The dynamic response of Kansas Perpetual Pavements under vehicle loading

by

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ABSTRACT

In response to the public expectation for a longer lasting transportation infrastructure, the asphalt paving industry has developed a concept that enjoys an increased popularity throughout the country: Perpetual Pavements. Kansas Department of Transportation conducted a field trial to investigate the suitability of this concept for Kansas highway pavements. The experiment involved the construction of four thick flexible pavement structures on a new alignment on highway US-75 near Sabetha, Kansas. They were designed to have a perpetual life and have layer thicknesses close to those recommended by the current KDOT's structural design method for flexible pavements, which is based on the 1993 AASHTO Pavement Design Guide. To verify the approach of designing perpetual pavements based on an endurance strain limit, the four pavements were instrumented with gages for measuring the strains at the bottom of the asphalt base layers. Two sessions of pavement response measurements under known vehicle load were performed in July and October 2005, before the pavement sections were opened to traffic. The analysis of the strain data indicated that the strain values are affected by the temperature in the asphalt layers and the speed of the loading vehicle. The paper describes the Kansas Perpetual Pavements Experiment and presents the major findings related to dynamic strain measurements.

INTRODUCTION

The increasing traffic volumes and loads as well as the public expectation for a longer lasting transportation infrastructure has brought the necessity of designing flexible pavements to a life of up to 50 years. The response of the asphalt paving industry to this demand is a concept that enjoys an increased popularity throughout the country: Perpetual Pavements. The main concept is that the asphalt pavement should be constructed with a impermeable, rut and wear resistant top layer placed on a rut resistant and durable intermediate layer and with a fatigue resistant and durable base layer.

The Perpetual Pavement concept is to prevent cracks from initiating at the bottom of the asphalt concrete. Thick and stiff pavement layers reduce the strains and stresses at the bottom of the asphalt concrete layer, thus reducing the potential for cracking of the material. Fatigue resistant bottom asphalt layers allow the material to stretch repeatedly without breaking, and thus, reduce the risk of crack formation.

The fatigue cracks may develop in the surface layer and propagate horizontally in the top lift. Since they appear at the pavement surface, these so-called “top-down” cracks can be observed and an action can be applied to eliminate them. Asphalt overlays or inlays are the most common solutions currently applied for “top-down” cracks. The cracks that initiate at the surface are not eliminated through the Perpetual Pavement concept; the concept leads to pavement structures that crack only at the surface and that need repair only at the surface. This leads to significant monetary saving for the repair, rehabilitation and reconstruction of these pavements.

Two main approaches are recommended in the Perpetual Pavements concept. The first recommends the construction of a bottom lift for the base layer with softer binder grade and/or higher binder content. This type of mix in the bottom lift can stretch without cracking at strains that will cause cracking in conventional mixes. The bottom layer will thus have an increased fatigue life.

The second approach recommends the increase of the total thickness of asphalt layers and the increase of stiffness for all layers such that the tensile strains at the bottom of the asphalt layer will be so small that the fatigue life of the material will be virtually infinite. This approach is very much tied to the results obtained in laboratory fatigue testing of asphalt concrete, which revealed that, if asphalt concrete is subjected to a small enough strain, it will reach failure after billions of load repetitions; it has a virtually infinite fatigue life. The limiting strain that leads to this infinite fatigue life is called endurance limit, a term borrowed from the terminology used for the fatigue of metals. Even though no common accepted value for the tensile strain associated to the endurance limit exists, research reported in the literature indicates than the endurance limit tensile strain ranges between 60 and 100 microstrain, and that it is not the same for all mixes.

Kansas Department of Transportation (KDOT) developed a field trial to investigate the suitability of this concept for Kansas highway pavements. The experiment involved the construction of four thick pavement structures on a new alignment highway US-75 near Sabetha, Kansas, in Brown County. They were designed to have a perpetual life and have layer thicknesses close to those recommended by the current KDOT’s structural design method for flexible pavements, which is based on the 1993 AASHTO Pavement Design Guide.

To verify the approach of designing perpetual pavements, based on an endurance strain limit, the four pavements were instrumented with gages for measuring the tensile strains at the bottom of the asphalt base layers. A research team from Kansas State University placed the instrumentation systems in the four pavement structures during their construction, in June 2005.

Two sessions of pavement response measurements under known vehicle loads were performed in July and October 2005, before the test sections were opened to traffic. Laboratory tests were performed to measure the stiffness of the materials used in the construction of the four pavements.

This paper presents the project objectives and describes the design and construction of the pavement and the installation of the pavement response instrumentation. It also provides a summary of the major findings related to the effects of vehicle speed and temperature on the horizontal longitudinal and transverse strains measured at the bottom of the asphalt concrete layer, for the four perpetual pavement structures.

A follow-up study supported by KDOT, currently in progress, aims to compare the laboratory fatigue life models of the HMA mixes used in the construction of the bottom asphalt lift in the four perpetual pavement structures, to estimate the relative cracking lives of the four pavement structures and to continue the bi-annual measurement of pavement response for two years after the test sections were opened to traffic.

BACKGROUND

Kansas Department of Transportation (KDOT) developed a field trial to investigate the suitability of the Perpetual Pavement concept for Kansas highway pavements in 2005. The experiment involved the construction of four thick pavement structures on a new segment of highway US-75 near Sabetha, Kansas, in Brown County. A four mile long segment connecting Fairview and Sabetha was constructed since the exiting US-75 (a North-South corridor) was overlapping a two mile stretch US-36 (a East-West corridor). KDOT selected this construction project since it is a new construction in the 2005 construction season, that serves on a corridor with medium to high truck traffic volume and, it is long enough to accommodate four 500 feet-long experimental sections on an uniform natural subgrade.

The development of the field trial aimed to:

- Validate the two approaches of the Perpetual Pavement Concept, by comparing the endurance limit recommended in the literature with the measured horizontal tensile strains induced in the pavements by a 18,000 lbs single axle load;
- Evaluate the cost effective full-depth asphalt pavements HMA Designs, by comparing four alternate design of long-lasting full-depth asphalt pavements;
- Compare the measured horizontal tensile strains at the bottom of thick full-depth asphalt pavements with those computed with linear elastic models for flexible pavement structures.

The pavement structures are given in Table 1, the sections being numbered in order they are constructed, from South going North. The estimated design cumulative traffic for these pavements is 2.6 million (10 years) and 5.7 million (20 years) ESALs/lane. The traffic volume in the initial year was estimated to be 240,000 ESALs/lane. The annual growth rate was estimated to be close to 1.8 percent.

For this traffic data, KDOT provided the design for a long-lasting pavement structure. With and estimated average resilient modulus for the subgrade soil of 2,500 psi, the total thickness of asphalt concrete layers obtained for this pavement section (Section 4) was 16 inches. Kansas Asphalt Pavement Association provided the design of three other pavement structures, for which it was estimated that the tensile strain at the bottom of the asphalt layer is smaller than

70 microstrain (10^{-6} in/in), the endurance limit proposed in the literature based on laboratory fatigue tests on asphalt mixes.

Marshall (*3*) provided the design for the KAPA Standard structure (Section 1) assuming that flexural strains at the bottom of the HMA layer less than 70 micro-strain (10^{-6} in/in) do not contribute to Cumulative Fatigue Damage, so HMA bottom-up fatigue distress should not occur. He calculated the flexural strain for each moth of the year based on the ILLI-PAVE algorithm:

$$\mathrm{Log}(e_{HMA}) = 5.746 - 1.589 * \log(T_{HMA}) - 0.774 * \log(E_{HMA}) - 0.097 * \log(E_{Ri})$$

Where:

e_{HMA} – HMA flexural strain, in micro-strain (10^{-6} in/in)
T_{HMA} – HMA thickness (inches)
E_{HMA} – HMA modulus (ksi)
E_{Ri} - Subgarde modulus (ksi)

The HMA modulus for each month was estimated based on the volumetric properties of the HMA mix, binder grade and Mean Monthly Pavement Temperature (MMPT), (*3*). The 6-inch lime-treated subgrade layer was not considered in the analysis. The subgrade modulus, E_{Ri}, was assumed to be 5.0 ksi.

The following HMA fatigue algorithm was considered in estimating, for each month, the number of load application, N_a, to initiate a fatigue crack,:

$$N_a = (8.2 * 10^{-8}) * [1/ e_{HMA}]^{3.5}$$

For those months when the HMA strains were less than 70 micro-strain, it was considered than no fatigue damage accumulates (*3*).

TABLE 1. The configuration and design lives of the Kansas Perpetual Pavement Structures

Section	1	2	3	4
Acronym	KAPA (Standard)	High Reliability	KAPA 2 (Modified)	KDOT
Wearing Course	1.5 inches, SM 9.5A (PG70-28)			
Binder Course	2.5 inches, SM 19A (PG70-28)			
Base Course	9.0 inches, SM 19A (PG70-28)	7.0 inches, SM 19A (PG64-22)	6.0 inches, SM 19A (PG64-22) (*)	12.0 inches, SM 19A (PG64-22)
Chemically Stabilized Embankment Soil	6.0 inches, 6% hydrated lime mixed to the natural soil			
Natural Subgrade	High plasticity clay (A-7-6)		High plasticity clay (A-7-6)	
Years of Design Life @ Reliability 1993 AASHTO method	6 @ 85% 18 @ 50%	2.5 @ 85% 7 @ 50%	6 @ 85% 18 @ 50%	10 @ 85% 68 @ 50%

(*) the bottom 3” was designed at 3% air voids for a binder rich layer
($P_b = 6.0\%$, $VTM = 3\% \pm 2\%$; $VFA = 77\%$)

In order to validate the second approach of the Perpetual Pavement concept, KAPA proposed another pavement structure, that was build in Section 3. This structure has the same thicknesses for the HMA layers as section one. However, a softer binder was used in the construction of the base HMA mix (PG 64-22 instead of PG70-28) and a richer and more ductile HMA mix was used in the bottom lift of the base layer. This mix had a binder content, P_b= 6.0%, and different volumetric properties (VTM = 3%±2%; VFA=77%) than the mix used in the same lift in Section 1 (P_b= 5.7%, VTM = 4%±2%; VFA=72%). It is expected that this mix will have a longer fatigue life.

Marshall (3) provided the design of a thinner section, with a predicted fatigue life of 30 million ESALs/lane, which corresponds to a reliability factor of about 5.2 or a reliability level of 85%. This section, named the High Reliability Structure, was built in Section 2. It has a total thickness of the HMA layers of 11 inches.

For the four sections, Gisi (*4*) has estimated the lives, in years, with the statistical-empirical design method recommended by the 1993 AASHTO Design Guide for Pavement Structures. The estimated lives are given in Table 1.

Construction of the Experimental Sections

The test sections were constructed on a fill and each was approximately 1,300 feet long with approximately 500 ft transition zones between them. The contractor, Dobson Brothers, commenced the earthwork in July 2004.The geotechnical investigation identified two natural subgrade soils along the project, based on their appearance. However, the laboratory tests indicated that they are both high plasticity clays. No significant statistical difference was found between the resilient moduli of the two natural soils.

The top six inches of the natural subgrade soil was treated with lime on all four pavement sections, to ensure proper support to the asphalt concrete layers and to provide a stable support for the construction equipment. Measures were taken for the proper curing of the lime treated soil. The embankment was brought to grade and the top six inches of soil were stabilized with 6% by weight hydrated lime in May 2005.

The asphalt paving work was done in June 2005. The hot asphalt mixes were produced in a drum plant located approximately one mile from the experimental sections. The project was completed and the experimental sections were opened to traffic at the beginning of November 2005.

Response Monitoring Instrumentation and Measuring Procedure

To verify the approach of designing perpetual pavements, based on an endurance strain limit, the four pavements were instrumented with gages for measuring the tensile strains at the bottom of the asphalt base layers. The instrumentation systems were placed in the four pavement structures during their construction, in June 2005.

The configuration of the instrumentation was the same in sections 1, 2 and 4. The gages were placed on top of the lime treated subgrade soil layer; the first bottom lift of asphalt concrete was placed directly on these gages. A schematic diagram of the layout of the response measuring instrumentation is shown in Figure 1. The instrumentation was designed to obtain accurate and multiple measurements of the longitudinal and transverse strains under a single pass of the load vehicle, while minimizing the costs.

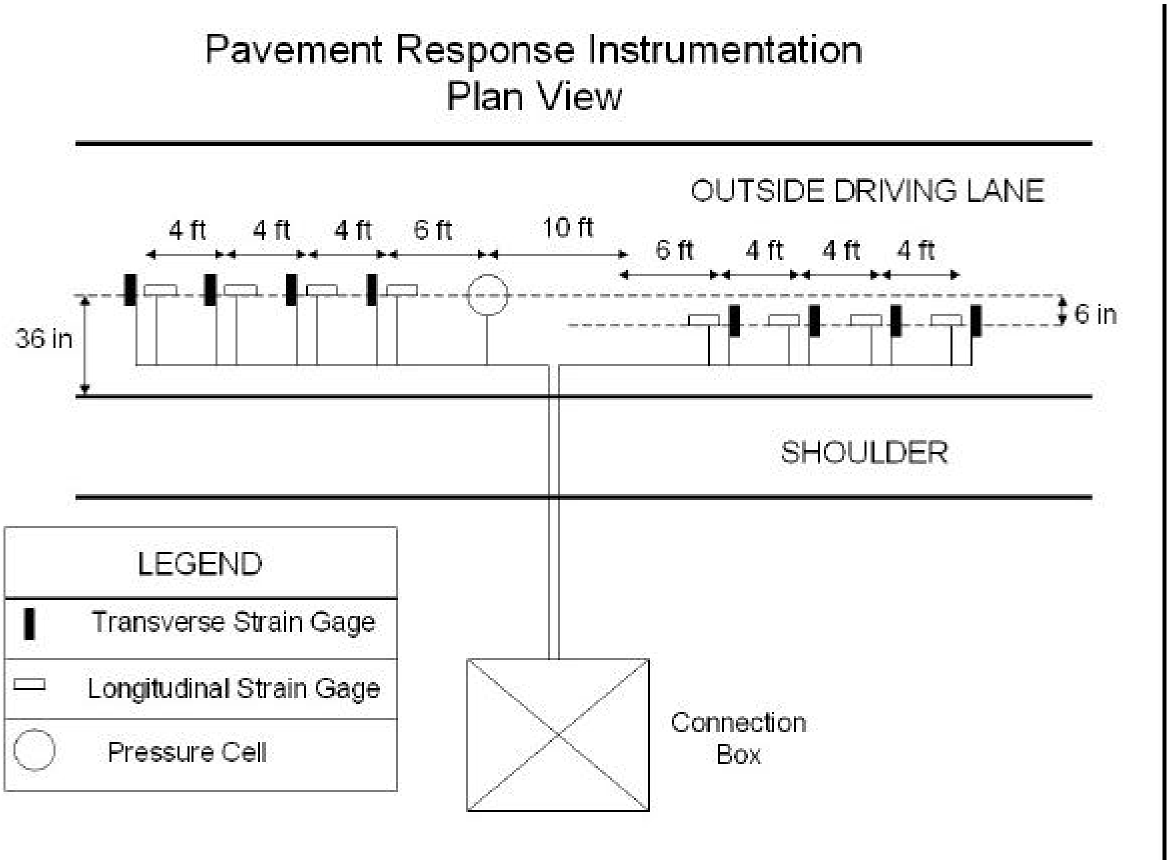

Figure 1. Plan View of the Instrumentation

The pavement response measuring instrumentation was composed of:

- *Eight pairs of strain gages*. In each pair, one gage was placed to measure the longitudinal strain and the other to measure the transverse strain. Texas Measurements gage model PML-120-2L were employed, due to their low cost and acceptable performance. Aluminum bars were glued at the ends of each strain gage to form H-bar gages. This significantly improves the bond between the gages and the surrounding asphalt concrete. Four pairs of gages were placed in the outside wheel path while the remaining four pairs were placed on a straight line six inched to the right of the outside wheel path.
- *One stress cell.* A Geokon stress cell, with a range of 0 to15 psi was placed centered in the outside wheel path.

The instrumentation was placed on the top of the compacted lime-treated embankment soil one day prior to the placement of the first lift of HMA. First, the location of the gages was marked relative to the centerline of the road and trenches were cut to bring the cables to a connection box mounted on a pole 15 feet away from the shoulder. The stress cells were placed in circular holes dug into the lime-soil embankment and filled with wet sand. They were seated in the wet sand so that they have a stable and horizontal position.

For each strain gage, a base of asphalt mortar, consisting of sand mixed with high grade asphalt cement, was placed first on top of the lime-soil layer. The gage was then pushed slowly into the mortar base and placed in position. The day of the HMA placing operation, hot loose asphalt mix was screened above the gage and compacted lightly by hand using a roller pin. The paver then placed the first lift of asphalt mix, followed by the compaction of the mix done with vibratory steel and pneumatic rollers. When passing above the gages, the vibration was turned off to reduce the probability of damaging the gages during construction.

The paving operation was done by unloading the hot asphalt mix in a windrow, in front of the paver and then feeding it into the hopper of the paver with a pick-up machine. This operation affected the survivability of the gages; the survival rate was between 50 and 70 percent.

The pick up machine removed all the strain gages placed in Section 3 (KAPA2); the stress cell buried in the lime treated embankment layer in Section 3 was not affected. Therefore, eight strain gages were retrofitted in Section 3 in the bottom lift of HMA by cutting four 12 inch diameter cores from the bottom lift of asphalt concrete and fixing the strain gages to the bottom of the cores with epoxy. Of the eight gages, four were positioned to measure transverse strain and four were positioned to measure longitudinal strain. The cores with the gages at their bottom were placed back in the same location and glued to the walls of the holes with a thick layer of epoxy.

Laboratory tests were performed on samples of materials were obtained during construction. Dynamic resilient modulus tests were performed on all asphalt concrete mixes used on this project. Triaxial resilient modulus tests were performed on these soils. Unconfined compression and resilient modulus tests were performed on the lime-treated subgrade soil at several curing times.

Two sessions of pavement response measurements were successfully performed in July and October 2005, before the test sections were opened to traffic. In each session consisted, a single axle dump truck, used as the loading vehicle, run multiple times on each of the four experimental pavement sections. The pavement response as well as truck speed and lateral position of the wheel were recorded for each pass.

The same loading vehicle was used for both sessions. Before the runs were performed the static weight of each wheel was measured by the Kansas Highway Patrol using calibrated scales. The dimensions of the tire imprints as well as the distance between tires were also measured. The dimensions of the tire imprints as well as the wheel weights are given in Table 2.

TABLE 2. Dimensions and weights of the loading vehicle

	Wheel			
	Front Left	Front Right	Rear Left	Rear Right
July 14, 2005				
Wheel load (lbs)	5,200	5,600	8,100	9,200
Inflation pressure (psi)	90	96	101	97
Imprint Length (inches)	7.7	7.3	6	6
Imprint Width (inches)	8.25	8.25	8.9	8.9
Space between double tires (inches)	-	-	4.25	4.25
September 29, 2005				
Wheel load (lbs)	5,400	5,800	10,000	10,400
Inflation pressure (psi)	92	98	101	100
Imprint Length (inches)	7.8	7.5	6.2	6.2
Imprint Width (inches)	8.25	8.25	8.9	8.9
Space between double tires (inches)	-	-	4.25	4.25

On each pavement, three sets of five passes of the loading vehicle were performed. Five passes each were performed with the truck passing at 20-25 mph, 40-45mph and 55-60mph, in order to determine the effect of vehicle speed on the magnitude of pavement response. Using reflective squares glued on the pavement surface as guides, the driver aimed to position the truck with the right wheels above the instrumentation. However, the lateral position of the wheels varied between passes; higher variability was observed at higher speeds.

Before the response measurements were performed two air rubber hoses connected to a triggering relay system were places across the pavement at a distance of 52.5 ft (16 m). When the front tire of the loading vehicle hit the rubber hoses, the system triggered an electronic switch connected to the same data acquisition system as the strain gages and the stress cell. The system was used to locate the position of the loading vehicle and to estimate its speed.

Putty strips were placed across the outer wheel path. The locations of the imprints made by the tires on the strips were recorded and used to determine the lateral position of the loading vehicle when it passed above the instrumentation.

The thermocouple of a temperature gage was lowered in holes drilled in the HMA layers and filled with oil to measure the temperature at the mid-depth of each HMA layer at the time of response measurements. The temperatures recorded at the mid-depth of each HMA layer as well as the temperature at the pavement surface are given in Table 3. The data shows that the recorded temperatures at the mid-depth of the HMA layers were higher for the July session than the corresponding temperatures recorded on September session. For both sessions, the temperature in the surface layers were the lowest in Section 1 and increased to the highest in Section 4, since the response measurements were done for Sections 1 and 2 in the morning, Sections 3 around noon and, Section 4 in the early afternoon.

TABLE 3. Temperature at the Mid-Depth of the HMA layers (°F)

Section	1	2	3	4
Acronym	KAPA	High Reliability	KAPA 2	KDOT
July 14, 2005				
Surface	98	108	124	122
Wearing Course	96.2	104.8	116.6	121.1
Binder Course	90	95.6	103.9	109.5
Base Course	88	89.1	93.5	96.6
September 29, 2005				
Surface	70	78	90	92
Wearing Course	58	76	90	92
Binder Course	60	70	79	86
Base Course	67	66	67	70

The horizontal strains and the vertical stress at the bottom of the asphalt concrete layer, as well as the position of the loading vehicle, were recorded with a National Instruments data acquisition system at a rate of 300 records per second. A sampling rate of 3,000 Hz was used and the average value for ten samples was recorded. The data was recorded in text format in separate files for each pass of the vehicle and then was processed using Microsoft Excel. Each strain signal was plotted and the peak values of the longitudinal and transverse strains were extracted.

The Measured Response of the Perpetual Pavements

The analysis of the measured response data recorded in the July and September 2005 sessions indicate the following:

a) The variability of the strains measured by gages placed in the same position relative to the wheel path was significant; variations of 30 to 60% were not uncommon. Possible reasons for the high variability include the inherent variability of the pavement structure and dynamic loading effects. Also, even though the same installation procedure was used for all strain gages, the degree of bonding with the surrounding asphalt concrete might vary from a gage to another, and thus, influence the strain reading.

b) Pavement response was influenced significantly by the speed of loading vehicle, illustrating the visco-elastic behavior of the asphalt concrete. Higher strains were recorded for the truck speed of 20 mph than for the speed of 40 mph. A smaller decrease was observed when the measurements were performed for the truck speed of 60 mph relative to those recorded at 40 mph. In general, it was observed that the strains recorded at the truck speed of 60 mph are close to half, and sometimes less than half, the strains recorded at the truck speed of 20 mph. Figure 2 illustrates the effect of vehicle speed on the longitudinal strain at the bottom of the HMA layer recorded in July for pavement Section 1.

c) As expected, the magnitude of horizontal strains and vertical stresses at the bottom of the asphalt layer was influenced by the temperature in the asphalt layers. Higher stresses and strains were recorded in July than in September (Figures 3 to 6). The significant effect of temperature limits the comparison of the strain values recorded on all sections; the response measurements being performed at different times of day.

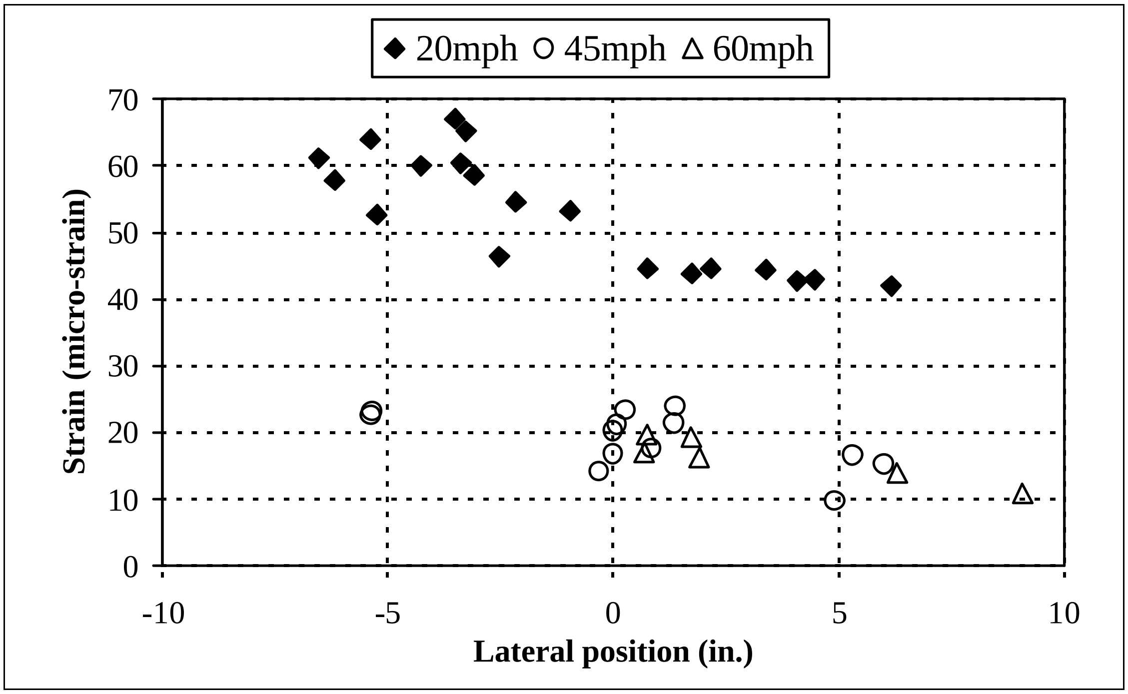

FIGURE 2 Longitudinal Strain vs. Truck Speed - Section 1 (KAPA) – July 8, 2005

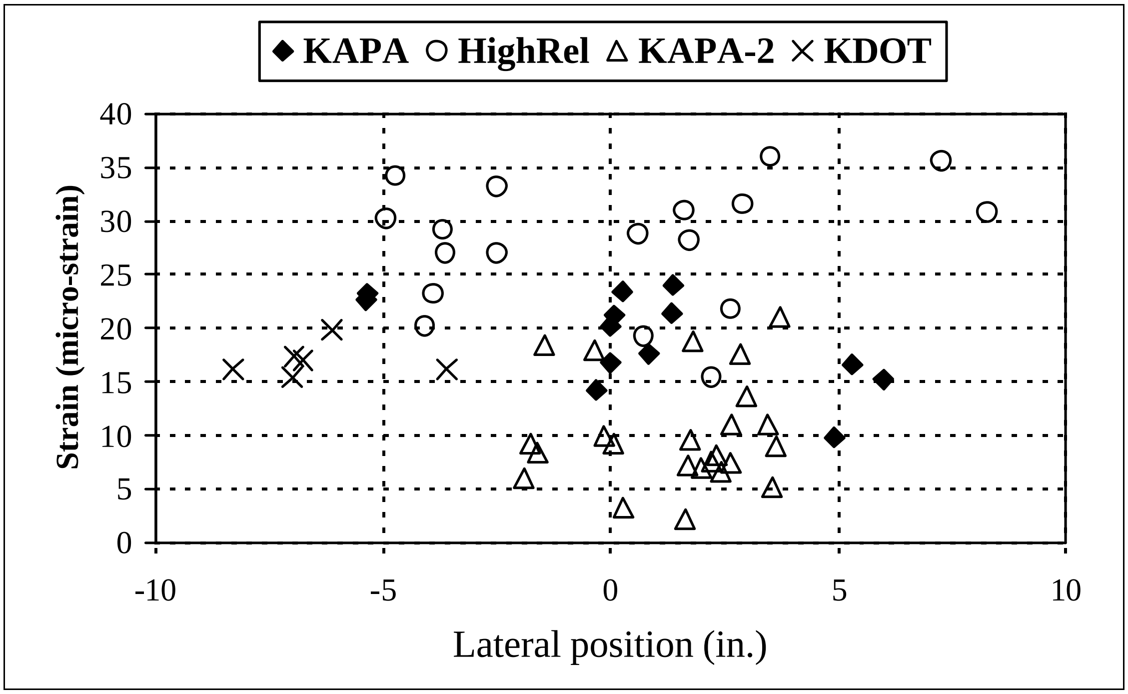

FIGURE 3 Longitudinal Strain at 45mph truck speed – July 8, 2005

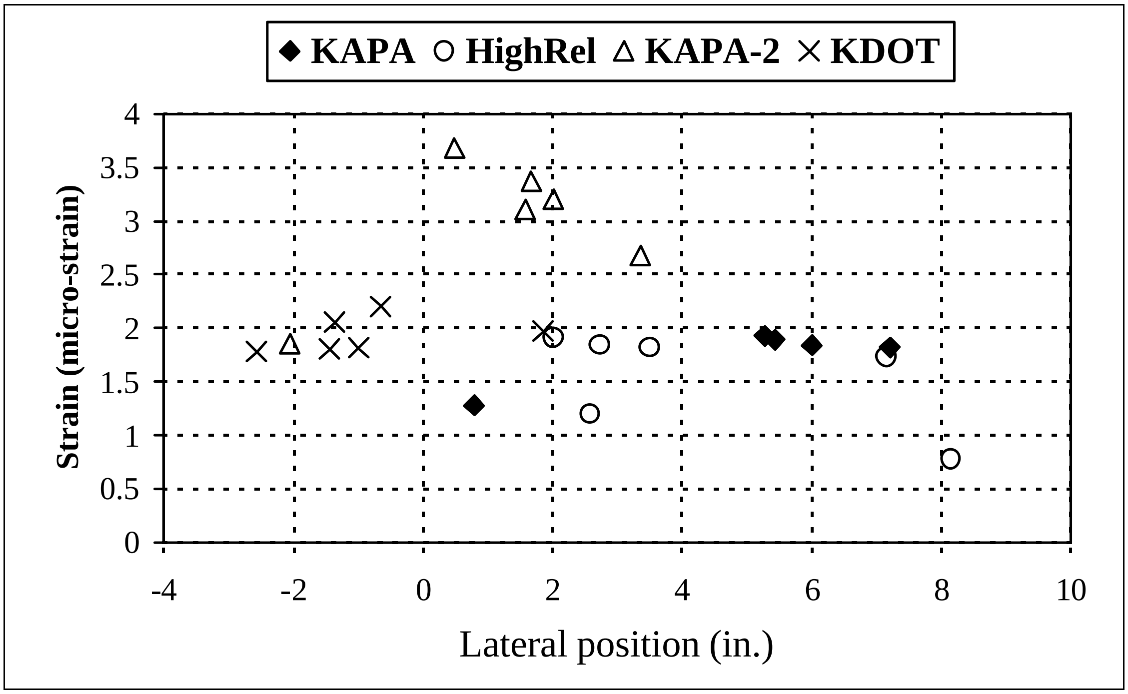

FIGURE 4 Transverse Strain at 45mph truck speed – July 8, 2005

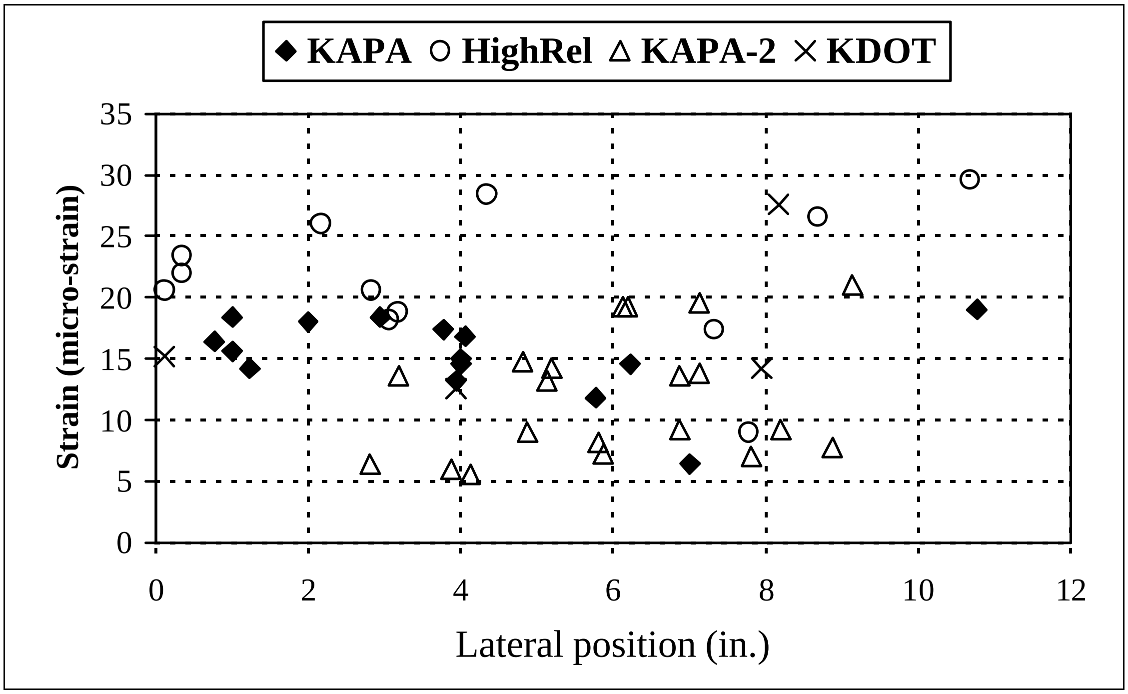

FIGURE 5 Longitudinal Strain at 45mph truck speed – September 29, 2005

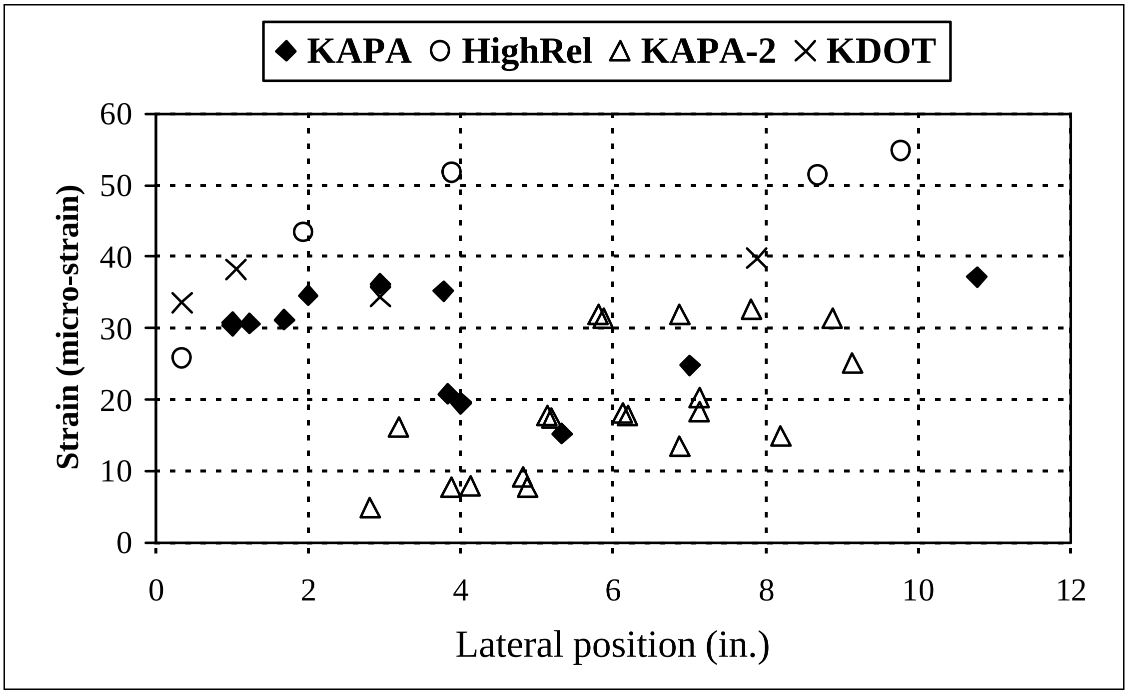

FIGURE 6 Transverse Strain at 45mph truck speed – September 29, 2005

d) For the single axle truck loading used in the response measurement, the measured transverse strains under the dual tire- single axle were larger than the corresponding longitudinal strains (Figures 3 to 6). This was observed for all sections, all three truck speeds and for both response measurement sessions. For a dual tire single axle load, the calculation of pavement response using a linear-elastic theory applied to a semi-infinite layered pavement system would estimate that longitudinal strains higher than transverse strains, contradicting the results of the field experiment. However, the pavement structure is not infinite in transverse direction and in the proximity of the shoulder, the stress computation using a semi-infinite layered model leads to erroneous response estimation. Therefore, it is reasonable to assume that the measured transverse strains were higher tran the longitudinal strains because of the proximity of the shoulder; the strain gages were installed in the outer wheel path, about 3 feet from the outside edge of the driving lane,

e) As expected, for the same temperature and truck speed, the highest measured strains and stresses were recorded for the thinnest pavement structure, Section 2 (High Reliability). However, even for this pavement, the transverse and longitudinal strains measured at 45 mph and 60 mph in September were lower than 70 micro-strain, the endurance strain limit recommended in the literature for asphalt concrete.

f) At the same loading speed, the corresponding strains recorded for the section designed by KDOT (Section 4) were similar to the strains recorded on the stiff Perpetual Pavement section proposed by KAPA (Section 1). However, the recorded temperatures at the mid-depth of the HMA layers were lower for Section 1 than for Section 4 (Table 3); the response measurements were performed in Section 1 in the morning and Section 4 in the afternoon.

g) Without considering the temperatures at the mid-depth of the HMA layers, the strains in Section 3 were the lowest. This may be explained by the higher viscous behavior of the mix with high binder content, that may lead to accentuated dampening of the dynamic wheel loading, and thus to lower dynamic strains at the bottom of the asphalt layer. This second approach for designing Perpetual Pavements seems promising. Further investigation, which may include a comparison study of fatigue behavior may reveal if the binder rich bottom lift is the best solution for constructing long-lasting asphalt pavements.

CONCLUSIONS

Kansas Department of Transportation conducted a field trial to investigate the suitability of this concept for Kansas highway pavements. The experiment involved the construction of four thick flexible pavement structures on a new alignment on highway US-75 near Sabetha, Kansas. They were designed to have a perpetual life and have layer thicknesses close to those recommended by the current KDOT's structural design method for flexible pavements, which is based on the 1993 AASHTO Pavement Design Guide.

To verify the approach of designing perpetual pavements based on an endurance strain limit, the four pavements were instrumented with gages for measuring the strains at the bottom of the asphalt base layers. Two sessions of pavement response measurements under known vehicle load, consisting of multiple runs of a single axle dump truck at three speeds, were performed in July and October 2005, before the pavement sections were opened to traffic. The analysis of the measured strain data led to the following major conclusions:

- With few exceptions, the longitudinal and transverse strains were lower than 70 micro-strains the endurance strain limit recommended in the literature for asphalt concrete.
- The pavement response is affected significantly by the temperature in the asphalt layers and by the speed of the loading vehicle. The strains recorded for the truck speed of 20 mph were almost double the strains recorded for the speed of 60 mph.
- The measured transverse strains under the dual tire - single axle were higher than the corresponding longitudinal strains. This was attributed to the proximity of the shoulder, which may affect the stress distribution in the outer wheel path, where the instrumentation was installed.
- The strains recorded for the stiff perpetual pavement structure were similar with the corresponding strains recorded on the thick full-depth asphalt pavement designed by Kansas DOT using the statistical-empirical procedure recommended by 1993 AASHTO Pavement Design Guide.

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