

First Findings from the Kansas Perpetual Pavements Experiment

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To investigate the suitability of the perpetual pavements concept for Kansas highway pavements, the Kansas Department of Transportation (KDOT) constructed four thick, flexible pavement structures on a new alignment on US-75 near Sabetha, Kansas. They were designed to have a perpetual life and have layer thicknesses close to those recommended by KDOT's structural design method for flexible pavements, which is based on the 1993 AASHTO Design Guide. To verify the approach of designing perpetual pavements on the basis of an endurance strain limit, the four pavements were instrumented with gauges for measuring the strains at the bottom of the asphalt base layers. Seven sessions of pavement response measurements under known vehicle load were performed between July 2005 and October 2007, before and after the pavement sections were opened to traffic. The analysis of the strain data indicated that, even during hot summer days, the strains of all four test sections were smaller than the endurance limit of asphalt-concrete. As expected, the strains were affected by the temperature in the asphalt layers and the speed of the loading vehicle. The analysis of the strain signals revealed that the transverse strain under the front axle did not recover completely before the arrival of the rear axles, a situation causing the accumulation of dynamic transverse strain to values higher than those of the corresponding longitudinal strains. A comparison between the measured response and that predicted by a linear-elastic model indicated that the predicted transverse strains were close to half the corresponding measured dynamic transverse strains, while the predicted longitudinal strains were close to twice the measured dynamic longitudinal strains. Furthermore, the predicted vertical stresses at the top of the subgrade layer were close to five times the measured stresses.

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

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The perpetual pavement concept is intended 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 (1).

Fatigue cracks may develop in the surface layer and propagate horizontally in the top lift. Because they appear at the pavement surface, these so-called top-down cracks can be observed, and action can be taken 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, therefore, need repair only at the surface. This failure mode leads to significant monetary saving for the repair, rehabilitation, and reconstruction of these pavements.

Two main approaches are recommended in the perpetual pavements concept (1). The first recommends the construction of a bottom lift for the base layer, with softer binder grade, higher binder content, or both. 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 in the total thickness of asphalt layers and the increase in 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; this testing 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 (1). The limiting strain that leads to this infinite fatigue life is called the 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 with the endurance limit exists, research reported in the literature indicates that the endurance limit for tensile strain ranges between 60 and 100 microstrain and that it is not the same for all mixes (2).

The 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 layer thicknesses close to those recommended by KDOT's current structural design method for flexible pavements, which is based on the 1993 AASHTO Design Guide.

To verify the approach of designing perpetual pavements on the basis of an endurance strain limit, the four pavements were instrumented with gauges 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. Seven sessions of pavement response measurements under known vehicle load were performed between July 2005 and October 2007, before and after the pavement 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 first 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 hot-mix asphalt (HMA) mixes used in the construction of the bottom asphalt lift in the four perpetual pavement structures and to estimate the structures' relative cracking lives.

BACKGROUND

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 US-75 near Sabetha. A 4-mi segment connecting Fairview and Sabetha was constructed because the existing US-75 (a north–south corridor) was overlapping a 2-mi stretch of US-36 (an east–west corridor). KDOT selected this project because it was new to the 2005 construction season, it served on a corridor with medium-to-high truck traffic volume, and it was long enough to accommodate four experimental sections 500 ft long on a 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 an 18,000-lb single-axle load;

- Evaluate the cost-effective full-depth asphalt pavement HMA designs by comparing four alternative designs of long-lasting, full-depth asphalt pavements; and
- 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 described in Table 1, numbered in the order that they were constructed, from south to north: Section 1 (KAPA), Section 2 (High Reliability), Section 3 (KAPA 2), and Section 4 (KDOT). The estimated design cumulative traffic for these pavements is 2.6 million (10 years) and 5.7 million (20 years) equivalent single-axle loads (ESALs) per lane. The traffic volume in the initial year was estimated to be 240,000 ESALs per lane. The annual growth rate was estimated to be close to 1.8%.

For these traffic data, KDOT provided the design for a long-lasting pavement structure. With an estimated average resilient modulus for the subgrade soil of 2,500 psi, the thickness of the asphalt layer obtained for this pavement section (Section 4) was 16 in. The Kansas Asphalt Pavement Association (KAPA) provided the design of three other pavement structures, for which it was estimated that the tensile strain at the bottom of the asphalt layer was smaller than 70 microstrain, the endurance limit proposed in the literature on the basis of laboratory fatigue tests on asphalt mixes.

Thompson (3) provided the design for the KAPA (Standard) structure (Section 1) under the assumption that flexural strains at the bottom of the HMA layer less than 70 microstrain (10^{-6}) do not contribute to cumulative fatigue damage, so that HMA bottom-up fatigue distress should not occur. Thompson calculated the flexural strain for each month of the year on the basis of an ILLI-PAVE algorithm:

$$\log(\epsilon_{\text{HMA}}) = 5.746 - 1.583 * \log(T_{\text{HMA}}) - 0.774 * \log(E_{\text{HMA}}) - 0.097 * \log(E_{\text{Ri}})$$

where

- ϵ_{HMA} = HMA flexural strain (microstrain),
- T_{HMA} = HMA thickness (in.),
- E_{HMA} = HMA modulus (ksi), and
- E_{Ri} = subgrade modulus (ksi).

TABLE 1 Configuration and Design Lives of Kansas Perpetual Pavement Structures

| | Section and Acronym | | | |
|---------------------------------------|---|---------------------------|--|----------------------------|
| | 1 KAPA (standard) | 2 High Reliability | 3 KAPA 2 (modified) | 4 KDOT |
| Wearing course | 1.5 in., SM 9.5A (PG70-28) | | | |
| Binder course | 2.5 in., SM 19A (PG70-28) | | | |
| Base course | 9.0 in., SM 19A (PG70-22) | 7.0 in., SM 19A (PG64-22) | 9.0 in., SM 19A (PG64-22) ^a | 12.0 in., SM 19A (PG64-22) |
| Chemically stabilized embankment soil | 6.0 in., 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 | 6 @ 85% | 2.5 @ 85% | 6 @ 85% | 10 @ 85% |
| 1993 AASHTO method | 18 @ 50% | 7 @ 50% | 18 @ 50% | 68 @ 50% |

^aThe bottom 3 in. was designed at 3% air voids for a binder rich layer ($P_b = 6.0\%$; Design air voids = $3\% \pm 2\%$; VFA = 77%).

The HMA modulus for each month was estimated on the basis of the volumetric properties of the HMA mix, the binder grade, and the mean monthly pavement temperature (3). The 6-in. 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 applications, N_a , to initiate a fatigue crack:

$$N_a = (8.2 * 10^{-8}) * \left(\frac{1}{\epsilon_{HMA}} \right)^{3.5}$$

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

To validate the second approach of the perpetual pavement concept, KAPA proposed another pavement structure that was built in Section 3 (KAPA 2). This structure has the same thicknesses for the HMA layers as Section 1 (KAPA). However, a softer binder was used in the construction of the base HMA mix (PG 64-22 instead of PG 70-22), 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 [design air voids = $3\% \pm 2\%$, voids filled with asphalt (VFA) = 77%] than the mix used in the same lift in Section 1 ($P_b = 5.7\%$, design air voids = $4\% \pm 2\%$; VFA = 72%). It was expected that this mix would have a longer fatigue life.

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

For the four sections, Gisi and Romanoschi (4) had estimated the lives, in years, with the statistical-empirical design method recommended by the 1993 AASHTO *Guide for Design of Pavement Structures* (5). The estimated lives are given in Table 1.

Construction of Experimental Sections

The test sections were constructed on a fill, and each was approximately 1,300 ft long with transition zones of approximately 500 ft between them. The contractor, Dobson Brothers, commenced the earthwork in July 2004. The geotechnical investigation identified two natural subgrade soils along the project on the basis of their

appearance. However, the laboratory tests indicated that both subgrade soils were high-plasticity clays. No significant statistical difference was found between the resilient moduli of the two natural soils.

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

The asphalt paving work was done in June 2005. 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 on the basis of an endurance strain limit, the four pavements were instrumented with gauges 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 gauges were placed on top of the lime-treated subgrade soil layer; the first bottom lift of asphalt-concrete was placed directly on these gauges. 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 cost of the instrumentation.

The pavement response-measuring instrumentation was composed of

- Eight pairs of strain gauges. In each pair, one gauge was placed to measure the longitudinal strain and the other to measure the transverse strain. Texas Measurements gauges Model PML-120-2L were employed, due to their low cost and acceptable performance. Aluminum bars were glued to the ends of each strain gauge to form H-bar gauges. This modification significantly improved the bond between the gauges and the surrounding asphalt-concrete. Four pairs of gauges were placed in the outside wheel path while the remaining four pairs were placed on a straight line 6 in. to the right of the

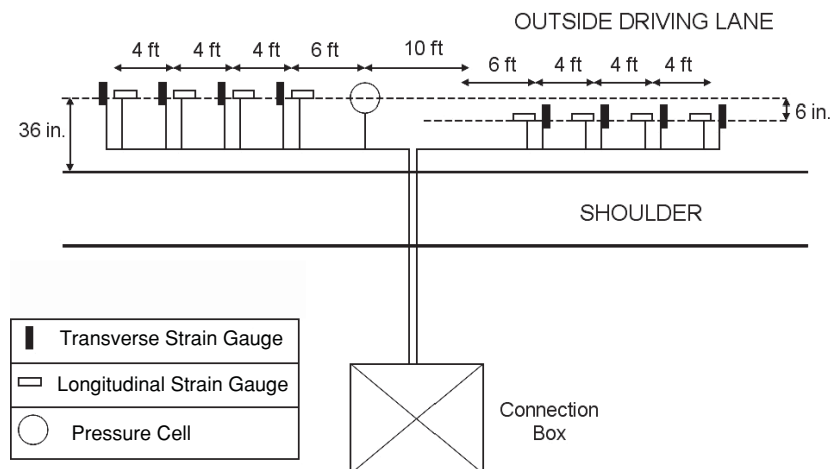


FIGURE 1 Plan view of instrumentation.

outside wheel path, to determine the effect of the lateral position of the loading wheel on the measured pavement response.

- One stress cell. A Geokon stress cell with a range of 0 to 15 psi was centered in the outside wheel path.

The instrumentation was placed on the top of the compacted lime-treated embankment soil 1 day before the placement of the first lift of HMA. First, the location of the gauges 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 ft from the shoulder. The stress cells were placed in round holes dug into the lime-soil embankment and filled with wet sand. They were seated in the wet sand so that they had a stable, horizontal position.

For each strain gauge, 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 gauge 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 gauge and compacted lightly by hand with a roller pin. The paver placed the first lift of asphalt mix on top of the gauges, which was followed by compaction of the mix with vibratory steel and pneumatic rollers. When passing above the gauges, the vibration was turned off to reduce the probability of damaging the gauges during construction. Field density measurements with a nuclear-density gauge proved that stopping the vibration did not affect the density of the compacted asphalt-concrete.

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 pickup machine. This operation affected the survivability of the gauges; the survival rate was between 50% and 70%.

The pickup machine removed all the strain gauges in Section 3 (KAPA 2); the stress cell buried in the lime-treated embankment layer in Section 3 was not affected. Therefore, eight strain gauges were retrofitted in Section 3 in the bottom lift of HMA by cutting four cores 12 in. diameter from the bottom lift of asphalt-concrete and fixing the strain gauges to the bottom of the cores with epoxy. Of the eight gauges, four were positioned to measure transverse strain and four

to measure longitudinal strain. The cores with the gauges at their bottom were placed back in the same location and glued to the walls of the holes with a thick layer of epoxy. The wires were rerouted to the connection box through grooves cut into the bottom lift of HMA and then through a plastic conduit buried in the soil at a depth of about 3 ft.

Laboratory tests were performed on samples of materials 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 the subgrade soils. Unconfined compression and resilient-modulus tests were performed on the lime-treated subgrade soil at several curing times.

Seven sessions of pavement response measurements under known vehicle load were performed between July 2005 and October 2007, before and after the pavement sections were opened to traffic. In each session, a single-axle dump truck owned by KDOT was used as the loading vehicle. According to the FHWA vehicle classification system, this truck is a Class 5 vehicle.

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

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 to 25 mph, 40 to 45 mph, and 55 to 60 mph to determine the effect of vehicle speed on the magnitude of pavement response. Using reflective squares glued to 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 rubber air hoses connected to a triggering relay system were placed across the pavement at a distance of 52.5 ft (16 m). When the front tire of the loading vehicle hit the hoses, the system triggered an electronic

TABLE 2 Dimensions and Wheel Loads of Tire

| | Steering Front Left | Steering Front Right | Tractor Rear Left | Tractor Rear Right | Trailer Rear Left | Trailer Rear Right |
|-------------------------------------|-----------------------------|-----------------------------|-------------------------|--------------------------|------------------------------|------------------------------|
| Inflation pressure (psi) | 90 | 96 | | | 101 | 97 |
| Imprint length (in.) | 7.7 | 7.3 | | | 6 | 6 |
| Imprint width (in.) | 8.25 | 8.25 | | | 8.9 | 8.9 |
| Space between double tires (in.) | — | — | | | 4.25 | 4.25 |
| Wheel Load (lb.) | | | | | | |
| July 14, 2005 | 5,200 | 5,600 | — | — | 8,100 | 9,200 |
| September 29, 2005 | 5,400 | 5,800 | — | — | 10,000 | 10,400 |
| April 13, 2006 | 4,900 | 4,800 | — | — | 12,000 | 10,400 |
| August 1, 2006 | 5,500 4,600 ^a | 5,400 4,300 ^a | — 9,700 ^a | — 9,500 ^a | 11,400 9,000 ^a | 11,200 9,000 ^a |
| October 13, 2006 | 5,400 | 5,300 | — | — | 9,800 | 10,000 |
| May 10, 2007 | 5,000 | 5,300 | — | — | 9,500 | 9,300 |
| October 5, 2007 | 5,500 | 5,100 | — | — | 10,400 | 10,000 |

^aRWD truck.

switch connected to the same data acquisition system as the strain gauges 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 gauge was lowered into holes drilled in the HMA layers and filled with oil to measure the temperature at the middepth of each HMA layer at the time of response measurements. The values of the recorded temperatures are not given here for brevity. However, the recorded temperatures at the middepth of the HMA layers were higher for the July 2005 and August 2006 sessions than the corresponding temperatures recorded during all the five remaining sessions. Furthermore, for all sessions, the temperatures in the surface layers were lowest in Section 1 and increased to highest in Section 4, because response measurements were done for Sections 1 and 2 in the morning, Sections 3 around noon, and Section 4 in the early afternoon.

Sections 1, 2, and 4 were loaded with an additional vehicle for the August 1, 2006, measurement session. The FHWA's rolling wheel deflectometer (RWD) measured deflection on the experimental sections, as well as on several other sections of state highways that day. The RWD truck had an 8,900-lb, single-axle, single-tire steering axle; a 19,200-lb, dual-tire tandem axle at the back of the tractor; and an 18,000-lb, dual-tire single axle in the rear of the trailer. Only five runs of the RWD truck, all at the speed of approximately 60 mph, were performed on each of three sections.

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 10 samples was recorded. The data were recorded in text format in separate files for each pass of the vehicle and then processed with Microsoft Excel. Each strain signal was plotted, and the peak values of the longitudinal and transverse strains were manually extracted.

Measured Response of Perpetual Pavements

The analysis of the measured response data recorded in the six measurement sessions indicated the following:

1. The variability of the strains measured by gauges 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. Furthermore, even though the same installation procedure was used for all strain gauges, the degree of bonding with the surrounding asphalt-concrete might vary from one gauge to another and, thus, influence the strain reading.
2. Pavement response was influenced significantly by the speed of the loading vehicle, illustrating the viscoelastic behavior of the asphalt-concrete. Higher strains were recorded for a truck speed of 20 mph than for a speed of 40 mph. A much smaller decrease was observed when the measurements were performed for a truck speed of 60 mph relative to those recorded at 40 mph. In general, the strains recorded at a truck speed of 60 mph are close to half, and sometimes less than half, the strains recorded at a truck speed of 20 mph. Figures 2 and 3 illustrate the effect of vehicle speed on the longitudinal

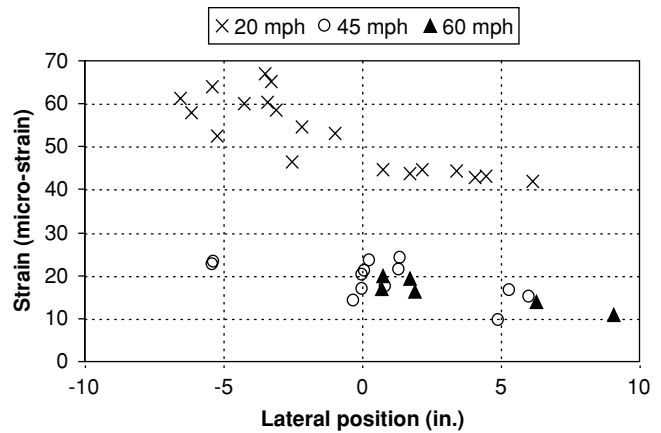


FIGURE 2 Longitudinal strain versus truck speed, Section 1 (KAPA), July 8, 2005.

and transverse strains at the bottom of the HMA layer recorded in July 2005 for pavement Section 1.

3. 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 during the summer than in late spring or early fall (6). The significant effect of temperature limits the comparison of the strain values recorded on all sections in different measuring sessions.

4. For the truck loading used in the response measurement, the measured transverse strains under the dual-tire, single-axle load were larger than the corresponding longitudinal strains (Figures 2 to 6). This difference was observed for all sections, for both the KDOT and RWD trucks, for all three truck speeds, and for all response measurement sessions. For a dual-tire, single-axle load, the calculation of pavement response with a linear-elastic theory applied to a semi-infinite layered pavement system estimated that longitudinal strains were higher than transverse strains, contradicting the results of the field experiment. The most reasonable explanation was that the strain under the front axle did not recover completely before the arrival of the rear axles, causing the accumulation of dynamic strain and higher transverse strains than the corresponding longitudinal strains (Figures 5 and 6). This situation is possible because, under the pass

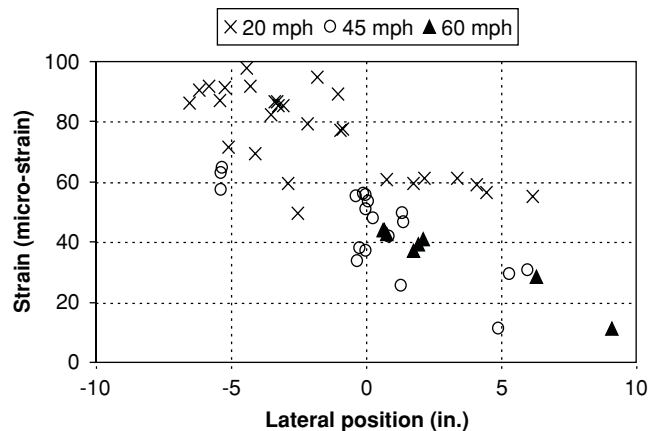


FIGURE 3 Transverse strain versus truck speed, Section 1 (KAPA), July 8, 2005.

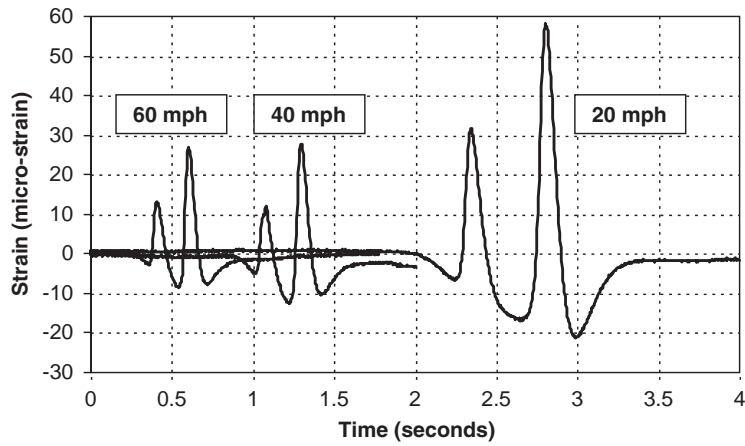


FIGURE 4 Longitudinal strain signal versus truck speed, August 1, 2006.

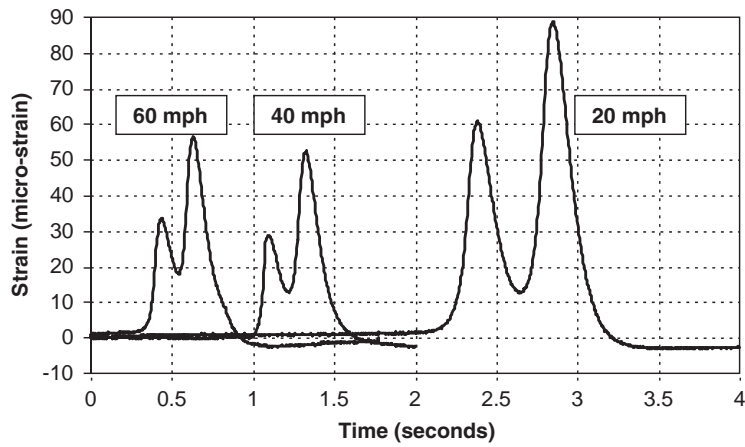


FIGURE 5 Transverse strain signal versus truck speed, August 1, 2006.

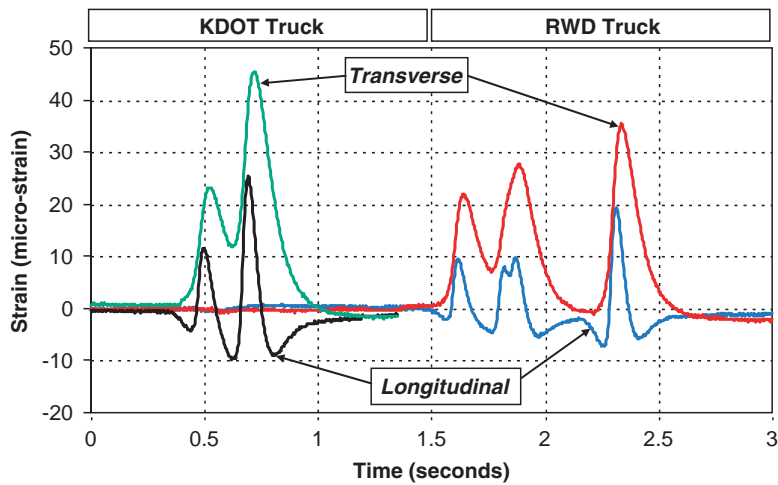


FIGURE 6 Transverse strain at 60-mph truck speed, August 1, 2006.

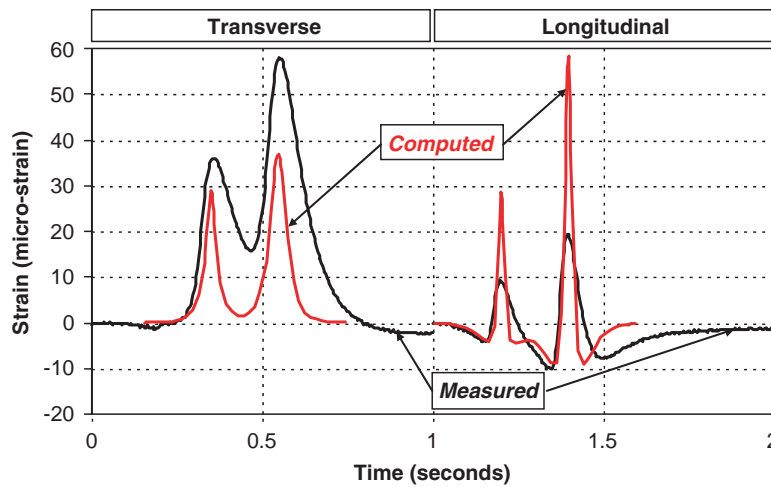


FIGURE 7 Measured and computed strains at 60-mph truck speed, August 1, 2006.

of an isolated wheel above the point of interest, the transverse strain remains tensile. Under the pass of an isolated wheel, the longitudinal strain is first negative (compression), then positive (tension), and then negative again, a circumstance that prevents the accumulation of dynamic strain in the longitudinal direction when multiple axles pass above the same point.

5. The Everstress (7) linear-elastic model was used to calculate the theoretical pavement response. For each asphalt-concrete layer, the modulus at the temperatures recorded at middepth was predicted from the results of the dynamic modulus laboratory tests at 25 Hz. The measured transverse strains at a truck speed of 60 mph were almost twice the transverse strains computed with the Everstress linear-elastic program, while the measured longitudinal strains were about half the computed transverse strains (Figure 7). The measured vertical compressive stresses at the top of the lime-treated embankment soil layer were about one-third the computed stresses (Figure 8). The wheel loads were modeled in Everstress as uniformly distributed over circular areas, with the same magnitude and average contact

stress as the field-measured wheel loads. However, the imprints of the truck tires in the field were rectangular and not circular.

6. The accumulation of dynamic transverse strain may also justify that the transverse strains measured at vehicle speeds close to 40 mph and close to 60 mph are very similar. At higher speeds, the stiffness of the asphalt-concrete layers is higher, and thus the transverse strains at the bottom of the asphalt-concrete layers should be smaller. However, the rear axles come more quickly after the front axles at higher speeds, allowing less time for the transverse strain induced by the front axles to recover. Therefore, the transverse strain at the arrival of the rear axles is higher, and this higher strain sometimes causes a higher peak in the dynamic transverse strain.

7. The magnitudes of the transverse and longitudinal strains measured under the steering axle were about 50% to 70% of the magnitudes of the corresponding strains measured under the rear axles. This observation suggests that the damage induced by the steering axles should be considered when the fatigue damage accumulated at the bottom of the asphalt layers is computed. Many structural design

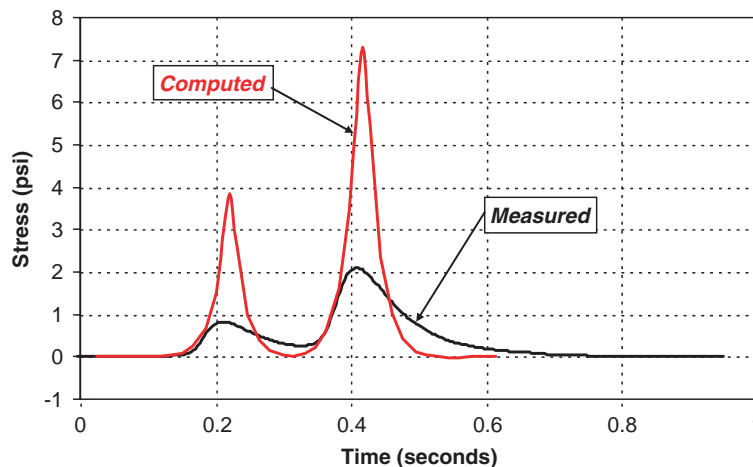


FIGURE 8 Measured and computed vertical stress at 60-mph truck speed, August 1, 2006.

methods for flexible pavements ignore the damaging effect of the steering axles.

8. 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 and 60 mph were higher than 70 microstrain (the endurance strain limit recommended in the literature for asphalt–concrete) only for the measurements taken on August 1, 2006. The temperatures recorded that day at the middepth of the asphalt layers in Section 2 were very high, between 99°F and 118°F, and the total load of the rear axle was 22,600 lb.

9. 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 middepth of the HMA layers were always lower for Section 1 than for Section 4 because the response measurements were always performed starting with Section 1 in the morning and progressing to Section 4, which was tested in the afternoon.

10. Without consideration of the temperatures at the middepth of the HMA layers, the strains in Section 3 were the lowest. This observation may be explained by the more-viscous behavior of the mix with high binder content, which may lead to accentuated dampening of the dynamic wheel loading and thus to lower dynamic strains at the bottom of the asphalt layer. In addition, laboratory beam fatigue testing of the mixes placed at the bottom of the base layer indicated that, at 20°C and strains between 25 and 50 microstrain, the fatigue life of the mix with high binder content was about twice that of the mix used in Section 4. Thus, it is expected that bottom-up fatigue cracking life of Section 3 would be at least double that of Section 4. Therefore, this second approach for designing perpetual pavements, which recommends the placement of a mix with high binder content at the bottom of the base layer, is very promising.

CONCLUSIONS

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

To verify the approach of designing perpetual pavements on the basis of an endurance strain limit, the four pavements were instrumented with gauges for measuring the strains at the bottom of the asphalt base layers. Seven sessions of pavement response measurements under known vehicle load, consisting of multiple runs of a single-axle dump truck at three speeds, were performed between

July 2005 and October 2007, before and after the pavement sections were opened to traffic. The analysis of the measured strain data recorded so far led to the following major conclusions:

- With few exceptions, the longitudinal and transverse strains were lower than 70 microstrain, the endurance strain limit recommended in the literature for asphalt–concrete.
- The pavement response was affected significantly by the temperature in the asphalt layers and by the speed of the loading vehicle. The strains recorded for a truck speed of 20 mph were almost double the strains recorded for a speed of 60 mph.
- The measured transverse strains under the dual-tire, single-axle load were higher than the corresponding longitudinal strains. The transverse strain under the front axle does not recover completely before the arrival of the rear axles, and this condition causes the accumulation of dynamic strain and higher transverse strains than the corresponding longitudinal strains.
- The measured transverse strains were almost twice the transverse strains computed with the Everstress linear-elastic program, while the measured longitudinal strains were about half the computed transverse strains, and the measured vertical compressive stresses at the top of the lime-treated embankment soil layer were about one-third of the computed stresses.
- The strains recorded for the stiff perpetual pavement structure were similar to the corresponding strains recorded on the thick full-depth asphalt pavement designed by KDOT by means of the statistical–empirical procedure recommended by the 1993 AASHTO Design Guide.

REFERENCES

1. *Transportation Research Circular 503: Perpetual Bituminous Pavements*. Transportation Research Board of the National Academies, Washington, D.C., Dec. 2001.
2. Thompson, M., and S. Carpenter. *Fatigue Design Principles for Long Lasting HMA Pavements*. Proc., *International Conference on Long Lasting Asphalt Pavements* (CD-ROM), Auburn, Ala., 2004.
3. Thompson, M. *Perpetual Pavement Review: Kansas DOT US-75 Project Fairview–Sabetha*. Kansas Asphalt Pavement Association, Topeka, May 2003.
4. Gisi, A., and S. A. Romanoschi. *Perpetual Pavement: US-75 Project Update*. Presented at 49th Annual Kansas Asphalt Paving Conference, Lawrence, Nov. 3, 2005.
5. *Guide for Design of Pavement Structures*. AASHTO, Washington, D.C., 1993.
6. Romanoschi, S. A., A. Gisi, and C. Dumitru. The Dynamic Response of Kansas Perpetual Pavements Under Vehicle Loading. Proc., *International Conference on Perpetual Pavement*, Columbus, Ohio, Sept. 13–15, 2006.
7. *Everseries User's Guide: Pavement Analysis Computer Software and Case Studies*. Washington State Department of Transportation, Olympia, Aug. 2005. www.wsdot.wa.gov/biz/mats/pavement/EVERSERS/EverseriesUserGuide.pdf.

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