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FIELD EVALUATION AND COMPUTER SIMULATION OF UNDOWELED TRANSVERSE JOINTS IN RIGID PAVEMENTS

P. Balmaceda and M. De Beer

Division of Roads and Transport Technology, C.S.I.R., PO Box 395, Pretoria, 0001

SUMMARY

A methodology for evaluating the condition of jointed portland cement concrete pavements (JCP) by non-destructive deflection testing was recently applied on the National Route 4 (N4) between Middelburg and Witbank. A set of two calibrated Multidepth Deflectometers (MDD) measured traffic-associated vertical absolute deflections at both sides of a transverse joint. A piezo-electric film trip triggered the data accumulation process. Joint efficiencies were then calculated from absolute deflections measured by both MDDs. Joint efficiency is one of the inputs of theoretical-mechanistic models for the calculation of stresses and deflections in the pavement structure. In this paper, charts developed from the ILLI-SLAB program code illustrate how stresses in concrete pavements vary for different joint efficiencies and moduli of subgrade reaction.

OPSOMMING

'n Metode om die toestand van voëë op Portland sement beton paale d.m.v. nie-destruktiwe toetse te evalueer is onlangs toegepas op Nasionale Roete (N4) tussen Middelburg en Witbank. Twee stelde Multi-diepte Deflektometers (MDD) is weerskante van die voeg geplaas en verkeersgeassosieerde vertikale absolute defleksie is gemeet. Meting is outomaties deur die meetvoertuig d.m.v. 'n Piezo-elektriese strook geaktiveer. Voegdoeltreffendheid is vanaf die absolute defleksies bereken, soos deur die MDD gemeet, en is een van die mees belangrikste insette vir 'n teoreties-meganistiese model vir die berekening van spannings en vervormings in die plaveiselstruktuur. In hierdie referaat word resultate bespreek wat vanuit die ILLI-SLAB rekenaarprogram ontwikkel is, vir illustrasie van die variasie van spannings a.g.v. voegdoeltreffendheid en modulus van grondaagreaksie.

P BALMACEA et al

INTRODUCTION

A variety of types of concrete (rigid) pavement designs are available. Most require a jointing and/or reinforcing system to prevent undesired failures. Of the three joint types normally installed in any concrete pavement (contraction, construction and expansion joints) this paper focuses only on contraction joints in jointed concrete pavements (JCP). These are installed in rigid pavements to control transverse cracking. Transverse cracking may occur because of restrained contraction and the combined effect of warping restraint and traffic loads. In the Republic of South Africa, most concrete pavements have skewed plain transverse contraction joints with spacings of approximately 4.5 metres. The skew is necessary to ensure that the wheel loads of each axle cross over the transverse joint one at a time reducing stresses and deflections at the joint. Besides skewed joints improve the riding quality (functional condition) of the pavement because they cause less impact reaction to vehicles crossing over the joints.

Transverse joints may deteriorate, sometimes at a very high rate even though, in many cases, the whole pavement structure is structurally sound. This results in dramatic reductions in structural capacity and serviceability of concrete pavements. The most common types of distress found at the joints due to poor load transfer and poor subbase quality are:

- ▶ corner cracking caused by traffic loads applied close to the pavement edge,
- ▶ pumping caused by traffic loads on pavements with a combination of free water and erodible subbase or subgrade leading to faulting or cracking of slabs,
- ▶ joint spalling, restrain cracking and blow-ups which are caused by the infiltration of incompressible material into joints, reducing the space available for the slabs to expand.

There are many ways to repair and/or prevent joint distresses.

- ▶ Some preventive methods are: Subsealing to restore sub-base support, subdrainage, resealing of joints, construction of pressure relief joints and construction of rigid shoulders, while
- ▶ diamond grinding of faults, full depth repair and partial-depth repair are some of the repair methods normally applied.

The more comprehensive the evaluation, the better and more cost-effective rehabilitation method selected. In any pavement behaviour evaluation, type and severity of distresses, pavement material properties, traffic loads, environmental conditions as well as information based on deflection measurements may be considered.

The scope of this paper is not a comprehensive study of the structural and functional conditions of a rigid pavement. Only a technique for measuring joint load transfer efficiencies from in situ deflection measurements is evaluated using field-data from nondestructive tests performed on a rigid pavement. This technique may be used in the future to determine whether a rigid pavement is in structural adequate state and provide guidelines for estimating the pavements remaining structural life. In doing so, the effect of temperature at the time of testing must be considered since joint efficiencies tend to decrease significantly at low temperatures due to the contraction of concrete slabs.

Furthermore, the impact of the joint load transfer efficiency on stresses and deflections is analysed by means of a finite element computer program code called ILLI-SLAB.

DETERMINATION OF JOINT EFFICIENCY OF A PLAIN TRANSVERSE JOINT

Test Procedure

The system used for measuring vertical traffic-associated absolute deflections has three main components:

- i) a set of two Multi-Depth Deflectometers (MDD) which were extensively used countrywide,
- ii) a piezo-electric film strip which triggers the data accumulation process,
- iii) the data acquisition system for logging the MDD pulses which uses a micro-computer with an PC30 analog-to-digital conversion circuit board.

The system is robust and can be permanently installed in any pavement type for longer term pavement response measurements¹⁰. Both MDDs, which were placed at both sides of the joint being studied, measured the absolute deflections at different depths in the pavement. The first MDD module was placed at a depth of 50 mm, the second at 300 mm and the lowest at 450 mm. Both MDDs were anchored at 2 metres. The piezo-electric film strip was placed at either 2 or 4 metres depending on the vehicle speed. The average temperature within the slab at the time of testing ranged between 31 and 36 degrees Celsius. The truck was driven at different speeds ranging between 6 km/h and 52.5 km/h.

Figure 1 outlines this technique and gives an idea of how deflection data were recorded once the truck with a standard 80 Kn rear axle have passed the trigger. An ideal plotting of data is shown, with absolute deflections measured by the MDDs at 50 mm depth as a function of the distance *d* which is the distance between the front axle of the truck and the trigger. These basins can be drawn in the reality once all deflection data is recorded and converted to mm.

Deflections at other depths were not considered for the purpose of this paper, but may be used on other investigations for measuring relative deflections within the pavement layers (ie vertical strain). Figure 2 shows the location of the MDD set ups on site relative to the longitudinal and transverse joints. Two influence deflection basins under a truck with a standard 80 Kn rear axle as displayed by Lotus 123 are shown in Figures 3 and 4 respectively.

Calculation of joint efficiencies

In addition to structural capacity evaluation, nondestructive deflection testing can be used to evaluate the in situ load transfer capacity of either rigid pavement joints or cracks. There are a number of expressions in which the joint load transfer efficiency (JE) may be based either on stresses or on deflections. The AASHTO guide for design of pavement structures¹¹ expresses the joint efficiency in both ways, as follows:

$$JE_s (\%) = \frac{S_u}{S_l} 100 \tag{1}$$

where
 JE_s = joint load transfer efficiency based upon stress,
 S_u = stress in the unloaded slab,
 S_l = stress in the loaded slab.

and

$$JE_D (\%) = \frac{D_u}{D_l} 100 \tag{2}$$

where
 JE_D = joint load transfer efficiency based upon deflection,
 D_u = deflection in the unloaded slab,
 D_l = deflection in the loaded slab.

Joint load transfer efficiency may also be defined as the deflection of the unloaded slab divided by the average deflection of both slabs at the joint⁹, as expressed by Equation 3.

$$JE_D (\%) = \frac{D_u}{(D_u + D_l) / 2} 100 \tag{3}$$

In Figure 5 the concept of joint efficiency is graphically explained for the wheel load either on the leave or the approach slab.

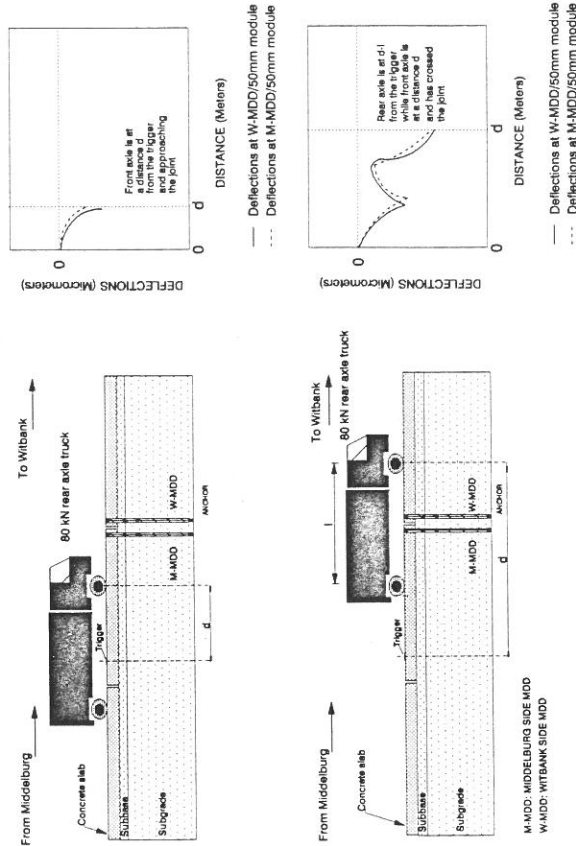


FIGURE 1: MEASURING ABSOLUTE DEFLECTIONS AT BOTH SIDES OF A TRANSVERSE JOINT ON THE N4 - INFLUENCE DEFLECTION BASINS

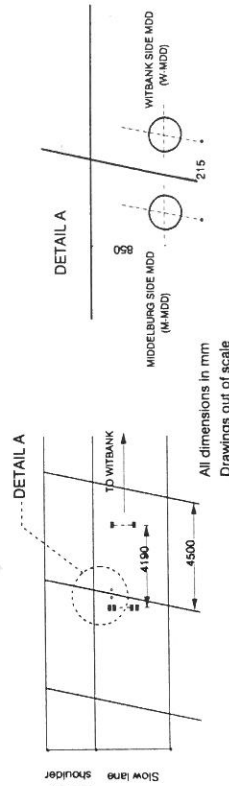


FIGURE 2: LOCATION OF MDD SET UPS FOR THE MEASUREMENT OF ABSOLUTE DEFLECTIONS AT BOTH SIDES OF A TRANSVERSE JOINT ON THE N4

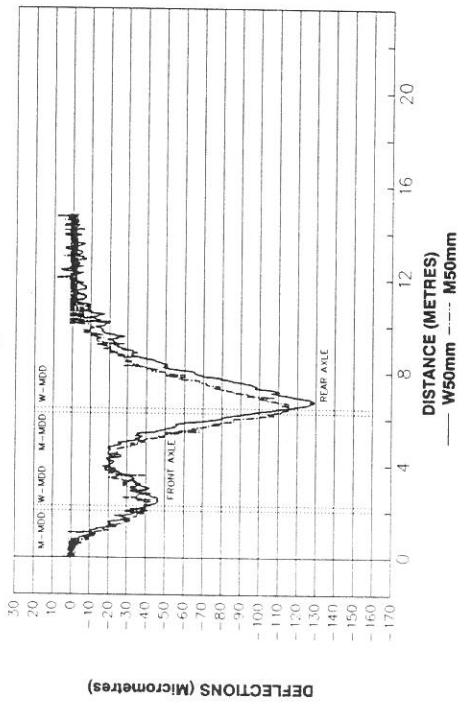


FIGURE 3: MDD DEFLECTIONS OF RSD TRUCK ON N4 MIDDELBURG 2.4km WITBANK - SPEED 17.7 km/h - DATE : 91/03/13

Note: W-MDD: Witbank side MDD
M-MDD: Middelburg side MDD

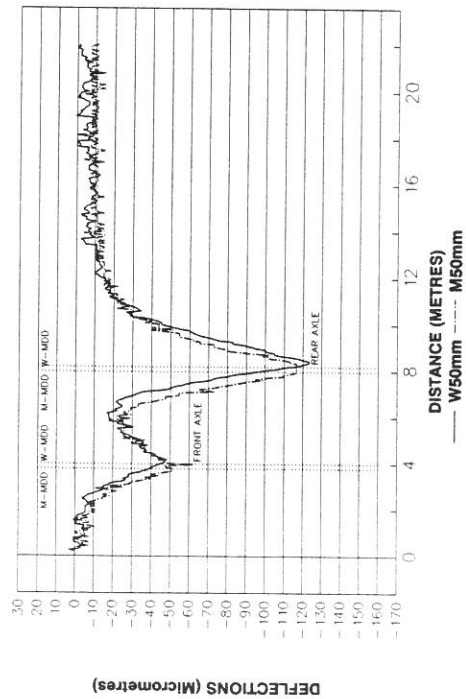


FIGURE 4: MDD DEFLECTIONS OF RSD TRUCK ON N4 MIDDELBURG 2.4km WITBANK - SPEED 49.6 km/h - DATE : 91/03/13

P BALMACEDA et al

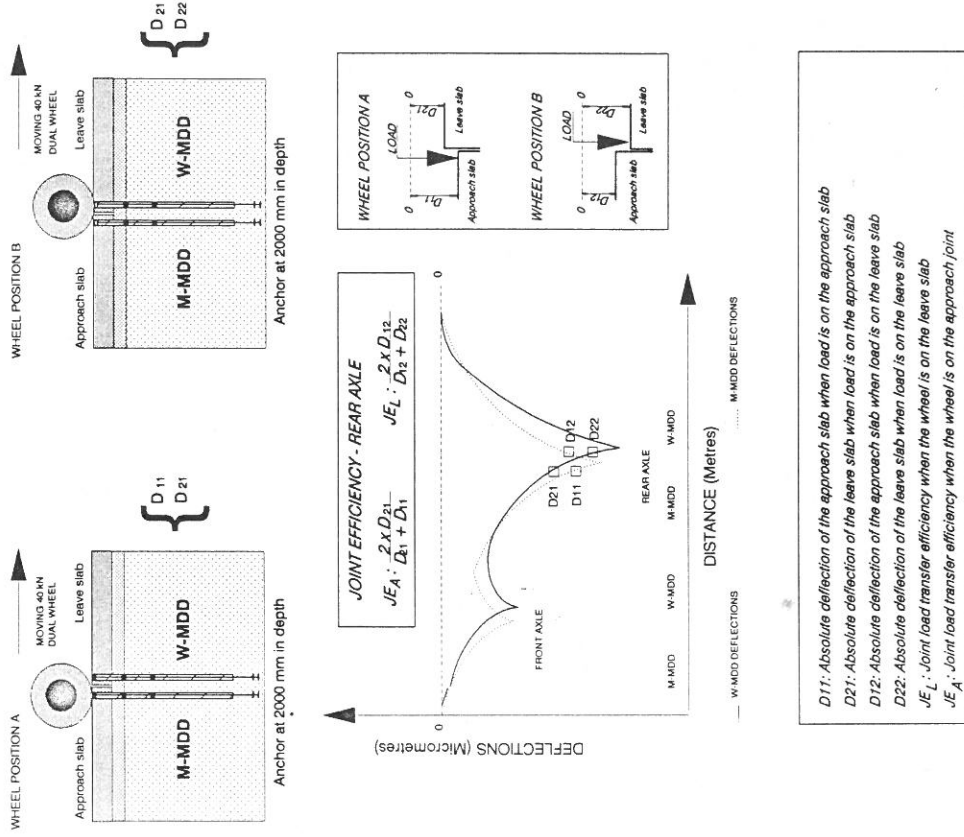


FIGURE 5: MEASURING ABSOLUTE DEFLECTIONS AT BOTH SIDES OF A TRANSVERSE JOINT - CONCEPT OF JOINT EFFICIENCY

P BALMACEDA et al

Results

From twenty one vehicle-passings at different speeds, inconsistent tendencies were obtained for maximum absolute deflections versus vehicle speed. The same occurred with the relative deflections (difference between absolute deflections). Therefore no correlation between calculated joint efficiencies and vehicle speed could be found from the twenty one data files displayed by Lotus 123, two of which are graphically shown in Figures 3 and 4. Joint efficiencies calculated with the Equation 3 ranged between 85 % and 95 % . Lower values must be expected if the AASHTO definition of joint efficiency based on deflection is used (Equation 2). For the purpose of this paper which is the description of a non-destructive technique, the effect of using either of the formulas available is not analysed.

Deflection basins were found to be of symmetrical shape and differ from those obtained in previous findings¹⁰ on asphalt pavements in which the visco-elastic response of the asphalt resulted in non-symmetrical basins.

It was also noticed that the majority of absolute deflections measured by the MDD at the leave slab were higher than those measured at the approach slab. This probably means that faulting is starting to occur below the approach slab.

EFFECT OF JOINT EFFICIENCIES ON STRESSES AND STRAINS

ILLI-Slab Computer Program

In this work, a revised version (April 9, 1988) of the program which has been obtained from the University of Illinois and modified at the Division for Roads and Transport Technology by C H Coetzee in October 1988⁵ was used. The program is operated at the Division through a virtual machine. This version of the program evaluates the structural response of slab/s with joints and/or cracks. Load transfer may or may not be considered at the joints or cracks. Where load transfer is taken into account, the program accommodates this by aggregate interlock or through steel bars or both. The program has the ability to analyse structures with up to two layers above the subgrade of any thickness, resilient moduli within a reasonable range and different subgrade models. The two layers, which can be perfectly bounded or non-bounded, can be either the concrete slab/s and a treated subbase or the slab/s and overlay. This version incorporated the two-parameter (Vlasov) and the elastic solid (Boussinesq) subgrade in addition to the Winkler type. For the purpose of this paper a Winkler energy consistent, uniform subgrade type was adopted.

The wheel loads can be applied to any of the slabs. The following may then be calculated:

- ▶ stresses and deflections at all nodes in the slab or system of slabs,

P BALMACEDA et al

- ▶ stresses in the stabilized subbase or overlay,
- ▶ vertical stresses in the subgrade and
- ▶ loads transferred by the dowel bars or aggregate interlock or both.

The modified program can also deal with the effect of temperature gradients and gaps underneath the slabs caused by faulting combined with traffic-associated effects. Unfortunately only one slab-system with spring-type subgrade can be adopted when dealing with temperature associated effects. This means that pavement performance cannot be analysed when considering a temperature differential (only one-slab system can be used) and joint efficiency problem (system with more than one slab must be used) at the same time.

Finite Element Model

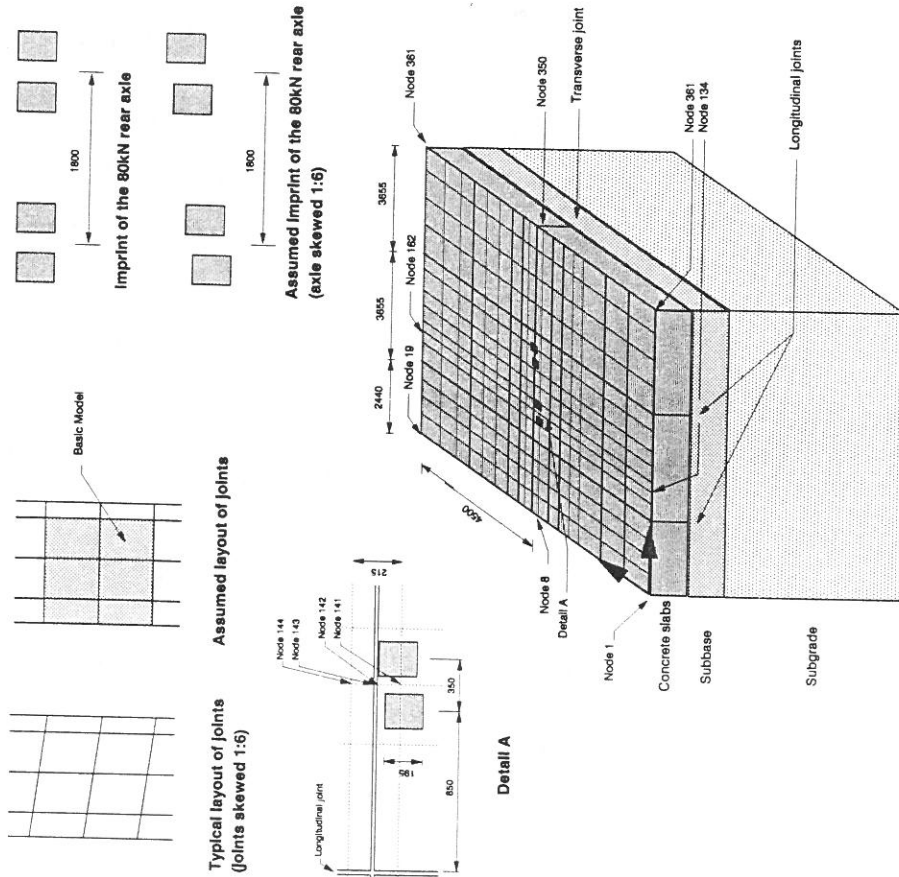
The pavement model included six slabs: two slabs on the shoulder and in the slow and fast lanes of the standard National Route 4 concrete pavement. Wheel loads were placed in such a way that the centre of the left dual wheel passed over the ideal position of the MDD installed in the approach slab. To simulate an 80 Kn axle load with dual wheels and meet the input requirements of the program (rectangular tyre imprints) and tyre pressure of 520 Kpa with 20 Kn per tyre, the wheel loads were assumed as 19 x 19 square cm. To simulate the effect of the skewed transverse joints and given that elements of the mesh must be rectangular in shape, the axle was placed skew at 1:6 anti-clockwise. The finite element model adopted with 361 nodes is shown in Figure 6.

An alternative mesh with 168 nodes, which is not shown in this paper, was used to ascertain the sensitivity of the program to changes in the mesh. This is discussed further in the paper.

The computer program was run for axle position at the transverse joint as shown in Figure 6. For this axle position, stresses and deflections which occurred at node 141 (Figure 6, detail A) were recorded for a combination of various moduli of subgrade reaction and joint efficiencies. Thicknesses of slabs and subbase were fixed as well as moduli of elasticity of both concrete and stabilized subbase material. It was known from a previous work⁸ that only the thickness of slabs, modulus of subgrade reaction and type of subbase (cemented-stabilized or granular) have significant influence on stresses and deflections. Elastic moduli of concrete and subbase materials (within the range in which the E-Moduli normally lie) will have less effect on pavement response. Therefore, to concentrate the attention on the effect of joint efficiency on pavement response, all parameters with the exception of joint efficiency and modulus of subgrade reaction, were fixed. An slightly cemented subbase (C3) which can be encountered in the N4 was adopted. The parameters adopted for this investigation were: 26 Gpa modulus of elasticity of concrete; 3 000 Mpa modulus of elasticity of subbase in the uncracked phase; 200 Gpa modulus of elasticity of steel bars; 0.20, 0.35 and 0.29 Poisson ratios for concrete, subbase material and steel respectively. These values are only tentative since no tests were performed to determine them.

P BALMACEDA et al

In an attempt to reproduce the influence deflection bowls obtained from the deflections measured by the MDDs, from which some of them are shown in Figures 3 and 4, ILLI-SLAB runs with alternative axle positions were performed simulating a 80 Kn axle approaching the transverse joint. Results are discussed further in the paper.



Results

Traffic-associated stresses: Figures 7 and 8 show the minor principal stresses (major tensile stresses) which occurred at the bottom of the slab at node 141 (Figure 6) for the 80 Kn dual wheel axle at the transverse joint.

Modulus of subgrade reaction markedly affected the extent of pavement response. Stress rose to 30 % for Subgrade K values which varied between 200 Mpa and 50 Mpa for both composite action types discussed in this paper (bond between slabs and subbase).

Furthermore, stresses for perfectly bonded slabs and subbase were approximately 15 % lower than those which occurred in a pavement with unbonded slabs and stabilized subbase.

The influence of joint efficiency on stresses was significant. Where joint efficiency is 35 % stresses at the bottom of the slab are approximately double those of a pavement with 100 % joint efficiency. This will apply to any modulus of subgrade reaction.

Traffic-associated deflections: Figures 9 and 10 show the absolute deflections measured at node 141 (Figure 6) for a combination of moduli of subgrade reaction and joint efficiencies.

Deflections calculated by ILLI-SLAB for Subgrade K=50 Mpa/m were approximately 2.5 times those for K=200 Mpa/m, twice those for K=150 Mpa/m and 1.5 times the deflections calculated for K=100 Mpa/m.

Furthermore, absolute deflections increased at a ratio of approximately 25 µm per 10 percent decrease in joint efficiency for a composite system slab/subbase either perfectly bonded or unbonded.

ILLI-SLAB computer program was run a number of times with loads in different positions simulating a 80 Kn axle moving from the trigger point to the first MDD. The attempt was unsuccessful in that the deflection basin obtained from field data could not be reproduced. A possible interpretation of this inaccuracy could be that the actual mechanism of load application is dynamic and differs from the assumption of the program which is that wheel loads are static.

Variability of results: Thus so far only the effects of changes of some parameters of the pavement structure on stresses and deflections have been analysed. However, these outputs can be affected by a number of factors other than those related to the pavement and environment, such as those which depend on the characteristics of the finite element model adopted. Variation in stresses up to approximately 30 per cent were registered when the configuration of the mesh was changed and a

mesh with 168 nodes adopted. Furthermore, variation in results can be expected for changes in the number of slabs included in the analysis system as well as changes in the shape of each particular rectangular mesh element⁸.

CONCLUSIONS AND RECOMMENDATIONS

The methodology used for measuring absolute deflections at both sides of the joint and thus relative deflections between slabs and joint efficiencies represents a reliable way to evaluate the actual condition of joints at any stage of trafficking and under different environmental conditions for any length of time. This conclusion is based upon the application of loads reproducing accurately traffic effects, and the high level of confidence in the use of the MDDs. These have been widely used throughout the country mainly during accelerated testing with HVSSs fleet. Naturally, this method has some disadvantages. This includes:

- ▶ the relatively high initial cost of the MDD modules even though the Linear Voltage Differential Transducers (LVDTs) can be recovered and used in further tests. The overall cost of the equipment amounts to R4 000 out of which approximately 80 to 85 percent is recoverable after every test.
- ▶ specialized staff for installing and calibrating the system. Normally a technician and a assistant need approximately two days, excluding travelling time, for drilling the holes and setting up two to three stacks with 6 MDDs each. The more systems installed, the shorter the time consumed in the installation of each set up. A technician is also required for converting the raw data expressed in voltage into millimetres and drawing graphs containing the influence deflection bowls.
- ▶ distortions that may occur owing to unexpected movements of the trigger film and MDDs during load applications.

Possible applications of this method may be:

- i) inclusion in a pavement management system to determine whether resealing, restoration or reconstruction of joints is needed where other modes of assessment are either inadequate or complementary information is needed. This test is intended in its final phase to complement existing, faster and thus cost-effective non destructive tests currently being applied rather than replace them. The number of set ups to be installed on a section of a road to establish a statistical sample with a certain confidence level depends largely on the characteristics of the problem and mainly on the length of the sector under study, type of distress and economics. Only once visual assessments at a network level and testing by faster methods are carried out and deflections distributed into categories, a few MDD tests

may be carried out at joints for different categories. This test can be applied to corroborate results obtained by faster methods and in those cases where more answers are expected such as deflections at different depths in the pavement and more precision in the determination of deflection magnitudes.

- ii) further research which may include accelerated test to study the performance of different stabilized or unstabilized subbase types with the emphasis on joint condition. Visual assessments would be included. The effect of temperature and water-related problems pavement on joint performance may also be investigated.

Finite element computer programs may be used to evaluate mechanically deflection and stresses in concrete pavements for different loading conditions and characteristics of road building materials. This can be applied to any pavement layout with or without dowel bars. Deflection measurements discussed in this paper may be used as input data. However, it must be taken into account that packages available must be upgraded to allow analyses of combined load- and temperature-associated effects on joint load transfer efficiencies since, as stated above, joint load transfer efficiency decreases with a decrease in temperature. Criteria for the number and size of the elements of the mesh should be established to avoid significant variability in the results. The ideal would be a locally-developed program representing South African environment conditions and characteristics of pavement building materials.

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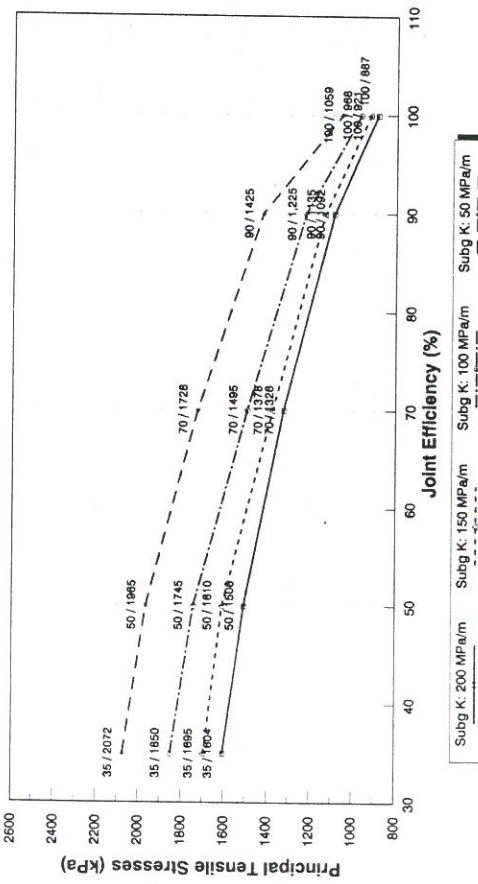


FIGURE 7: MINOR PRINCIPAL (MAX. TENSILE) STRESSES AT NODE 141 - SLAB AND SUBBASE COMPLETELY BOUNDED

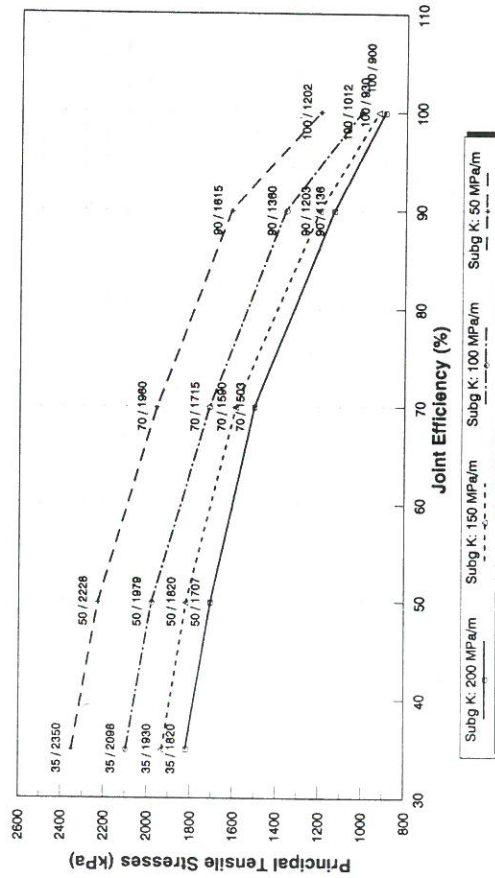


FIGURE 8: MINOR PRINCIPAL (MAX. TENSILE) STRESSES AT NODE 141 - SLAB AND SUBBASE UNBONDED

P BALMACEA et al

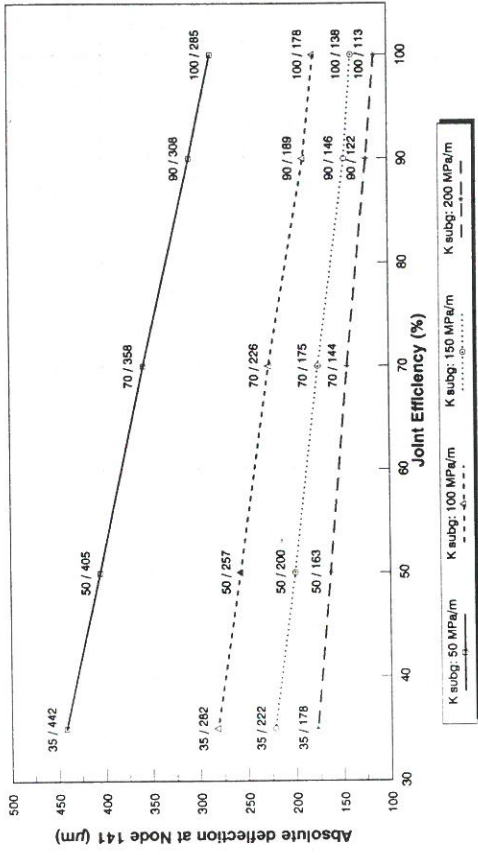


FIGURE 9: ABSOLUTE DEFLECTION - BOTTOM SLAB AT NODE 141 - SLAB AND SUBBASE COMPLETELY BOUNDED

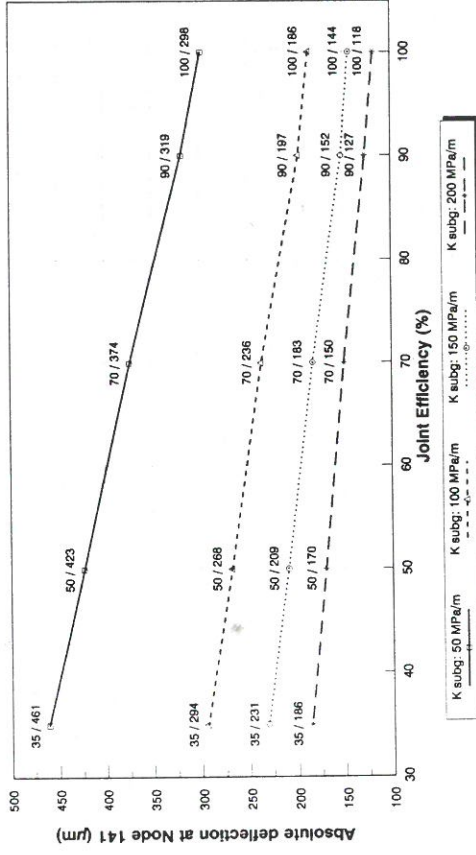


FIGURE 10: ABSOLUTE DEFLECTION - BOTTOM SLAB AT NODE 141 - SLAB AND SUBBASE UNBONDED

P BALMACEA et al

REFERENCES

- 1 DARTER, M I; BARENBERG, J F; DALEIDEN, J F. Repair of joint-related distress in PCC pavements. University of Illinois at Urbana-Campaign. Paper presented for publishing at the Third International Conference on Concrete Pavement Design and Rehabilitation, Purdue University, Indiana, 1985.
- 2 TRANSPORTATION RESEARCH BOARD. Joint-related distress in PCC pavement: cause, prevention and rehabilitation. National Cooperative Highway Program, Synthesis of highway practice No. 56, Washington, D C; January 1979.
- 3 NATIONAL TRANSPORT COMMISSION. Rehabilitation work on the existing concrete road between Swartbosweg and Vandyksdriif interchanges on National Route 4 sections 3 and 4. N T C, Chief Directorate: National Roads, Contract No. NVK 40343, Pretoria, April 1988.
- 4 COETZEE, C H. Evaluation of different concrete pavement designs with finite element analysis and HVS testing. Paper 4 of the 1989 Annual Transportation Convention (ATC), C.S.I.R., Pretoria, August 1989.
- 5 COETZEE, C H. User's manual for ILLI-SLAB Finite Element Program. Compiled for internal use of the Division of Roads and Transport Technology, C.S.I.R., Pretoria, September 1989.
- 6 IOANNIDES, A M, THOMPSON, M R, and BARENBERG, E J. Westergaard solution reconsidered. Grant No. AFOSR-82-0143, Transportation Research Laboratory, Department of Civil Engineering, University of Illinois, U.S.A, 1986.
- 7 IOANNAIDES, A M. Finite difference solution for plate on elastic solid. Journal of Transportation Engineering, American Society of Civil Engineering, Vol. 114, No. 1, January 1, 1986.
- 8 BALMACEDA, P, and PROZZI, J. Analysis of rigid pavements by a finite element program: ILLI-SLAB. Research Report 1/FP/4/91. Division for Roads and Transport Technology, C.S.I.R., February 1991.
- 9 MARAIS, L R. The design and construction of concrete pavements. The South African Portland Cement Institute, Johannesburg, 1980.
- 10 DE BEER, M. Pavement response measuring system. Paper presented for publication at the American Society for Civil Engineers (ASCE), June 1991.
- 11 AASHTO. AASHTO guide for design of pavement structures. 1986

P BALMACEDA et al