Structural Response of Concrete Pavements under Moving Truck Loads

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Abstract: While there has been a great deal of research conducted on concrete pavement performance and deterioration under static loads, only very limited research has been carried out on its dynamic response. Furthermore, opinions differ as to which type of loading (static or dynamic) results in greater values of slab deflection or flexural stress. In the present study, a test section consisting of two jointed reinforced concrete pavement and two jointed plain (unreinforced) concrete pavement was constructed and tested under both quasistatic and dynamic truck loads. Truck load was allowed to wander at predetermined locations on the instrumented pavement at speeds from 5 to 55 km/h. Strain gauges and displacement transducers were installed along the test section to monitor the pavement responses. Time history responses of the test section were recorded and used to validate a finite-element model developed in the ANSYS platform for further sensitivity study on those parameters affecting the dynamic response of concrete pavements. Results indicate the significance of dynamic amplification in concrete pavement design.

DOI: 10.1061/(ASCE)0733-947X(2007)133:12(670)

CE Database subject headings: Concrete pavements; Field tests; Dynamic structural analysis; Dynamic model; Finite element method; Dynamic response; Dynamic tests.

Introduction

Concrete pavement deterioration is a function of several parameters including thickness of concrete slab and subbase, material properties, boundary condition between concrete slab and subbase, subgrade characteristics, environmental effects and configuration, and magnitude and position of the vehicular loads.

While there has been a great deal of research conducted on concrete pavement performance and deterioration under static loads, only a very limited number of studies have been carried out in the past on dynamic response of concrete pavements. Vehicular loads have been considered as static loads in concrete pavement design guidelines as dynamic analyses and experimental tests on concrete pavements in the past showed that dynamic effects were not significant. The American Association of State Highway Officials research (AASHO 1962) showed that an increase in vehicle speed from 3.2 to 95.6 km/h decreases the value of pavement response by about 29%. Since the most critical failure mode in AASHO (1962) test sections was erosion of subbase or subgrade materials, a question arose whether or not results of the AASHO (1962) test can be extended to other conditions.

Analytical studies of concrete pavements under dynamic loads carried out by Stoner et al. (1990), Gillespie et al. (1993), Zaghloul and White (1993), Chatti et al. (1994), Bhatti and Stoner (1998), Kim et al. (2002), and Shokry and Fahmy (2002) showed that speed has significant effects on slab deflection. However, a greater stress can be captured in concrete pavements if a static analysis of concrete pavement is performed. On the other hand, Liu and Gazis (1999) found that concrete pavements in the presence of pavement roughness experience a greater tensile stress under dynamic loads than static loads. Izquierdo et al. (1997) in an experimental study of plain concrete pavement resting on a subbase with low stiffness under very heavy truck loads found that velocity can noticeably change the value of slab deflections or stresses.

Recent analytical studies on concrete pavements under moving axle group loads carried out by Darestani et al. (2006a) showed that vehicle speed has a significant effect on responses of concrete pavement even if the pavement has a smooth top surface. However, this needs to be validated by a field test. Furthermore, the above-mentioned finding was based on a bonded boundary condition between a concrete slab and subbase and in the absence of environmental effects. Consequently, further study needs to be carried out to address effects of different boundary conditions between a concrete slab and subbase, traffic wander, and environmental effects on dynamic responses of the concrete pavements so as to provide adequate design information.

Toward this end, a sophisticated finite-element model (FEM) of concrete pavements will be developed and validated to study the influence of the various parameters. To efficiently do this, a fully instrumented concrete pavement test section consisting of...
two concrete pavements, namely, jointed plain concrete pavement (JPCP) and jointed reinforced concrete pavement (JRCP), was constructed and tested under both quasistatic and dynamic truck loads. This test will not only enable calibration of the FEM but it also will enable the physical observation of the pavement response under dynamic loads. This paper briefly describes the test procedure and validates a finite-element model developed in the ANSYS platform for dynamic analysis of concrete pavements that can be used in future sensitivity studies on pavement parameters.

**Project Description**

This experimental work on concrete pavement performance under dynamic truck loading was conducted by Queensland University of Technology (QUT) and a major Australian concrete producer, Rinker Australia, at Rinker sand quarry in Oxley Creek, southwest of Brisbane.

The test section had 32 m length, 5.1 m width, and 250 mm thickness. It consisted of two JPCP and two JRCP, which were constructed over a 150 mm concrete subbase resting on a stiff subgrade [California bearing ratio (CBR) of 14%]. The widths and lengths of the concrete slab were 3.6 and 4.6 m for JPCP and 3.6 and 10 m for JRCP, respectively. Fig. 1 shows the layout of the test section. An additional JPCP section (1.5 m × 3.6 m) was placed at each longitudinal end of the test section to restrain the free transverse edges and simulate the conditions of a long stretch of pavement. A reinforcement mesh of 9 mm round bars was used in the JRPCs. The reinforcements were positioned about 100 mm away from the transverse and longitudinal joints.

Each transverse joint was dowelled by eight evenly spaced flat plate dowels (300 mm × 50 mm × 6 mm). Information on the reinforcement and dowel location can be seen in Fig. 1. One of the longitudinal edges of the test section was confined by a shoulder. Hence, round tie bars (12 mm ⌀, 1,000 mm long) were positioned at middepth of longitudinal joints. Four tie bars were used in each JPCP and eight in each JRCP. To determine the effects of bonded and partially bonded boundary conditions on pavement responses, half of the test section incorporated a single-layer polyethylene sheet between the slab and subbase (see Fig. 1).

Early age sawing methods with sawing depths less than 0.25d (d = slab depth), should provide better crack control than conventional methods with depths of 0.25 or 0.33d (Zollinger et al. 1994). Therefore, transverse joints were prepared using the early entry sawing method 3 h after the initial set. The width and depth of the saw cuts were 10 and 50 mm, respectively. The width of the saw cut joints allowed easy installation of instrumentation wires across the test section.

An unreinforced shoulder having a 1.5 m width and 250 mm thickness was poured about 15 h after constructing the concrete slabs. It contained five dowelled transverse joints. Four flat plate steel dowels were evenly installed at each transverse joint. Dowel dimensions were similar to those used in the concrete slabs. The transverse joints of the shoulder were also saw cut. To examine the results of the dynamic analyses of smooth concrete pavements carried out by Darestani et al. (2006a), the surface was subsequently floated by a power trowel to enhance the surface smoothness. The average elevation of the top surface layer for the 300 mm interval was 0.55 mm. Further information on the test section can be found elsewhere (Darestani et al. 2006b).

**Instrumentation**

A total of 120 electrical strain gauges (ESGs) and 15 linear displacement transducers (LDTs) were used to investigate the structural response of the test section under static and dynamic loads. Two types of ESGs, embedded and surface, were used. Embedded strain gauges should be fully covered by concrete to accurately measure the induced strains in the concrete slab. Hence, they were installed at a depth of 225 mm from the top surface of the concrete slabs using a rebar chair. The locations of the strain gauges are shown in Fig. 2, while those of the LDTs are shown in Fig. 3.

**Material Properties**

Subgrade CBR was 14%. The average 28-day concrete compressive and flexural strengths were 7.3 and 1.55 MPa for the subbase, 50.5 and 5.45 MPa for the slabs, and 38.5 and 4.1 MPa for the shoulder, respectively.

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**Fig. 1. Layout of the test section**

**Fig. 2. Locations of ESGs**

**Fig. 3. Locations of LDTs**
Truck Characteristics, Movement, and Speed

A semitrailer truck with a gross weight of 477.3 kN was used to apply the traffic load in one direction. This truck had three different axle groups, namely, the single-axle single-tyre (SAST), tandem-axle dual-tyre (TADT), and triple-axle dual-tyre (TRDT) with 60.6, 206.2, and 210.5 kN loads, respectively. Tyre inflation pressure in all tyres was set to be 750 kPa. Exact measurement of the tyre contact area could be done using methods such as the multiple overlay technique (Sharma and Pandey 1996). However, for simplicity, in this study the contact area was determined by measuring the size of the imprint left by the tyre on the top of the slab after spraying paint around the tyre. Information on the truck configuration and tyre pavement contact area are shown in Fig. 4.

The truck was driven along the predetermined locations at various nominal speeds of 5, 20, 35, and 55 km/h. These predetermined locations were close to the free longitudinal edge, close to the confined longitudinal joints, and between them to symmetrically apply the truck loading on both sides of the center line of the test section (Fig. 5). Pavement time history responses under moving truck load were recorded with a frequency of 500 Hz and thrice for each individual speed and position of the applied load to accurately determine the structural responses of the test section. Real truck speeds for each individual channel were finally calculated based on the configuration and distance between the axle groups and pavement time history responses.

Results and Discussion

InField analysis software was used to develop time history responses of the concrete slab, JPCP, and JRCP, under a moving truck load for different locations within the test section. Results were then redrawn to appropriate scales using Microsoft Excel for comparison. The dynamic amplification (DA), which is defined as (dynamic response/static response)-1 × 100, was then calculated for each individual channel and speed. A comprehensive analysis of the captured data has been carried out and the results will appear in another paper. The significant findings, however, can be summarized as follows:

Concrete Slab Deflection

A comparison between slab deflections at the corner and at the midlength of the free edge was first done for results validation as a corner deflection was expected to be greater than the deflection of other locations. Furthermore, for subsequent validation processes, it was also expected that slab deflections along a free edge would be higher than the corresponding deflections along a confined edge.

The results showed that slab deflection decreases from the corner of the free edge towards the midspan and confined edge. Slab deflection at the corner is about 60% greater than those at the middle of the free edge. Concrete slab deflection is strongly affected by truck speed so that dynamic amplification varies between 55 and 313% depending on the pavement type, boundary condition between the concrete slab and subbase, and the location of the measurement. Greater dynamic amplifications occur along the confined longitudinal edge of the test sectional, though the slab deflection values of these points are relatively lower than those along the free longitudinal edge. Fig. 6, as an example of the current study outputs, shows the time history of slab deflections for different speeds at the middle of the free longitudinal edge (DL10, see Fig. 3) in JRCP. The critical truck speed (which creates maximum slab deflection) depends on several factors such as the location of instrumentation and type of pavements. Hence, medium speed in some cases results in greater slab deflection.

A comparison between time histories of slab deflections at the corner of the confined edge (Fig. 7) shows the importance of the dowel position in the depth of the concrete slab. The slab deflection under TADT and TRDT significantly decreases when dowels are positioned at the middepth of the concrete slab. On the other hand, lower slab deflections were observed under SAST loading where dowels were placed close to the top surface layer of the

![Fig. 4. Tyre configuration](image)

![Fig. 5. Longitudinal colored lines to help driver for maintaining the truck](image)

![Fig. 6. Time histories of slab deflection from DL10](image)
concrete slab. Hence, for the flat dowels used in this work, the best dowel location would be at, if not slightly above, the mid-depth of the concrete slab.

**Induced Tensile Stresses**

Tensile stresses are also affected by truck speed. Dynamic amplification of tensile stresses varies between −10.8 and +108.9%. A small number of recorded stress time histories shows a decrease in the magnitude of tensile stresses when truck speed increases. Table 1 presents information on maximum induced tensile stress in the magnitude of tensile stresses when truck speed increases. Table 1 presents information on maximum induced tensile stress in the magnitude of tensile stresses when truck speed increases. While the difference in panel lengths may have contributed to the results (the length of the concrete slab panel in JRCP is about twice the length of the concrete slab panel in JPCP), the reinforcement may also have some effects. Commonly, the recommended position of the longitudinal steel is between one-third and one-half of the depth of the slab as measured from the surface. However, effects of reinforcement location on pavement dynamic tensile stresses in the current study are still unclear at this stage as analyses of time history responses have not lead to a specific conclusion.

A comparison between the results of the current study with those published by AASHO (1962) indicates the significance of the location of instruments in the field test. Note that the strain gauges were traditionally placed only at midlength of the concrete slab between the transverse joints in the AASHO (1962) test sections. However, results of the current study showed that greater stresses may be captured elsewhere within concrete pavement due to dynamic excitations. The critical location depends on several factors including the boundary condition between the concrete slab and subbase, type of concrete pavement, temperature fluctuation, and location of truck loads upon the pavement.

**Table 1. Maximum Induced Tensile Stress and Dynamic Amplification in TCL12 and TCL8**

<table>
<thead>
<tr>
<th>Location of Instrument</th>
<th>Nominal speed (km/h)</th>
<th>Real speed (km/h)</th>
<th>MITS (MPa)</th>
<th>DA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCL12</td>
<td>5</td>
<td>4.74</td>
<td>0.312</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>16.77</td>
<td>0.542</td>
<td>73.72</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>31.27</td>
<td>0.523</td>
<td>76.62</td>
</tr>
<tr>
<td></td>
<td>55</td>
<td>47.05</td>
<td>0.652</td>
<td>108.97</td>
</tr>
<tr>
<td>TCL8</td>
<td>5</td>
<td>4.86</td>
<td>0.585</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>16.35</td>
<td>0.593</td>
<td>1.37</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>33.29</td>
<td>0.79</td>
<td>29.74</td>
</tr>
<tr>
<td></td>
<td>55</td>
<td>41.54</td>
<td>0.694</td>
<td>18.63</td>
</tr>
</tbody>
</table>

Note: NA = not available.

**Finite-Element Model**

A three-dimensional (3D) finite-element model with similar dimensions to the test section was developed using the ANSYS platform (Version 10.0). The model contains three layers, namely,
the concrete slab, cement-stabilized subbase, and subgrade, which is resting on a rigid layer. Solid64 with Drucker–Prager material properties was used to simulate subgrade soil behavior. The length and width of the soil layer were considered to be 2 and 1.5 m larger than the length and width of the subbase layer. This was assumed to avoid applying unnecessary boundary conditions on the side elements as it restricts deformation of the subgrade layer in the longitudinal and transverse directions and may also affect pavement responses. Since results of the soil test were not available at this stage, typical values for this site were used. Hence, a thickness of 1,000 mm, modulus of elasticity (E) of 33 MPa, Poisson’s ratio (ν) of 0.4, cohesion (c) of 0.001 MPa, and angle of internal friction (φ) of 32° were assumed for the subgrade layer.

The subbase layer with 150 mm thickness (E=5000 MPa and ν=0.2) was modeled at the top of the subgrade. As explained earlier in this paper, a polyethylene sheet was positioned along half the length of the test section between the concrete slab and subbase as a debonding layer. This was modeled with a contact pair in the finite-element model with a coefficient of friction of 1.2, a value based on the results of Suh et al. (2002).

Solid65 was used to simulate the concrete behavior in both the concrete slab and subbase. This element is capable of cracking in tension and crushing in compression. The E and ν of the concrete were considered to be 28,000 MPa and 0.2, respectively. The modulus of elasticity of concrete used in the slab and subbase was determined from laboratory compression tests on field-cured cylindrical concrete specimens. Beam elements with bending and shear capabilities were used to simulate dowels and tie bars. Truss elements (link8-3D spar, one-directional element with tensile capability) were used to simulate reinforcement in the JRCP. Saw cuts with 10 mm width and 50 mm depth were modeled at transverse joints (Fig. 8). No boundary condition was applied on the side elements of the slab and subbase.

As mentioned earlier, the real speed of the truck was calculated across each individual instrument, i.e., ESG or LDT, based on the truck dimensions provided in Fig. 4 and the recorded time history for that particular instrument (see Table 1). Since the calculated speeds varied from one instrument to another, a speed of 49.3 km/h was used in the dynamic analysis. The truck was assumed to pass along the free longitudinal edge.

The truck suspension system affects the dynamic response of the concrete slab in the presence of pavement roughness (Liu and Gazis 1999). However, this effect was ignored in the current study as the average elevation of the top surface layer for a 300 mm interval was 0.55 mm. Axle group load was assumed to be equally distributed between axles and then between the wheels. Each of these wheel loads were then distributed between the nodes representing the tyre pavement contact area at the top surface layer of the concrete slab. These nodal loads were then moved along the longitudinal direction of the pavements based on relevant time steps (TS). The TS is the most significant parameter in the transient analysis, which can affect the accuracy of the results. The TS was calculated to be 0.0146 s, which is the time interval between adjacent nodes that a truck with a speed of 49.3 km/h needs to pass along them.

### Validation of the FEA
Since the finite-element model of the concrete pavement contains a variety of elements with different properties and nonlinearities, the validation of the FEM is the most important part of this paper, which needs to be done before further study on dynamic responses of the concrete pavements is undertaken. Two categories were considered as follows:

#### Deflection Validation
The induced slab deflections from finite-element analysis (FEA) are in good agreement with those captured in the test section for a speed close to 49.3 km/h. Note that the truck driver was not able to constantly maintain either the truck wheel path along the predetermined locations or the truck speed during the test. This increases or decreases the recorded value of the slab deflection for some of the LDTs. However, the truck speed was constant in the FEA (i.e., 49.3 km/h). Table 2 presents the experimental and the FEA results for deflection at different locations. It is evident that the two sets of results compare well.

#### Stress Validation
Results of the FEA show that the induced tensile stress is much influenced by the value of the TS. In other words, the considered value of the TS is not small enough to capture the maximum induced tensile stresses for all the points of interest. A comparison between influence lines developed in the FEA for some of the points of interest and the experimentally recorded time histories for a similar location within the test section shows a very good agreement between them. Figs. 9 and 10 show the time histories for stress at BCR3 obtained from the test and the FEA, respectively. A comparison between these time histories indicates that the induced tensile stresses due to SAST and TADT are comparable to those captured in the field test. However, there was a lower induced tensile stress in the FEA for TRDT. This may be due to several factors such as invisible crack initiation, pavement thermal curvature, locations of TRDT on the pavement, and truck

### Table 2. Comparison in Slab Deflection between FEA and the Test Section

<table>
<thead>
<tr>
<th>Location</th>
<th>Real speed (km/h)</th>
<th>Results captured at the test section</th>
<th>Speed in FEA (km/h)</th>
<th>Results of dynamic FEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>DL2</td>
<td>48.7</td>
<td>−0.4</td>
<td>49.3</td>
<td>−0.45</td>
</tr>
<tr>
<td>DR4</td>
<td>48</td>
<td>−0.175</td>
<td>49.3</td>
<td>−0.193</td>
</tr>
<tr>
<td>DL6</td>
<td>43.16</td>
<td>−0.414</td>
<td>49.3</td>
<td>−0.52</td>
</tr>
<tr>
<td>DL7</td>
<td>49.3</td>
<td>−0.645</td>
<td>49.3</td>
<td>−0.642</td>
</tr>
<tr>
<td>DL8</td>
<td>49</td>
<td>−0.608</td>
<td>49.3</td>
<td>−0.617</td>
</tr>
<tr>
<td>DL10</td>
<td>41.25</td>
<td>−0.28</td>
<td>49.3</td>
<td>−0.297</td>
</tr>
<tr>
<td>DR13</td>
<td>34.6</td>
<td>−0.115</td>
<td>49.3</td>
<td>−0.377</td>
</tr>
</tbody>
</table>
speed during the test, which are not considered in the FEM. But as mentioned earlier, the use of a smaller TS, i.e., half of the considered TS, can significantly decrease the difference between the calculated stress in the FEA and that captured in the test section. Note that nonlinear dynamic finite-element analysis of a complex model such as that considered in the current research not only needs a high storage capacity but it also is highly time dependent and needs more than one month to be run if a super computer is used. Hence, the use of a smaller TS, i.e., half of the considered TS, is not economical as it rapidly increases both the solving time and required data storage capacity.

**Conclusion**

A fully instrumented concrete pavement test section was constructed and tested under quasistatic and dynamic truck loadings. Brief information on the test section, instrumentation layout, material properties, and truck characteristics were described. A finite-element model of the test section was developed in the ANSYS platform. The FEM results were validated by comparing with those captured in the test section.

Results from the present test for stress and deflection of the pavement validate the results of the previous research carried out by Darestani et al. (2006a). The significant findings of this study can be summarized as follows:

- Dynamic analysis of the concrete pavement is important as dynamic loads result in greater induced tensile stress and deflection, which can ultimately cause severe deterioration in the concrete slab.
- The results indicate that there is an optimum depth for dowel location, which may minimize joint faulting.
- The validated FEM can be used in further study on those pa-

![Graph](image1.png)

**Fig. 9.** Time history of stress at BCR3 from the test

![Graph](image2.png)

**Fig. 10.** Time history of stress at BCR3 from the FEA
rameters affecting pavement responses such as environmental effects, different boundary conditions between the concrete slab and subbase, and the position of the dowel and reinforcement in the depth of the concrete slab. This will enable the determination of DA for different conditions, which can be used in the concrete pavement design guides to minimize deteriorations of the concrete slabs.

Acknowledgments

The original work of this study was sponsored by the Queensland University of Technology (QUT), Australia, and Rinker Australia under R&D Project RD835. The writers wish to acknowledge this support and to thank Mr. Glenn Carson for help with project planning and execution.

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