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IMPACT OF FARM EQUIPMENT LOADING ON LOW-VOLUME CONCRETE ROAD STRUCTURAL RESPONSE AND PERFORMANCE

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Abstract. The rapid increase in farm equipment size in the United States of America agricultural industry has raised significant concerns regarding its impact on the low-volume road infrastructure. The study described in this paper investigated the impact of heavy farm equipment (or agricultural vehicle) on the structural behaviour of rigid pavement system. A series of full-scale traffic tests were conducted at the Minnesota's Cold Weather Pavement Testing Facility (more commonly known as MnROAD) on two existing low-volume rigid pavement sections: (1) to study the effects of agricultural vehicle and weights, traffic wander pattern, pavement structure, and environmental factors on rigid pavement responses (deflections, strains and stresses), and (2) to compare these responses with those of a standard 356 kN (80 kips) five-axle, semi-trailer truck for assessing relative rigid pavement damage caused by heavy farm equipment. Numerical analyses were also carried out for rigid pavement fatigue damage estimations by simulating field test conditions. The Finite Element Model was able to predict rigid pavement responses under complicated heavy agricultural farm equipment loading. The study findings revealed that seasonal change, traffic wander, vehicle loading/configurations, pavement thickness, slab length and modulus of subgrade support are all important factors to be considered in designing rigid pavement subjected to heavy farm equipment loading. The use of tandem or tridem axles is recommended for all farm equipment because those axles help to distribute the load and minimize rigid pavement damage.

Keywords: concrete, farm equipment, finite element, full-scale tests, pavement, structural responses.

1. Introduction

Over the past decade, the average farm size in the USA is increasing as the number of farms is decreasing. This trend has led to increased agricultural production per individual farm. To have higher efficiency in the farm industry, the farm equipment or agricultural vehicles is simultaneously becoming larger to transfer more agricultural products from individual farms. This rapid shift in farm equipment size has raised concerns about their potential to cause significant damage to road infrastructure.

A limited number of studies (Fanous *et al.* 2000; Oman *et al.* 2001; Phares *et al.* 2005; Sebaaly *et al.* 2002) appear in the literature addressing the pavement damage issue caused by heavy farm equipment. However, the results of these previous studies were inconclusive in drawing correspondence between farm equipment type and loading to specific pavement distresses. The latest reported study conducted in 2005 (Phares *et al.* 2005) recommended a comprehensive investigation, including a detailed field study, to better document the impact of farm

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equipment on low-volume roads. Additionally, there was not enough information available to quantitatively estimate the pavement damage caused by heavy farm equipment.

A pooled-fund study *Effects of Implements of Husbandry (Farm Equipment) on Pavement Performance* (Lim *et al.* 2012) was initiated in early 2007 to gain a better understanding of the interaction of farm equipment with the pavement structures in the USA especially in the Midwest region including Minnesota, Iowa, Illinois, and Wisconsin. The overall objectives of this pooled fund study were to determine the pavement responses under various types of farm equipment and to compare these responses with a standard five-axle, semi-trailer truck. A wide range of vehicle types, axle load magnitudes, tire type, and vehicle wander patterns was used to determine the effect of farm equipment loading on pavement structures through a full-scale test program. A detailed description of this pooled-fund study is presented elsewhere (Lim *et al.* 2012).

The study reported in this paper, a subset of the pooled-fund study, focused on investigation of the effects of heavy farm equipment loading on rigid pavement performance through both field work as well as numerical analysis. Note that the previous studies reported in the literature have mainly focused on flexible pavement in this regard. Two instrumented Portland cement concrete (PCC) pavement sections at the Minnesota's Cold Weather Pavement Testing Facility (MnROAD) were utilized to determine pavement responses generated by various types of farm equipment including a grain cart (G), a Terragator (R), a straight truck (S), and a tanker (T). An additional standard semi-trailer truck (Mn80) was included in the test program to be used as a reference (control) vehicle for determination of relative damage caused by farm equipment. Pavement response data collected were analysed to identify the effects of vehicle types, vehicle weight, traffic wander pattern, pavement structure, and environmental factors on pavement responses under heavy farm equipment loadings. The results of experimental and analytical work are discussed in this paper highlighting the significant impact of farm equipment or agricultural vehicles on rigid structures under different traffic loading and environmental conditions.

2. Overview of full-scale test program

2.1. Test sections

Two PCC pavement sections at the MnROAD test facility were utilized to determine pavement responses generated by various types of agricultural vehicles and a typical five-axle semi-trailer truck. MnROAD is a full-scale accelerated pavement testing facility that gives researchers a unique, real-life laboratory to study and evaluate pavement performance (Snyder 2009). MnROAD is located along Interstate 94 (I-94) from about 64 km (40 miles) northwest of Minneapolis/St. Paul. It contains more than 50 test cells on three different segments including a portion of I-94. The cells represent a high traffic volume road and a low traffic volume road loop. Each testing cell is approximately 152 m (500 ft) long and varies from types of subgrade, aggregate base, and surface material to roadbed structure and drainage methods.

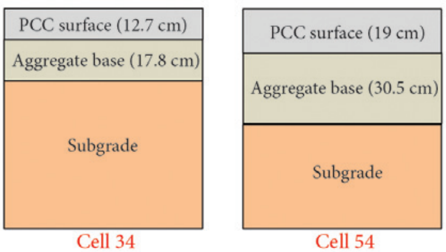

Fig. 1. Schematic cross-section of rigid pavement sections tested (not to scale)

The rigid pavement sections used for testing were cell 32 and cell 54 of the low-volume loop at the MnROAD test facility. Cell 32, representing thin PCC pavements, consists of 12.7 cm (5 in) thick concrete slab over 17.8 cm (7 in) thick gravel base while cell 54 (representing thick PCC pavements) consists of 19 cm (7.5 in) thick concrete slab over 30.5 cm (12 in) thick gravel base (Fig. 1). It is arguable that these thicknesses are not represent the whole of USA, but only the Midwest region. Note that the focus of the study was on testing low-volume road pavements. The PCC slab panel lengths are 3 m (10 ft) for cell 32 and 4.6 m (15 ft) for cell 54. The PCC slab panel width of both cells is 3.6 m (12 ft). Cell 32 does not have dowel bars, but cell 54 has 2.54 cm (1 in) dowel bars in the transverse joints. Granular shoulders were adjacent to both lanes of cell 32 and cell 54. Both cells have strain gages instrumented at various locations to measure strain responses under loads. Cell 54 also has linear variable differential transformers (LVDTs) at the edge of the concrete slabs to measure vertical deflection responses.

Data acquisition was accomplished with various types of electronic data collection equipment at MnROAD. All sensors embedded into each test cell were wired into the data acquisition system. The MnROAD data acquisition system was set up in such a way that it begins to record response measurements when a test vehicle approaches a testing cell and passes a trigger. These systems collected response measurements at a rate of 1200 data points per second (1200 Hz) and each vehicle pass typically has a collection time of 15 s to 18 s. Approx 18 000 to 22 000 data points per sensor were recorded under one vehicle run. Lim *et al.* (2012) provided a more detailed description of the instrumentation and data acquisition system in both cells.

2.2. Test vehicles

A total of seven field test runs with various types of test vehicles were conducted from 2008 to 2010. Two rounds of testing in each year were conducted, one during spring when pavement experiences freeze-thaw environments and another during fall when agricultural vehicles operate at a higher frequency. For each round of testing, a test program was developed to include a range of vehicle load levels (weights), target wheel path (wander distance) and redundancy of vehicle passes in order to obtain a more complete and repeatable data set. However, the number of vehicle passes was governed by time and manpower constraints.

Table 1. Five representative test vehicles analysed

Vehicle ID	G1		R6		T6		S5		Mn80
Testing Round	Fall 2010		Spring 2010		Fall 2010		Spring 2009		All
Type/Volume	Grain cart/1000 bushels		Terragator/4200 gal		Tanker/6000 gal		Straight Truck/4400 gal		Standard Semi-trailer Truck
Number of total axles/rear axles	3/1		2/1		4/2		3/2		5/2
Load level	0%	100%	50%	100%	0%	100%	50%	80%	356 kN
Axle 1 weight, t	5	5	13	15	5	5	6	7	5
Axle 2 weight, t	7	9	13	19	8	10	6	9	8
Axle 3 weight, t	5	26			3	11	7	9	8
Axle 4 weight, t					4	14			7
Axle 5 weight, t									8
Total weight, t	17	40	26	34	20	40	19	25	36

A total of twelve agricultural vehicles were tested throughout the duration of project. Each agricultural vehicle had 0% (empty), 50% (half-loaded), 80% or 100% (fully-loaded) loading during testing. In addition, a standard semi-trailer truck was included in the test program to be used as the reference (control) vehicle. This semi-trailer had a gross vehicle weight of 356 kN (80 kips) and labelled as "Mn80". Again, detailed descriptions of all test vehicles are provided by Lim *et al.* (2012).

The test vehicles were categorized into five groups: a grain cart, a Terragator, a straight truck, a tanker and a standard semi-trailer truck. The heaviest vehicle in each group was utilized as the representative vehicle for the analysis in this paper. Table 1 lists the total vehicle weights along with axle loads for five representative vehicles labelled as G1 representing the grain cart, R6 – the Terragator, S5 – the straight truck, T6 – the tanker, and Mn80 – the standard semi-trailer truck. The dimensions of these vehicles are presented in Fig. 2.

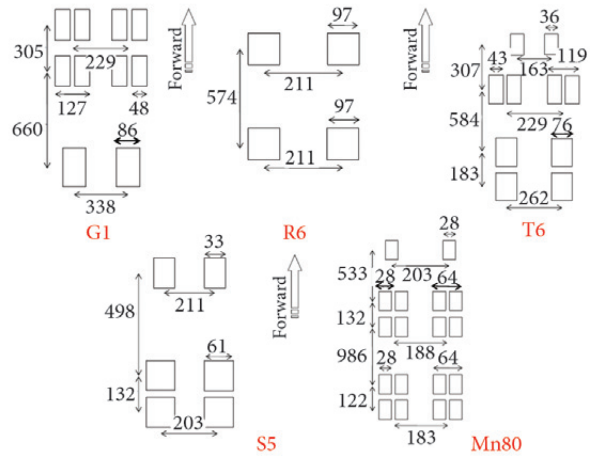

Fig. 2. Dimensions for test vehicles (dimension unit – cm; not to scale)

2.3. Traffic wander characterization

An exact account of the traffic wander was required since the lateral movement of the passing vehicle tires dictates where the loads were placed (Buiter *et al.* 1989; Willis, Timm 2008). The test vehicles were directed to travel at 0 cm (0 in), 30.5 cm (12 in) and 61 cm (24 in) of traffic wander distance defined as the distance from the pavement edge to outside wheel edge. The actual traffic wander distance were some different from the target distance. To provide the necessary precision for interpreting the data, the actual vehicle wander positions were measured. Length scales were installed to help the vehicle drivers properly align the vehicle tires on the desired distance. Video cameras were placed at each test section to record the vehicles' actual position at the time each vehicle passing the scale. Videos were reviewed afterward and the exact traffic wander position of each vehicle pass was determined.

For consistency in analysis of sensor data, traffic wander pattern was also characterized in terms of relative offset to sensor defined as the distance from the centre of the rear wheel to the sensor location. Since the sensor location is known, relative offset for a specific vehicle run for a specific sensor is calculated as: (traffic wander distance) – (sensor location) + (one-half the tire width). A positive value of relative offset means that the wheel was driven toward the centreline of the pavement while a negative value of relative offset means that the wheel was driven toward the pavement shoulder. Fig. 3 illustrates how vehicle traffic wander patterns were characterized in terms of traffic wander distances.

Fig. 3. Traffic wander characterization

a – aggravated corner break during spring 2010 b – additional corner break during spring 2010 c – logitudinal cracking after fall 2010

Fig. 4. Pavement distress observed nearby cell 32

2.4. Data mining: Peak-Pick analysis

Large amount of data points were collected from all installed sensors when one vehicle passed. A data mining process was necessary to extract the desired responses from properly functioning sensors. To achieve this, a Peak-Pick program developed for Minnesota Department of Transportation (MnDOT) by the University of Minnesota researchers was employed. Peak-Pick analysis was performed on data collected from all sensors with two available analysis modes (automatic and manual Peak-Pick mode). In automatic mode, Peak-Pick automatically locates peaks and troughs (maximum and minimum) values from the time-history response measurements of properly functioning sensors. However, there were some occasions when Peak-Pick automatic mode did not detect the peaks and troughs.

The sensor measurements that were not analysed by Peak-Pick in automatic mode were reviewed under the manual mode. In the manual mode, the Peak-Pick user manually picks the peaks of the time-history response measurements. Improperly functioning sensors were determined when no trace of the response was found or the response was too noisy. The response measurements from improperly functioning sensors were excluded from the data analysis. A *Microsoft Excel's Visual Basic for Application* (*Excel Macro*) was also employed to automatically summarize Peak-Pick analysis results. Further elaboration of the information related to the Peak-Pick program it is possible to find in *MnROAD Offline Data Peak-Picking Program User Guide* of 2007.

3. Pavement distress monitoring

After each round of testing, manual distress surveys were conducted. The first observed distress was the corner break in cell 32 (12.7 cm or 5 in PCC slab) during the fall 2009 field testing cycle. This corner crack was aggravated during the spring 2010 test cycle as shown in Fig. 4a. Additional new corner cracks (Fig. 4b) were observed in cell 32 during spring 2010. These corner cracks were due to the bending of the concrete slab and lack of the subgrade support as well as the heavy loading of test vehicles. Water was also responsible for all those corner breaks because pumping occurred while test vehicle were traveling through those pavement joints. As the vehicle approached the joint, the tire pushed the concrete slab downward. Water accumulating underneath the concrete pavement slab was then extruded upward. The extruded water brought fine soil particles with them and therefore left a hollow space underneath the concrete slab.

In addition to previously observed corner cracks, longitudinal cracking (Fig. 4c) was observed on a slab nearby cell 32 after fall 2010 field testing cycle. The investigation using finite element analysis indicated that the upward slab curling from the built-in temperature gradient increased the bending stress on top of the slab (Wang *et al*. 2011). The increase in the bending stress on top of the slab has led to these surface cracks. No significant distress was observed in cell 54 representing thick PCC pavements (19 cm or 7.5 in PCC slab) in this study.

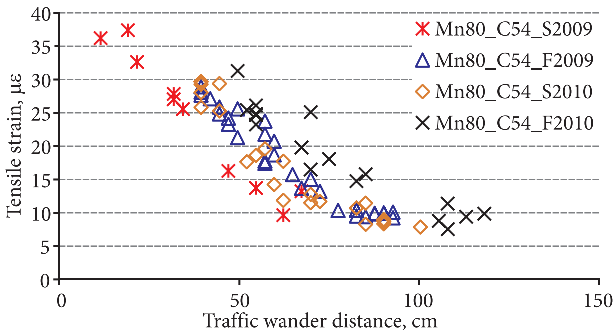

Fig. 5. Effect of testing seasons and traffic wander on tensile strains at the bottom of the PCC slab near mid-slab edge

4. Analysis of field testing data

An evaluation of relative pavement damage induced by five representative test vehicles was conducted by comparing measured critical pavement responses (strain and deflection) generated by these vehicles. The analysis results presented in this paper were based on a comparison of measured responses near mid-slab edge which are recognized as critical location for fatigue damage on rigid pavements. Other factors affecting pavement responses are also discussed.

4.1. Effect of seasonal variation and traffic wander

Test vehicles were selected based on availability, application frequency, and recommendations by the farm equipment industry. Ideally, each test vehicle has been tested at the same time. However, due to availability constraints, this was not fulfilled. Mn80 was used as the control vehicle during all testing rounds. Therefore, Mn80's pavement responses were used as the reference measurements to evaluate the effects of seasonal condition on pavement responses. Seasonal conditions incorporated in test program include spring weather condition when pavement experiences freeze-thaw environments and fall weather condition when agricultural vehicles operate at a higher frequency.

Fig. 5 presents the comparisons of the tensile strain responses at the bottom of the PCC slab near mid-slab edge produced by Mn80 during spring 2009, fall 2009, spring 2010 and fall 2010, respectively. In these comparisons, strain responses produced by Mn80 during spring 2009 are slightly lower than those produced during other seasons. Strain responses produced by Mn80 during fall 2010 are slightly higher than those produced in the other seasons. It has been recognized that frozen base and subgrade layers have higher stiffness and thawing base and subgrade layers have lower stiffness (Christopher *et al.* 2006; Dempsey, Thompson 1973; Janoo, Berg 1990, 1998). Although the spring test programs designed in this study were expected to represent weakest state experiencing freeze-thaw cycle, the base and subgrade layers were still experiencing freezing at the time of field testing due to prolonged harsh winter conditions. Therefore, strain responses observed during spring test program did not exhibit higher measurements. However, the results still demonstrated that the seasonal conditions have an effect on the pavement responses.

The pavement strain responses produced by Mn80 decreased when traffic wander distances increased up to about 51 cm (20 in). As the traffic wander distances exceeded 51 cm (20 in), strain produced during all seasons became identical. This result demonstrated that traffic wander have a pronounced effect on the pavement responses. Rigid pavement damage was reduced to minimal if the vehicle was driven 0.5 m (1.5 ft) to 0.6 m (2.0 ft) away from PCC slab edge.

4.2. Effect of vehicle type and weight

Fig. 6 compares tensile strain responses from farm equipment tested in this study at different load levels to the reference Mn80 under same test (seasonal) periods. As a general trend, an increase in vehicle weight leads to an increase in pavement responses. However, the magnitude of increase in the maximum tensile strain is not proportional to the increase in the load level. This is attributed to the complexity of the agricultural vehicle's configuration. Another factor related to this trend is that the increase in gross vehicle weight is not proportional to the increase in each axle weight (Table 1).

G1 with 100% loading produced the highest tensile strain responses among all five vehicles. This is attributed to higher rear axle weight of G1 than the other vehicles when G1 is fully loaded. R1 with 100% loading produced slightly higher tensile strain responses than Mn80. However, T6 with 100% loading and S5 with 80% loading did not produce higher tensile strain responses than Mn80. Agricultural vehicles tested in this study produced lower tensile strain responses than Mn80 when they were empty (G1 and T6) or partially loaded (R6 and S5). Similar to Mn80 vehicle traffic wander effect, rigid pavement damage was reduced to minimal even when agricultural vehicles were fully loaded if these vehicles were driven 0.5 m (1.5 ft) to 0.6 m (2.0 ft) away from PCC slab edge.

Fig. 7 compares vertical deflection responses from G1 and T6 at fully-loaded and empty conditions to Mn80

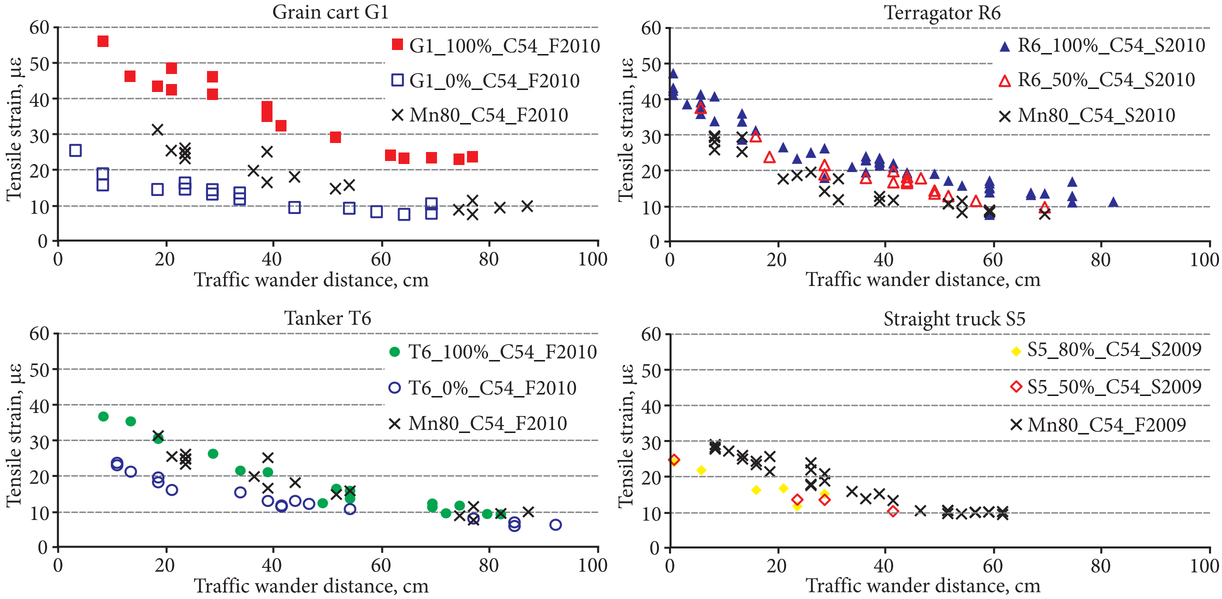

Fig. 6. Effect of vehicle type and weight on tensile strains at the bottom of the PCC slab near mid-slab edge

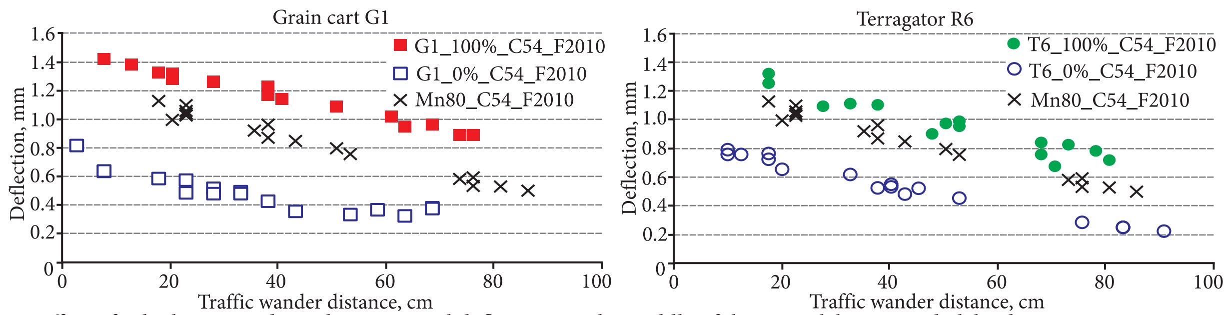

Fig. 7. Effect of vehicle type and weight on vertical deflections at the middle of the PCC slab near mid-slab edge

under same test (seasonal) periods. Similar to findings from previous comparisons, G1 with 100% loading produced higher vertical deflections and both empty agricultural vehicles produced lower vertical deflections than Mn80. However, T1 with 100% loading produced higher vertical deflections than Mn80.

4.3. Effect of tire type

The use of flotation tires in agricultural vehicle are becoming increasingly popular due to its wider footprint and lower inflation pressure which allows the vehicle to travel over soil and unbound aggregate material with minimal compaction and deformation (Lim *et al.* 2012). An issue arose as to whether this characteristic was translated directly to rigid pavement performance.

Two similar straight trucks with the same tank capacity of 4400 gallons were fitted with two different tire types. S5 was with flotation tires and S4 was fitted with regular radial ply dual tire configuration. Fig. 8 compares the axle weight and the tensile strain responses produced by both straight trucks at 50% and 80% loading. The S5 with flotation tires produced slightly lower axle weight and tensile strain responses than S4 with radial tires. However, these lower measurements from S5 with flotation tire did not provide significant benefits to rigid pavement performance.

4.4. Effect of PCC pavement structure

As stated previously, two rigid pavement sections were utilized to evaluate the effect of PCC pavement thicknesses on pavement responses. The tensile strain responses for G1 and T6 at fully-loaded (100%) and empty (0%) conditions were compared between cell 32 (thin section) and cell 54 (thick section) along with the responses from Mn80. Fig. 9 presents these comparisons. The thicker PCC slab thickness (cell 54) resulted in lower tensile strains than the thinner PCC slab thickness (cell 32) when both G1 and T6 were fully loaded. However, less significant reduction in tensile strain responses were observed for cell 54 in comparison to the cell 32 when both G1 and T6 were empty and Mn80 travelled.

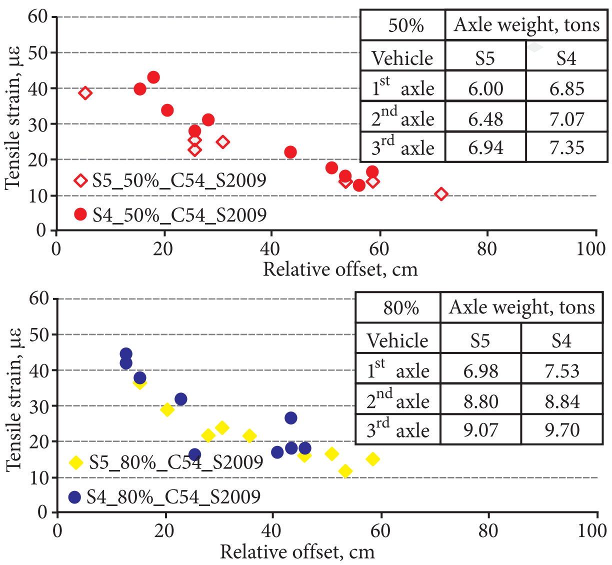

Fig. 8. Effect of tire type on tensile strains at the bottom of the PCC slab near mid-slab edge (S5 is fitted with flotation tires and S4 is fitted with radial tires)

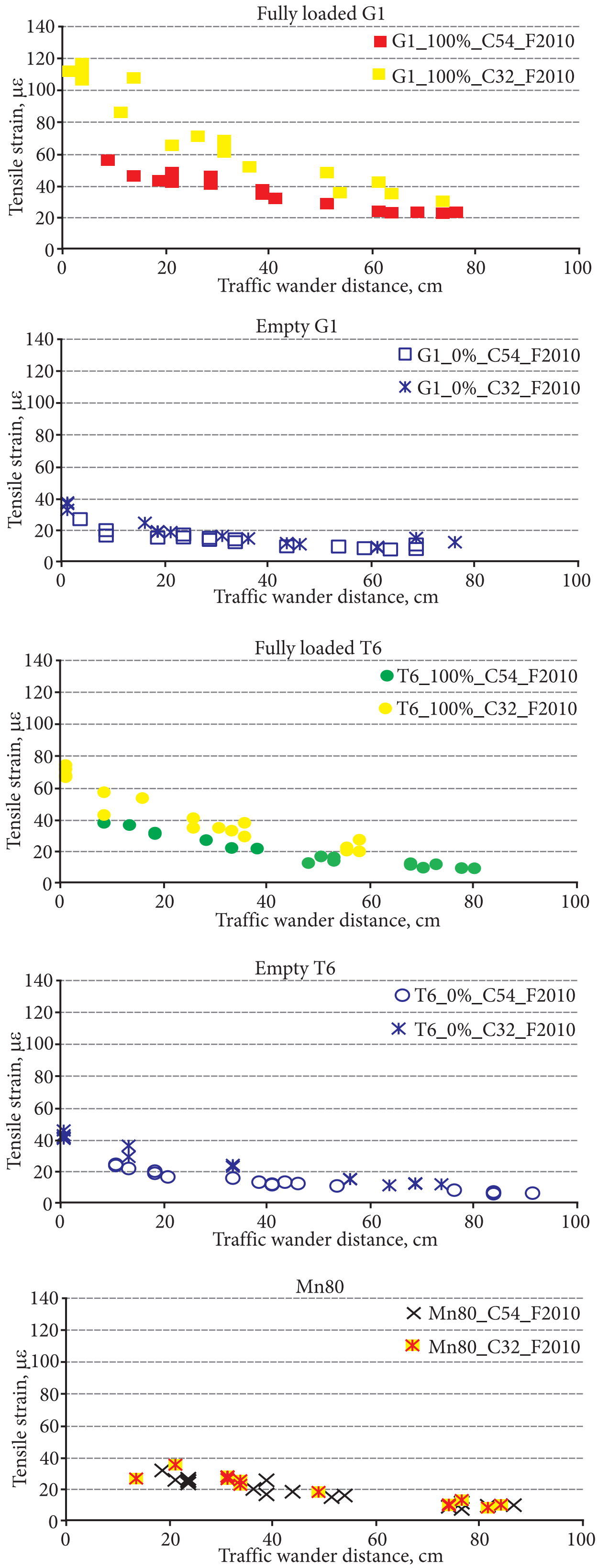

Fig. 9. Effect of PCC pavement structure on tensile strains at the bottom of the PCC slab near mid-slab edge

5. Numerical simulation for fatigue damage characterization

Although the full-scale testing provided a wealth of information on pavement responses produced by each farm equipment in comparison to Mn80, all agricultural vehicles were not tested under exactly similar conditions due to test vehicle availability constraints. To address this limitation, numerical simulations using Finite Element Model (FEM) was conducted to estimate rigid pavement fatigue damage resulting from agricultural vehicles. Many fatigue models for concrete pavement have been developed using field and laboratory data. Most of these models relate the stress ratio, the ratio of the tensile stress to the PCC modulus of rupture (MOR), to estimate the number of loads until failure for fatigue damage estimations. For consistency in evaluation, this study utilized the stress ratio as an evaluation index for fatigue damage characterization. It is speculated that fatigue damage is expected to occur to the PCC slab if the stress ratio is over 0.5 in accordance to *Pavement Analysis and Design* of 1993 by Yang H. Huang.

An *ISLAB2005* was utilized to estimate the critical pavement stress produced by full loaded agricultural vehicles (G1, R6, T6, and S5) and Mn80 on cell 32 (thin PCC section) and cell 54 (thick PCC section). The *ISLAB2005* is a FE based structural analysis program specially developed for rigid pavement analysis by *Applied Research Associates, Inc.* in the United States of America. It has been utilized by many previous studies (Hansen *et al.* 2002, 2006; Heath *et al.* 2003; Jeong, Zollinger 2005; Kim *et al.* 2011; 2014) to investigate rigid pavement behaviours under various load conditions.

The *ISLAB2005* allows the user to manually define rigid pavement layer properties, vehicle loading with wheel configuration, and the number of the nodes. A set of required inputs was prepared from field testing program and sensitivity analysis results. Detailed description of input preparation for the *ISLAB2005* is available in Wang (2011). The PCC MOR estimated from compressive strength and elastic modulus was 4826 kPa (700 psi) based on the PCC strength and stiffness correlation specified in the *AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG)* of 2008.

Fig. 10 presents the stress ratio comparisons for fully-loaded agricultural vehicles and Mn80 on cell 32 and cell 54. All fully-loaded agricultural vehicles exhibited higher stress ratios than standard semi-trailer truck on both cell 32 and cell 54. Since higher stress ratio indicates higher fatigue damage potential, G1 has the highest fatigue damage potential, followed by R6, T6, and S1. All examined test vehicles have higher potential to induce fatigue failure in thinner PCC section (cell 32) than in thicker PCC section (cell 54).

6. Summary and conclusions

A full-scale traffic test program was conducted under a pooled-fund study to investigate the effects of farm (agricultural) vehicles on rigid pavement performance. Key observations from this study are as follows:

1. The field experiment demonstrated that the pavement structural characteristics, axle weights, seasonal effects, traffic wander, and vehicle type/configuration have a pronounced effect on the rigid pavement responses.

2. In comparison to the standard 356 kN (80 kips) five-axle semi-trailer truck (Mn80), higher levels of tensile strains at the bottom of the Portland cement concrete slab near mid-slab edge were caused by a fully-loaded 1000 bushel grain cart and a fully loaded 4200 gallon Terragator. However, fatigue damage estimations through numerical simulations indicate that a fully loaded tanker and a fully loaded straight truck also have higher potential to induce fatigue damage rather than the standard 356 kN (80 kips) five-axle semi-trailer truck (Mn80).

3. Several corner breaks were observed in the 12.7 cm (5.0 in) thick Portland cement concrete pavement section (cell 32) which were further aggravated by increased traffic loading causing pumping and loss of subgrade support. However, no significant distress was observed in the 19 cm (7.5 in) thick Portland cement concrete pavement section (cell 54) which is relatively thicker than cell 32.

4. The thicker Portland cement concrete slab (cell 54) resulted in lower tensile strains than the thinner Portland cement concrete slab (cell 32) when the grain cart was fully loaded. However, less significant reduction in tensile strains was observed in cell 54 compared to cell 32 when grain cart was empty.

5. Straight truck with flotation tires produced slightly lower axle weight and tensile responses than the one with radial tires. However, these lower measurements from straight truck with flotation tires did not provide significant benefits in terms of rigid pavement performance.

6. Analysis of measured and simulated pavement responses demonstrated that pavement damage was reduced to minimal even when farm equipment was fully loaded if the vehicle is driven 0.5 m (1.5 ft) to 0.6 m (2.0 ft) away from the edge of the Portland cement concrete slab.

7. The field experiment confirmed that pavement responses are governed mainly by axle weight, not gross vehicle weight. Hence, increasing the number of axles is beneficial, although it is important to ensure even load distribution among axles.

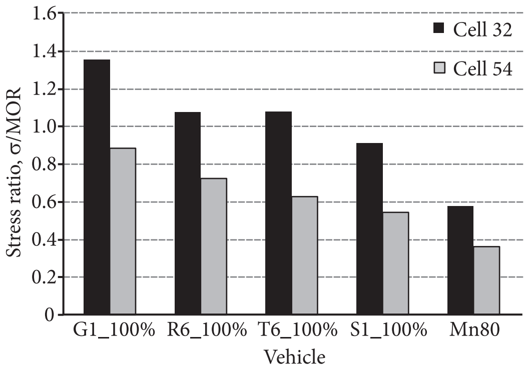

Fig. 10. Fatigue damage (stress ratio) comparisons for examined test vehicles

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