Response of Iowa Pavements to Heavy Agricultural Loads

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IOWA STATE UNIVERSITY

Iowa Department of Transportation

Response of Iowa Pavements to Heavy Agricultural Loads

Interim Report

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EXECUTIVE SUMMARY

Iowa's county road system includes several thousands of miles of paved roads which consist of portland cement concrete (PCC) surfaces, asphalt cement concrete (ACC) surfaces, and combinations of thin surface treatments such as seal coats and slurries. These pavements are relatively thin pavements when compared to the state road system and therefore are more susceptible to damage from heavy loads for which they were not designed. As the size of the average farm in Iowa has increased, so have the size and weights of implements of husbandry. These implements typically have fewer axles than a truck hauling the same weight would be required to have; in other words, some farm implements have significantly higher axle weights than would be legal for semi-trailers. Since stresses induced in pavements are related to a vehicle's axle weight, concerns have been raised among county and state engineers regarding the possible damage to roadway surfaces that could result from some of these large implements of husbandry.

Implements of husbandry on Iowa's highway system have traditionally not been required to comply with posted weight embargo on bridges or with regulations regarding axle-weight limitations on roadways. In 1999, with House File 651, the Iowa General Assembly initiated a phased program of weight restrictions for implements of husbandry.

To help county and state engineers and the Iowa legislature understand the effects of implements of husbandry on Iowa's county roads, the following study was conducted. The study investigated the effects of variously configured grain carts, tank wagons, and fence-line feeders on Iowa's roadways, as well as the possible mitigating effects of flotation tires and tracks on the transfer of axle weights to the roadway. The study was accomplished by conducting limited experimental and analytical research under static loading conditions.

A section of an ACC pavement on County Road K52 in Sioux County and a section of a PCC pavement on E-29 in Jones County were instrumented for testing and were analyzed under different loading types. The pavements selected were instrumented to measure strains, temperature, and moisture. These sensors were installed during construction. Instrumentation was positioned as close as possible to areas that typically resist high tension stresses due to vehicle traffic. In the PCC pavement, these areas are near the surface at the joint/edge corners and near the bottom along the pavement edge. In the ACC pavement, the sensors were attached to the top of the first lift or about 3 inches up from the sub-grade and under the wheel path. The pavements were tested at crawl speeds, less than 5 mph, under vehicle-of-husbandry and standard-truck loads. Data were collected at 100 samples per sensor per second. Tape switches were also positioned on the pavement surface during testing so that vehicle position could be determined in correlation with the collected data. The data were then used to calibrate and verify the analytical models.

The two pavement types were analyzed under the loads used in the test. The analyses were accomplished using simplified methods. Finite element analyses were also conducted to verify the simple analysis results of the PCC pavements. Soil-pavement interaction was included in the finite element analyses utilizing plate on dense liquid foundation theories. The sensitivity of the results to the size elements was investigated. To gain confidence in the analytical

modeling, the results were compared to those obtained from the field test. Some discrepancies between the analytical and the field test results were noticed. These most likely were due to the uncertainty of the values of the parameters, such as the soil sub-grade reaction, and the actual elastic modulus and the thickness of the pavement. In spite of this discrepancy, both analytical and field test results revealed similar behaviors for the PCC and ACC pavements. Three additional PCC and ACC pavements with different thicknesses and under different loading configurations and seasonal conditions were also analyzed. PCC pavements with thicknesses of 7, 8, and 9 inches and ACC pavements with thickness of 8 inches, along with typical design values of sub-grade reactions and pavement material properties, were considered. The dual-wheeled, single-axle configuration (20,000-lb) was taken as the reference loading. The critical strain or stress calculated under this load was taken as the reference response. The other tire/axle configuration weights and consequently the tire-pavement contact areas were varied until the program indicated the same critical response as the reference loading had been returned.

The analyses illustrated that during the spring season, a single-axle, single-tire grain cart or liquid manure tanks ("honey wagons") with flotation tires and an axle load of approximately 24,000 lb. would have the same effect on ACC pavements as that caused by a 20,000-lb.,single-axle, dual-tire semi-trailer. During the fall season, this load capacity was increased to 28,000 lb. due to the seasonal change in the soil sub-grade reaction. In addition, the increase of the axle weight of multiple-axle wagons was insignificant. This was expected, since the spacing between the axles is large enough compared to the pavement thickness. In other words, one can analyze the behavior of a pavement structure under multiple axles by considering each axle separately. Similar behavior was observed when analyzing the PCC pavements. However, a slight increase in the axle load was obtained when considering the fall condition. This can be attributed to the difference in the behavior of the flexible ACC and rigid PCC pavements.

The field test and the analytical results demonstrated that tracked vehicles induce lower stress or strain values in both PCC and ACC pavements when compared to other loads. However, these results must be interpreted with caution since the analysis assumed that the load of these vehicles is transferred to the pavement uniformly over the track-pavement contact area rather than at discrete locations along the lugs of the track. Exact load path to pavement must be carefully investigated prior to making firm conclusions regarding the benefits associated with these types of implements.

1. BACKGROUND

Iowa's county road system includes 15,505 miles of paved roads which consist of portland cement concrete (PCC) surfaces, asphalt cement concrete (ACC) surfaces, and combinations of thin surface treatments such as seal coats and slurries. The predominant load-related distress type for rigid (i.e., PCC) pavements is cracking through fatigue, while rutting and fatigue cracking are the distress types in ACC pavements. County pavements are typically relatively thin when compared to the pavements in the state roadway system and therefore are more susceptible to damage from heavy loads for which they were not designed.

As the size of the average farm in Iowa has increased, so have the size and weights of implement of husbandry. This is represented by the larger grain carts and wagons that are being produced and used. A similar trend is occurring in the hog finishing industry that resulted in the use of larger liquid manure tanks, sometimes referred to as honey wagons. These implements typically have fewer axles than a truck hauling the same weight would be required to have. The result is significantly higher axle weights on some implements of husbandry than would be legal for a semi-trailer. Since stresses induced in pavements are related to a vehicle's axle weight, concerns have been raised among county and state engineers regarding the damage to county roadways that could result from some of these large implements of husbandry now in use.

Implements of husbandry on Iowa's highway system have traditionally not been required to comply with posted weight embargoes on bridges or with regulations regarding axle-weight limitations on roadways. For the last several years, state and county officials have worked together to bring to the attention of equipment manufactures and the legislature the impacts and the consequences that some of these implements could have on Iowa's roads and bridges.

With House File 651, in 1999 the Iowa General Assembly initiated a phased program of weight restrictions for implements of husbandry. First, effective July 1, 1999, all targeted implements of husbandry (fence-line feeders, grain carts, and tank wagons) must comply with weight restrictions posted on bridges. Second, targeted implements of husbandry manufactured on or after July 1, 2001, must be within 20 percent of commercial vehicle axle weight restrictions to travel legally on Iowa's roadways. Finally, all targeted implements of husbandry must be within 20 percent of commercial vehicle axle weight restrictions by July 1, 2005.

The phase-in schedule for compliance of vehicles of husbandry with axle-weight restrictions gives the legislature time to more carefully study axle-weight issues. To help the legislature in its task, the following study was conducted to investigate the effects of variously configured grain carts, tank wagons, and fence-line feeders on Iowa's roadways, as well as the possible mitigating effects of flotation tires and tracks on the transfer of axle weights to the roadway.

2. OBJECTIVE

The overall objective of this study was to determine the effects of the above listed implements of husbandry on Iowa's paved county roadways. A full study to determine the relative damaging power of different vehicle configurations on a wide array of pavement structures would require several years. This type of study should consider the seasonal variations in the material of the supporting soil properties, the dynamic characteristics of an implement, roughness of the pavement surface, non-linear nature of pavement and soil materials, and the uncertainty associated with these variables. Such a full study was clearly impossible to accomplish given the time constraints of this study. Therefore, the work presented herein serves to provide only preliminary results based on limited experimental and analytical work under static loading, i.e., crawling moving loads.

3. PAVEMENT SELECTION FOR TESTING

After consultation with the Office of Local Systems at the Iowa Department of Transportation, researchers identified several pavements that were to be constructed from July through September 1999 as candidates for instrumentation in this study. Two flexible and five rigid pavements with different thicknesses were identified. Factors such as geographic locations and the availability of loading vehicles and loads were considered in the final selection of two pavements for testing. An ACC pavement on County Road K52 in Sioux County and a PCC pavement on E-29 in Jones County were selected for instrumentation, testing, and analysis under different loading types.

4. INSTRUMENTATION OF THE PCC AND ACC PAVEMENTS

The pavements selected were instrumented to measure strains, temperature and moisture. For this purpose strain gages, thermocouples and moisture sensors were installed during construction. The strain gages were placed near the top and bottom surfaces of the PCC pavement. In the ACC pavement, the gages were located near the neutral axis. Locations of the strain gages depend on number of variables. These include the pavement material modulus of elasticity, Poisson ratio, depth of pavement, and the modulus of the soil sub-grade reaction.

4.1 PCC Pavement Instrumentation

County Road E29 in Jones County, Iowa, was scheduled to have a complete PCC pavement constructed in August of 1999. This seven-mile stretch extends from Onslow, Iowa, to Monmouth, Iowa, in Jackson County. The section was a nominal 22-ft. wide and 15-ft. long. The thickness, h, was nominally seven inches across the complete section. Concrete compressive strength at the time of testing was 7533 psi., determined from three cylinder tests made during construction and tested at the Iowa State University structural engineering laboratory. A concrete core was removed from the pavement within the test section by the pavement by the Iowa Department of Transportation and measured to be 7¾ inches.

The gage locations were determined using procedures outlined in "Principles of Highway Engineering and Traffic Analysis" (Mannering, and Kilareski 1990). Assumptions made include a modulus of elasticity, E, equal to 4.5×10^6 psi, a modulus of sub-grade reaction, k, equal to 230 pci which was measured, and a Poisson ratio, μ, of 0.18. Substituting these values into equation 1 results in a radius of relative stiffness, l, equal to 27.5 inches. It is along this arc that maximum stress/strain levels should be seen.

$$l^4 = \frac{Eh^3}{12\left(1-\mu^2\right)k} \qquad (1)$$

Figure 1 shows the locations of the instrumentation. Critical strains in PCC pavement generally occur in the top of the slab near the corners and towards the bottom of the slab near the center edge. For this particular test, the gages in the corners were placed approximately 5.5 inches up from the sub-grade. Gages at mid-span were placed 1.5 inches up from the sub-grade. This required 11 embedment gages, which also allowed for some redundancy in the event some gages malfunction.

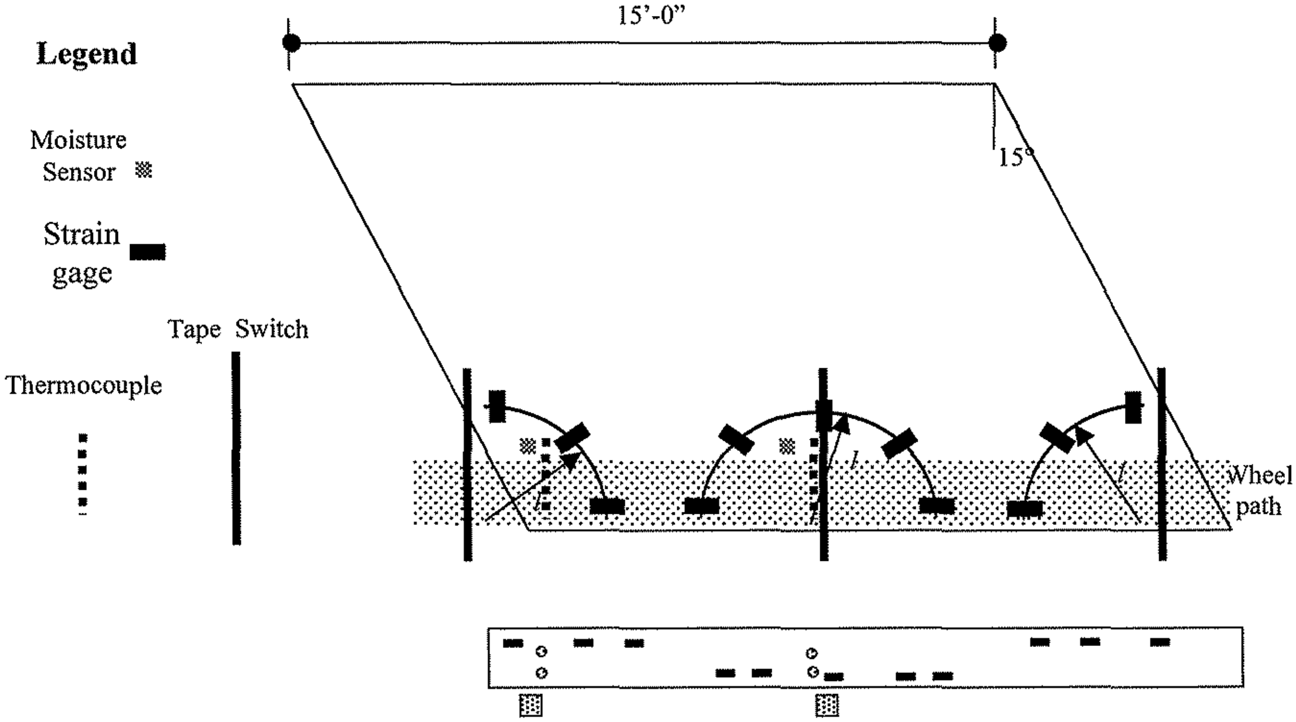


Figure 1. PCC Instrumentation Layout

The temperature thermocouples were located at two locations within the pavement at two depths. This will enable the research team to measure the temperature gradient in the pavement for use with the finite element model. The pavement was tested at crawl speeds, less than 5 mph under husbandry and standard-truck loads. Some consideration was given for higher speeds but since the pavement was new and smooth, very little dynamic action was expected. One test was conducted at higher speeds to verify that there was no increase in stresses at the increased speeds. Moisture sensors were embedded in the soil to help determine soil conditions. Three tape switches were used to record vehicle position along the test section.

4.2 ACC Pavement Instrumentation

County Road K52 in Sioux County, Iowa, was scheduled to have a complete ACC pavement constructed in September 1999. This five-mile stretch extends County Road B40 north to County Road B30. The section was a nominal 22 ft. wide continuous placed pavement. The thickness, *h*, was nominally nine inches across the complete section.

Instrumentation used in the ACC pavement was similar to that used in the PCC. Strain gages were ordered with Teflon™ leads to protect against the elevated temperatures (>300°F) of the material during placement. In addition, all wires within the ACC pavement were run through Teflon™ tubing for the same protection.

Gages were placed at four locations each 10 feet apart. Each location had two gages placed 90° to each other with one gage transverse to the direction of vehicle travel and one longitudinal. The gages were positioned so that the wheel path of the vehicles was directly above them, approximately three feet in from the edge. The gages were placed at the interface between the first and second lifts (three total lifts). This positioned them about four inches from the sub-grade. This level is also close to the mid-depth of the ACC section, which is a nominal nine-inch depth. One thermocouple was placed at each station. The researchers determined that soil conditions caused minimal effect with the ACC material response so no moisture sensors were placed in the sub-grade. As with the PCC pavement, tape switches were positioned at each end of the test section plus one in the middle to help determine vehicle position and velocity. This instrumentation is shown in Figure 2.

Note: Refer to Figure 1 for the legend used in Figure 2.

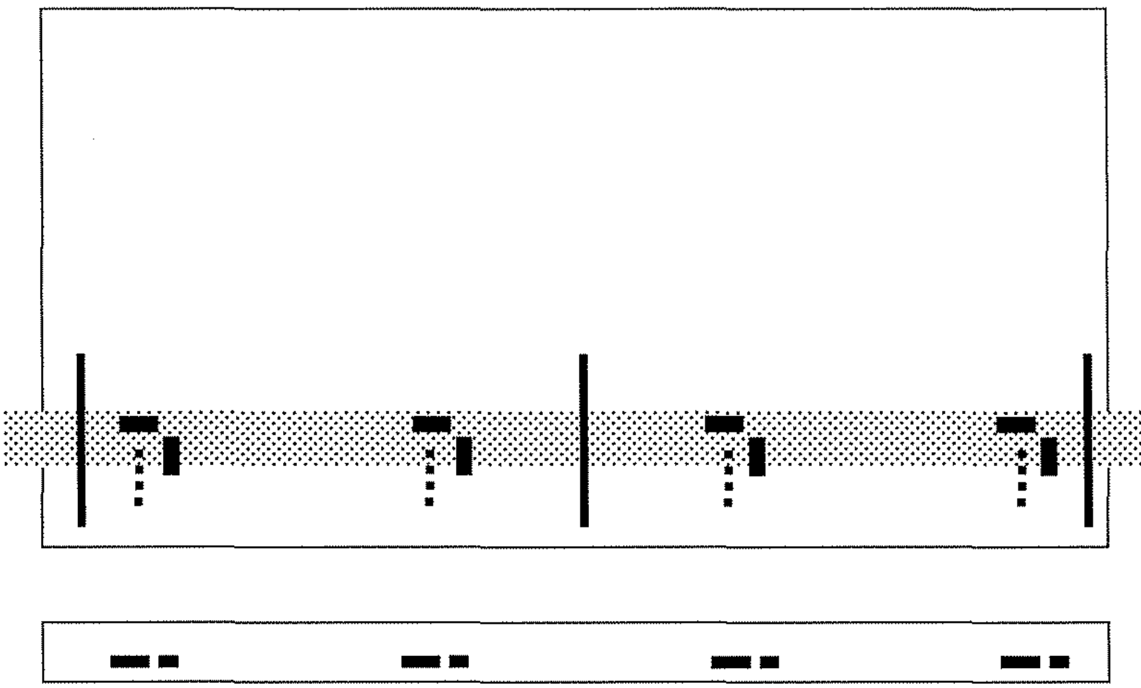


Figure 2. ACC Instrumentation Layout

5. FIELD TESTING AND ANALYSIS OF JONES COUNTY PCC PAVEMENT

5.1 Loading

The PCC pavement on highway E-29 was tested under the load configurations listed below. All tires marked with an asterisk were flotation tires.

1) Grain Semi

11R24.5 tires
90 psi tire pressure
48" centre-to-centre between axles;13" centre-to-centre of duals

Weights (lb.)	Tractor	(Front)	11,200
	1st Axle		17,300
	2nd Axle		17,460
	3rd Axle		16,600
	4th Axle		16,720
	GROSS WEIGHT		79,280

2) Single-Axle Grain Cart

FIRESTONE 30.5L-32 Tires*
Tire pressure = 36 psi

Weights (lb.)	Tractor	(Front)	7,230
		(Rear)	17,340
	Cart		39,140
	GROSS WEIGHT		63,710

3) HOULE 6000 Tandem Honey Wagon

FIRESTONE 28L-26 Tires*
68" centre-to-centre between axles and 120" centre-to-centre between wheels on same axle
wagon tire pressure = 28 psi

Weights (lb.)	Tractor	(Front)	6,740
		(Rear)	21,160
	1st Axle		25,100
	2nd Axle		29,500
	GROSS WEIGHT		82,500

4) HOULE Tridem Honey Wagon

Firestone 28L x 26 Tires*
68" centre-to-centre between axles and 120" centre-to-centre between wheels on same axle
Wagon tire pressure = 22 psi

Weights (lb.)	Tractor	(Front)	7,420
		(Rear)	18,140
	1st Axle		20,320
	2nd Axle		23,100
	3rd Axle		21,000
	GROSS WEIGHT		89,980

5) Tracked Tractor

Track: 18" wide and 8'-00" contact length

Weights (lb.)	1st Axle	(Front)	1,580
	2nd Axle		5,740
	3rd Axle		7,320
	4th Axle		9,420
	5th Axle	(Rear)	7,440
	GROSS WEIGHT		31,500

5.2 Testing Results

The pavement was tested twice under each loading at crawling speed. Data collections of the strains induced in the pavement started a few seconds before and continued a few seconds after each vehicle passed over the instrumented 15 ft. by 22 ft. slab. These results were recorded for all locations of the strain gages shown in Figure 1. Figures 3 through 7 show the time-strain relationship as each vehicle was traveling along the pavement.

As can be seen, the strains induced in the pavement under the semi-grain, tandem and tridem honey wagons range from 14 to 15 micro strains ($\mu\varepsilon$), while 10 $\mu\varepsilon$ were measured when the pavement was loaded by the tracked vehicle. The maximum measured strain value was obtained when the pavement was loaded by the single axle grain wagon. This demonstrates that grain carts could result in more damage when compared with other vehicles.

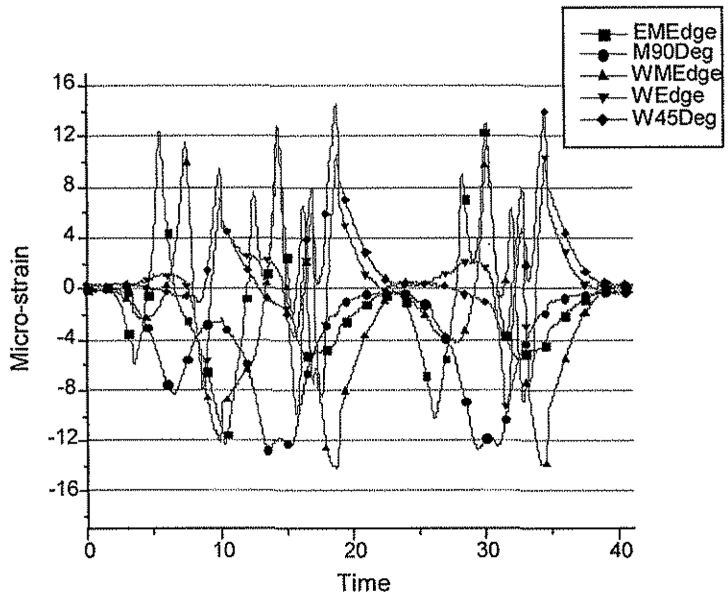


Figure 3. Field Test Strain Data for the PCC Pavement under Grain-Semi, Average Axle Weight = 17,000 lb.

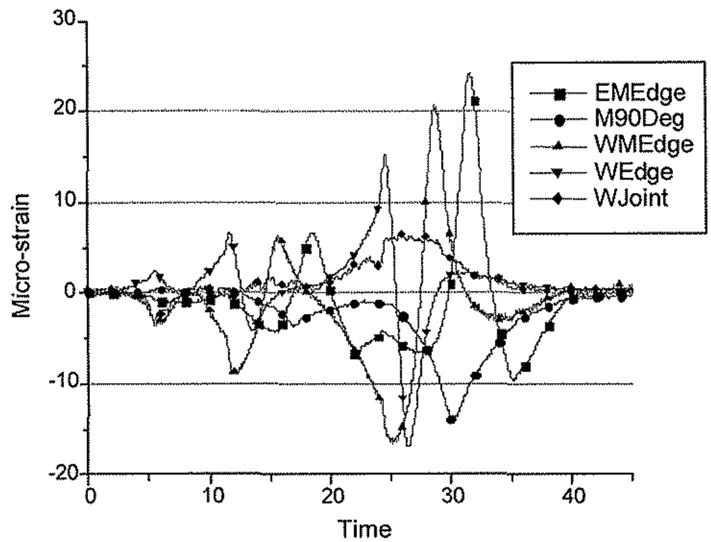


Figure 4. Field Test Strain Data for the PCC Pavement under Single Axle Grain Cart, Axle Weight = 39,140 lb.

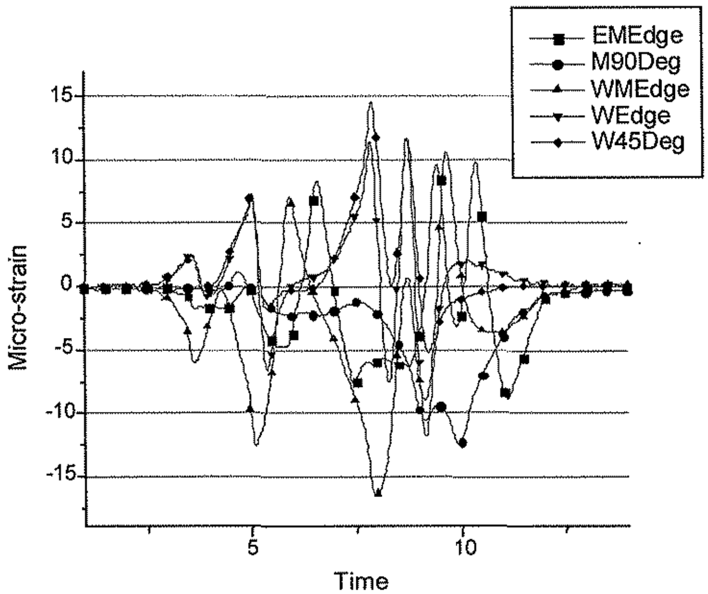


Figure 5. Field Test Data for the PCC Pavement under Tandem Honey Wagon, Average Axle Weight = 27,000 lb.

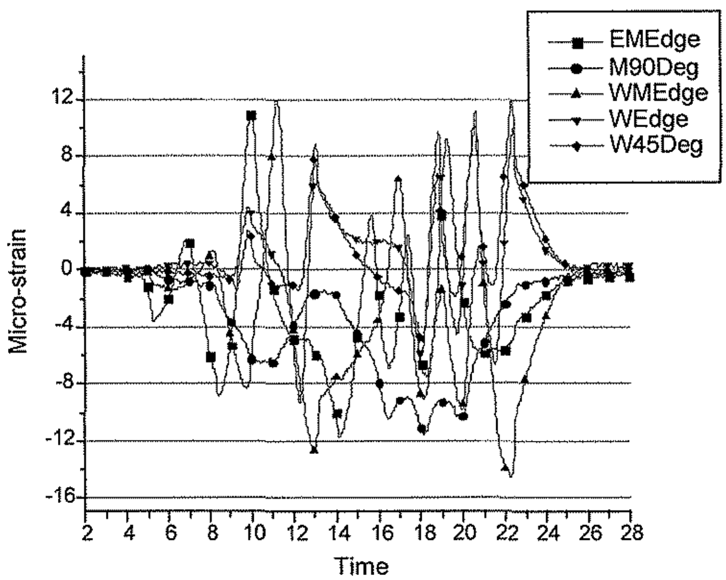


Figure 6. Field Test Strain Data for the PCC Pavement under Tridem Honey Wagon, Average Axle Weight = 22,000 lb.

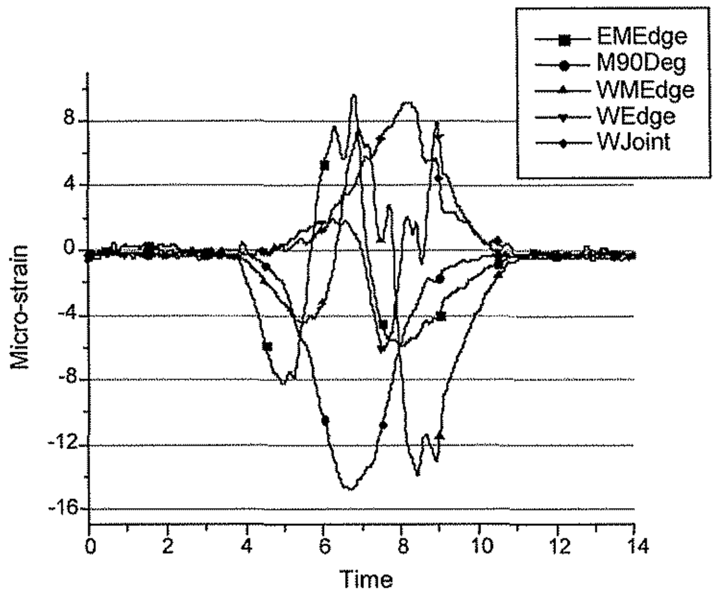


Figure 7. Field Test Strain Data for the PCC Pavement under Tracked Vehicle, Gross Weight = 31,500 lb.

5.3 Analytical Study

5.3.1 Software Selection

An accurate analysis to assess the performance of a pavement structure under the influence of various vehicle configuration taking into account the previously listed factors would require a complex nonlinear three-dimensional finite element model. An analysis of a pavement structure utilizing this approach would require several hours of computation time to analyze one pavement under one loading condition. Therefore, a more practical and simplified approach was desired for the work proposed here in.

The software KENSLABS developed by Huang (1993) permits the analysis of the response of any given pavement to any specified applied static loads. This software utilizes the finite element method to analyze PCC pavements under different loading conditions. Also, KENSLABS allows the user to analyze not more than nine slabs at a time, each of which can be modeled by a maximum of fifteen nodes along each edge. This constrains the element size to be used in modeling each slab, and can easily affect the accuracy of the results. For this reason, the ANSYS (1999) general-purpose finite element commercial program was used to carry out additional analyses of these pavements. This was necessary to calibrate the results obtained from KENSLABS and to obtain the strains induced in the PCC pavements. The latter are not provided by KENSLABS software. Furthermore, since the recommendations of this study are mainly based on the analytical work and very limited experimental testing, one must assure its reliability. This was accomplished herein by comparing the stresses obtained from KENSLABS and the ANSYS software. To further calibrate the analytical models, the measured strains from the field tests were compared to those obtained from the ANSYS results.

5.3.2 Modulus of Sub-grade Reaction

The modulus of sub-grade reaction used in this study was 230 psi/in. This was obtained from the field test conducted by Iowa Department of Transportation personnel in summer of 1999 using several soil samples obtained from E-29 in Jones County. However, modified values need to be used when analyzing the PCC pavement under different seasonal conditions. This is necessary to account for the soil properties from one season to another. In this work, the sub-grade reaction for the spring, summer, and fall and spring were assumed to be 175 psi/in., 230 psi/in., and 115 psi, respectively.

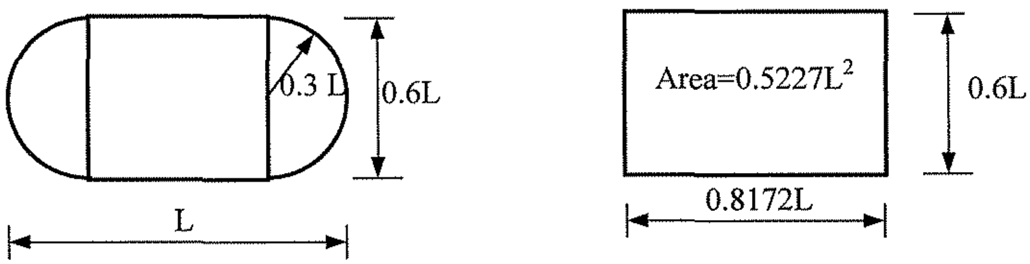
5.3.3 Analysis of the PCC Pavement with ANSYS

The PCC pavements described above were analyzed with the ANSYS (1999) finite element software. Each slab was modeled with several plate elements supported on an elastic foundation. The size of the elements did not exceed the thickness of the slab. Each finite element model was loaded with similar loads as those used in the field test. The element size was determined by a tire contact area. For the finite element analysis, the actual contact area used by Portland Cement Association (PCA) in 1966 (cited in Huang, 1993-page30), was replaced by that defined by PCA in 1984 (cited in Huang, 1993- page 30). In this case, the contact area is assumed to be rectangular as shown in Figure 8. Equations 2 and 3 were used to calculate the dimensions of the contact area:

$$Contact\ Area = \frac{P}{p} = 0.6l * 0.8712l \qquad (2)$$

$$\therefore l^2 = 1.913\frac{P}{p} \qquad (3)$$

Where P and p are the load per tire and the tire pressure, respectively. For example, for a 20,000-lb. single axle semi with dual tires and a tire pressure of 100 psi, the tire width and the length of the tire contact area shown in Figure 8(b) are 5.87 in. 8.52 in, respectively, for the tire contact area. These dimensions dictated the element size where the tires were positioned on the pavement.



(a) Actual Area (b) Equivalent Area

Figure 8. Dimension of Tire Contact Area

5.3.4 Results of the Analytical Study

The maximum measured strain and the maximum strain obtained from the finite element results caused by each load are summarized in Table 1. As can be noticed there are discrepancies between the measured and the calculated strains. These differences can be attributed to the location of the tire loads with respect to the location of the strain gage, the unknown exact values of the modulus sub-grade reaction, the as constructed thickness of the pavement and the actual compressive strength and the concrete modulus of elasticity. For example, the design thickness of this particular pavement is 7 in.; however, the investigators of this work were notified by Jones County engineer that core samples revealed that the actual thickness ranges from 7.75 to 8 inches. In addition, testing three concrete cylinders collected during construction from the site revealed a concrete compressive strength of 7533 psi. In the analysis of Jones County pavement, a modulus of elasticity of 5,000,000 psi that corresponds to a compressive strength of 7550 psi was used. In addition a thickness of 7.75 in was also assumed. In addition, a sub-grade reaction of 350 psi/in was assumed in the finite element model to adjust for the soil conditions at the time the test was conducted. This value does not match either the fall or winter conditions since it was noticed that the soil condition was neither wet nor frozen at the time of testing.

Despite these discrepancies of the results listed in Table 1, the finite element as well as the field data revealed the same behavior of the PCC pavement under the all tested loads. Both test and analysis demonstrated that loading the pavement with a single axle grain cart resulted in the largest strain values. In addition, the ratio between the strain induced by a specific loading to that of a semi grain obtained using either theoretical or measured strain is in agreement. This is a useful result since one may relate the behavior a pavement under any loading condition to the behavior of this pavement under a single axle load.

Table 1. Summary of Calculated and Measured Longitudinal Strains in the E-29 PCC Pavement

Load Configuration	Calculated Strains ε_{th} ($\mu\varepsilon$)	Measured Strains ε_m ($\mu\varepsilon$)	$\varepsilon_{th}/\varepsilon_{th\ (semi)}$	$\varepsilon_m/\ \varepsilon_{m\ (semi)}$
Semi	21	14	1	1
Tandem HW	25	15	1.2	1.07
Tridem HW	23	14	1.2	1
Grain Cart	40	25	1.9	1.78

6. ANALYSIS OF ADDITIONAL PCC PAVEMENTS

Three additional pavements with thicknesses of 7 in., 8 in. and 9 in. under the spring seasonal conditions were analyzed. The spring condition was selected since it is associated with the lowest soil sub-grade reaction of 115 psi/in. Each slab was subjected to the type of loading shown in Figures 9 through 12. The concrete modulus of elasticity of 4,000,000 psi that corresponds to a design concrete compressive strength of 5,000 psi was used.

In pavement technology, the reference design vehicle configuration is an 18,000-lb. single-axle. Conventionally, other axle configurations are reduced to an equivalent number of these reference loads in terms of equal damaging power or Equivalent Single-Axle Loads (ESALs). In comparing the relative damaging power of different axle configurations and weights, they must be expressed in terms of ESALs. One needs to realize that axle weight alone is no determinant of damaging power; the configuration of the load (contact area, tire pressure, suspension, and wheel spacing, etc.) as well as Average Daily Traffic (ADT) and temperature contribute decisively to damage. This approach however, was not employed herein due to the uncertainty associated with the variables that enter into the equation one uses to determine the ESALs. Another alternative is to determine the load that can be applied to a given axle configuration that induces stress, strain or deflection equal to that induced in the same pavement when subjected to a single axle load. Due its simplicity, the latter approach was selected and used to determine the effects of husbandry loads on Iowa highway pavements. In this work, a single axle-dual tire of 20,000-lb was used as a basis for comparison with other loads.

6.1 Analysis of the PCC Pavement Using KENSLABS

In this analysis, a 15 ft. long by 22 ft. wide PCC slab considering three different thicknesses were modeled by a 14 by 14 elements mesh. Symmetry conditions were employed when possible. This existed only when analyzing a pavement under symmetrical loads. The dimensions of the element in the vicinity of the applied loads were determined using Equations 2 and 3 in conjunction with Figure 8. Dimensions of other elements were controlled by the restriction on the number of nodes imposed by the program. Applied loads of grain carts and

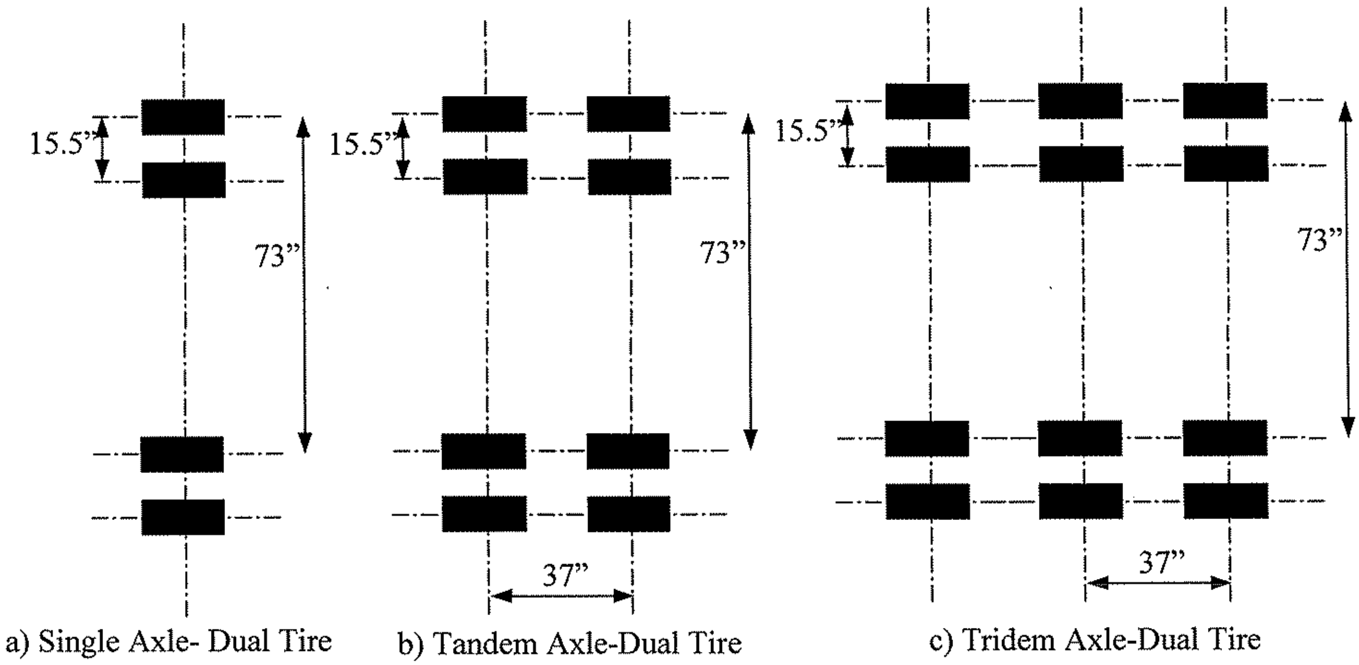


Figure 9. Different Configuration for Semi- Trailer Axles, Axle Weight 20,000 lb.

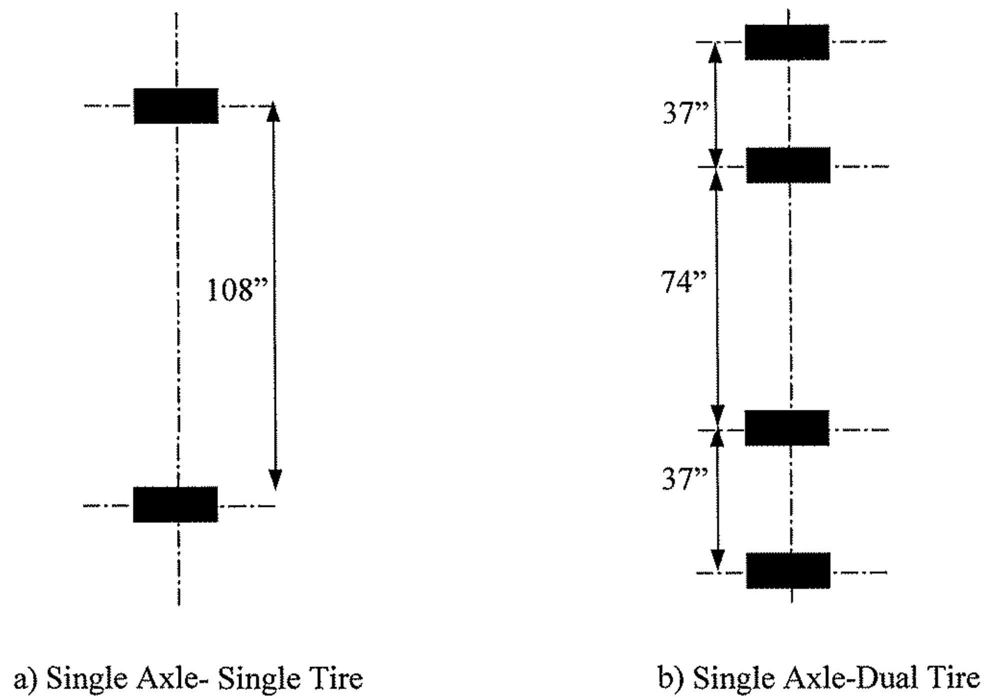
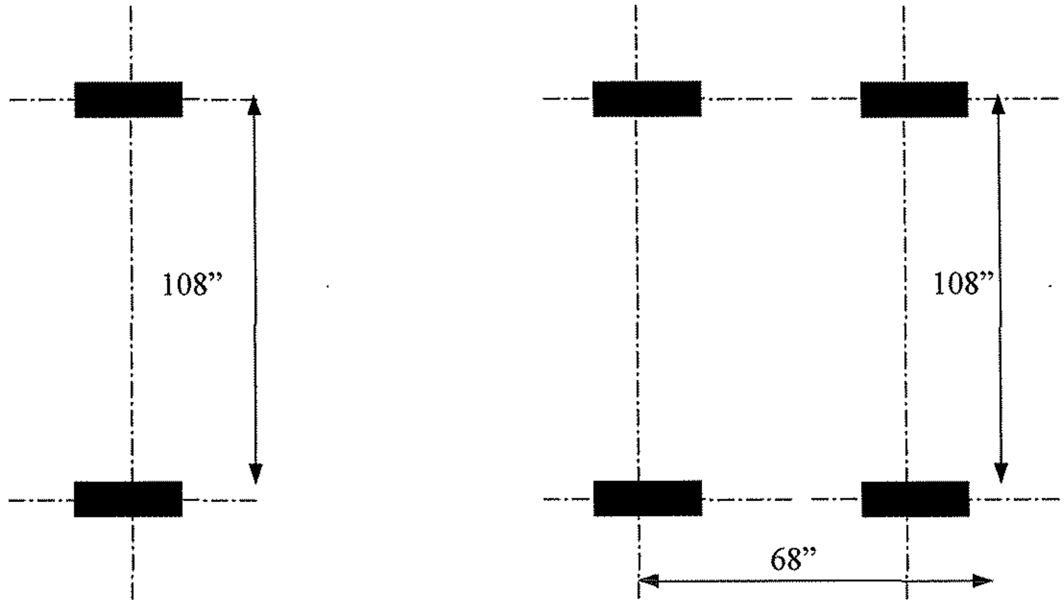
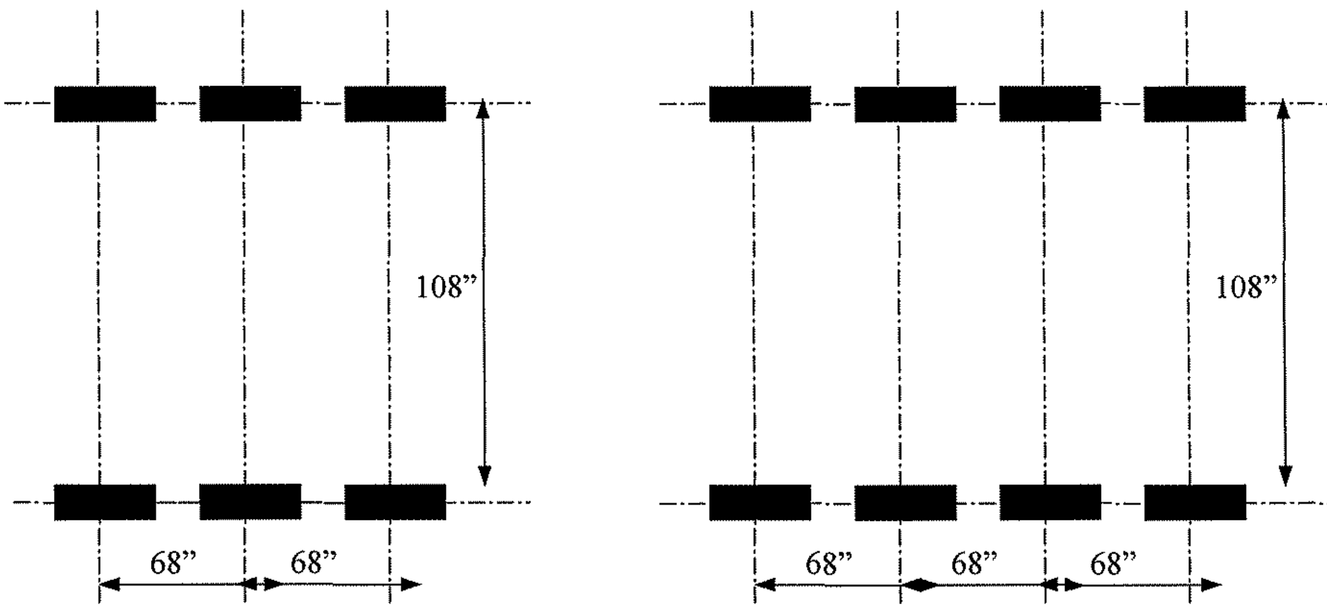


Figure 10. Different Configuration for Grain Wagons



a) Single Axle - Single Tire b) Tandem Axle - Single Tire

Figure 11. Different Configuration for Single and Tandem Axle Honey Wagons



a) Tridem Axle - Single Tire a) Quad Axles - Single Tire

Figure 12. Different Configuration for Tridem and Quad Axle Honey Wagons

honey wagons were increased until the maximum stresses in the pavement reached a value close to that induced by the 20,000 lb. single axle- dual tire semi.

6.2 Analysis of PCC Pavement with ANSYS

The additional PCC pavements described above were also analyzed with the ANSYS (1999) finite element software. Each pavement was modeled by several plate elements supported on an elastic foundation. The finite element model was loaded with similar loads as those used in the simplified analyses listed above. A sensitivity study on the element size was conducted to insure reaching converged results. This was accomplished by reducing the element size incrementally until an insignificant change in the maximum stress obtained from two consecutive solutions was reached. Table 2 shows the dimensions and the number of elements used to model tire-pavement contact area for a semi. As can be noticed, using element dimensions of 5.85x4.26 inches and 5.85x2.23 inches resulted in increases of the calculated maximum stress of 17% and 18% when compared to the results obtained using an element size of 5.85x8.52 inches. However, an insignificant increase was noticed when comparing the results of using an element size of 5.85x4.26 inches to that obtained using an element size of 5.85x2.23 inches. Therefor; it was decided to use an element size with dimensions that do not exceed an element size of 6x4 inches to model the concrete pavement for the analysis under other load configurations.

Table 2. Results of Mesh Sensitivity Study

Element Size	No. of elements	Maximum stress (psi)	% increase
5.85x8.52	1	376	-
5.85x4.26	2	441	17
5.85x2.23	4	443	18

6.3 Summary of Results

The maximum stress induced in 7, 8 and 9 inch thick PCC pavements for a spring season, i.e., for a soil sub-grade reaction of 115 psi/in, were documented. These results were used to determine the magnitude of loads on grain wagons and honey wagons that induce similar stress in each pavement. The results obtained form the analyses using KENSLABS and the ANSYS finite element programs using the coarse and fine meshes are listed in Tables 3 and 4.

As can be noticed, except for the tandem-axle dual-tire semi, the simplified analyses and the finite element results are in good agreement. The significant differences between the results when analyzing the pavements under the tandem-axle dual-tire semi due to the restriction on the number of elements used in modeling the slab when analyzed by the KENSLABS program. In this case, this restriction could not be avoided since loading was not symmetrically placed on the pavement. The results in Tables 3 and 4 show that a load of 24,000 lb. on a single axle-single tire grain or honey wagon will induce a maximum stress close to that induced by the application of a 20,000 lb. single axle-dual tire semi. In addition the results show that this capacity increases to 36,000-lb. per axle for a tandem axle-single tire honey wagon and to 38,000-lb. on a single-axle dual-tire grain wagon. Notice that no analysis results related to tracked wagons are listed in the table. This load configuration was analyzes separately and the results are documented in section 6.5.

Table 3. Maximum Stresses in PCC Pavements with Different Thicknesses
KENSLABS Results (Spring Season)

Load	Load Configuration (Axle Load)	Stress (psi) Pavement Thickness		
		7 inches	8 inches	9 inches
Semi	Single-Axle Dual Tire 20,000 lb.	435	358	300
Semi	Tandem Axle Dual Tires* 20,000 lb.	385	320	270
Honey Wagon	Single-Axle Single Tire 24,000 lb.	430	358	302
Honey Wagon	Tandem-Axle Single Tire 36,000 lb.	420	348	295
Grain Wagon	Single-Axle Single Tire 24,000 lb.	424	351	297
Grain Wagon	Single-Axle Dual Tire 38,000 lb.	432	355	298

Table 4. Maximum Stresses in PCC Pavements with Different Thicknesses
ANSYS Results (Spring Season)

Load	Load Configuration (Axle Load)	Stress (psi) Pavement Thickness		
		7 inches	8 inches	9 inches
Semi	Single-Axle Dual Tire 20,000 lb.	441	363	304
Semi	Tandem Axle Dual Tires* 20,000 lb.	425	350	293
Honey Wagon	Single-Axle Single Tire 24,000 lb.	438	363	307
Honey Wagon	Tandem-Axle Single Tire 36,000 lb.	426	354	299
Grain Wagon	Single-Axle Single Tire 24,000 lb.	432	358	301
Grain Wagon	Single-Axle Dual Tire 38,000 lb.	444	375	320

* Note: The tandem-axle dual-tire load listed above exceeds the legal limits of 34,000 lb.

6.4 Effect of Soil Sub-grade Reaction

The previously described 7-in., 8-in and 9-in. thick concrete pavements were analyzed considering fall conditions. This was accomplished using soil sub-grade reactions of 175 psi/in. The finite element results are summarized in Table 5.

Table 5 illustrates that the stress in the concrete pavement decreases as the soil sub-grade reaction increases. This was expected since the deflections and hence the strains decrease as the sub-grade reaction increases. The table also summarizes the magnitude of the load for the different implements that is required to induce stress equivalent to that induced in the pavement in the spring season due a 20,000-lb. single-axle dual tire semi.

Table 5. Maximum Stresses in PCC Pavements with Different Thicknesses
ANSYS Results (Fall Season)

Load	Load Configuration (Axle Load)	Stress (psi) Pavement Thickness		
		7 inches	8 inches	9 inches
Semi	Single-Axle Dual Tire 20,000 lb.	379	312	261
	Tandem Axle Dual Tires* 20,000 lb.	365	289	252
Honey Wagon	Single-Axle Single Tire 24,000 lb.	397	329	278
	Tandem-Axle Single Tire 36,000 lb.	390	354	274
Grain Wagon	Single-Axle Single Tire 24,000 lb.	394	324	275
	Single-Axle Dual Tire 38,000 lb.	385	317	277

*Note: The tandem-axle dual-tire load listed above exceeds the legal limits of 34,000 lb.

6.5 Analysis of a PCC Pavement under a Tracked Wagon

A 108-in. long and 24-in. wide tire-pavement contact area that corresponds to an 840-20 tracked wagon was considered to investigate the response of a 7-in. PCC pavement. A uniform pressure was assumed over the entire contact area. This pressure was increased until the stress induced in the pavement was nearly equal to that caused by the single-axle dual tire semi. The maximum induced stress in the pavement during different seasons is listed in Table 6.

Table 6. Stress in a 7 in. PCC Pavement Due to a
Tracked Wagon (Axle Weight = 110,000 lb.)

Season	Spring	Fall
Stress (psi)	435	392

Utilizing the results in Tables 5 and 6, one can calculate the load of other implements that would induce stress equivalent to that resulting from a 20,000-lb. single-axle dual tire semi in a spring season. This can be attained multiplying the loads listed in Table 5 by the ratio of the stresses induced by a specific load in a given season to that caused by the reference semi loading. These results are summarized in Table 7.

Table 7. Load Capacity of Different Implements Resulting in Equivalent Stress to a 20 kips Semi in Spring and Fall Seasons

Load	Load Configuration	Axle Load (kips)	
		Spring	Fall
Semi	Single-Axle Dual Tire	20	20
	Tandem Axle Dual Tires	41	42
Grain Wagon	Single-Axle Single Tire	24.4	25
	Tandem-Axle Single Tire	36	37.5
Honey Wagon	Single-Axle Single Tire	24	25
	Single-Axle Dual Tire	38	39
Tracked Wagon	108 in. by 24 in. Track	110	110

The analytical results summarized in Table 6 and 7, the field test, and the analytical results demonstrated that tracked vehicles induce lower stress or strain values in both PCC and ACC pavements when compared to other loads. However, these results must be interrupted with caution since the analysis assumed that the load of these vehicles is transferred to the pavement uniformly over the track-pavement contact area rather than at discrete locations along the lugs of the track. Exact load pass to pavement must be carefully investigated prior to making such a conclusion.

7. FIELD TESTING AND ANALYSIS OF SIOUX COUNTY ACC PAVEMENT

7.1 Loading

The ACC pavement on highway K-52 was tested under the load configurations listed below. All tires marked with an asterisk were flotation tires.

1) BALZER Tandem Honey Wagon*
   20x20 Aircraft tires
   35psi tire pressure
   68" center to center between axles
   Tandem 33,160

2) HOULE Tridem Honey Wagon*
28L x 26 Tires
22psi tire pressure

Weights (lb.)	Tractor (Front)	7,100
	Tractor (Rear)	18,500
	1st Axle	25,520
	2nd Axle	25,100
	3rd Axle	25,120

3) BALZER QUAD Honey Wagon*
30.5Lx32 tires
20psi tire pressure
68" center to center between axles

Tractor (Front)	12,000
1st Tandem	34,100
2nd Tandem	34,100

4) Gravel Truck (1)
11R24.5 Tires
90psi tire pressure
48" center to center between axles; 13" center to center of duals

Tractor (Front)	12,000
1st Tandem	34,100
2nd Tandem	34,100

5) Gravel Truck (2)
11R24.5 Tires
87psi tire pressure
48" center to center between axles; 13" center to center of duals

Tractor (Front)	12,000
1st Tandem	34,000
2nd Tandem	34,000

6) Single-axle Grain Cart (1 axle)*
30.5L-32 Tires
50psi tire pressure

Cart Axle	40,040

7) Dual-Axle Grain Cart (2 Tires)*
30.5L-32 Tires
50psi tire pressure

Cart Axle #1	15,000
Cart Axle #2	14,980

7.2 Testing Results

The above vehicles were driven over the instrumented locations at a crawl speed. The data were collected by the data acquisition system when triggered by the passage of the leading axle over a trip-tape placed before the instrumented locations. The results were recorded and are reported in Figures 13 through 19. These figures show the strain-time relationship as the vehicle tested traveled over the tested pavement section. The peak strains recorded for each axle-type is given in Table 8.

Table 8: Measured Strains

Vehicle	Peak Strain (με)
Balzer Tandem Honey Wagon	9.0
Houle Tridem Honey Wagon	12.0
Balzer Quad Honey Wagon	7.6
Gravel Semi (1)	6.8
Gravel Semi (2)	7.9
Single Grain Cart	15.7
Dual Grain Cart	12.6

In ranking these results in terms of damaging power (i.e., greater strain), it is seen that both the honey-wagons and grain carts impart greater damage to the pavement that the dual-wheeled semi trailers, and that generally grain carts are more damaging than honey-wagons. These observations must be tempered with the knowledge that the various tires used at this location were very much a mixed bag, and were dictated by local availability.

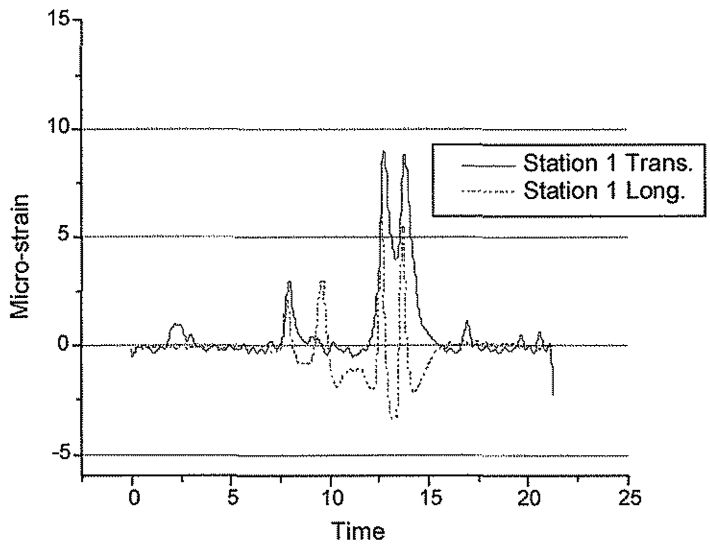


Figure 13. Field Test Strain Data for the ACC Pavement under Tandem Honey Wagon Vehicle, Axle Weight = 33,160 lb.

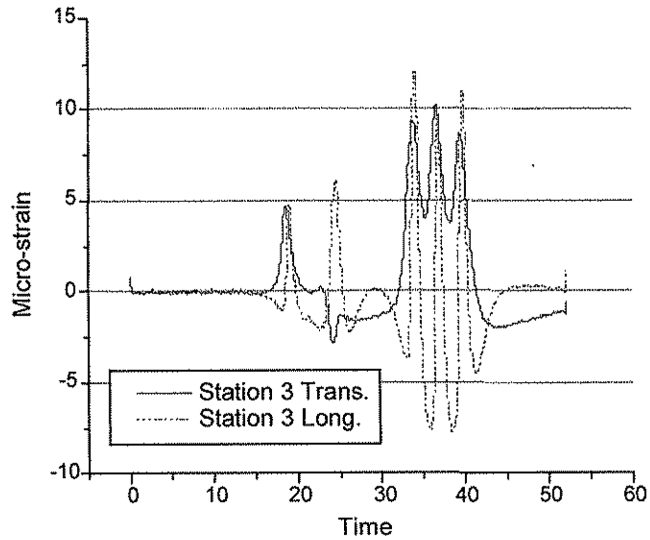


Figure 14. Field Test Strain Data for the ACC Pavement under Tridem Honey Wagon Vehicle, Axle Weight = 25,250 lb.

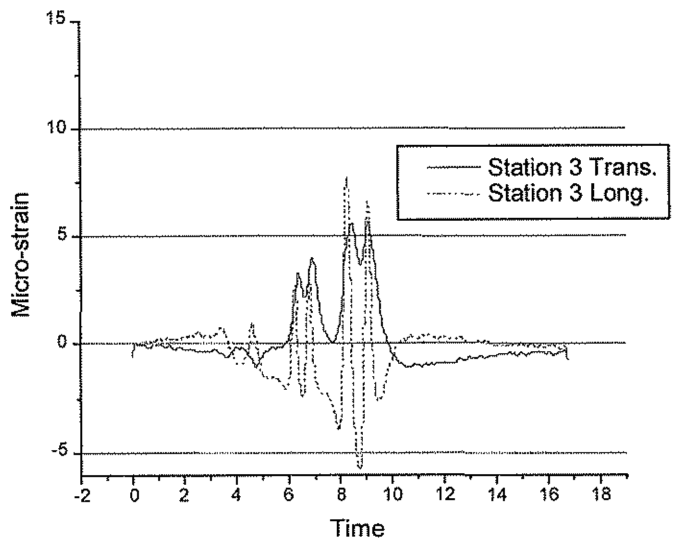


Figure 15. Field Test Strain Data for the ACC Pavement under Quad Honey Wagon Vehicle, Axle Weight = 34,100 lb.

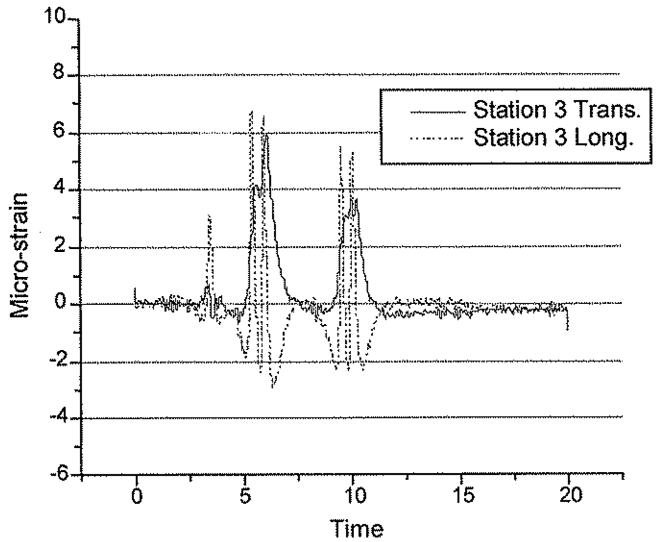


Figure 16. Field Test Strain Data for the ACC Pavement under Gravel-Semi Vehicle, Axle Weight = 34,000 lb.

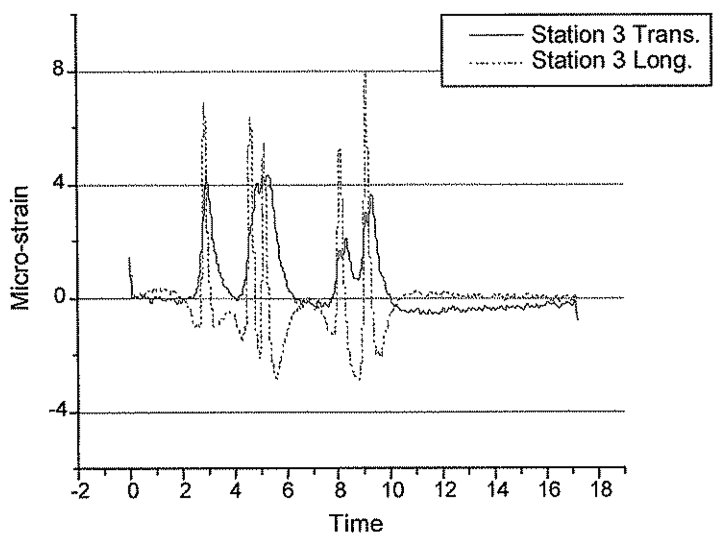


Figure 17. Field Test Strain Data for the ACC Pavement under Dual Gravel-Semi Vehicle, Axle Weight = 34,100 lb.

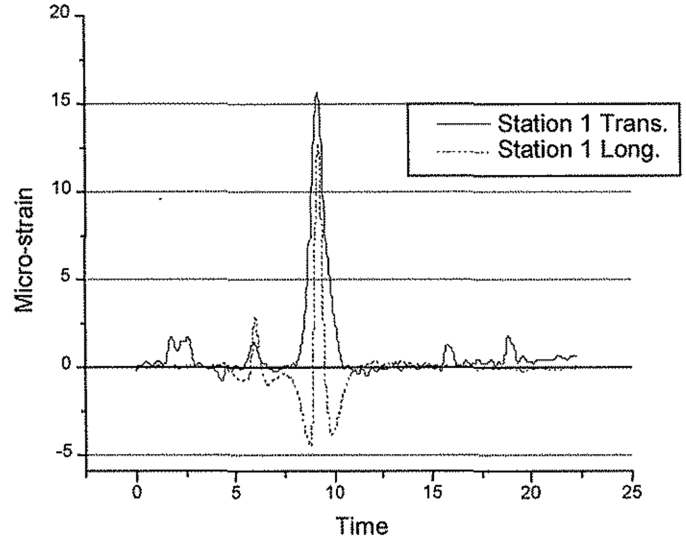


Figure 18. Field Test Strain Data for the ACC Pavement under Single-Axle Grain Cart Vehicle, Axle Weight = 40,040 lb.

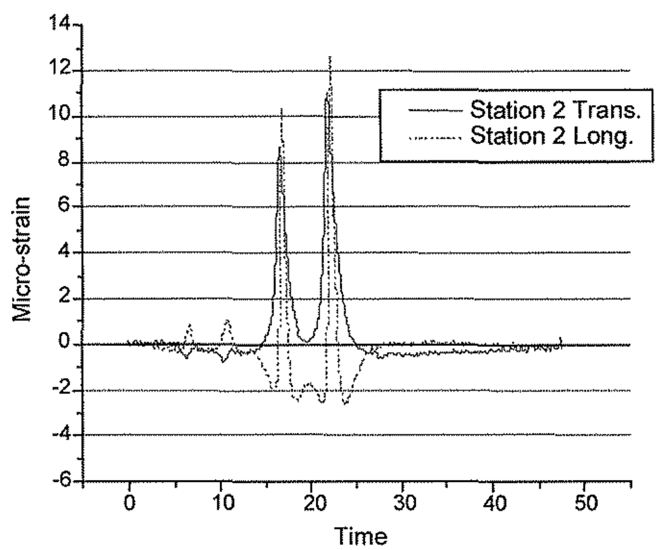


Figure 19. Field Test Strain Data for the ACC Pavement under Dual-Axle Grain Cart Vehicle, Axle Weight = 15,000 lb.

7.3 Analytical Study

7.3.1 Software Selection

For reasons similar to those for the PCC pavement, the software package KENLAYER, developed by Huang (1993), was used. This software is based on Burmister's multi-layer elastic analysis. It assumes a circular loading contact with a uniform distribution of pressure within the contact area. All layers are assumed to have fully frictional interfaces, and all materials are assumed to be linear elastic.

7.3.2 Material and Seasonal Effects

The generic pavement analyzed was taken to be a three-layer system comprising an asphalt layer overlying a thin granular base on the sub-grade. The asphalt layer was analyzed at 4, 6, and 8 inch thicknesses. The base layer was fixed at a nominal 6-inch thickness. It may be arguable that granular bases are common or universal in use; however, the top 6 inches of sub-grade are frequently significantly different to the remainder of the sub-grade soil, so that the assumption of this layer is in no way unrealistic.

Previous work by the authors of this work, analyzing the full 12-month year, had examined the effects at the four seasons (summer, fall, winter and spring). The elastic modulus assigned to each layer for the various seasons is given in Table 9. These analyses demonstrated that spring condition is the most critical. However, since not all implements of husbandry are used in the spring season, it was decided to study the response of the ACC pavement considering also the fall season. Fall was also selected over the winter and summer seasons since it represents the second most likely season for using implements of husbandry. Similar behavior was also noticed when analyzing the PCC pavement.

Table 9: Seasonal Material Modulus (psi)

	Summer	Fall	Winter	Spring
Asphalt	350,000	500,000	2,000,000	500,000
Base	50,000	50,000	50,000	50,000
Sub-grade	25,000	17,500	50,000	10,000

7.3.3 Field Trial Validation

In order to validate the computation analysis, the same procedure was used to analyze the results of the field-testing. In this case, the temperature of the asphalt was known (40° F) and the elastic modulus of the asphalt layer could be reasonably estimated. The summer value of the sub-grade modulus was selected due to the fact that there had been little or no precipitation in the previous two months, and the material was certainly not yet frozen.

The tested axle/tire configurations were entered into the KENLAYER program, and the strains computed at the depth of the embedded strain gauges. The comparative results are given in Table 10.

Table 10: Comparison of Measured vs. Computed Strains

Axle Type	Computed Strain (με)	Measured Strain (με)
Tandem Honey wagon	12.4	9.0
Tridem Honey wagon	11.7	12.0
Quad Honey wagon	10.7	7.6
Gravel Semi (1)	8.9	6.8
Gravel Semi (2)	8.9	7.9
Single Axle Grain Cart	14.4	15.7
Single Axle (x2) Grain Cart	12.1	12.6

The correspondence between the two sets of results is fair. That there is not perfect agreement is not surprising, due to a number of causes:

1. Vehicles traveled at a nominal crawl speed. Not all drivers could maintain the same speed. Consequently there was some variation in speed between vehicles.

2. Vehicles were directed to pass directly over the embedded instrumentation. There was, however, some variability.

3. The software assumes a circular area of tire-pavement contact. The range of tires tested was such that this was not necessarily a valid assumption in some cases.

4. The software assumes a uniform contact pressure within the area of contact. This is also not always valid. It is probably closer to reality with true balloon or flotation tires than with normal "street" tires on the reference semi.

5. While the weight on any given axle had been measured on a certified scale, it was assumed that this weight was equally distributed between the tires on that axle. This may not always be valid.

There is, however, no indication that the analytical model is inappropriate.

8. ANALYTICAL STUDY OF ADDITIONAL ACC PAVEMENT

One pavement with an asphalt thickness of 8-in. was analyzed using the KENLAYER software under an array of vehicle axle and tire configurations. Two series of analyses were conducted:

1. Vehicles run over Spring pavements: Critical number of load repetitions was compared to those generated under a 20,000-lbs single axle dual tire semi axle with a tire pressure of 100 psi under Spring conditions.

2. Vehicles run over Fall pavements: Critical number of load repetitions was compared to those generated under a 20,000-lbs single axle dual tire semi axle with a tire pressure of 100 psi under Fall conditions.

The results are presented in Table 11. In this table, the axle weight for the stated axle and tire types are given that yield the same number of load repetitions as that associated with the 20,000 lb. single-axle dual tire semi to cause either fatigue cracking in the asphalt or permanent deformation in sub-grade. Strains within the asphalt pavement or the sub-grade as generated by this axle load were employed to determine the critical number of load repetitions for each material. For fatigue cracking, this number depends on the tensile strain in the asphalt while the permanent deformation is controlled by the compressive strain in the sub-grade that is induced by different implements. For more details regarding the process for calculating these loads, the reader is referred to Huang (1993). A similar approach was not used in analyzing the PCC pavement. This is due the fact that the performance of a PCC pavement is controlled only by the strain induced in the concrete under a specific loading that could result in fatigue cracking of a concrete pavement.

Table 11. Effect of Seasonal Conditions on Pavement Capacity under Different Implements

Season	Reference Axle	Single Grain Wagon	Dual Single Grain Wagon	All Honey wagons
Spring	20,000	25,200	33,200	25,200
Fall	20,000	27,800	44,500	27,800

9. REFERENCES

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Mannering, F.L., W.P. Kilareski, (1990), Principles of Highway Engineering and Traffic Analysis, John Wiley & Sons, Inc., N.Y., New York, USA.