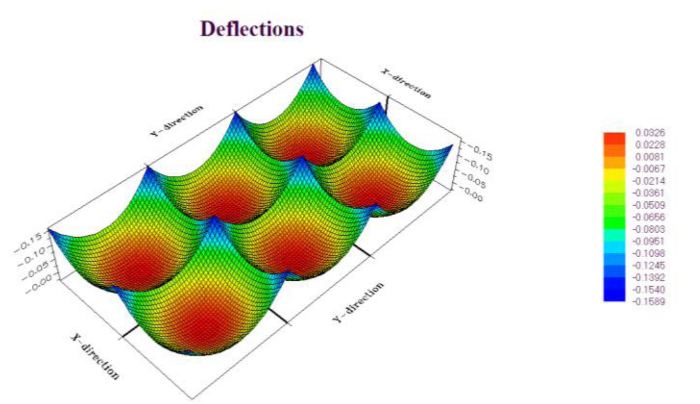
<td>
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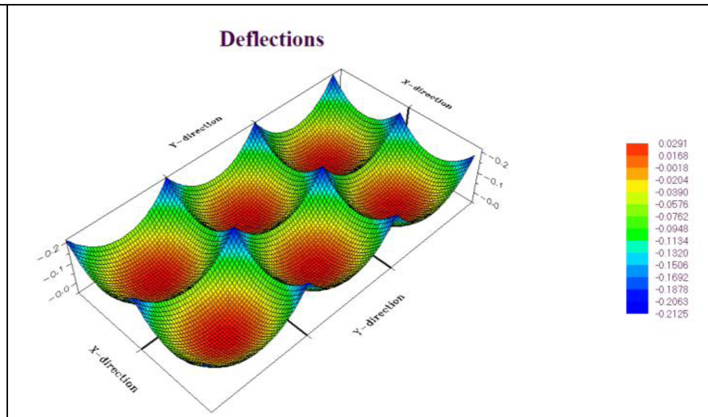
<td>
</td>
</tr>
<tr>
<td>450 cm x350 cm
Thickness= 25 cm
Delta T°=-14 C° Linear
Curling= 0,1915
Top Tensile stress= 9,24 kg/cm2</td>
<td>450 cm x350 cm
Thickness= 18 cm
Delta T°=-14 C° Linear
Curling = 0, 2416 cm
Top Tensile stress= 14,02 kg/cm2</td>
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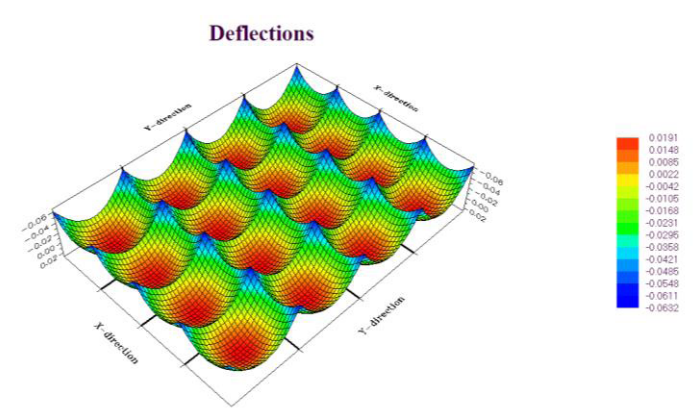
<td>
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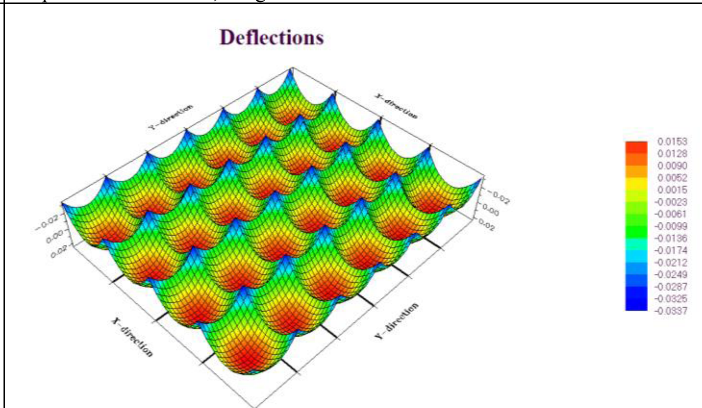
<td>
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<tr>
<td>240 cm x175 cm
Thickness= 18 cm
Delta T°=-14 C° Linear
Curling = 0,0824cm
Top Tensile stress= 3,66 kg/cm2</td>
<td>140 cm x175 cm
Thickness= 18 cm
Delta T°=-14 C° Linear
Curling = 0,049 cm
Top Tensile stress= 1,83 kg/cm2</td>
</tr>
</table>

Table 3: Curling and stresses for a equivalent temperature gradient, comparison between slabs of different lengths an thicknesses

C) Stresses on Slabs: Normally, on 3.5 to 6 meters long slabs * (AASHTO, 1993), 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 short, of a length where the front and rear axles will never load the edges simultaneously (Table 4), the configuration of the loading and the rocking of the slabs change the stresses configuration within the slab. Only one set of wheels will move over the slab and the slab will rock in a way that the load will always be touching the ground, therefore well supported. In this case the slab will have no stresses produced by the cantilever and the loading. In rocking, the slab will be lifted and the weight of the slab will induce tensile stresses at the surface (Table 5). The main loading for top tensile stresses will depend on the geometry of the slab and not on the traffic loading.

The following is a finite element analysis of the principal described above:

- Thickness: 20 cm of concrete
- Loads 1500 kg on each side

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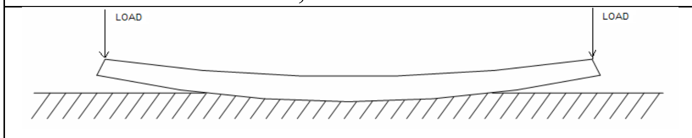
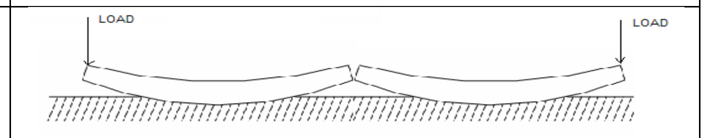
<tr><td>
</td><td>
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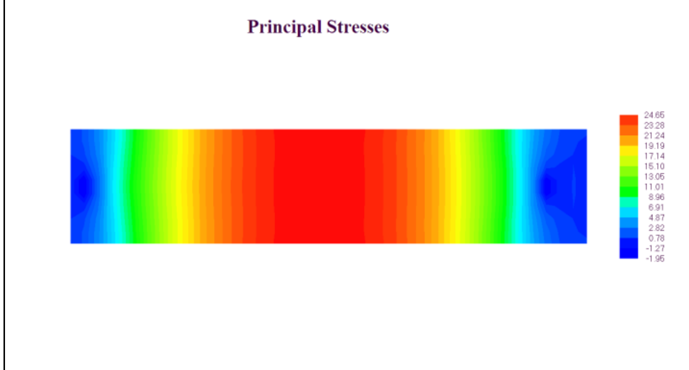
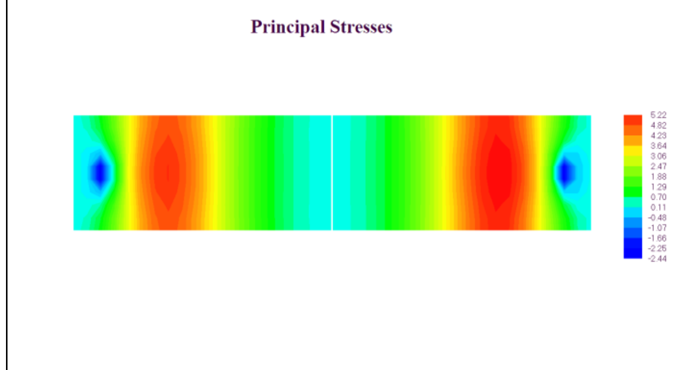
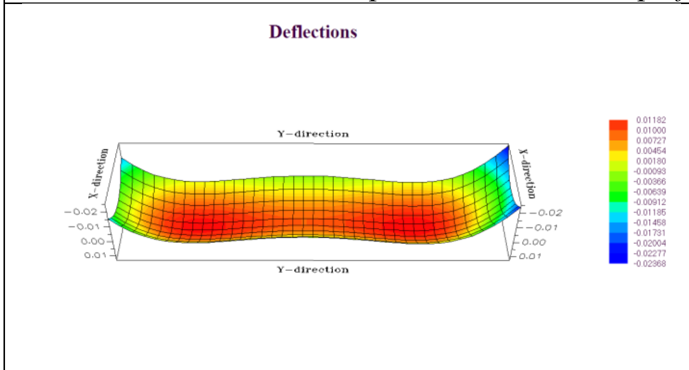
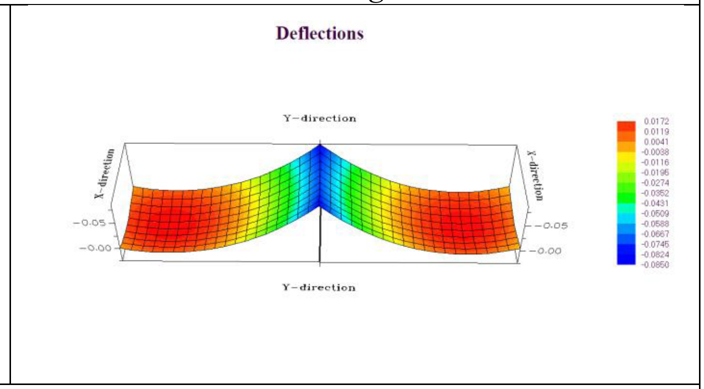
<tr><td>
</td><td>
</td></tr>
<tr><td>Maximun tensile stress = 24.65 Kg/cm2</td><td>Maximun tensile stress = 5.22 Kg/cm2</td></tr>
<tr><td colspan="2">Principal stresses on the top of the slab, Red is tensile strength</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">Deformation of the slab</td></tr>
</table>

Table 4: Compararison between long and short slabs loaded by the same truck.

TCP Design Procedure:

A) Introduction: The concept behind the "TCP" design is that each slab of the pavement is loaded by only one wheel or a set of wheels at the same time. This significantly reduces the top tensile stresses of the slabs. With this configuration of loads versus the dimensions of the slab the cantilever effect is reduced, so each slab supports the loads under the wheels, supported on the ground.

B) Theory: To achieve this condition, it is necessary to dimension the slabs in such a way that with a given truck; each wheel, or a set of wheels, load a different slab at the same time (Fig 5). As different types of vehicles exist, it is designed for the most harmful, unless the traffic is known and it is designed for the vehicle type that will use the road

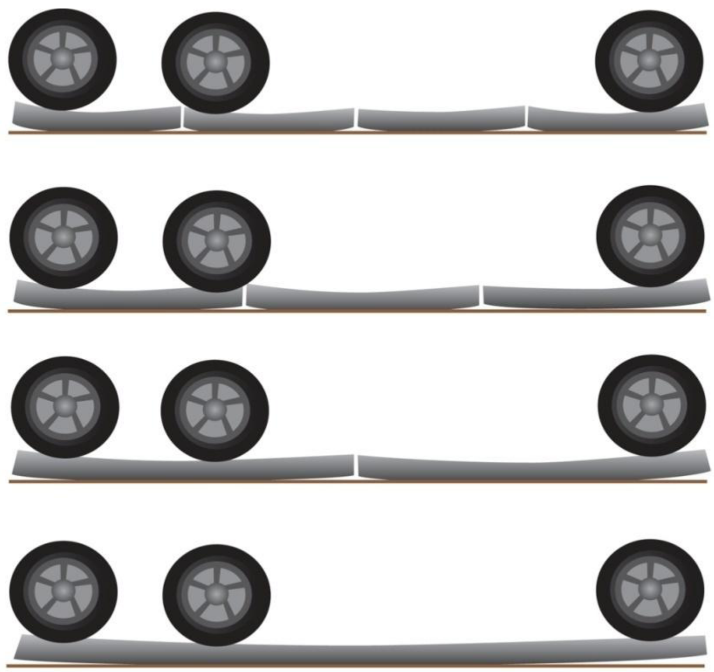


Fig5:- Lateral view of the patron vehicle load

Reducing the stresses on the top of the slab allows for a longer lifespan 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. It is in the last case where the stresses generated by the loads are smaller, so the pavements can be designed with thinner concrete slabs.

The previous outline can be represented by the following graph (Table 6) of stresses in the top of the slab, for different geometric configurations of the loads respect to their dimensions. Using ISLAB 2000, we can model different configurations of loads versus sizes and geometries of slabs. Every other variable (Soil, LTE, Temperature Gradients, etc) are the same.

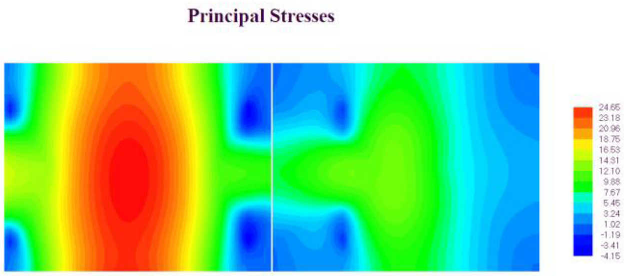
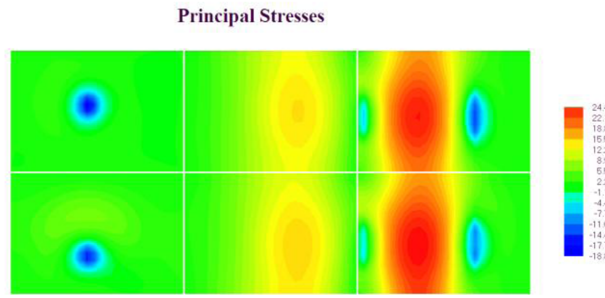
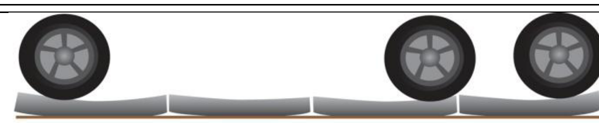
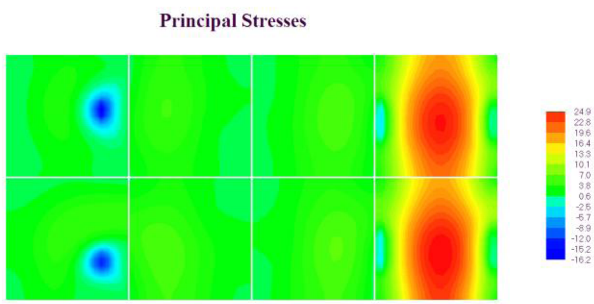
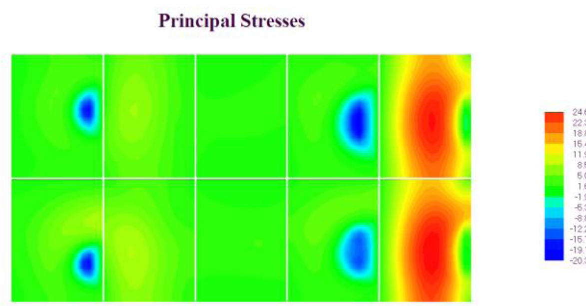
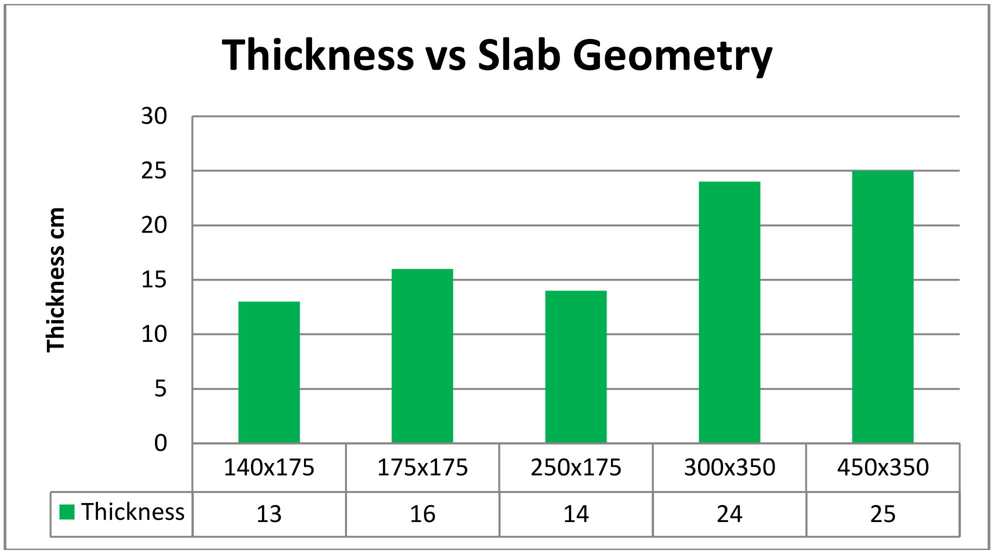
	
 	
Thickness: 25 cm Concrete Slabs 4,5m x 3,6m Top Stress = 24.65 kg/cm2	Thickness: 14 cm Concrete Slabs 2.5m x 1.8 m Top Stress = 24.4 kg/cm2
	
 	
Thickness: 16 cm Concrete Slabs 1.8m x 1.8 m Top Stress = 24.9 kg/cm2	Thickness: 13 cm Concrete Slabs 1.4m x 1.8 m Top Stress = 24.6 kg/cm2

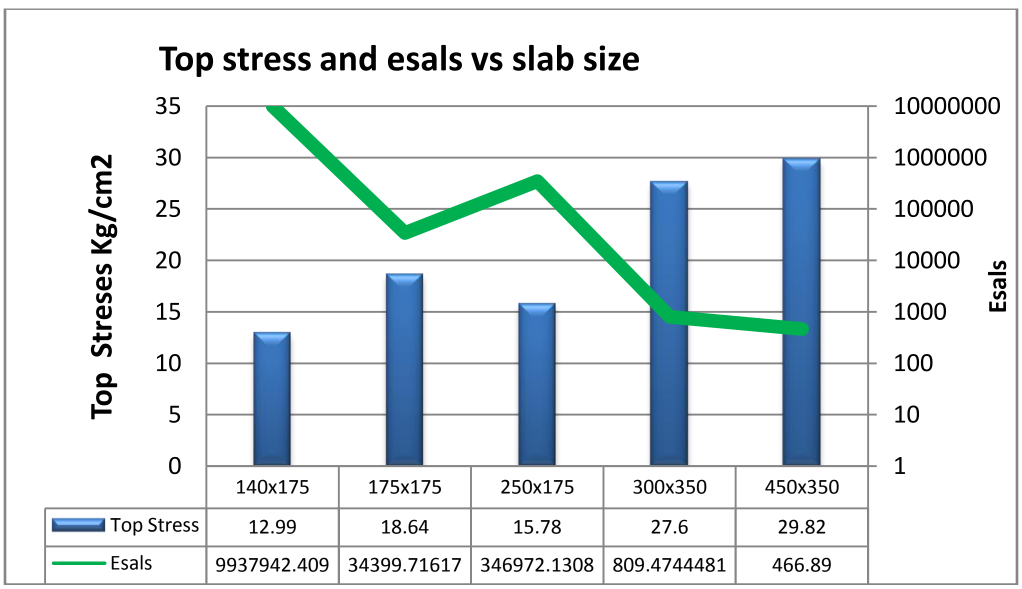
Table 6:- Comparison between slab sizes optimized with the load geometry and the thickness needed to achieve the same tensile stresses

In the previous table is shown that stresses are similar on the top of the pavement, although the thickness diminishes considerably. (Graph 7)



Graph 7: Equivalent Thickness for the same performance (Equal top tensile stresses in all cases) for different slab

Another way of analyzing the phenomenon is to maintain the thickness and simulate the stresses on the top of the slab (Graph 8). Also in the graph one can see the amount of Esals each geometry can withstand.



Graph 8: Top stresses and equivalent Esals for different slab geometry given a patron truck.

As shown on the graphs 7 and 8, the design of the geometry of the slab is very important in the performance of the pavement, it is also shown that there are optimum solution so is it not a random selection of a certain joint spacing. The interaction of the load geometry and the size of the slab is a very important issue and it has to be considered in the design. One can also see that shorter slabs don't always perform better.

C) Soil Support Model Another important aspect in TCP design is the stiffness of the soil layers model. It has always been considered that the concrete slabs are sufficiently rigid to support the loads of the vehicles. In the case of a thick slab (Over 15 cm thick) the base should be soft to support the slab with a bigger area (k value of 8 kg/cm3 to 14 kg/cm3). As the slab is in this condition the cantilevers are smaller and the tensile stresses on top are reduced.

When using TCP design, the cantilevers are reduced, because the design optimizes the size of the slab so this happens, the product is a thinner slabs in which the main tensile stresses, are on the bottom of the slab just under the wheel, and a stiff base will reduce them by collaborating with the slab to support the loads. It could be considered as semi-rigid pavements (fig 9).

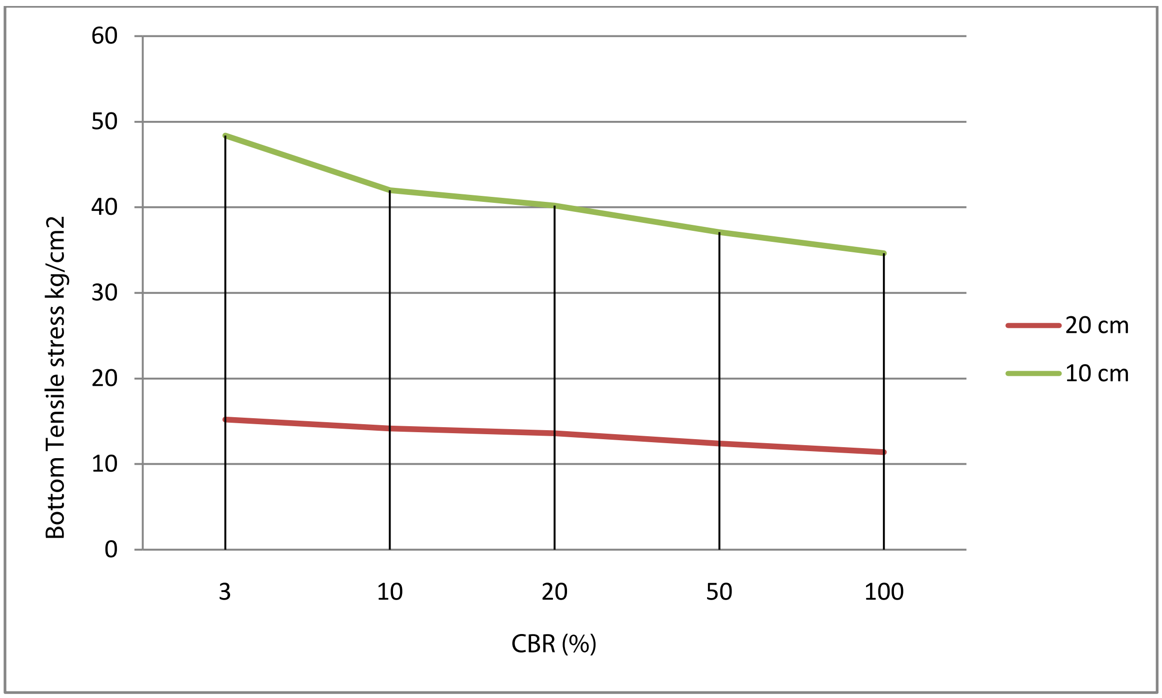


Fig 9: Comparison en the effect on bottom stresses for 20 cm and 10cm thick slabs

Graph 10 shows the difference between 10 cm and 20 cm thick slabs. ISLAB2000 runs show slabs thinner than 15 cm, require a stiffer base to collaborate with the loads under the wheels that produce bottom tensile stresses. It is for this reason that for these thicknesses, the base should have enough rigidity to take these loads (CBR > 80%)

D) *Design procedure*

1. Design de dimensions of the slab so that only one set of wheels load any given slab a time.
2. Calculate the stresses generated (top and Bottom) in the concrete for different conditions (Curling, Thickness, traffic, type of axle, etc)in different control points on the slab.
3. Calculate the amount of admissible passes given the stresses for every given condition. The methodology uses the fatige model: Corps of Engineers y ERES Consultants, Inc. (ERES/COE). Used by M-EPDG (NCHRP, 2007)

$$\log (N) = 2 \cdot SR^{-1.22}$$

   Where:

   - N = Number of passes
   - SR= (Stress on any given control point) / (C x MOR)
   - C = Calibration Constant

4. Addition of the fatigue damage in all the control points (Miner's Law)
5. Calculation of % crack slabs

$$\%CRACK = 1 / (FD^{(-1.98)})$$

6. Optimum is calculated by iteration.

E) New technology: The TCP design requires a great amount of saw cuts in the pavement, because of this, it is necessary to use new technologies in its construction and maintenance. Within these technologies are:

1. 2mm wide joints using thin saw blades to prevent spalling by uncompressibles in the joint. These blades have been used in Chile from the year 2003.
2. Granular Base with less than 6% fine below sieve #200: Due to the quantity of unsealed cuts, it is necessary to have a base whose structure is not affected by water. When the granular base material has less than 6% fines, the particles of bigger size are in touch with each other, so when the fines are washed out, volumetric change of the base doesn't exist and since it is confined, there is no loss of support. Also there is not enough fines to lift the slab by pumping.
3. Impermeable or geotextile layer between Base and natural Soil: Natural soils usually contain fines, because of this, it is fundamental to isolate the base from the natural soil, to avoid transportation of fines to the base.
4. Lateral Bars for confinement: The TCP design is considering, as part of the design, the rocking of the slabs as the loads move over it. If the movement is restricted, the tensile stresses are increased, reducing the life of the pavement. The amount of saw cuts made, also make very difficult and expensive the use of dowel and tie bars. To solve this problem, the pavement is confined on the exterior preventing the lateral displacement of the slabs. This confinement consists on the placement of steel bars (16 mm) 50 cm long buried vertically in both external sides of the pavement.

F) Serviceability (IRI) and Faulting: Serviceability is a very important factor in pavements. Existing models to predict IRI don't apply directly to TCP Pavements, as they need calibration for this new condition.

In terms of construction, the IRI achieved should be similar to that of a normal pavement depending on the contractor's equipment and skill.

Also as curling and warping are smaller in terms of absolute height difference, the pavements stays flatter even with high moisture and temperature gradients, this should produce a smother surface and a better IRI

One of the main issues concerning the TCP Design is the possibility of faulting in long term periods. It could be an issue, but the design itself reduces drastically the probabilities of this happening as follows:

- Curling of the slabs produces faulting. TCP Pavement have about a fifth of the curling as normal Aashto design pavements (Table 5). This, because of the smaller slab size. As the curling is smaller faulting should be less.

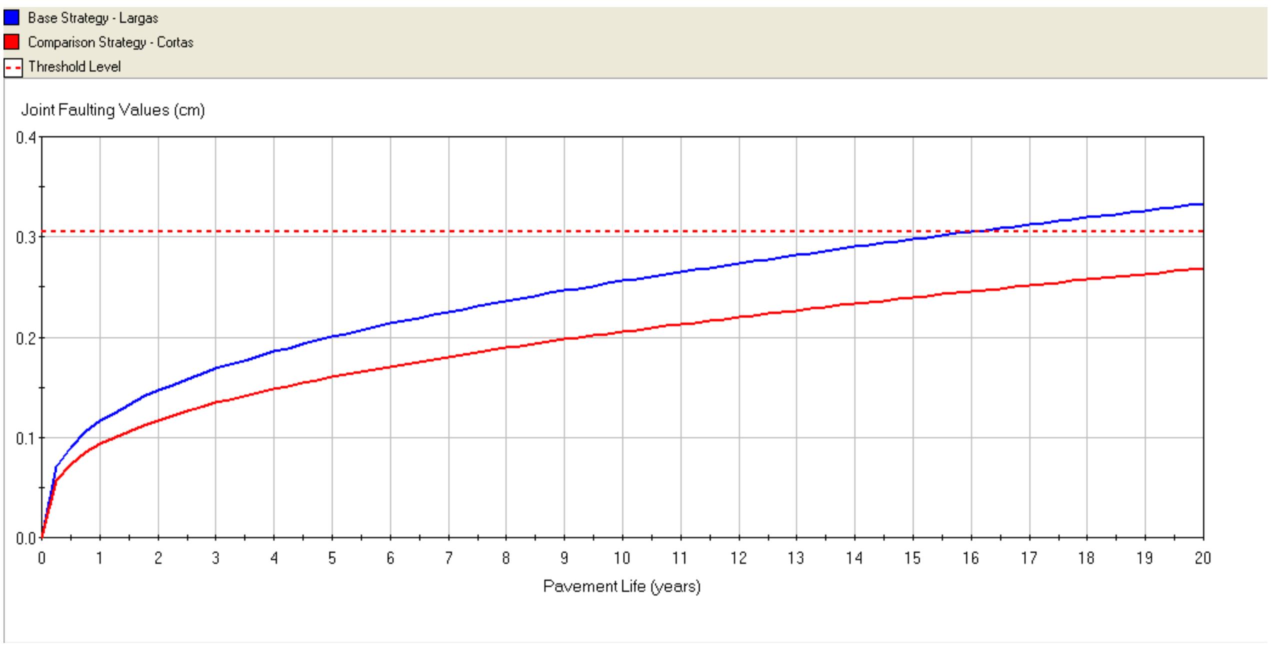


Figure 10 : Comparison using Hyperpave II Predicting Faulting Between 22 cm thick slab 4.5 m x3.5 m slab (Blue, Upper Line) and 17 cm 1.8m x 1.8m(red, Bottom line) Granular base and no dowels.

- TCP Pavements use a 6% or less fine in the base material, so stones within the base are touching each other (lack of fines between them). If water gets in and removes the fines, the structure of the base is unaltered because of this. So pumping will not produce a change in the structure of the base. Because of this, there is a considerable less amount of erosion of the base thus les faulting.
- As TCP slabs are smaller, crack width is smaller, improving load transfer. This will also help reduce faulting.

There isn't any long term experience respecting faulting of his type of pavements. As discussed before, the probability this happening is very small, since the conditions are favorable.

In Guatemala there are 17 cm thick roads 2.5 years old with TCP design, over granular base with 7.000.000 ESALS and don't show any sign of faulting, IRI has not changed after construction.

The TCP Pavements have a design such that the faulting is minimized. For Low to heavy traffic, it shouldn't be a problem. For Very heavy traffic a solution with 2.5 meters long slabs and over 18 cm thickness, could be designed with dowels to reduce the chance of faulting in the long term period.

The Faulting issue is being studied and measured in existing pavements in different projects and locations.

Other Considerations

With short slabs and half a lane wide, the design concepts change. With this geometry the stresses are mainly due to the own weight of the slab and the stresses under the wheel. .

To check the behavior of the TCP design, more than 100.000 runs with ISLAB 2000 have been executed, obtaining solutions optimized for most of the combinations of the design variables. Due to the quantity of information obtained, design software is being developed to facilitate the use of this technology. Parallel to this, a study is being carried out at the University of Illinois, USA.

The TCP design allows a reduction in thickness between 4 and 10 cm compared to concrete pavements designed by the AASHTO 98 method, reducing the construction cost in about US $ 25.000 per kilometer-lane, corresponding to about 20% of the initial cost, with a similar life. When comparing with asphalt solutions, the savings are similar.

In Chile test tracts have been constructed and some condominium contracts have been executed with very good results. Their behavior is considered superior to the projected one.

In Guatemala, from 2005 up to now, there are 100 km of 4 lanes highways designed and constructed with this system. The design is for a high traffic (50.000.000 EE), with thickness of 17 cm of traditional concrete.

The behaviors have been very well considered by the Ministry of Communications of this country.

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