Summary of Strategies of the Analysis and Structural Design of Concrete Block Pavements

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Abstract:
Concrete block pavement (CBP) is not a new paving system; however there is still no specific procedure for structural design and analysis. Furthermore, structural norms and design criteria can differ among various applications of CBP. Therefore, it is necessary that pavement engineers, contractors, and researchers know the premise of the various methods of structural design, which have evolved over the last five decades. In this paper, various methods of structural analysis and design of concrete block pavements are discussed briefly. In conclusion, some recommendations are proposed for the structural design of CBP.

Key Words: Block laying pattern; block paver, joint sand, base thickness, traffic loading,

1. Introduction

Concrete block pavement (CBP) is a pavement alternative that has great advantages over asphalt and concrete pavements; these include lower maintenance and rehabilitation costs, relatively long life, lower albedo, and higher sustainability. The importance of CBP is promoted while the challenges of pavement performance in the 21st century are considered. For example, global warming results in the occurrence of greater rutting in asphalt pavements, which decreases the efficient service life of the pavement [1]. Therefore, the higher cost caused by global warming of the pavement assets significantly affects the pavement management system (PMS) strategies of maintenance and rehabilitation, as well as the financial resources. As an example, climate change is expected to increase the cost of road pavements over US$200 million annually in the 2050 decade in South Africa [2]. In addition, a high temperature difference between day and night time results in high stresses stemming from warping and curling in concrete pavements. Therefore, pavements are more vulnerable to thermal cracking. Although crack width can be limited using more tie bars, this increases the construction cost of the concrete pavement. In contrast, CBP is free from any stress or strain originating from the temperature gradient. In other words, CBP is not vulnerable to the effects of climate change. Therefore, its lack of sensitivity to environmental temperature is one of main impetuses of CBP application in urban design and industrial yards. However, it is necessary to adopt an efficient structural design method that covers structural performance criteria related to realistic conditions. In this regard, various methodologies for structural analysis and design of CBP are discussed briefly in this study. The aim is to enable pavement engineers and contractors to choose appropriate structural design and performance methodologies for both road and industrial applications.

2. Mechanism of Load-bearing and Distribution

The load-bearing capacity and distribution in asphalt pavements is based on the interlocking of the aggregate particles, bonding between the asphalt binder and aggregate, base/sub-base properties, and the increased stiffness of the asphalt mix owing to the aging phenomenon. However, post-construction compaction due to traffic loading increases the asphalt mix density. The load-bearing capacity in concrete pavements depends on the curing of concrete; aggregate interlocking in the conceret matrix; base/subbase properties; laying patterns and mechanical properties of load-transferring elements, including tie and dowel bars. Since concrete pavements are designed as rigid pavements, post-compaction does not play a significant role in densifying the concrete mix. However, the mechanism of the load-bearing capacity in CBP depends on the block shape, block thickness, laying patterns, and base/sub-base properties. In addition, the load distribution in CBP is based on the interlocking of block paver units connected via joint sands. The blocks are laid on a thin layer of bedding sand (20–50 mm), which performs like a pad. This pad provides a consistent support for all of the block pavers. Rolling compaction results in initial interlocking, which makes the pavement structure sufficiently strong to withstand the traffic load. After exposure to the traffic, post-compaction due to traffic loading increases interlocking which results in lock-up. Then, neither the magnitude of the load nor load repetition have any effect on the pavement structural performance. This is valid

for wheel loads less than 7 tons. Therefore, the mechanisms of load-bearing and distribution in CBP do not depend on the curing of and aging in concrete and asphalt pavements, respectively.

3. Traffic Loading

Historically, the estimation of traffic loads can be categorized into two main groups [3]: (1) fixed traffic level (FTL); and (2) fixed standard vehicle type (FSVT). For the analysis of the effect of traffic using the FTL method, all of the damaging effects of various vehicle types are converted to a particular critical or design type. Therefore, the damaging effects of other vehicles are ignored. For example, the heaviest vehicles or aircraft are chosen as the critical type. Pavement thicknesses are determined based on the number of the critical vehicle passes. Moreover, it is necessary to equate multiple-wheel gear to an equivalent single-wheel load (ESWL). Although appropriate pavement thicknesses can be estimated, the calculation of stress distribution using ESWL is unrealistic. In addition, fatigue attributed to vehicles lighter than the critical vehicles is neglected. The methods based on FSVT are based on the damaging effects of all of the vehicles converted to the standard vehicle using equivalent wheel-load factors (EWLF). There are various test procedures to estimate EWLF. For example, AASHTO developed EWLF for a standard vehicle with axle load of 8.2 tons; and the British Port Association (BPA) uses equation (1) to calculate EWLF for various wheel loads.

$$D = \left(\frac{W}{1200}\right)^{3.75} \times \left(\frac{P}{0.8}\right)^{1.25} \quad [4] \qquad (1)$$

where D: damaging effect or EWLF; W:wheel loadP: tire pressure; the wheel load is 12 ton with tire pressure 0.8 MPa.

Also, the national concrete masonary association of the USA chose a Hyester 620 forklift, which is typical vehicle in the industrial yards and ports, as standard vehicle for CBP [5]. The maximum wheel load is approximately 15 ton. To analyze traffic flow, there are some methodologies that consider traffic based on average daily traffic (ADT). Since, the various vehicles are converted to the standard vehicles using conversion factors, such methodologies fall within category of FSVT. However, it should be noted that the traffic on the road fundamentally is different from ports and airports. The load frequency, rate, load magnitude and mode of loading are three important differences between road and industrial pavements. Another difference is traffic channelization. Since, the load-bearing capacity of CBP is based on inter locking, the channelization and direction of traffic flow can affect the development of interlock in the industrial pavement. In addition, there are both dynamic traffic, or moving vehicles, and static traffic loadings, such as container stacking yards in the ports, apron and hangar in the areas of an aiport. But mjor traffic loadings in the highways are dynamic rtaher than static. It is obvious that the pavement response is different in different pavement applications. It should be noted that pavement response in CBP means interaction between the non-homogenous surface course, consisting of block paver, joint and bedding sand, and the below layers, base/subase and capping layer (if appliable), while the surface course of asphalt or concrete pavements are homogenous.

4. Structural Performance Criteria

The main task of a pavement designer is to find appropriate performance criteria for the structural design of the pavement based on the engineering properties of the materials in each layer, traffic loads, as well as the environmental factors. Main criteria adopted to evaluate pavements is fatigue cracking and rutting. Since there are no binding materials in the surface course of the block layer, fatigue cracking initiates from the layers below. Since the construction and building materials are vulnerable to cracking, the horizontal strain at the bottom of the bound layer, cement, and asphalt-treated bases, can be considered as a criterion. In contrast, vertical compressive strain at the top of the subgrade is assumed to be a criterion for CBP laid on a granular base. There are numerous formulae that correlate the number of repetitions of the loads to the horizontal and vertical strains; these can be used for the estimation of layer thickness. It should be noted that the boundary conditions, such as traffic load, base material engineering properties and test conditions, time at which interlocking occurs, can differ for each equation. Therefore, the estimated thickness varies. However, such equations can be considered as guides by which to correlate the material properties, stress, or strain generated owing to the traffic loading and number of repetitions. In addition, it should be noted that the equations are usually used for road pavements. Therefore, further equations are required for industrial applications. However, engineering experience plays a key role in the selection of pavement thickness, material type, and structural performance criteria in CBP.

$$\varepsilon_v = \frac{2800}{N^{0.25}} \qquad \text{Granular base} \qquad (2)$$

$$\varepsilon_T = \frac{993500 \times f_c^{`}}{E_b^{1.022} \times N^{0.0502}} \quad [5] \quad \text{Lean concrete base} \quad (3)$$

$$\varepsilon_T = \left(\frac{2.37 \times 10^{-12} \times 1.16^{(1.8T+32)}}{N}\right)^{0.25} \quad [6] \quad \text{Asphalt-treated base} \quad (4)$$

$$\varepsilon_T = \left(\frac{1.06 \times 10^{-10}}{N}\right)^{\frac{1}{3.86}} \quad [6] \quad \text{Cement-treated base} \quad (5)$$

$$\varepsilon_v = \left(\frac{8.60 \times 10^{-8}}{N}\right)^{\frac{1}{4}} \quad [6] \quad \text{Granular base} \quad (6)$$

ε_v: vertical strain; ε_T :horizebtal strain; N: number of repitations; T: temperature; E_b: elastic modulus of the base; $f_c^{`}$: compressive strength of the base layer

5.Various Methods of Structural Analysis and Design

Althoug there are various methodologies to analyse structural stresses and strains of CBP, the approaches can be divided into three methods[7]: (1) the modified slab analysis;(2)layed elastic analysis; (3) finite element methods. However, structural design methodologies are developed based on results yielded from the structural analysis methodologies. Generally, all the structural design methods are categorised in four main methods[5]:(1) ad hoc modifications of various methods applied for structural design of traditional asphalt and concrete pavemnts; (2) design based on the experience;(3) mechanistic methodologies; and (4) experimental design based on results of scale trafficking tests. In this regard, various structural criteria and proximity factors for different base/subbase material were developed. The laboratory test results and field investogations clearly show that the current methods of structural design is reliable. However, use of computer packages such as ABACUS and LUSAS result in more precise analysis and design of CBP constructed on various types of base and subbase. In addition, such packages enable designers to choose various block shapes and laying patterns. Based on various structural design methods, different guidelines and standards of structural analysis and design of CBP were developed, which are dicussed briefly as follow:

5.1.Australia

The premise of the methodology of CBP design in Australia is full-scale traffic tests (category 4). The recommended proximity factors for the ratio of the strength of the block layer and asphalt surface course are 1.1 to 1.15 [7]. Based on the traffic category, material type, and rutting of the pavement surface, a set of design charts are used to estimate the base and sub-base system. The same procedure was developed for concrete flags in Australia. In addition, LOCKPAVE is used as a mechanistic tool for the structural design of CBP in Australia. The traffic load can be assigned based on the ADT or axle load for the road CBP. In industrial pavement design, various container-handling facilities can be selected with various loads. Finally, the package has a module for the cost analysis of CBP. In other words, LOCKPAVE as a user-friendly computer package based on elastic analysis has facilitated simple structural design of CBP.

5.2.USA

In the USA, CBP is designed based on the modification of methodology used for the structural design of asphalt pavement (category 1). In addition, the Interlocking Concrete Pavement Institute [8] developed a guideline that can be used to choose appropriate base and subbase materials. Moreover, design resilient moduli of subgrades based on drainage condition are proposed. Design charts were developed to estimate the base thickness using ESAL and the design subgrade CBR for granular, cement, and asphalt-treated bases. These charts were developed based on equations obtained by Rada et al. (Equation 6).

$$EAL_s = 365 \times ADT \times \frac{EAL_0}{100} \times \frac{DS}{100} \times \frac{LF}{100} \times \frac{\left(\left(1 + \frac{i}{100}\right)^n - 1\right)}{\frac{i}{100}} \quad [9] \quad (6)$$

EAL_s:estimated EAL; EAL_0: number of EAL repetitions per 100 vehicles at the start of the design period; DS = directional split, in percent; LF = lane distribution factor; i = traffic growth rate, in percent; and, n = pavement design life, in years/

5.3.UK

CBP is primarily designed based on modified methods used for the structural design of flexible pavements for

roads. In addition, pavement design charts were developed to estimate the base thickness using cumulative single-axle loads and base material type, e.g., lean concrete, dense macadam, and rolled asphalt [10]. Moreover, elastic layer methodology was used for the structural design of CBP for heavy-duty applications [11]. The successful experiences gained using the method of BPA resulted in international recognition. For example, Kawasaki Port in Japan was paved using CBP and was designed based on this method [12]. The latest version of the heavy-duty pavement design manual describes the finite element model developed by Knapton [11] using LUSAS software. Further, a design chart was developed to estimate the thickness using the ESWL concept.

5.4.Japan

Structural design of CBP in Japan is also based on ad hoc modification. Therefore, a methodology based equivalency factors and California bearing ratio (CBR) was used for two diffrent wheel loads of 49 and 17kN(Equations 7 and 8). This methodology is primarily based elastic layer method.

$$T_A = \frac{3.84N^{0.16}}{CBR^{0.3}} \quad \text{For wheel kload of 49 kN [13]} \quad (7)$$

$$T_A = \frac{1.95N^{0.16}}{CBR^{0.3}} \quad \text{For wheel kload of 17 kN [13]} \quad (8)$$

There is no manual for the design of port and industrial container yards in Japan. Furthermore, CBP was not used in the airports in a large scale. There is a computer package developed by Nishizawa 14] for structural analysis of CBP using the finite element methology. This software can be used for analysis and structural design of port pavements due to its strong processor.

6. Conclusion

Major methodologies usually used for the structural design of CBP are based on modified methodologies used for the structural design of flexible pavement. The long-term performance of CBP in different countries, especially Japan and Australia, show that this methodology is relatively reliable. Therefore, this method can be used as the main strategy for CBP analysis and design. However, the use of computer packages and FEM can assist engineers in computing stresses and strains with higher accuracy. However, if there is no design guideline nor computer package, 80 or 100-mm blocks with 25 to 30 mm of bedding sand can be assumed to be equal to a 100-mm asphalt surface course. Then, the remaining layers are designed in a similar manner to the asphalt pavement. Therefore, the strategies adopted for the structural design of CBP are based a combinations of design methods of flexible pavements, mechanistic procedures, empirical approaches, and experiences gained in previous projects. In conclusion, current methodologies are sufficient for the current requirements of structural design of CBPs for heavy-duty applications.

Acknowledgements

The authors would like to acknowledge the University of the Sunshine Coast for financial and the technical suoport.

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