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DEVELOPMENT OF SLAB THICKNESS DESIGN GUIDE

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Abstract—Sustainability of concrete pavements depends on the rate of pavements deterioration. Cracks, as the main reason behind the deteriorations of concrete pavements, are initiated at the top or the bottom surface layer of concrete slab and then, propagated into depth of concrete slab due to fatigue of concrete. The load transfer efficiency across joints and cracks depends on the shear transfer capability of aggregate interlock and cement paste. The shear transfer capability of aggregate interlock and cement paste is an important factor. Using Miner's rule, equations for calculating the fatigue damage of concrete slab were developed.

Keywords— Concrete, pavement, slab, subbase, fatigue.

INTRODUCTION

The use of concrete pavement without an asphalt top layer dates back to Scotland in 1865 (Croney and Croney, 1998). With the growing worldwide interest in this field during the 20th century, concrete pavement technology has been embraced in Australia since the 1970s (Cruickshank, 1981). Concrete pavements were traditionally designed based on theoretical equations developed by Westergaard (1926, 1933, and 1947). Using finite element techniques, mechanistic approaches for designing of concrete pavements were developed. The mid-edge bottom-up transverse fatigue cracking was the only failure mode of the concrete pavements considered in the mechanistic design guides. Initiation and propagation of other fatigue related cracks in concrete pavements, designed based on the mechanistic approach, led to the development of mechanistic-empirical approaches in concrete pavement design guides.

While the mechanistic part of design guides provides required information on calculation of the critical stresses and deflections in pavements, the empirical part specifies possible failure modes of pavements under the applied loads. The applied loads can be vehicular and/or environmentally related. Vehicular loads have been considered as static loads in concrete pavement design guides but in reality, they are dynamic in nature as their locations upon pavement change with time.

Magnitude and configuration of vehicular loads together with environmental effects have a significant effect on induced tensile stresses within concrete pavements (Yu et al. 1998 and Hiller and Roesler 2002). Since a variety of axle group configurations is employed in heavy vehicle industries and across countries, further study is required to determine the interrelationship between concrete pavement distresses and pavement responses to the applied loads. Furthermore, the fact that structural responses of concrete pavements may be affected by the frequency and speed of vehicular loads (Izquierdo et al., 1997) has not been yet considered in concrete pavement design guides.

The most serious problem in concrete pavements is crack generation and propagation (Hossain et al., 2003). Cracking occurs in the first days after placement due to plastic shrinkage and the reaction between cement and aggregates in the setting time (Nawy, 2001). It then spreads over the pavement surface and propagates deeper in the concrete due to external factors such as drying shrinkage and fatigue. Although the use of appropriate curing methods could reduce the development of early edge cracking in pavement, current concrete pavement guides normally require the provision of reinforcement and / or concrete joints to minimise the development of secondary cracks in the pavement surfaces.

The fatigue life of concrete is traditionally estimated based on laboratory fatigue tests of concrete prism beams under one-directional cyclic loading using third point loading configuration. Since concrete pavements curl upward or downward during nighttime or daytime temperature gradients, results of the traditional fatigue test may be insufficient as the pavement curvature is not considered during the test. This also is a shortcoming which needs to be addressed.

CONCRETE PAVEMENT

Concrete as a versatile construction material has been used in many civil applications such as pavement. Since performance and deterioration of concrete pavements can be related to concrete properties, it is necessary to know how to achieve a better quality of concrete. Regarding the possible fatigue failure modes of concrete pavements, the most important concrete properties are concrete strength, modulus of elasticity, coefficient of thermal expansion, shrinkage and concrete fatigue life.

Concrete strength

The applied loads on concrete pavements are usually transferred to sublayers by bending actions which subsequently induce a tensile stress at the top or the bottom surface layer of the concrete slab. If the magnitude of induced tensile stress is equal or more than the flexural strength of the concrete, cracks as the main reason behind concrete pavement deteriorations are initiated at the surface layers and then propagated into the depth of the concrete slab. As a result, and in contrast with other structures where concrete compressive strength is used to design the concrete members, concrete flexural strength or modulus of rupture becomes an important concrete property used in concrete pavement design guides.

Factors affecting concrete strength are:

- Cement characteristics and content
- Water/cement, liquid/ cement, and/or water/cementitious ratios
- Aggregate quality and interaction with cement paste
- Type and percentage of chemical and mineral admixtures
- Procedure and mixing time of constituents
- Degree of compaction
- Degree of hydration which is related to curing methods
- Quality control and assurance.

Since a relationship between compressive and flexural strengths of conventional concrete is known to exist, the former is normally used to estimate the latter for practical reasons. Note that the performance of a concrete pavement under loads depends on several factors and consequently monitoring the concrete strength alone is not sufficient to produce a sustainable pavement.

Concrete Pavement

Structural responses of concrete pavements are affected by a number of factors including distance between joints, thickness of concrete slab, concrete properties, load transfer devices, joint width, boundary condition between concrete slab and subbase, subbase type, thickness and properties of subbase, subgrade characteristics, environmental effects and configuration, magnitude and location of vehicular loads upon pavement.

Concrete pavement contains a number of relatively thin concrete bases, known internationally as concrete slabs, finite in length and width, over a subbase resting on a foundation soil known also as subgrade (Fig.1). The width of concrete slab is equal to the width of traffic lane, normally 3600 mm. However, the length of concrete slab varies depending on concrete pavement types. Concrete slabs are connected to each other or shoulder in the longitudinal and transverse directions through transverse and longitudinal joints respectively. Joints allow them to expand / shrink with temperature fluctuations. A debonding layer is placed between the concrete slab and the subbase to reduce early age cracking.

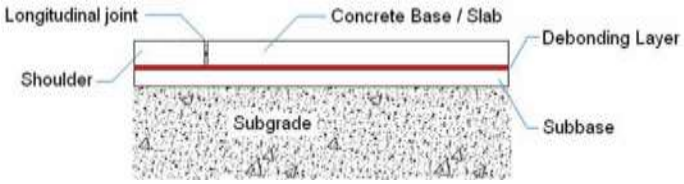

Figure 1. Cross section of a typical concrete pavement

Concrete pavement cross section

Subgrade

Subgrade is the foundation soil which is compacted to achieve an appropriate strength. While soils also exhibit some nonlinear behaviour and other interesting characteristics, a full investigation of this layer is beyond the scope of this research. Because of its strong effect on concrete pavement responses, however, a brief background of soil modelling idealization as pavement foundation is illustrated in this section.

A variety of subgrade model idealizations including Winkler, Dense Liquid (DL), Elastic Solid (ES), Two Parametric (TP), Zhemochkin-Sinitsyn Staerman (ZSS), and Kerr-Vlasok (KV) have been developed during the past centuries. Only, those employed widely in relevant research are subsequently discussed here.

Debonding layer

In terms of the classical friction model, the magnitude of interface frictional force between two layers depends on the smoothness of the contact surface presented as coefficient of friction and the normal force applied to the sliding plane. However, classical friction model can not be used in concrete pavement systems as friction force between concrete slab and subbase depends on different components including adhesion, shear and bearing (Wimsatt et al. 1987 and Wesevich et al. 1987). This results in a greater friction between the concrete slab and the subbase than that calculated based on the classical friction model.

Note that different boundary conditions including bonded, unbonded and partially bonded may be created between the concrete slab and the subbase depending on the magnitude of friction force. While the bonded boundary condition keeps the concrete slab and subbase together with no vertical separation, a fully unbonded boundary condition allows them to be separated under tensile force without inducing any frictional force between these layers. A partially bonded boundary condition, on the other hand, keeps the concrete slab and the subbase together for a certain frictional force. Beyond this frictional force, a vertical separation will occur between these layers.

Concrete slab (base)

The concrete slab is the top layer in the pavement section (see Fig. 3-1). It contains a concrete with a compressive strength more than 32 MPa to ensure the durability of the wearing surface and to provide sufficient flexural strength to avoid unpredictable deteriorations in pavements. Although the concrete slab thickness was traditionally considered to be between 200 mm and 250 mm, it is now designed based on damage processes considered in concrete pavement design guides.

Thickness of concrete slab is affected by the fatigue flexural strength of the concrete, type of joints, the value of load transfer efficiency (LTE), availability of the shoulder, strength of foundation soil and subbase, erosion of the subbase and subgrade materials, environmental effects and expected traffic load. In accordance with the provision of transverse joint and the availability of reinforcement, concrete pavements are classified as Jointed Plain Concrete Pavement (JPCP), Jointed Reinforced Concrete Pavement (JRCP) and Continuously Reinforced Concrete Pavement (CRCP).

Jointed Plain Concrete Pavement (JPCP)

JPCP has a natural configuration compared with other concrete pavements. In this configuration, the joint's pattern closely resembles natural cracks in an unreinforced concrete pavement. Distance between longitudinal joints depends on traffic lane configuration and vary from 3.6 m to 4.6 m. Transverse joints, on the other hand, are located 4.2 m or 4.5 m apart from each other in undowelled skewed joints or in dowelled square joints respectively. Distance between transverse joints is affected by joint and concrete slab integrities. Since slab length is much more affected by joint integrity than slab integrity, transverse joints of concrete pavement with more than 4.2 m length are modified with dowel.

Surface roughness

Surface roughness is a longitudinal profile of pavement surface elevations in 305 mm intervals (Huang, 2004). In accordance with ASTM E867, pavement roughness is "the deviation of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics and ride quality". Pavement roughness is normally measured based on International Roughness index (IRI) to provide a more realistic, practical and comparable approach. The IRI is a longitudinal surface profile along the wheel path of the pavement. It is calculated based on surface elevation data collected from either mechanical profilometer or a topographical survey. The method for calculation of the IRI can be found elsewhere (Sayers et al., 1986). It is presented in units of m/km.

Concrete pavement has a smooth surface when it is relatively new but its surface becomes rougher during its performance under the traffic loads. As a result, a rough surface can be observed at the end of pavement service life (Bhatti and Stoner, 1998).

Shoulder

The positive effects of shoulders in structural response and performance of concrete pavements have been accepted worldwide. Bituminous shoulders when placed next to a concrete pavement will experience further compaction from the traffic after road opening. Consequently, a vertical gap between the top surfaces of concrete slab and shoulder is produced which results in a loss of restrain at the longitudinal edge of the concrete slab. This ultimately results in deteriorations of concrete slab. As a result, concrete shoulders have been widely used in concrete pavements to prolong the pavement life.

Joints

Joints are usually utilised to reduce effects of climatic forces on the concrete slab. The climatic forces are due to shrinkage-loss of moisture contents and temperature gradients through depth of the concrete slab. Load transfer devices and sealant are the main components of joints. In terms of the economical point of view, the distance between joints should be long enough to minimise the number of load transfer devices but short enough to eliminate transverse cracking (Kelleher and Larson, 1989).

A variety of joints namely, isolation joints, contraction joints, construction joints and expansion joints is used in pavement constructions (CCAA, 1999). Byrum and Hansen (1994) indicated that joint opening is the key factor in stress distribution around the joint.

Load Transfer Efficiency (LTE)

LTE is an important factor in performance of transverse joints and cracks. It is measured to evaluate joint operation under the applied load. It can be calculated by the following equation:

$$LTE\% = \delta_U/\delta_L * 100 \qquad (1)$$

Where δU is deflection of the unloaded slab and δ L is deflection of the loaded slab. LTE is affected by dowel size, aggregate interlock, width of joints, and subbase or subgrade strength.

Based on results of Harvey et al. (2003), the LTE did not change by changing the traffic volume on the sections reinforced with DBR. Furthermore, the LTE was less sensitive to temperature changes. In addition to the use of suitable dowels, the improvement of subgrade strength can improve the LTE as reported by Hossain and Wojakowski (1996).

Differential Deflection

Differential deflection is another important factor, which provides further information on joint performance. It is the value of difference between the edges of adjacent slabs and presents the vertical distance between the loaded and unloaded slabs on the opposite sides of the joint. It is computed by using Equation (2).

$$DD = \delta L - \delta U \qquad (2)$$

It is noteworthy that LTE does not correlate with the amount of differential deflection. In other words, different values of the LTE can result in the same value of the DD. The differential deflection defines the sensitivity of the pavement to impact loads, applied at the edge of transverse joints of unloaded slab. The impact load results in further deterioration or joint faulting. Hence, the DD becomes an important factor when dynamic behaviour of rigid pavement is investigated (Popehn et al., 2003).**ACKNOWLEDGMENT**

If acknowledgement is there wishing thanks to the people who helped in work than it must come before the conclusion and must be same as other section like introduction and other sub section.

CONCRETE PAVEMENT ANALYSIS

A. Analytical Solution

Westergaard (1926, 1927, 1933, 1939, 1943 and 1947) developed comprehensive analytical solutions for analysing concrete pavements under centre, edge and corner loadings using the classical thin-plate theory. In Westergaard study, concrete pavement was modelled as a homogenous, isotropic, elastic thin slab resting on a Winkler foundation. To simplify the analysis procedure, Westergaard assumed that:

- The foundation soil acts like a bed of springs (the use of dense liquid foundation)

- A fully bonded boundary condition exists between concrete slab and foundation soil
- Shear and frictional forces are negligible
- The semi-infinite foundation is not restricted by a rigid layer
- Concrete slab has a uniform thickness
- Neutral axis is at mid-depth of the concrete slab
- Vehicular loads are uniformly distributed at tyre-pavement contact area having a circular (for centre and corner loadings) or semi circular (for edge loadings) shape.
- The load is applied normal to the surface of concrete slab
- Pavement acts as a single semi-infinitely large, homogenous, isotropic elastic slab with no discontinuities.

The above mentioned simplifications imply some limitations as follows:

- stresses and deflections can be only calculated for centre, edge and corner loadings
- Shear and frictional forces acting on concrete slab surfaces are ignored
- Availability of voids under concrete slab and discontinuities in concrete slab due to crack generation or provision of joints is not considered
- The method was developed for single wheel load and consequently real axle group configurations cannot be taken into consideration.
- Since no discontinuities were considered in the Westergaard method, effects of the LTE at joints or cracks on pavement performance were not addressed. Despite limitations associated with Westergaard analytical solution, his equations are still used. Ioannides et al. (1985) revised the original Westergaard equations for edge loading. Since all Westergaard's equations are based on single tyre with a circular tyre pavement contact area, Huang (1993) developed an equation to convert effects of dual tyres to single tyre with circular tyre pavement contact shape. Further information on Westergaard method can be found in the work of Westergaard (1926, 1927, 1933, 1939, 1943 and 1947).

B. Numerical Solution

The expensive cost of experimental studies associated with progressive development in numerical computation together with a rapid growth in software and hardware technologies leads to the use of numerical analysis for investigation of those problems with a complex geometry, boundary conditions, and material properties.

C. Discrete Element Method (DEM)

Hudson and Matlock (1966) were the first to apply the DEM in concrete pavement analysis using Winkler foundation. In their contribution, the original bending stiffness of the concrete slab at joints was reduced to simulate joint effects in concrete pavement behaviour. This model was then modified by Vora and Matlock (1970) to take into consideration different element sizing and anisotropic skew slabs. Furthermore, foundation soil was idealized using semi-infinite elastic solid elements.

This method does not allow incorporating elements with different sizes into the analysis easily. Furthermore, stress estimations at free edges are not converged to unique values.

D. Finite Element Method (FEM)

The initial idea of dividing a given domain into discrete parts goes back to ancient mathematicians. The concept of finite element technics was firstly used by Hrenikoff (1941) for aircraft analysis using truss and beam elements. To efficiently analyse the torsion problem, the use of triangular elements was then incorporated into the method (Courant, 1943). Seven years later in 1950, the Boeing Company used triangula elements for wing analysis. Further research on finite element technics by Argyris and Kelsey (1960) and Turner et al. in 1956 represented the new form of this method. The term "finite element" was used by Clough in 1960. It is important to note that the accuracy of a finite element analysis depends on several factors such as meshing size and element types.

Nowadays, finite element techniques are extensively used to treat complex engineering problems in several areas such as structural, mechanical, electrical, geological and thermal (Reddy, 1993). In general, finite element analysis packages can be divided into two categories, general purpose finite element programs such as ABAQUS and ANSYS, which are very powerful for nonlinear dynamic analysis, and specific finite element programs developed for concrete pavement analysis using the classical thin plate theory or 3D solid elements.

DEVELOPMENT OF SLAB THICKNESS DESIGN GUIDE

As mentioned earlier, concrete pavements were traditionally designed based on theoretical solutions such as Westergaard method (1926, 1933, and 1947). Contribution of finite element analysis for determining stress distribution within concrete slabs later led to a mechanistic approach which was extensively adopted in the PCA (1985) and Austroads (2004) slab thickness design guides. The bottom-up mid-edge transverse cracking due to mid-edge loading was the only fatigue damage mode of concrete pavements considered in the mechanistic approach.

A. Cross section of the concrete pavement

Based on the concrete pavement technology in Australia, the cross section of the pavement considered in this guide contains concrete slabs, debonding layer, subbase and subgrade. This guide was developed to design JPCP and JRCP. Since Austroads recommendations for selection of concrete slab dimensions were used in this research, distances between transverse joints and longitudinal joints (length and width of the concrete slab) are in accordance with Austroads (2004).

B. Concrete Characteristics

The concrete pavements are subjected to environmental effects simultaneously of construction. If the pavement is subjected to an environmentally induced stress before having adequate strength to resist the stress, a crack is initiated in the pavement. As a result, a minimum concrete flexural strength is considered in the design guides.

C. Subbase

The longevity of concrete pavements is affected by the provision of subbase layer. A LMC subbase of 150 mm thick and compressive strength of 5 MPa is constantly considered in the finite element analyses performed in this research. Hence, further study is required to determine the optimum characteristics of subbase for different types of concrete pavements and variety of subgrade soil. While this guide is used, a LMC subbase with the aforementioned characteristics shall be constructed over the subgrade and under the concrete slab.

D. Prediction of the maximum induced tensile stress

A comparison between results of vehicular induced tensile stress in finite element analysis with corresponding stresses predicted by using Austroads stress prediction model shows that the Austroads is not able to accurately predict the induced tensile stresses in the pavement subjected to TADT and QADT loadings. Furthermore, the prediction of induced tensile stress in the Austroads method is based on this assumption that only 6 per cent of the traffic passes along the edge area of the traffic lane (Packard and Tayabji, 1985). The edge area is along the longitudinal edge of the concrete slab and in a transverse distance of 600 mm from longitudinal joints or edges. As a result, the Austroads equation cannot be used for other values of edge loading. The work of Lennie and Bunker (2005) showed that the volume of the traffic passing along edge area in the Queensland State is much higher than the above mentioned assumption.

For a bonded traffic lane of JPCP confined at one of its longitudinal edges by a shoulder, the maximum vehicular induced tensile stress is predicted using the following equations:

SAST:$\sigma V = Pi \text{ x } (0.0153 — 2.208 \text{ x}10\text{-}5 \text{ x } (Pf — 53))$ (3)
SADT:$\sigma V = Pi \text{ x } (0.0124 —1.1\text{x}10\text{-}5 \text{ x } (Pf —80))$ (4)
TAST:$\sigma V = Pi \text{ x } (0.00708 — 3.0 \text{ x}10\text{-}6 \text{ x } (Pf. — 90))$ (5)
TADT:$\sigma V = Pi \text{ x } (0.00607 —1.87 \text{ x}10\text{-}6 \text{ x } (Pi —135))$ (6)
TRDT:$\sigma V = Pi \text{ x } (0.00456 —1.623 \text{ x}10\text{-}6 \text{ x } (Pi —180))$ (7)
QADT:$\sigma V = Pi \text{ x } (0.00348 — 7.33 \text{ x}10\text{-}7 \text{ x } (Pi — 220))$ (8)

Where Cr, (MPa) is maximum vehicular induced tensile stress in a bonded confined lane due to mid-edge loading at free edge, and Pi (kN) is the ultimate axle group load and is equal to axle group load multiplied by load safety factor (LSF). This table is represented in this chapter as Table 1.

Table 1. Load safety factor for concrete pavement design Project Design

Project Design Reliability	85%	90%	95%	97.50
Load Safety	1.05	1.1	1.2	1.25

RESULTS

Results show the accuracy of the aforementioned equations for stress prediction in both bonded and unbonded pavements.

Results of finite element analyses were also used to contribute effects of different loading conditions and adjacent traffic lanes (provision of shoulders at both longitudinal edges of the traffic lane) into Equations 3 to 8 for prediction of maximum vehicular induced tensile stresses within the concrete pavement. Consequently, the following equation was developed:

$\sigma Vi = C1 \text{ X}C2 \text{ X}C3 \text{ X}CLS \text{ X } \sigma Vi \text{ - } V 1$ (9)

Table 2. Variations of coefficient C2

Type of Axle Group	Unbonded Pavement		Bonded Pavement	
	Centre Loading	Corner Loading	Centre Loading	Corner Loading
SAST	0.535	0.547	0.546	0.644
SADT	0.617	0.468	0.61	0.565
TAST	0.55	0.84	0.585	1.13
TADT	0.654	0.725	1.45	0.842
TRDT	0.656	0.791	0.656	0.992

QADT	0.738	1.045	0.485	1.025

Table 3. Variations of coefficient C3

Type of Axle Group	Centre Loading		Mid-Edge Loading		Corner Loading	
	Bonded Pavement	Unbonded Pavement	Bonded Pavement	Unbonded Pavement	Bonded Pavement	Unbonded Pavement
SAST	0.892	0.932	0.496	0.757	0.866	0.903
SADT	0.896	0.937	0.611	0.764	1.063	1.118
TAST	0.936	0.965	0.526	0.669	0.671	0.849
TADT	0.891	0.937	0.578	0.658	0.913	1.013
TRDT	0.866	0.953	0.639	0.693	0.827	0.857
QADT	1.08	1.04	0.554	0.725	0.757	0.795

CONCLUSION

Dynamic amplifications and the concept of stress repetition described in this work were factored into the design procedure of concrete pavements. Using Miner's rule and taking into the consideration of results, prediction model of slab thickness for concrete pavements, mid-edge, edge and longitudinal cracks were developed. Finally, the design procedure was developed.

It is recommended that the use of debonding layer between concrete slab and subbase in regions with harsh environmental conditions be restricted.

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