Asphalt Concrete Strain Responses at High Loads and Low Speeds At the National Airport Pavement Test Facility (NAPTF)

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Abstract

Results are described from asphalt strain gage measurements made during pavement response tests on the flexible pavement test items at the National Airport Pavement Test Facility (NAPTF). Tests were run at speeds of 0.08, 0.15, 0.23, 0.3, 0.6, 1.5, and 2.2 m/sec (0.25, 0.5, 0.75, 1.0, 2.0, 5.0, and 7.33 feet/sec) with dual-wheel configurations at wheel loads of 106.8, 133.5, and 160.2 kN (24,000, 30,000, and 36,000 pounds) and tire pressures of 1378 kPa (200 psi). The strain gages were located at the bottom of the 125-mm- (5-inch)-thick surface asphalt layer of the conventional and stabilized-base test items and additionally at the bottom of the 125-mm- (5-inch)-thick stabilized-base asphalt layer of the stabilized-base test items. Gages were oriented along the travel direction and transverse to the travel direction. Measurements were made at asphalt temperatures of 11.1°C (52°F) and 22.2°C (72°F). Significant permanent deformations were found in the measurements, particularly in the transverse direction. The measured strains were found to vary strongly with temperature and test speed, spanning the range of 300 to 2,000 microstrains. The upper range of these values is much larger than was anticipated, and the strains are 2 to 3 times higher than layered elastic computer program predictions of asphalt strain responses for the structural and load conditions existing during the tests. Longer duration of loading results in reduced asphalt stiffness. However, the longer duration of loading at slow speeds increases the amount of viscous flow and leads to significant increases in the total strain within the asphalt mix as speed decreases.

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Introduction

Fatigue in the asphalt concrete (AC) layer is one of the criteria for flexible pavement design. Fatigue failure of the AC layer is related to the magnitude of tensile strains at the bottom of the layer. The magnitude of the flexural strains in the AC is dependent on the wheel loading conditions, thickness of the paving material layers, and the properties of the various paving layers and the subgrade soil. Fatigue transfer functions relate the number of load repetitions to reach certain pavement cracking failure conditions (i.e., crack initiation, 10-percent cracking area, etc.) to the maximum tensile strain in the AC layer. It is therefore important to measure AC strains so that pavement response and cracking performance can be properly evaluated. Horizontal strains in the AC layers of the NAPTF flexible pavement test items are measured by means of H-Bar-type asphalt strain gages (ASG). A total of 96 H-bar type ASGs (transverse and longitudinal) were installed when the test pavements were constructed.

As a supplement to the slow-speed response tests and the trafficking tests performed on the flexible test items, a series of special tests were conducted to study the ASG responses at low vehicle speeds and high wheel loads. This paper summarizes the results from the supplemental tests.

National Airport Pavement Test Facility

The NAPTF is located at the Federal Aviation Administration (FAA) William J. Hughes Technical Center, Atlantic City International Airport, New Jersey. A 5340-kN (1.2 million-lb) pavement testing machine spans two sets of railway tracks that are 23.2 meters (76 feet) apart. The vehicle is equipped with six adjustable dual-wheel loading modules. A hydraulic system applies the load to the wheels on the modules. The major specifications for the test track are as follows:

- Test pavement 274.3 meters (900 feet) long by 18.3 meters (60 feet) wide.
- Nine independent test items (six flexible and three rigid) along the length of the track. The pavement cross-sectional details can be found on the FAA Airport Technology Branch web site www.airporttech.tc.faa.gov.
- Twelve test wheels capable of being configured to represent two complete landing gear trucks having from two to six wheels per truck and adjustable up to 6.1 meters (20 feet) forwards and sideways.
- Wheel loads adjustable to a maximum of 333.75 kN (75,000 lbs) per wheel.

Asphalt Strain Gages Used at the NAPTF

The ASGs were fabricated by Construction Technology Laboratories, Inc. (CTL). Strain gages were applied at midlength on round polyester bars between end flanges. Four 350-ohm gages, two axial and two transverse (rotated 90 degrees from the active gages), are used on each bar. They are connected electrically in a full Wheatstone bridge circuit and arranged on the polyester bar so that the longitudinal strain of the bar is measured. A schematic showing details of the principal features of the design and construction of the ASGs is shown in Figure 1.

The strain gage is encapsulated in polyamide with large, rugged copper-coated solder tabs. The strain gage sensor circuitry is encapsulated in wax and epoxies for physical and environmental protection. Specifications for the ASGs are as follows:

Manufacturer/Model:	CTL Strain Gage Sensor
Quantity:	96
Accuracy:	1-microstrain
Resolution:	0.1-microstrain
Measurement Range:	2000-microstrain
Temperature Range:	0 to150° C
Dynamic Response:	> 1000 Hz
Static/Dynamic:	Dynamic (100 readings/sec)

The ASGs were installed in both the longitudinal and transverse directions. Figure 2 shows the locations of the ASGs in the test item designated HFS. Test item HFS has a 125-mm- (5-inch)-thick P-401 AC surface layer, a 125-mm- (5-inch)-thick P-401 asphalt stabilized-base layer, over a high-strength sand subgrade.

Typical ASG Responses

Longitudinal ASG response signal time histories are similar in shape even if the tire does not pass directly over the gage. Figure 3 shows a typical response signal for a longitudinal ASG with dual loading. There is always compression first, then tension, and subsequently compression. After the axle has passed over the gage, the strain level reduces rapidly with very little permanent deformation. In the case of dual-tandem (Boeing 747-type) and dual-tridem (Boeing 777-type) loading, compression is always observed between axles. Longitudinal ASG response to a dual-tridem axle loading is shown in Figure 4. Relaxation is observed in Figures 3 and 4 because of the viscoelastic nature of the bituminous materials.

In contrast to the response of the longitudinal gages, transverse gage responses are very sensitive to the transverse position of the passing wheels. There is no compression but only tension, and the tension decreases very slowly to zero (relaxation) as the wheels move away from the gage position. Figure 5 shows a typical response signal from a transverse ASG subjected to a dual-wheel axle. If the following axle (as in the case of dual-tandem or dual-tridem axles) comes before the complete relaxation has taken place, the tension accumulates. This accumulation is higher at higher temperatures. Figure 6 shows the response of a transverse ASG to a dual-tridem axle loading.

ASG Responses From the Slow-Rolling Response Tests

Slow-rolling response tests were performed at the NAPTF during August 1999 to September 1999 to study wheel load interaction effects. Pavement responses (stresses, strains, deflections, etc.) were measured at various depths in each of the pavement test items for different combinations of truck configurations and load levels. The main objectives of the stationary tests were to measure pavement response with precise control of magnitude and position of load, measure interaction of pavement response at different wheel and gear spacing, and compare response with static and moving loads. The slow-rolling response tests were carried out with the vehicle moving at a speed of 0.15 m/s (0.5 feet/sec).

Significantly higher peak strain values (ranging from 500 microstrain to 2000 microstrain) were observed. The peak AC strain values for test items HFS recorded by different ASGs for tests with wheels over the ASGs located at 4.5 m (15 feet) offset from the centerline of the pavement are shown in Figure 7.

The ASG measured responses were about 2 to 3 times higher than the values predicted by layered elastic analysis pavement analysis programs.

Special Tests on ASGs

(Huhtala, 1989), (Ullitz, 1989), (Anderson, 1989), (Huhtala, 1991), (Vogelzang, 1991), (Sebaaly, 1991), (Krarup, 1991), (Huhtala, 1997), (Al-Qadi, 2000), and other studies report results on AC strain measurements using ASGs. (Sebaaly, 1991) reported that a reduction of 50 to 70 percent in the measured strains was observed as a result of increasing the vehicle speed from 32 to 80 kph (20 to 50 mph).

(Christison, 1978) studied ASG responses for 280-mm- (11-inch)- and 180-mm- (7-inch)-thick full-depth AC pavements (inbound and outbound lanes respectively). The AC strains were measured using sheet asphalt plates with embedded wire resistance strain gages to measure the longitudinal strain at the bottom of the AC layer. Test speeds ranged from 3 to 56 kmph (2 to 35 mph). Average AC temperatures ranged from 2°C to 30°C (36°F to 86°F). The test results showed the dependency of strains on vehicle speed and AC temperature. For example, at 17.8°C AC temperature the AC strain values reduced from 425 microstrains to 200 microstrains by increasing the vehicle speed from 3 kmph (2 mph) to 30 kmph (19 mph). The maximum rate of change in the AC strain values occurred at low vehicle speeds and high AC temperatures, reflecting the viscoelastic behavior of the pavement structure at the test conditions. However, most of the test results are for highway-type loading conditions with wheel loads less than 20,000 lbs.

To provide more information on the effects of speed of load application on the strain responses in the AC layers, additional tests were planned and performed on the flexible pavements on the high-strength subgrade. Tests were conducted at vehicle speeds of 0.08, 0.15, 0.23, 0.3, 0.6, 1.5, and 2.2 m/sec (0.25, 0.5, 0.75, 1.0, 2.0, 5.0, and 7.33 feet/sec). A vehicle speed of 2.2 m/sec (7.33 feet/sec) corresponds to the vehicle speed used in the traffic tests (i.e., 5 miles per hour).

Tests were run at wheel loads of 106.8, 133.5, and 160.2 kN (24,000, 30,000, and 36,000 lbs) at each speed. Module 1-1 and Module 2-1 on Carriages 1 and 2, respectively, were used for testing (for carriage and load module details, refer to Hayhoe, 2001). Carriage offset was 3.81 m (12.71 feet) on either side of the pavement centerline. This configuration placed the outside wheel on both carriages over the top of the ASGs located at offsets of 4.5 m (15 feet) from the pavement centerline. The tests were performed on 4/20/00 (pavement temperature approximately 52°F) and 6/23/00 (pavement temperature approximately 72°F). Pavement temperatures were fairly constant for the duration of testing.

Effect of Vehicle Speed on Measured AC Strains From ASGs

Figures 8 and 9 show the peak AC strains measured on 04/20/00 from longitudinal and transverse ASGs respectively for test item HFS. The effect of vehicle speed (load duration) on the AC strains is very clear. Higher speeds (lower load durations) produce lower strains. The rate at which the AC strains reduce with increase in speed is higher at vehicle speeds less than 0.6 m/sec (2 feet/sec). In Figure 9, AC strain measurements from Channel 46 are larger than the other three gages (Channels 43, 45, and 48). This difference could be attributed to the position of the gage with respect to the wheel. The magnitudes of AC strain measurements are very sensitive to the position of the load with respect to the gage.

For the longitudinal ASGs, an increase in speed from 0.08 m/sec (0.25 feet/sec) to 2.2 m/sec (7.33 feet/sec) reduced the AC strains by 50-55 percent for a given load. In the case of the transverse ASGs, the AC strains reduced by about 45-50 percent for the same increase in speed.

Figures 10 and 11 show the relationship between time of loading (Figure 3) and AC strains for the longitudinal and transverse ASGs, respectively, for the three load levels of 106.8, 133.5, and 160.2 kN (24,000, 30,000, and 36,000 lbs). The load durations range from 0.8 seconds (for a vehicle speed of 2.2 m/s (7.33 feet/sec)) to 18.6 seconds (for a vehicle speed of 0.08 m/s (0.25 feet/sec)). Modulus tests conducted in a laboratory (ASTM D3497-79) typically use load durations ranging from 1 second (a frequency of 1 Hz) to 0.0625 seconds (a frequency of 16 Hz). For heavy weight deflectometer (HWD) tests, the load duration ranges from 0.02 seconds to 0.03 seconds. When the speed tests were repeated on 6/23/00, HWD tests were also conducted over the ASG locations. For the HWD tests, the load pulse duration was 30 milliseconds. Figure 12 shows the relationship between duration of loading and AC strains for the tests conducted on 6/23/00.

Effect of Pavement Temperature on Measured AC Strains From ASGs

Pavement temperatures in the AC layer were monitored using Omega Thermistor temperature gages. The temperature gages (TGs) are placed at 13 mm (0.5 inches), 64 mm (2.5 inches), and 114 mm (4.5 inches) below the AC surface. In the case of pavements with asphalt stabilized-base, TGs are placed at the bottom of the asphalt stabilized-base layer. Figures 10 and 12 show the effect of temperature on measured AC strains. An increase in the AC temperature (middepth of the AC surface layer) from 11.1°C (52°F) to 22.2°C (72°F) resulted in an increase in AC strains ranging from 100 to 120 percent (for the three load levels at all speeds).

Discussion

The test results clearly show the effect of vehicle speed and temperature on the measured AC strains. AC mixtures exhibit viscoelastic behavior, and the load duration has a significant effect on the magnitude of AC strain response. AC stiffness can be estimated from a relationship published by the Asphalt Institute (Asphalt Institute, 1982), relating dynamic modulus and the properties of the mix

$$\log\left|E^*\right| = 5.553833 + 0.028829\left(\frac{P_{200}}{f^{0.17033}}\right) - 0.03476\left(V_v\right) + 0.070377\left(\eta_{70^\circ F,10^6}\right) +$$

$$0.000005\left[t_p^{(1.3+0.49825*\log f)} P_{ac}^{0.5}\right] - 0.00189\left[t_p^{(1.3+0.49825*\log f)} \frac{P_{ac}^{0.5}}{f^{1.1}}\right] + 0.931757\left(\frac{1}{f^{0.02774}}\right)$$

$R^2 = 0.939$ Standard Error of Estimate (SEE) = 0.1235

where

$|E^*|$ = dynamic modulus of the AC (psi)
P_{200} = percent aggregate passing No. 200 sieve
f = frequency of loading (Hz)
V_v = air voids (%)
$\eta_{70^\circ F,10^6}$ = absolute viscosity at 70°F (poise*10^6)
P_{ac} = asphalt content (% by weight of mix)
t_p = temperature of the mix (ºF)

For comparison with the measured strains, the dynamic modulus of the AC, |E*|, for the NAPTF mix was first computed from the Asphalt Institute equation given above. The dynamic modulus was then converted to a complex compliance D* (ASTM, 1999), where

$$D^* = 1/\left|E^*\right|$$

The variation of D* at different loading durations and for pavement temperatures of 11.1°C (52ºF) (4/20/00) and 22.2°C (72ºF) (6/23/00) is shown in Figure 13. Increasing the AC temperature from 11.1°C (52°F) to 22.2°C (72°F), increases the compliance by slightly more than a factor of two. The measured longitudinal strains show an almost identical increase as shown in Figures 10 and 12. At very long loading durations, the dynamic modulus continues to decrease, but at a uniform rate, and the behavior may be considered to be purely viscous. At the extreme of very long loading durations the AC strain gages measure the flow in the AC mix resulting from shear stresses. Figure 14 shows the changes in AC strains and D* as a function of vehicle speed. Rate of change in both D* and AC strains is higher at low vehicle speeds (speeds less than 0.61 m/s (2 feet/sec)).

Conclusions

Asphalt strain gages (ASGs) are used at the NAPTF to measure AC strains. Results from speed tests (vehicle speeds ranging from 0.08 m/sec (0.25 feet/sec) to 2.2 m/sec (7.33 feet/sec)) performed on flexible pavements on a high-strength subgrade are presented. Tests were conducted at pavement temperatures of 11.1°C (52ºF) (4/20/00) and 22.2°C (72ºF) (6/23/00). The objective was to measure AC strains at low speeds and heavy wheel loads. Vehicle speed and pavement temperature both have a significant effect on the strains induced in the asphalt layers. Increasing the vehicle speed from 0.08 m/sec (0.25 feet/sec) to 2.2 m/sec (7.33 feet/sec), reduced the longitudinal strains by 50-55 percent and reduced the transverse strains by 45-50 percent (for a given load level). The rate of change in strain with speed was higher at slow speeds (speeds less than 0.61 m/s (2 feet/sec)). Slower speeds result in higher load durations, which reduces the AC dynamic modulus (increasing the amount of viscous deformation relative to the elastic deformation). This results in very high strains at the bottom of the AC layers. An increase in the temperature of the pavement from 11.1°C (52°F) to 22.2°C (72°F) resulted in an increase in AC strains ranging from 100 to 120 percent (for the three load levels at all speeds). The effect of increasing temperature is also to increase the proportion of viscous deformation relative to the elastic deformation.

Acknowledgements/Disclaimer

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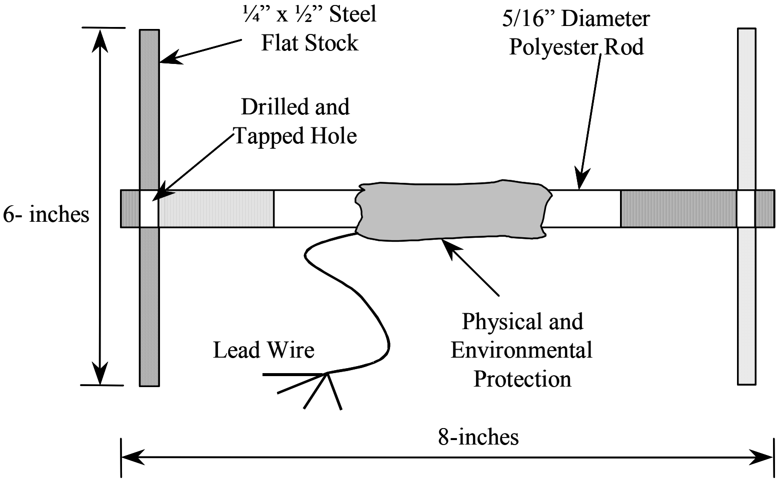

Figure 1. Asphalt concrete strain gage (ASG) used at the NAPTF.

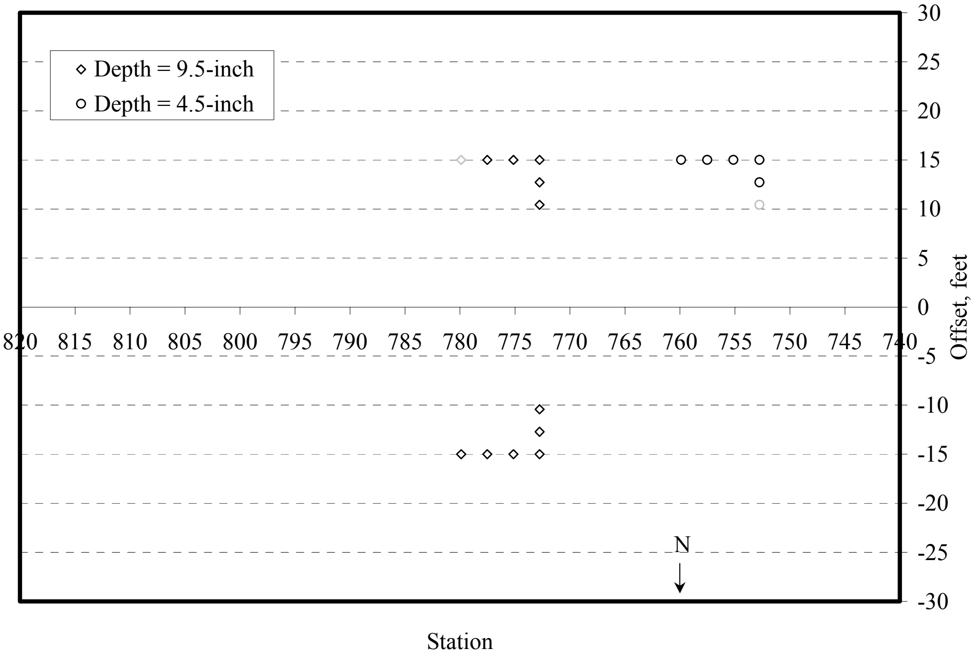

Figure 2. ASG Locations in Test Item HFS.
(1 feet = 0.3048 m)

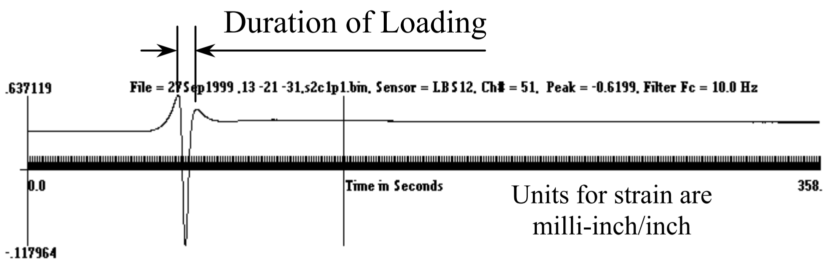

Figure 3. Longitudinal ASG response signal (dual gear configuration).

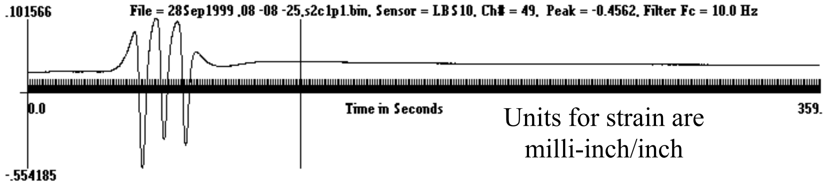

Figure 4. Longitudinal ASG response signal (dual-tridem configuration).

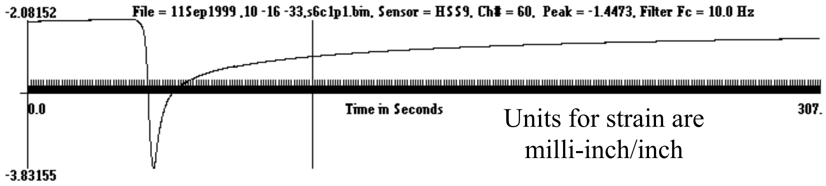

Figure 5. Transverse ASG response signal (single axle load gear).

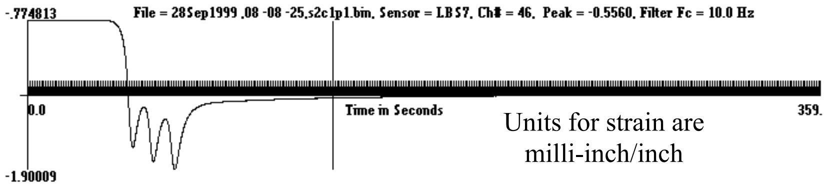

Figure 6. Transverse ASG response signal (tridem gear).

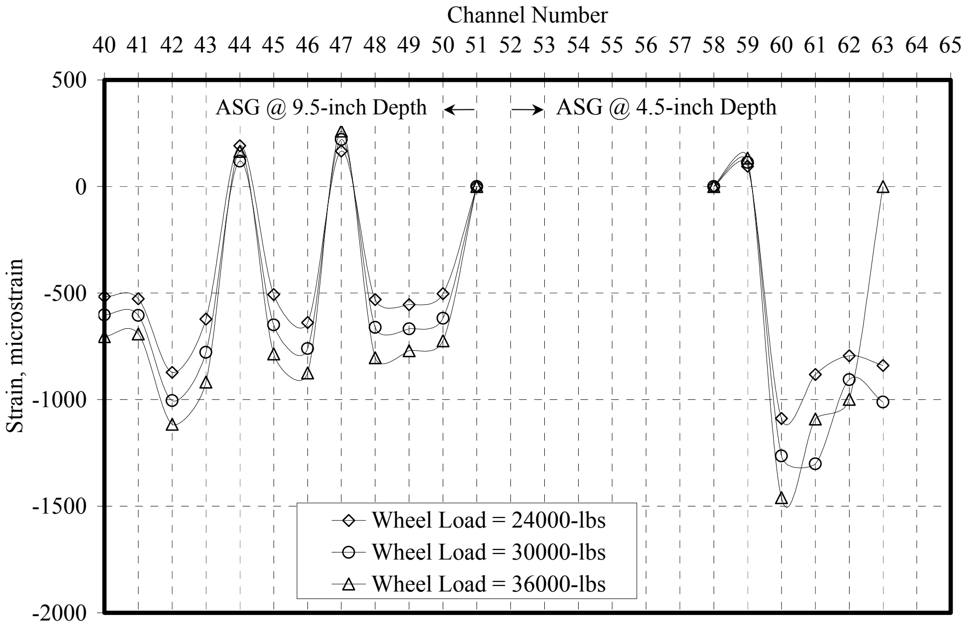

Figure 7. Peak AC strains for test item HFS for slow-rolling response tests. *(1000 lb = 4.448 kN; 1 inch = 25.4 mm)*

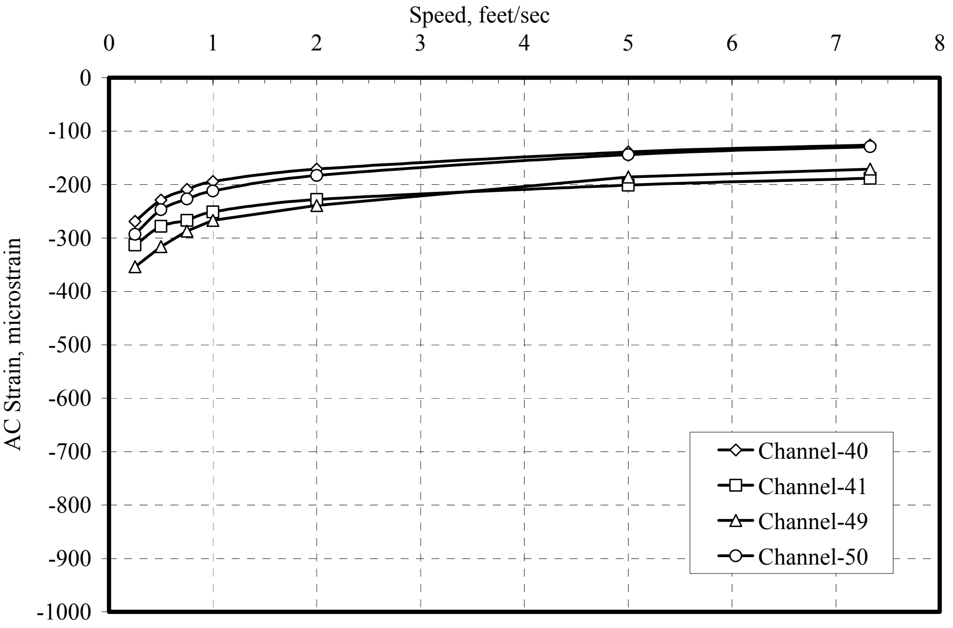

Figure 8. Peak AC strains from longitudinal ASGs for test item HFS (test date 4/20/00; gage depth = 9.5 inches; wheel load = 36,000 lbs). *(1 feet/sec = 0.3048 m/sec; 1000 lb = 4.448 kN; 1 inch = 25.4 mm)*

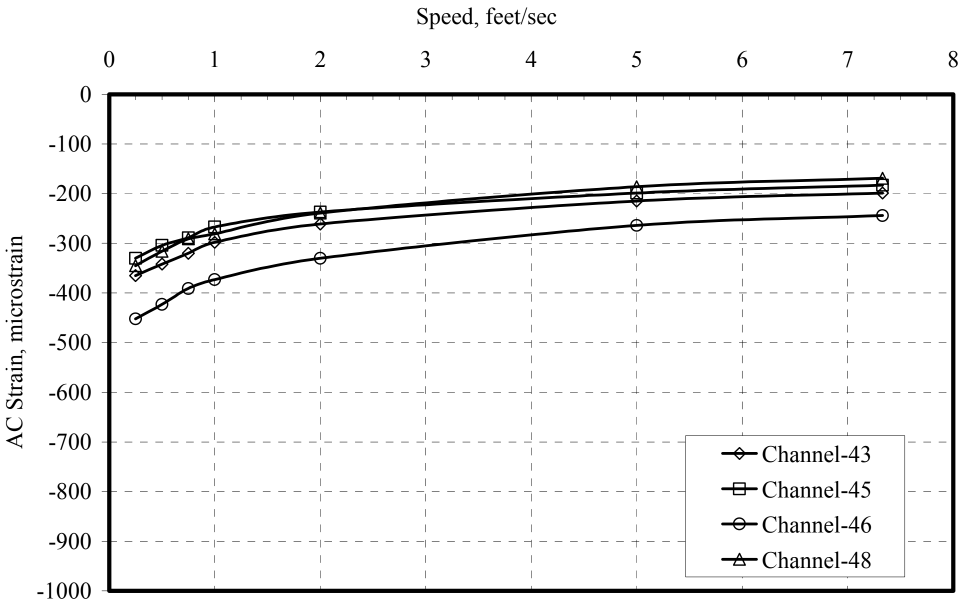

Figure 9. Peak AC strains from transverse ASGs for test item HFS (test date 4/20/00; gage depth = 9.5 inches; wheel load = 36,000 lbs). *(1 feet/sec = 0.3048 m/sec; 1000 lb = 4.448 kN; 1 inch = 25.4 mm)*

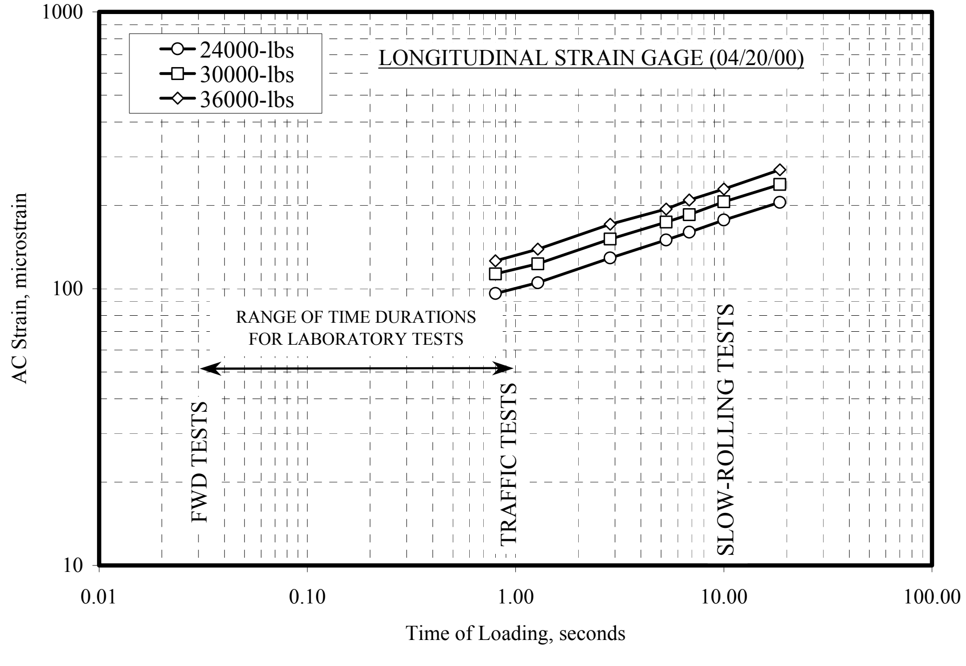

Figure 10. AC strains – time of loading relationship for test item HFS (test date 4/20/00; gage depth = 9.5 inches). *(1000 lb = 4.448 kN; 1 inch = 25.4 mm)*

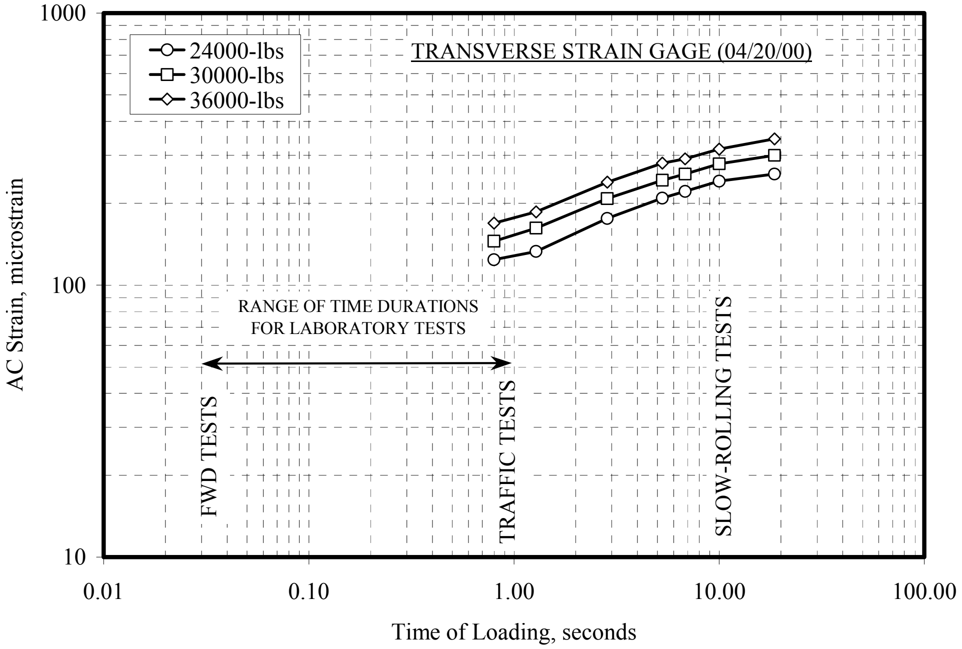

Figure 11. AC strains – time of loading relationship for test item HFS (test date 4/20/00; gage depth = 9.5 inches). *(1000 lb = 4.448 kN; 1 inch = 25.4 mm)*

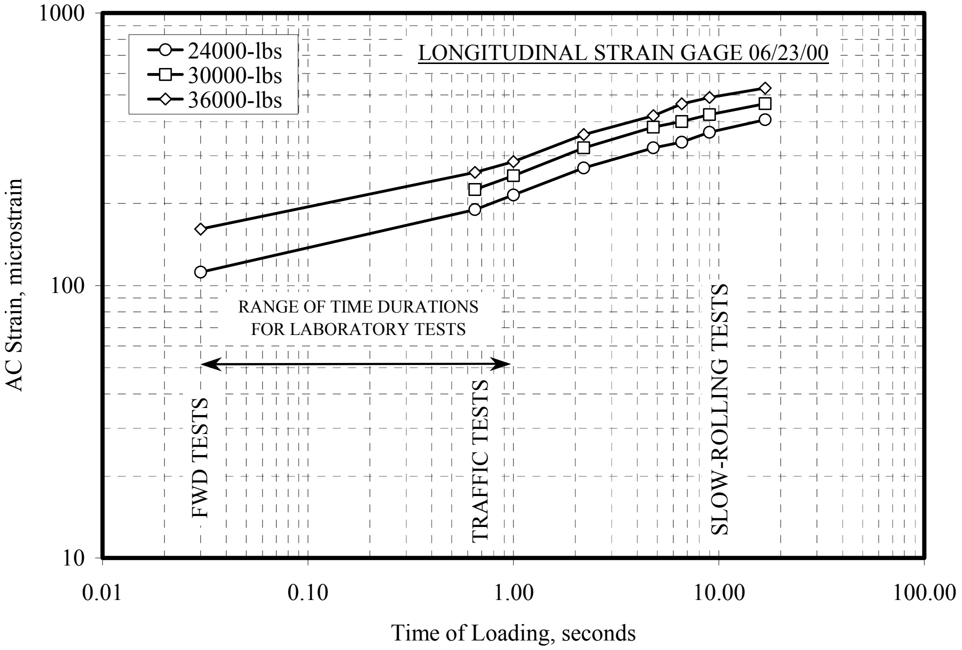

Figure 12. AC strains – time of loading relationship for test item HFS (test date 6/23/00; gage depth = 9.5 inches). *(1000 lb = 4.448 kN; 1 inch = 25.4 mm)*

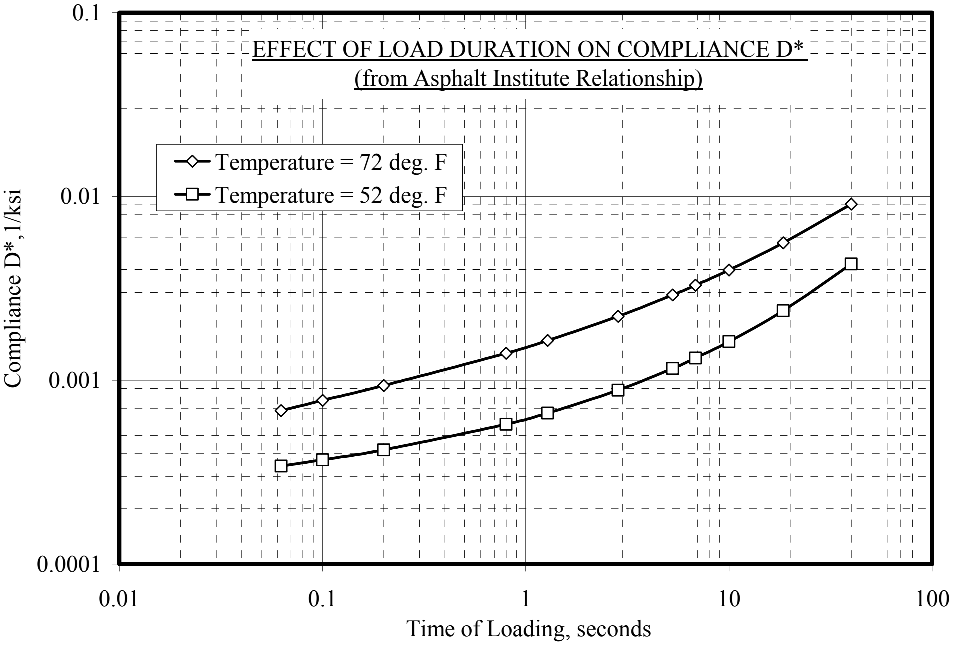

Figure 13. Effect of time of loading on compliance D*.
(1 psi = 6.89 kN/m²)

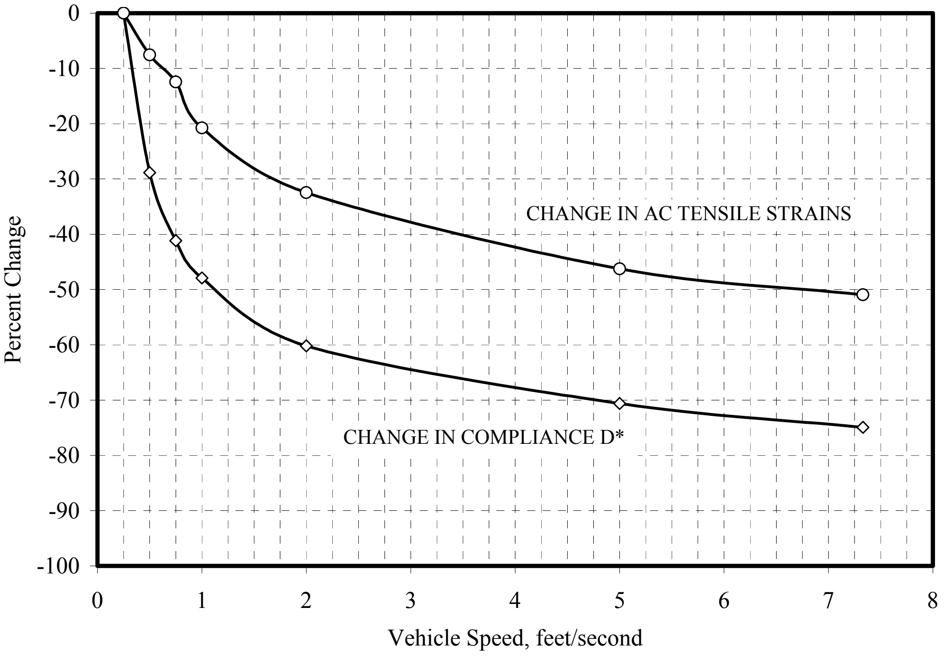

Figure 14. Effect of vehicle speed on AC strains and compliance D*.
(1 feet/sec = 0.3048 m/sec)