

NON DESTRUCTIVE TESTS PROCEDURE FOR FIELD EVALUATION OF TRANSVERSE JOINTS IN CONCRETE PAVEMENTS

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SUMMARY

A methodology for evaluating the condition of jointed portland cement concrete pavements (JCP) by non-destructive deflection testing was recently applied on the N4 (National Route 4) between Middelburg and Witbank in South Africa. A set of two calibrated Multi-Depth Deflectometers (MDD) measured traffic-associated vertical absolute deflections at both sides of a transverse joint. An 80 kN rear axle truck was used to simulate traffic. A piezo-electric film strip triggered the data accumulation process. Joint efficiencies were then calculated from absolute deflections measured by both MDDs. It was found that temperatures at the top and at the bottom of the slab, as well as temperature gradient, have a significant effect on maximum absolute deflections and hence joint load transfer efficiencies. For the range of vehicle speeds considered in this study, the effect of speed on deflections and joint efficiencies was found to be insignificant if compared with the temperature effect. Deflections decreased for increasing surface temperatures while joint load transfer efficiencies calculated by means of the AASHTO formula did not follow a definite trend owing to the influence of the temperature gradient, the surface temperature and the front axle of the test vehicle. Joint load transfer 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 have been developed for deflection vs joint efficiency and stresses vs joint efficiency. Stresses and deflections have been calculated by the ILLI-SLAB finite element computer program code. Calculated stresses and deflections increased significantly for decreasing joint efficiencies. There was a discrepancy between theoretically calculated results and deflections measured in the field. The effect of temperature, the curvature of the slab, the load configuration and the dynamic application of loads were not considered in the parametric study. This is seen to be the major cause of this discrepancy.

INTRODUCTION

A variety of types of concrete (rigid) pavement designs are available today. 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 constructed 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 South Africa, most concrete pavements have skewed plain transverse contraction joints with spacings of approximately 4,5 metres, thus the load is transferred between slabs by aggregate interlock (1). The skew joint is necessary to ensure that the wheel loads of each axle cross over the transverse joint at a time, thus reducing stresses and deflections at the joint. Skewed joints also 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 (2,3). This results in dramatic reductions in structural capacity and serviceability of concrete pavements. The most common types of distress found at the joints owing 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, restrained cracking and blow-up failure 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: sub-sealing to restore subbase support, sub-drainage, resealing of joints, construction of pressure relief joints and construction of rigid shoulders.
- 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 the 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 to study the influence of the temperature (at the top and bottom of the slab as well as the gradient) and vehicle speed on the absolute vertical deflections as measured by MDDs. The second part is to study the effect of joint load transfer efficiencies on stresses and deflections theoretically using a finite element computer code. The load transfer efficiencies used as input in this theoretical study are calculated from the data collected in-situ on a normal concrete road in South Africa.

DEFLECTION MEASUREMENTS

Test Procedure

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

- i) a set of two Linear Variable Differential Transformers (LVDT's) deflection measuring devices were retrofitted into pavement layers. These devices are known as Multi-Depth Deflectometers (MDD) (4,5). Three modules were installed in each of the two 40 mm diameter holes, one hole per slab. The modules were secured against the sides of the hole at a required depths and the centre core was attached to an anchor located approximately 2 meters below the pavement surface,

- ii) a piezo-electric film strip mounted on the road surface in line with the MDD location triggered 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 measurements. MDDs have been extensively used countrywide mainly during tests carried out with the Heavy Vehicle Simulator (HVS) in South Africa (6).

Both MDD arrangements were placed at both sides of the joint being studied. The pavement structure consisted of 200 mm concrete slab, 100 mm lightly cement-treated subbase and a compacted subgrade (7). Absolute deflections were measured at different depths in the pavement. The first module was placed at a depth of 50 mm, the second at 300 mm and the lowest at 450 mm. Deflections measured by the MDD module installed at 50 mm depth were recorded and analysed for the purpose of this paper. Both MDDs were anchored at 2 metres. The vehicle activated the trigger before crossing over the MDDs. The piezo-electric film strip was placed 5 metres before the joint being monitored. The vehicle used was an 80 kN dual wheel rear axle truck with an inter-axle distance of 5.16 m; it was driven at different speeds ranging from 5 km/h to 60 km/h. The temperatures at the top of the slab varied between 11 and 34°C, and those at the bottom from 14 to 21°C, thus the average temperature within the slab at the time of testing varied from 14 to 27°C. For these range of temperatures the gradient changed from +6°C at the beginning of the test to -14°C close to the end of the test. For the purpose of this study, the temperature gradient was considered as the difference between temperatures at the bottom and at the top of the slab, thus a positive gradient means that the temperature at the bottom is higher than the one at the top.

Figure 1 indicates the extreme positions of the 80 kN rear axle truck and the positions of the MDD's. The deflections measured while the truck was moving between these two points were recorded and analysed. The figure outlines the location of the MDD set ups on site relative to the longitudinal and transverse joints. Deflections at depths other than that of 50 mm were not considered for the purpose of this paper, but may be used on other investigations for measuring relative deflections within the pavement layers.

The test was performed in one day, from early morning when air temperatures were relatively low (approximately 10°C) thus producing a positive temperature gradients in the slab (temperature increases with depth), midway through the morning when temperatures at the top and bottom of the slab were approximately the same (zero gradient), and after midday when air temperatures were relatively high (30 to 35°C) with gradients markedly negative. Figure 2 indicates the temperature vs gradient relationship obtained during the test.

A hundred and twenty (120) tests were performed at different temperatures and vehicle speeds. The tests were grouped into six ranges according to vehicle speed:

- Group 1: less than 10 km/h,
- Group 2: 10 km/h - 20 km/h,
- Group 3: 20 km/h - 30 km/h,
- Group 4: 30 km/h - 40 km/h,
- Group 5: 40 km/h - 50 km/h,
- Group 6: more than 50 km/h.

Figures 3, 4 and 5 indicate the deflection basins measured for three different temperature conditions (positive, zero and negative gradient, respectively) within the same range of vehicle speed. Group 3 was selected in order to minimize the possible influence of the speed. Upwards deflections of the slab were recorded in some cases. This caused difficulties in the calculation of joint efficiencies by the AASHTO formula as explained in the following paragraphs.

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 formulations in which the joint load transfer efficiency (JE) may be based either on stresses or on deflections. The AASHTO guide (8) for design of pavement structures expresses the joint efficiency based on deflections, as follows:

$$JE_D(\%) = \frac{D_u}{D_l} 100 \quad (1)$$

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 efficiencies were calculated in this study by means of Equation 1, firstly for the 80 kN axle in the approach slab (JE_A) and then for the same axle on the leave slab (JE_L). This is illustrated in Figure 6. A typical shape of a deflection basin is shown in Figure 7 where the points representing the deflection values used in the calculation of joint efficiencies are also identified. The notations used in these figures are as follows:

- D_{11} = absolute deflection of the approach slab when the load is on the approach slab,
- D_{21} = absolute deflection of the leave slab when the load is on the approach slab,
- D_{12} = absolute deflection of the approach slab when the load is on the leave slab,
- D_{22} = absolute deflection of the leave slab when the load is on the leave slab,
- JE_L = joint load transfer efficiency for the wheel load on the leave slab,
- JE_A = joint load transfer efficiency for the wheel load on the approach slab.

RESULTS

Deflections

The maximum absolute deflection as measured by the MDD modules on both the approach slab (AS) and the leave slab (LS) is strongly dependent on the surface temperature (see Figure 8). Even though the pavement response is not only dependent on this temperature but also on the slab curvature which is caused by differential temperature and/or humidity, the surface temperature is relatively easy to measure. In most cases the surface temperature is directly related to the gradient because the temperature at the bottom of the slab varies at a slower rate and within a relatively narrow range.

Environmental influences like temperature and humidity apparently act on the slab mainly in two different ways. Firstly, the slab can expand or contract, closing or opening the joints respectively, and therefore increasing or decreasing the joint efficiency. The second effect is caused by differential temperature and/or humidity states between the top and the bottom of the slab. These gradients tend to bend the slab upwards or downwards, changing its original shape if they differ from those in the non-stressed states (when the slab was curing).

The results of the field test show some of these effects very clearly. Figure 3 shows what to expect in a slab with a positive gradient (16°C minus 13°C = +3°C). The edges of the slab are curled upwards and when the front axle of the vehicle enters the slab a negative deflection is registered in the other edge (edge moving upwards). As the vehicle approaches the joint being monitored, the deflections start to increase but the leave slab does not follow this movement because at this stage the temperature is low, the slab contracted and the load transfer efficiency insignificant.

During the tests with positive gradients, the deflections were relatively high, up to 728 microns in the approach slab and 885 microns in the leave slab. The major deflection always appears to occur in the second MDD (leave slab). These high deflection are not totally related to the pavement response but to the slab response itself. The edges of the slab (joints) are curled up and then the measured deflections represent the deflection of the edge until it touches the subbase after which the pavement response is also included.

Figure 4 shows a similar deflection basin. However, this was obtained for a small negative gradient (15°C minus $19^{\circ}\text{C} = -4^{\circ}\text{C}$). Even though the gradient is negative, according with its response the slab is supposed to be very close to its non-stressed state. This assumption is based upon the measured deflection basin (no or insignificant upwards movement). In this case the full slab is in contact with the subbase except for the edges at the transverse joints where gaps are suppose to have been developed underneath the edges to a minor extenry. The temperature of the slab is still low, the slab is still contracted and hence the resultant joint efficiency relatively poor. In this case the deflections of the leave slab are up to 20% higher than those of the approach slab.

In Figure 5 the deflection basin for a high slab temperature and an important negative gradient (20°C minus $34^{\circ}\text{C} = -14^{\circ}\text{C}$) is illustrated. At this stage the slab is in contact with the subbase and the measured vertical deflection represent also the actual pavement response. The average temperature within the slab is considerably high (27°C) then the slab is expanded, the joints are closed and a very high transfer efficiency is obtained.

Joint Efficiencies

The AASHTO formula to evaluate joint load transfer efficiency based upon deflection is a very useful tool to evaluate the state of a joint or a crack. Nevertheless some precautions must be taken when applying it to a real vehicle (more than one moving axle load) and with the interpretation of the results. The wheel configuration of the vehicle must be taken in consideration together with the dimensions of the slab. It is also important to understand that the joint efficiency is not only dependent on the state of the joint itself but also on the load applied. Figures 3 and 4 indicate that the joint efficiency (based on deflections) varies according with the position of the load.

For a certain slab shape, a specific vehicle and a precise load application point, the joint efficiency calculated by means of Equation 1 permits the comparison of the state of the joint at different temperature conditions. The point selected was 140 mm from both sides of the joint in line with the MDDs. In this way the entire wheel imprint is on one slab just next to the joint (position for which the AASHTO formula is valid). Joint load transfer efficiencies were calculated for the load in the approach slab and then for the load in the leave slab. The same trend was found in both cases but the absolute values differed significantly (see Figure 9). In some cases the upward movement of the slab at the joint resulted in negative values of joint efficiency even though they should be positive according to the definition. Circumstances like the existence of a gaps underneath the slab, the curvature of the slab and the load configuration were among the possible causes (see Figure 3).

When the load was on the approach slab, temperatures low and gradients positive, the joint efficiencies were about 40%. Slightly negative gradients and relatively low temperatures were found to be most critical. Furthermore in some cases, the leave slab moved upwards while the approach slab deflected. This resulted in negative calculated efficiencies (see Figure 2). Finally, as the slab started expanding because of the increasing temperatures, the joints started to work properly and the joint efficiencies increased up to values higher than 90%.

Even though the efficiencies were higher when the load was on the leave slab, the same trend was observed. For negative gradients and low temperatures the efficiencies were around 60%. For low temperatures and slightly negative gradient the efficiencies decreased to 48% (critical state). As the temperature increased so did the efficiencies, reaching the same values as the previous case (92 to 93%).

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 had been obtained from the University of Illinois and modified at the Division for Roads and Transport Technology by C H Coetzee in October 1988 was used (9,10). 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 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,
- 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 used 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 each of the slow and fast lanes of the standard layout of the N4 (National Route 4). 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 the 80 kN dual wheel axle with tyre pressure 520 kPa and meet the input requirements of the program (rectangular tyre imprints) the wheel loads were assumed as 19×19 cm squares. To simulate the effect of the skewed transverse joints, and given that the 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 10.

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 10. For this axle position, stresses and deflections which occurred at node 141 (Figure 10, 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. 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. A slightly cemented subbase (C3-quality, Unconfined Compressive Strength (UCS) 1.5 MPa to 3.0 MPa), which is encountered in the N4, was adopted. The parameters adopted for this investigation were: modulus of elasticity of concrete: 26 GPa; modulus of elasticity of subbase in the uncracked phase: 3000 MPa; modulus of elasticity of steel bars: 200 GPa; Poisson ratios for concrete, subbase material and steel 0.20, 0.35 and 0.29 respectively. These values were only tentative since no tests were performed to determine them.

Results

Traffic-Associated Stresses

Figure 11 indicates the major tensile stresses which occurred at the bottom of the slab at node 141 (Figure 10) for the 80 kN dual wheel axle at the transverse joint, with slab and subbase completely unbounded.

Modulus of subgrade reaction markedly affected the extent of pavement response. Stresses rose to 30% for subgrade K values which varied between 200 MPa and 50 MPa.

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

Traffic-Associated Deflections

Figure 12 shows absolute deflections measured at node 141 for combinations of moduli of subgrade reaction and joint efficiencies. Calculations were made for slab and subbase completely unbounded.

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, calculated absolute deflections increased at a ratio of approximately 25 m per 10 per-cent decrease in joint efficiency for a composite system slab/subbase totally unbounded.

The ILLI-SLAB computer program was run a number of times with loads in different positions simulating the 80 kN dual wheel rear 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. Another difference is that temperature effect can only be considered for one slab.

Variability of results

Thus so far only the effects of changing 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 (11). 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 element.

CONCLUSIONS AND RECOMMENDATIONS

The monitoring of the transverse joints in South Africa once again examined the capability of the MDD technology to assess the structural behaviour of concrete pavements. The aim of this paper was to monitor the joint under investigation for different conditions of slab temperature and vehicle speed. The effect of varying the speed was found to be of secondary importance to the system slab-joint behaviour. However, to minimise its influence in the interpretation of the results only one group of results was analysed.

The main findings derived from this study are the relationship between surface pavement temperature and maximum deflection at the joint (Figure 8) and, most important, the effect of surface temperature on joint efficiency (Figure 9). It is necessary to emphasise that tests were carried out under specific conditions. Material characteristics, slab shape, joint condition, load configuration, environmental conditions were in a particular combination. Further research must be done to apply these findings more generally. So far the monitoring of the joint has been extremely successful and has given a better understanding of the actual behaviour of the slab in the field under different conditions.

The methodology used for measuring absolute deflections at both sides of the joint and consequently load transfer 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 traffic effects accurately, and the high level of confidence in the use of the MDDs. The MDD technology has been widely used throughout the country mainly during accelerated testing with HVS fleet. Naturally, this method has some disadvantages:

- The initial cost of the MDD modules is relatively high even though the LVDTs can be recovered and used in further tests. Approximately 80 to 85 per-cent of the overall cost of the equipment is recoverable after every test.
- Specialized staff are needed for install and calibrate the system. Normally a technician and a assistant need approximately two days to drill the holes and set up two to three stacks with 6 modules each. The more systems installed, the shorter the time of installation for each set-up. A technician is also required to convert the raw data into millimetres and to prepare relevant graphs.
- Distortions 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 (PMS) to determine whether resealing, restoration or reconstruction of joints is required where other modes of assessment are either inadequate or complementary information is needed. In its final phase this test is intended 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 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 have been carried out and deflections distributed into categories, may a few MDD tests be carried out at selected joints of different categories. This test can be applied to corroborate results obtained by faster methods. It may also be needed in 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 testing to study the performance of different stabilized or unstabilized subbase types with the emphasis on joint condition. Visual assessments would be included.

Finite element computer program codes may be used for the mechanistically evaluation of 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 current available codes must be upgraded to allow analyses of combined load- and temperature-associated effects on joint load transfer efficiencies. Criteria for the number and size of the elements of the mesh should be establish 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.

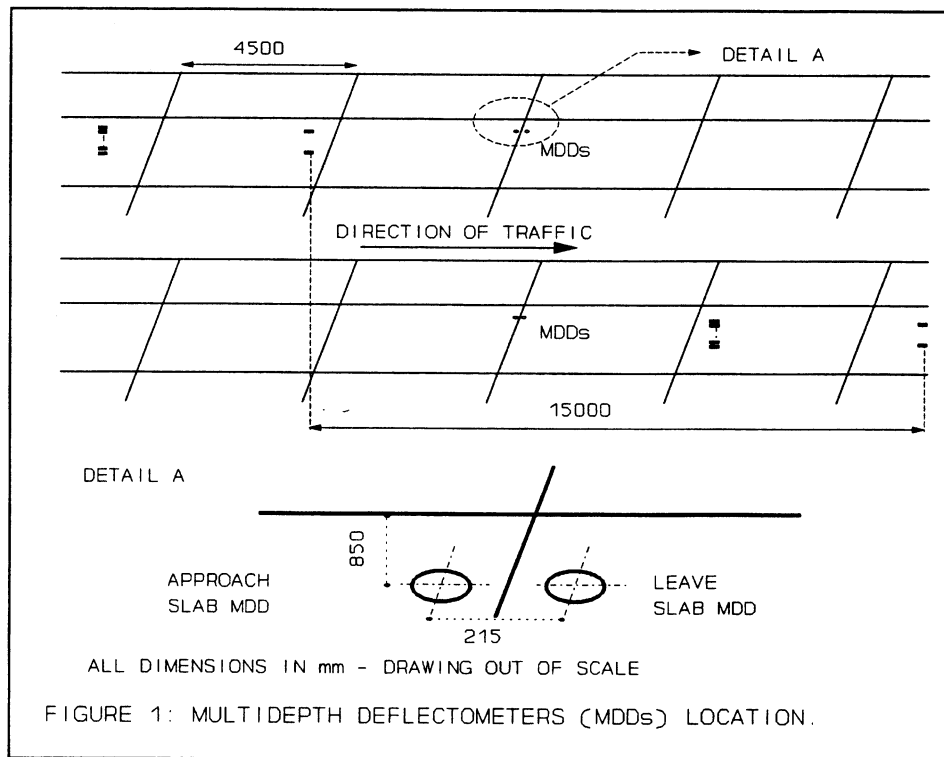
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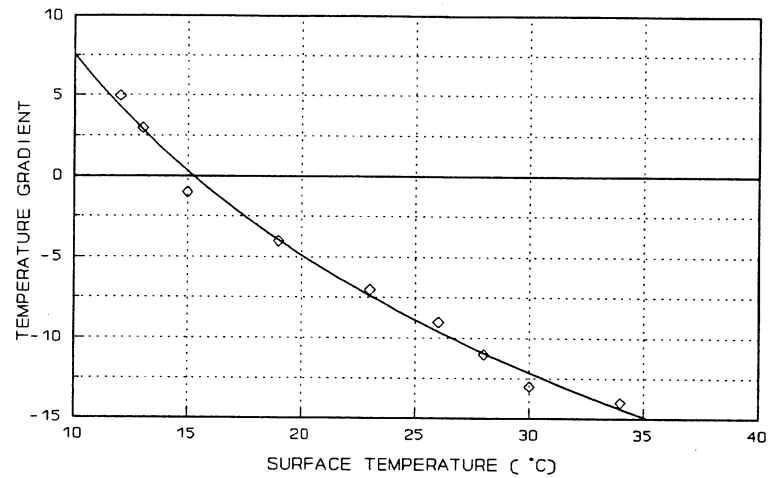


FIGURE 2: VARIATION OF THE TEMPERATURE GRADIENT WITH SLAB SURFACE TEMPERATURE DURING THE TEST.

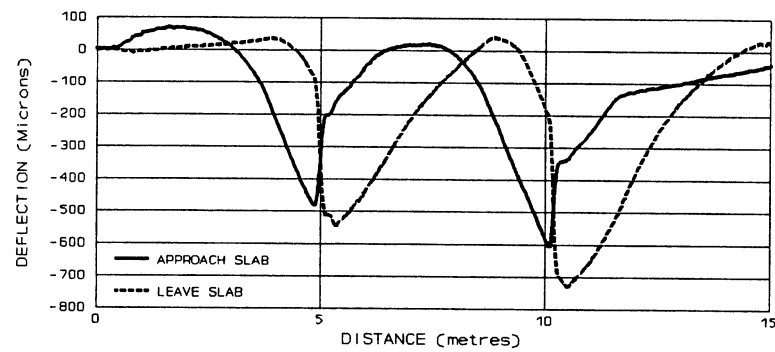


FIGURE 3: MDD DEFLECTION MEASUREMENTS AT BOTH SIDES OF THE JOINT. TEMPERATURE: 16-13 °C. SPEED: 26.9 km/h.

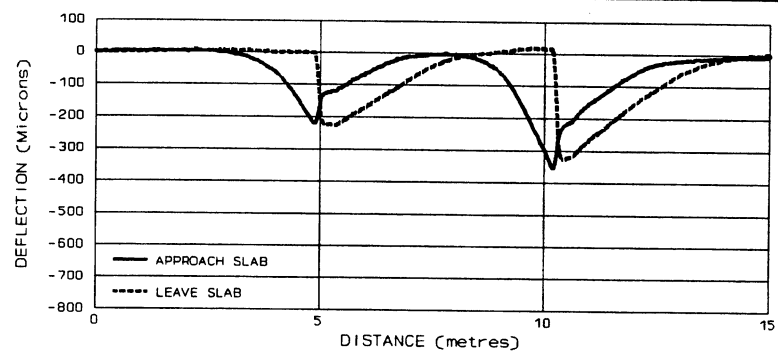
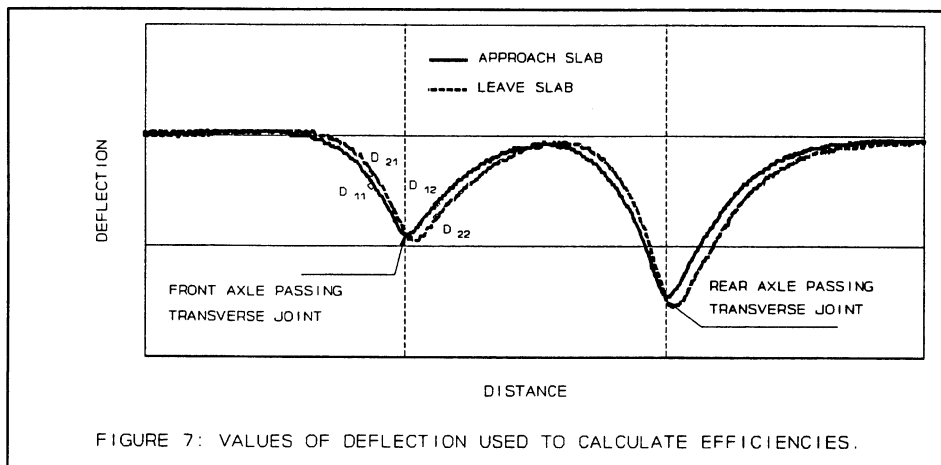
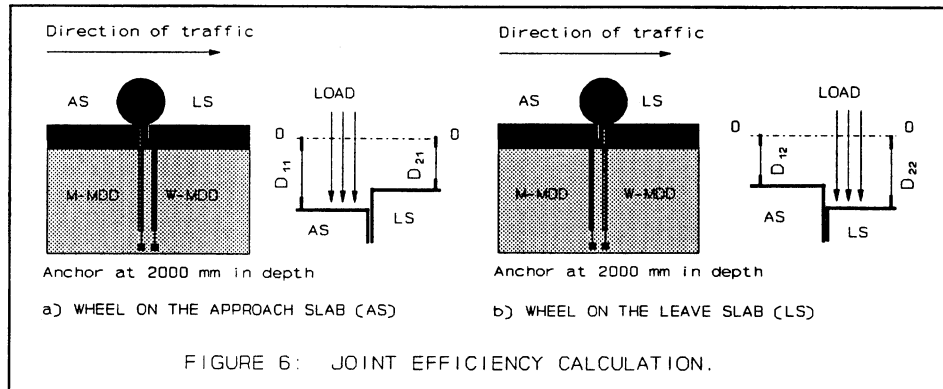
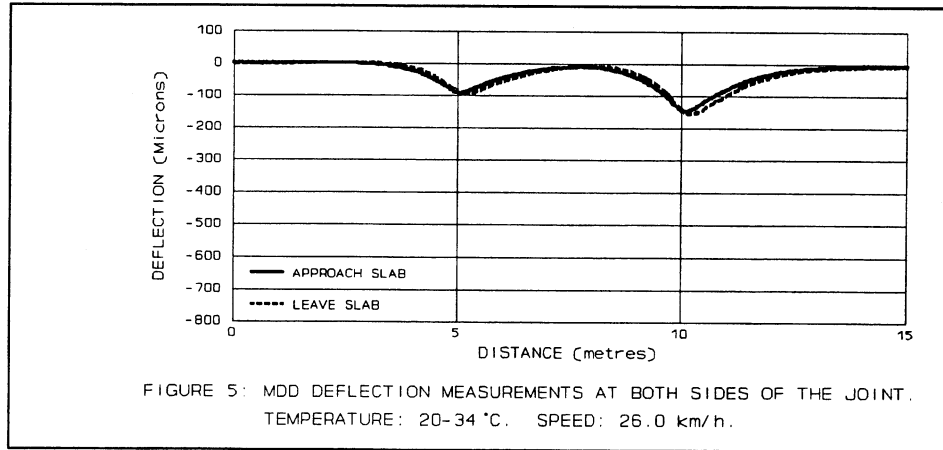
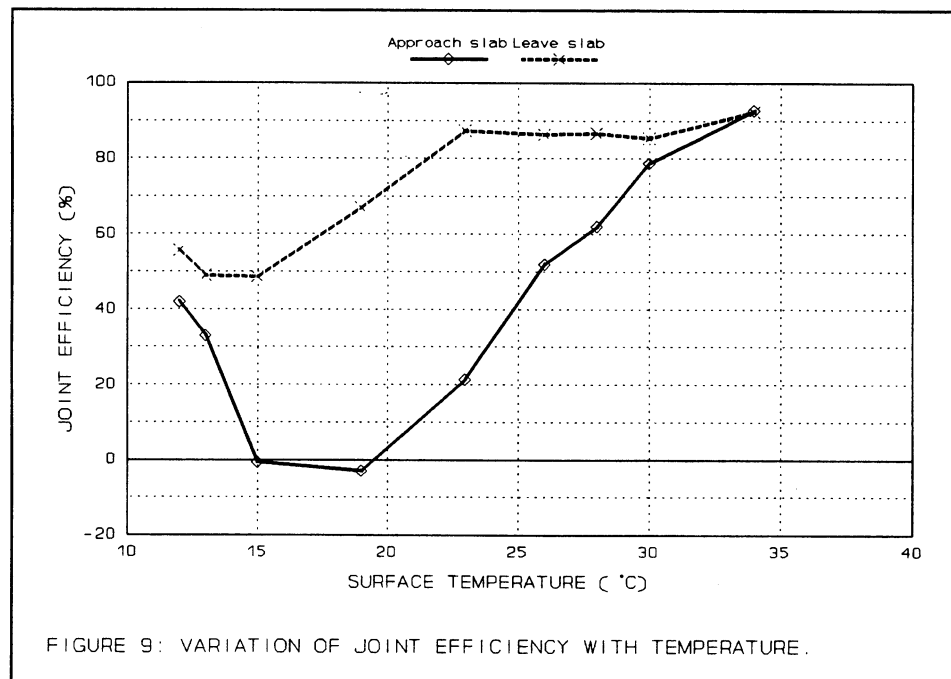
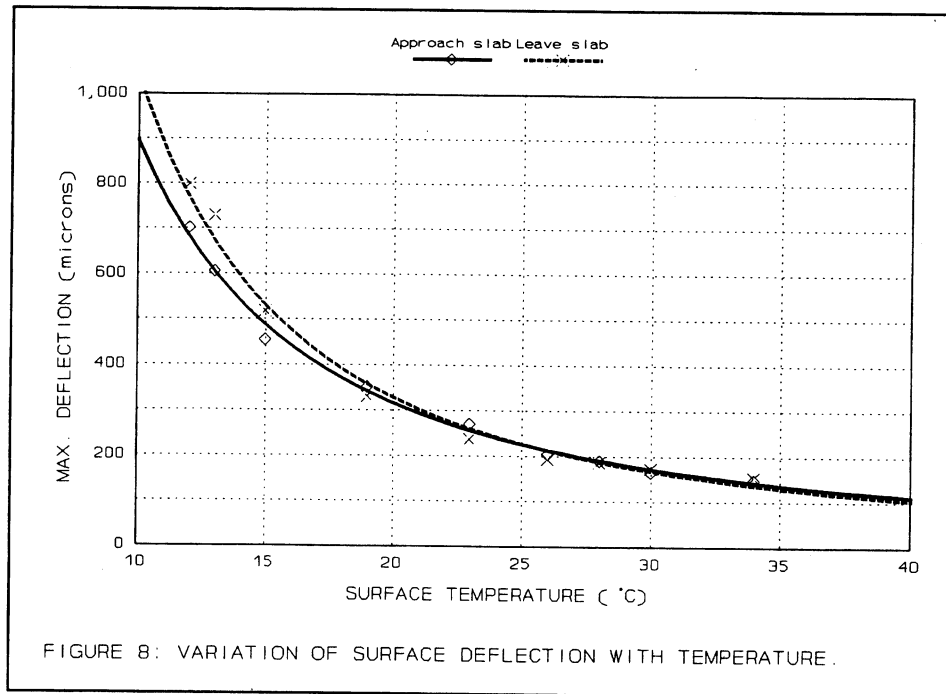
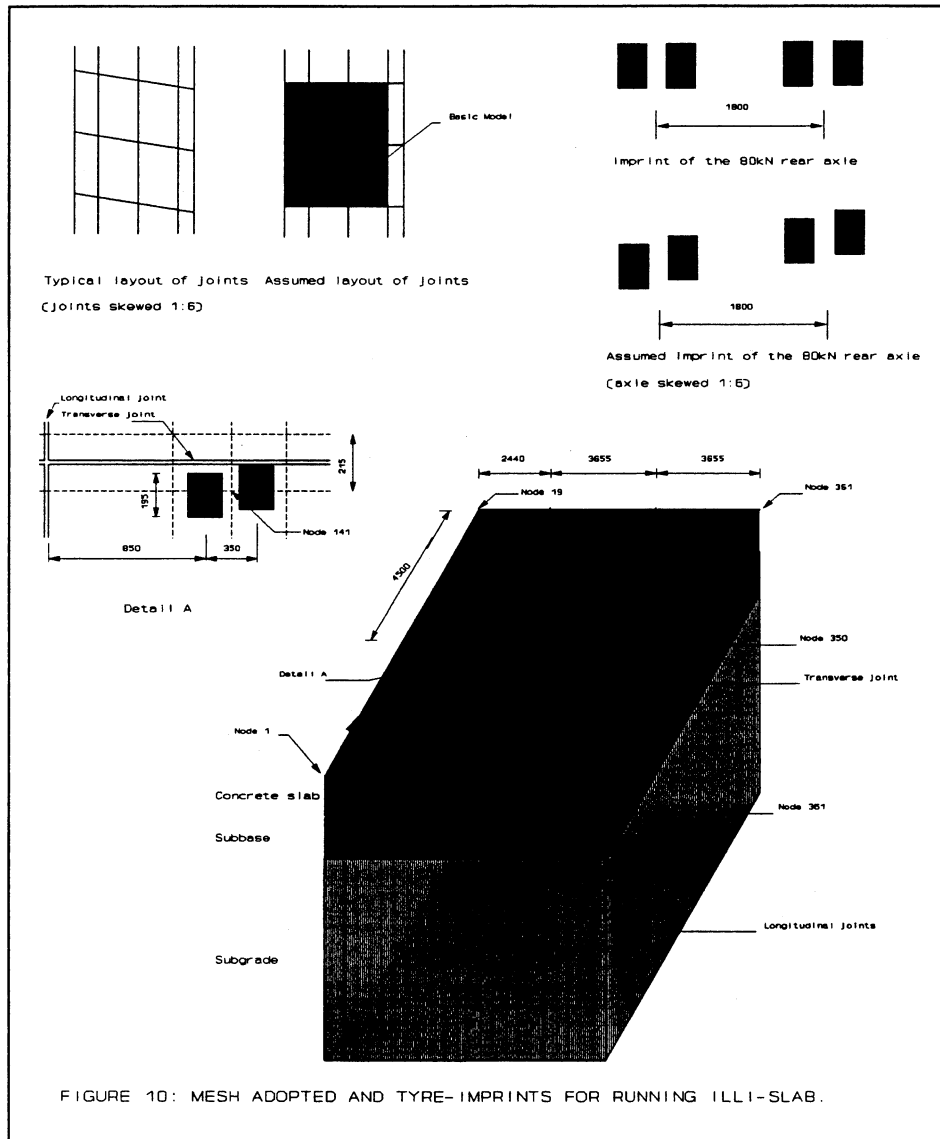


FIGURE 4: MDD DEFLECTION MEASUREMENTS AT BOTH SIDES OF THE JOINT. TEMPERATURE: 15-19 °C. SPEED: 26.2 km/h.







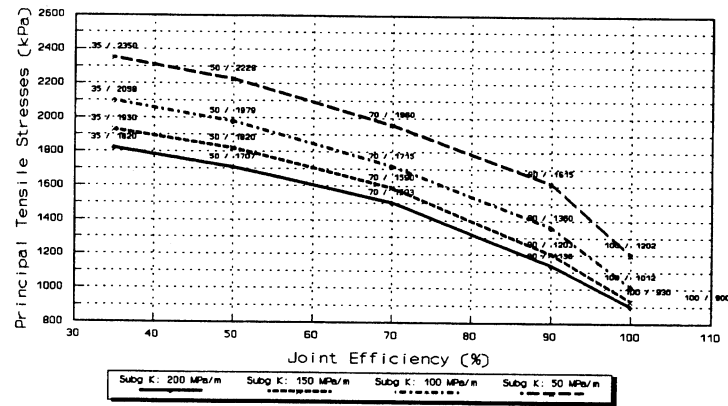


FIGURE 11: MINOR PRINCIPAL (MAX. TENSILE) STRESSES AT NODE 141
SLAB AND SUBBASE UNBONDED.

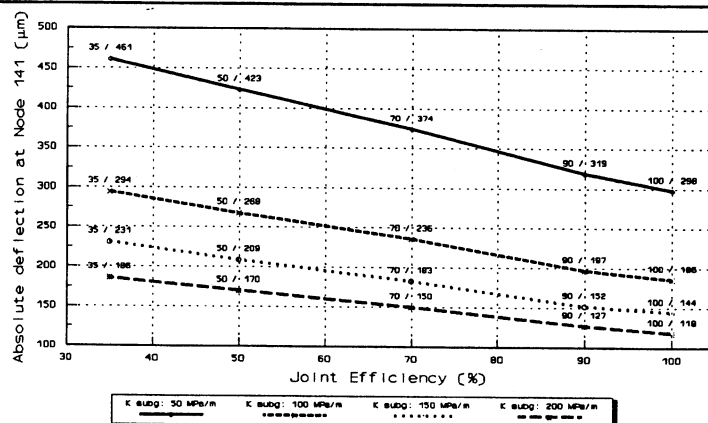


FIGURE 12: ABSOLUTE DEFLECTION - BOTTOM SLAB AT NODE 141
SLAB AND SUBBASE UNBONDED