FAA RIGID PAVEMENT INSTRUMENTATION AT ATLANTA HARTSFIELD-JACKSON INTERNATIONAL AIRPORT

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ABSTRACT

Recent experiments at the Federal Aviation Administration's (FAA) National Airport Pavement Test Facility (NAPTF) have confirmed the importance of accounting for warping and curling behavior in even relatively thick concrete slabs. However, there is a lack of available field data from airports that might indicate if vertical movement of concrete slabs in response to environmental loads is a significant factor for design. In response to this need, and in cooperation with the Atlanta Department of Aviation (DOA), the FAA has instrumented a group of three slabs in the recently reconstructed portion of Taxiway E at Atlanta Hartsfield-Jackson International Airport. Sensors were installed in the concrete to detect small vertical slab movements over time (on the order of thousandths of an inch), including possible separation of the slab from the base layer. In addition, strain gages were installed at various depths to measure strain variations related to slab movements. Sensors were installed in September 2006, at the time the new pavement was placed. It is planned to monitor the responses periodically over the life of the taxiway, or for as long as possible. Instrumentation layouts and sensor types were based on experience gained from the FAA's "twin" single slab (indoor/outdoor) experiment conducted at the NAPTF, which was another project intended to monitor slab curling behavior over a several year period. However, for the current Atlanta project, a more rugged type of deflection transducer was required, in order to better withstand construction traffic and long-term wear, including exposure to moisture. In contrast to the FAA's previous rigid pavement instrumentation project at Denver International Airport, the Atlanta project will not concentrate on recording dynamic strain responses to individual aircraft loads. Nevertheless, one of the three instrumented slabs will receive regular traffic loads, and it is expected that the data received from that slab will provide significant new information on the total slab response (environmental plus aircraft load).

INTRODUCTION

Reconstruction of Runway 8R-26L at Atlanta Hartsfield-Jackson International Airport (Georgia) took place during a 60-day period from September to November, 2006. The project included reconstruction of an approximately 3,000 LF (90 m) section of parallel Taxiway E near the 26L threshold. Reconstruction of both the runway and taxiway pavements consisted of removal of the existing 16-in. (40.6 cm) concrete slabs and 6-in. (15.2 cm) stabilized base course, and placement of new 20-in. (50.8 cm) thick portland cement concrete (PCC) slabs on a nominal 2-in. (5 cm) hot-mix asphalt (HMA) leveling course. The existing soil-cement subbase was left in place. During preparations for the reconstruction, the Atlanta DOA invited the FAA Airport Technology R&D Branch to install instrumentation in some of the newly placed slabs as a research and development project. It was decided to instrument three slabs, located in Taxiway E, as shown in the location map in figure 1.

The primary purpose of this research project is to obtain long-term data on vertical slab movements in response to slab aging and environmental loads. Although there is evidence from recent full-scale tests conducted at the NAPTF and elsewhere that temperature- and moisture-induced slab curling has a significant effect on rigid pavement life, there is a lack of reliable data from real airports on in-situ slab curling. The sensors installed in Atlanta Taxiway E include vertical deflection transducers (VDT) to measure slab displacements directly, as well as strain gages (SG) to record variations in horizontal strain at key locations.

Among the specific questions this project hopes to answer are the following:

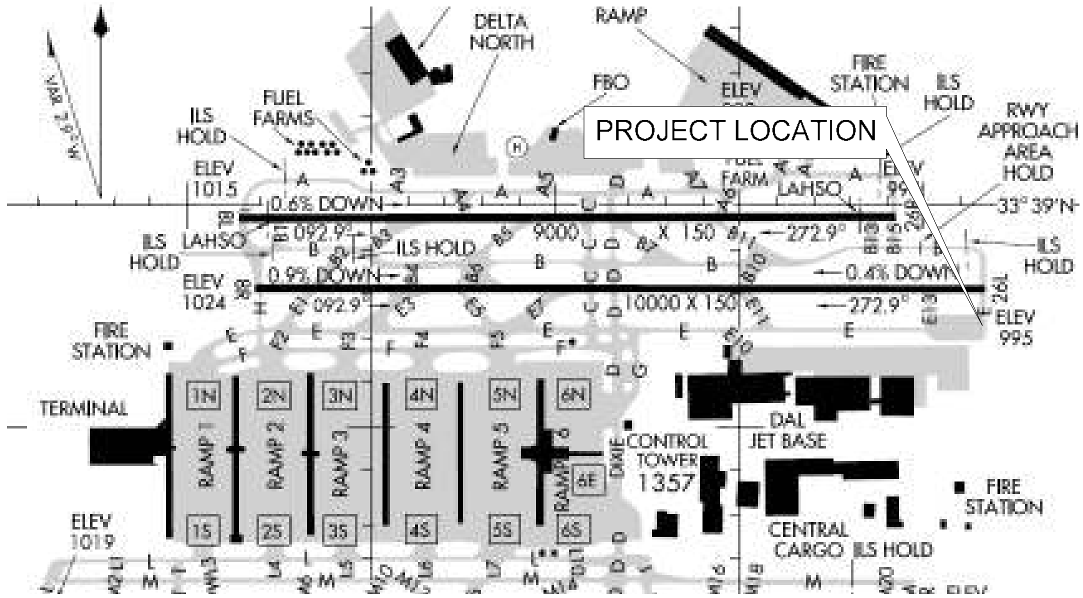
- Is slab curling a significant factor for the slab thicknesses (on the order of 20 in./50 cm) typical of many major airports?
- What are the differences in the responses of slabs subjected to frequent aircraft traffic versus those experiencing only environmental loads?
- How are the slab responses affected by different edge conditions (e.g., free edge versus doweled joint, construction joint versus formed joint)?

BACKGROUND

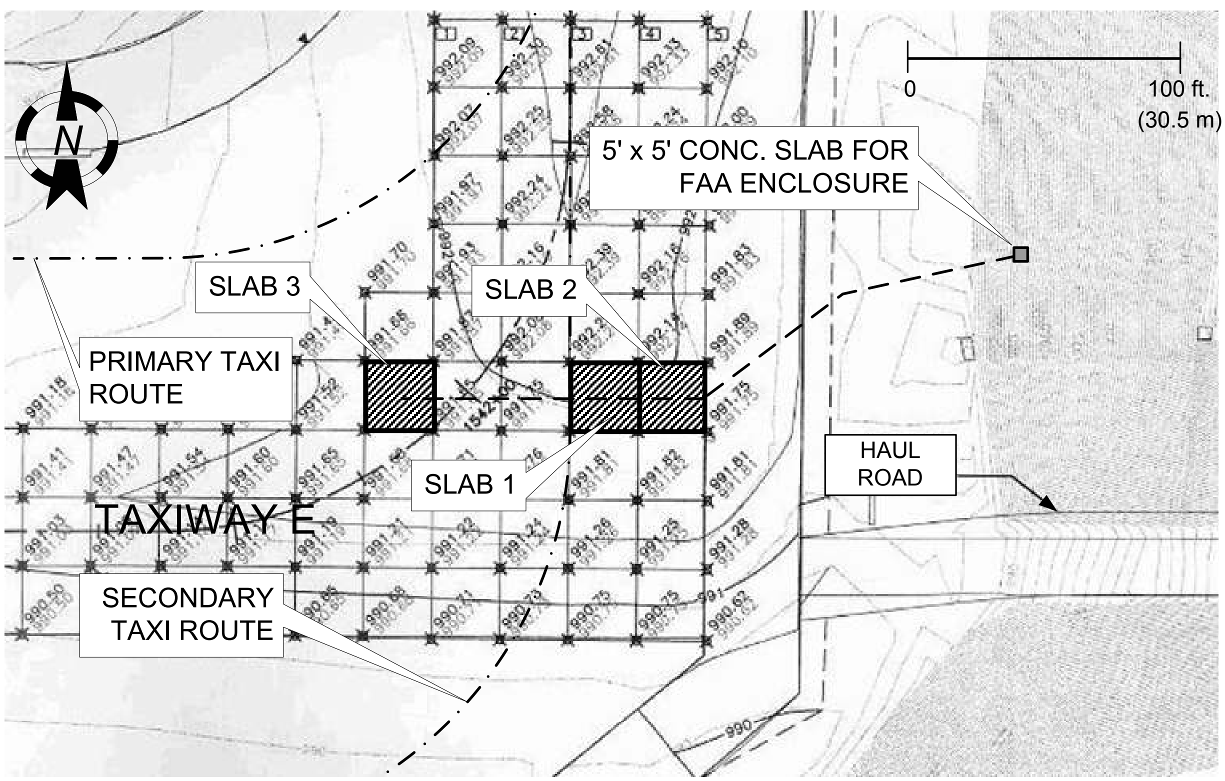
It has long been recognized that environmental loads (temperature, moisture and shrinkage) cause concrete slabs to curl and deform, resulting in distresses over the long term. Westergaard [1] presented a theory of stresses and deflections in concrete slabs due to temperature gradients, which is still the basis of most engineering analysis. For airport pavement design it has usually been assumed that the self-weight of thick slabs is sufficient to compensate for any tendency toward upward curling and to maintain full contact of the slabs with the supporting layer. Hence the FAA's standard thickness design procedures in FAA Advisory Circular (AC) 150/5320-6D [2] assume that slabs remain flat and in full contact with the base, and do not consider the case of explicitly curled slabs. Nevertheless, AC 150/5320-6D contains guidance for maximum joint spacing relative to the radius of relative stiffness *l*, intended to ensure that the slabs are protected against excessive warping and curling.

Recent experiments conducted by the FAA, as well as observations from full-scale tests at the NAPTF and the Airbus test facility in Toulouse, France, suggest that upward curling of airport pavement slabs may be a greater factor affecting structural life than assumed by current design methods, particularly when slabs are also trafficked by large, multiple-wheel or multiple-gear aircraft. Analysis of the cracking patterns in the FAA's CC2 series of full-scale tests at the NAPTF showed a significant proportion of top-down longitudinal cracks and corner breaks in both loaded and unloaded slabs resulting from 6-wheel and 4-wheel simulated gear traffic (figure 2). This was the case even though the upward displacements at slab corners were held to under 20 mils (0.5 mm) for the duration of testing, which was considered practically flat [3]. In the case of the CC2 tests, the slabs were somewhat thinner (12 in. / 30 cm) than typical airport slabs. However, results reported by the Airbus/LCPC/STBA testing team [4] confirm that simultaneous loading of opposite edges by multiple landing gears of the same aircraft can result in top-down longitudinal cracking even for full-thickness airport pavements.

The CC2 tests were conducted in an indoor environment, hence were not subject to the same diurnal temperature cycles and exposure to weather as would be experienced by a typical slab in the field. Recognizing these limitations, the FAA conducted a smaller-scale experiment at the NAPTF for the purpose of monitoring slab environmental responses, including corner uplift and strain, over a several year period. Known as the "twin slab" project, it involved two separate instrumented concrete slabs (single slabs), one located inside the facility and the other outdoors. Responses were compared over approximately two years. Data from the twin slabs project



(a) Project Location Map



(b) Detail of Instrumented Slabs Location

Figure 1. Location of Instrumented Slabs at ATL Taxiway E.

showed that for the indoor slab, following the wet cure, there was a continuous upward trend in corner displacements as measured by sensors. For the outdoor slab, in contrast, measured permanent upward deformation of corners was minimal, but there were significant daily "excursions" of vertical corner displacements from their mean values, tracking the temperature variations [5]. These results suggested that it would be valuable to have a permanent sensor installation in an active airport pavement that would monitor slab movements over an extended period.

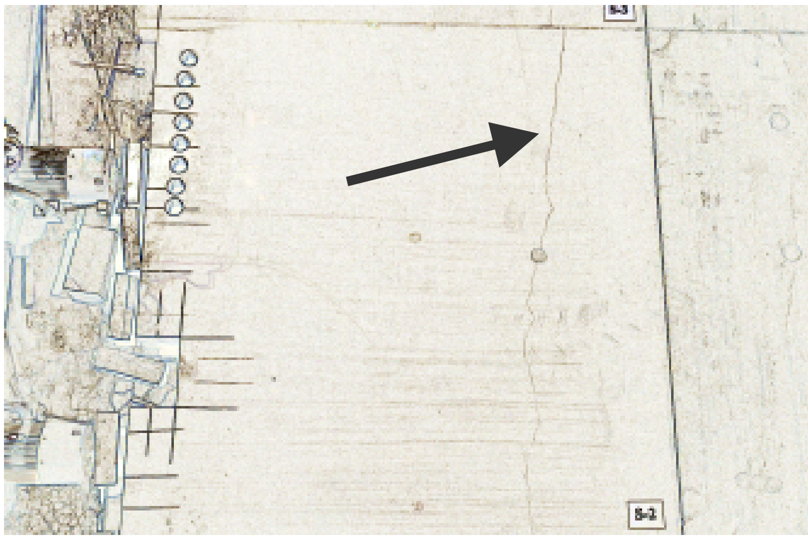


Figure 2. Top-Down Longitudinal Crack of Unloaded Slab Observed at NAPTF (CC2, Slab S-2).

PROJECT LOCATION AND SENSOR LAYOUT

Instrumentation was installed in the three slabs, labeled 1, 2 and 3, at the eastern end of Taxiway E as shown in the location map (figure 1). While DOA gave the FAA considerable latitude in selecting a site within the 8R-26L construction zone, there was consensus early on that the eastern end of Taxiway E near the 26L hold line would be the best location for an instrumentation project. Although the structural design for both runway and taxiway pavements was the same, the taxiway was preferred due to the possibility of more severe aircraft gear loads (including slow-moving and queued aircraft), and fewer access restrictions. Continued access to the site after opening was a significant consideration, as it is planned to collect data regularly over a period of years. As shown in figure 1(b), the selected site is convenient to a permanent haul road, which will permit access to the FAA data cabinet for purposes of maintenance or data download without crossing any active airport features.

The particular slabs were selected for three different load conditions. Slab 1 is designated the "loaded" slab since it is subject to frequent heavy wheel loads from taxiing aircraft. As shown in figure 1(b), slab 1 is adjacent to the centerline of the secondary taxi route. Aircraft using this route generally are coming from, or heading to, the holding area in Taxiway E. Although most traffic using Taxiway E will follow the primary taxi route to the north and west of the instrumented slabs, a significant number of aircraft will still traverse slab 1 over the life of the pavement. Slab 2, adjacent to slab 1 but out of the wheel path, will not experience direct

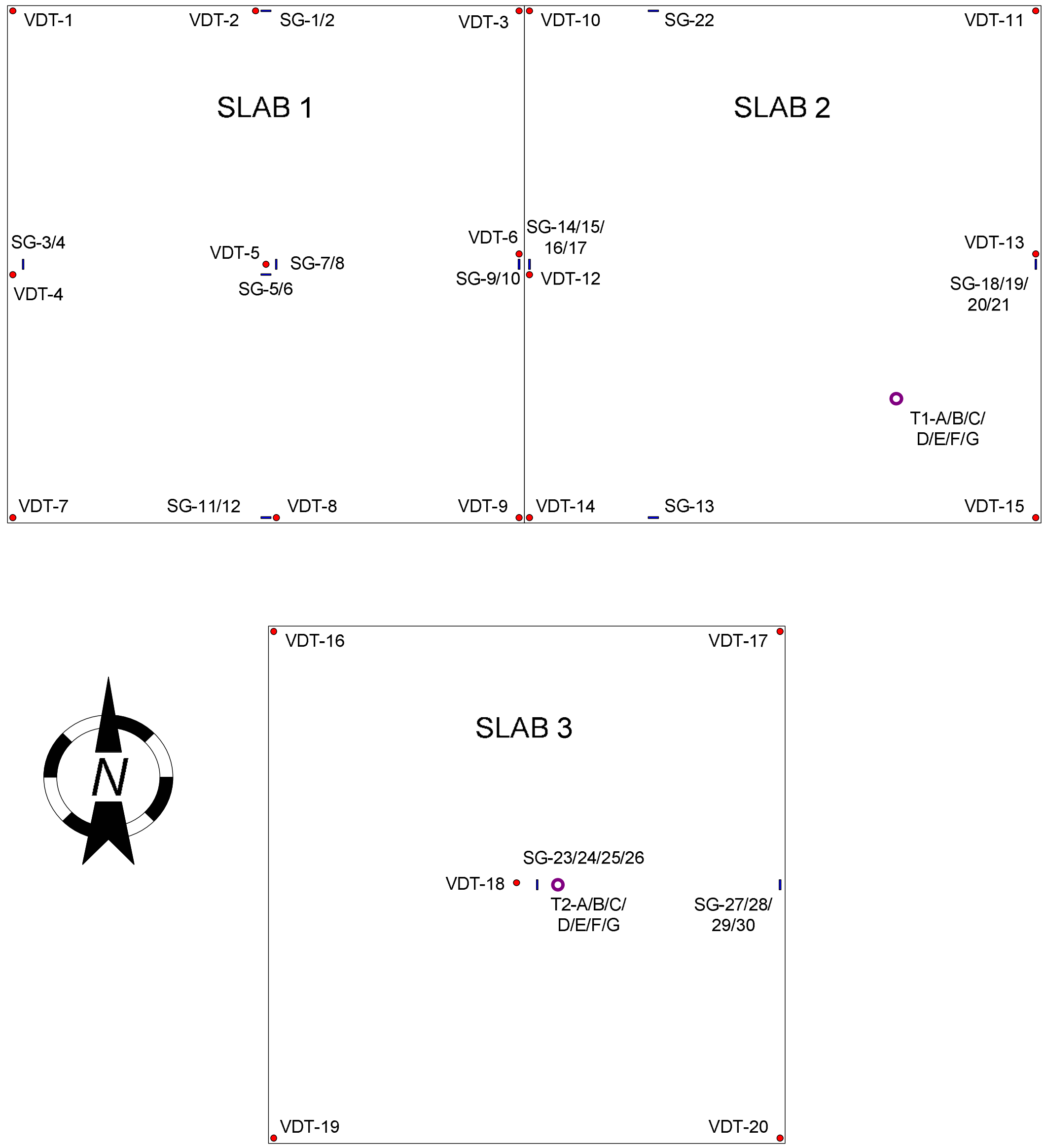


Figure 3. Sensor Layout in Taxiway E Instrumented Slabs.

wheel loads. However, a fraction of the wheel load applied to slab 1 will be transferred to slab 2 through the longitudinal joint. Combined with curling strains, the transferred wheel loads may induce significant tensile stresses in slab 2. Slab 3 (the “unloaded” slab) is located away from the designated wheel path and is therefore expected to experience only environmental loads.

The sensor layout for all three slabs is shown in figure 3. Three types of embedded sensors were installed. The vertical displacement transducers (VDT) are actually a type of joint meter manufactured by TML (Tokyo Sokki Kenkyujo Co., Ltd.) of Japan, and distributed in the United States by Texas Measurements, Inc. The joint meter (figure 4) was installed in a vertical position in order to measure displacements of the PCC slab relative to the AC support layer. The joint meters were used for two reasons:

- Due to the ruggedness of the joint meters, it was determined that they would be better able to survive construction operations intact (including possible slip-form placement of concrete) than would the lighter-weight displacement transducers used in the more protected environment of the NAPTF twin slabs experiment.

- Previous experience at the NAPTF was that displacement transducers are susceptible to problems with water intrusion. The joint meters are water-resistant, thus may be better able to survive long-term wear, including moisture exposure.

Concrete strain gages (SG) manufactured by CTL, Inc. were installed at the locations shown in figure 3. Where strain gage numbers are separated by a slash (/), strain gages were installed at multiple depths at the same location in order to obtain the variation of strain with depth. In slab 1, strain gages were installed at the top and bottom of the slab (1 in./2.5 cm and 19 in./48.3 cm below the slab surface). In slabs 2 and 3, gages were installed at 1, 4, 10, and 19 in. (2.5, 10.2, 25.4, and 48.3 cm) below the slab surface. Output from all four gages can be used to define the nonlinear distribution of strain in the slab [6]. The only exceptions were gages SG-13 and SG-22 in slab 2. At those locations, a single gage was placed 1 in. (2.5 cm) from the top surface.

Figure 4. Center of Slab 3 Prior to Placement, Showing Thermocouple Tree (left), Strain Gage Array (center), and Vertical Displacement Transducer (right) Installed.

Temperature sensors were installed at the two locations marked T1 and T2 in figure 3. In both cases, an array of thermocouple sensors (figure 4) was used, with sensors placed at the following vertical locations below the slab surface: 0.5, 1.5, 2.5, 6.0, 10.0, 14.0 and 19.0 in. (1.3, 3.8, 6.4, 15.2, 25.4, 35.6 and 48.3 cm). It was originally planned to install an array of three relative humidity gages along the vertical face of slab 2 adjoining the shoulder. Unfortunately, this was not feasible due to the fact that the concrete cap of the shoulder was placed first and used to form the slab, making the side face of the slab inaccessible.

DATA COLLECTION SYSTEM AND POWER SUPPLY

Figure 3(b) shows the location of the weatherproof enclosure for data collection equipment on a 8 ×8 ft (2.4 × 2.4 m) concrete pad. Due to airport safety requirements, the entire pad had to be located outside of the taxiway object-free zone, which extends 160 ft. (49 m) from the taxiway centerline. When completed (estimated late March 2007), the permanent data collection system will consist of an Iotech Wavebook™ Ethernet-based data acquisition (DAQ) system with seven 8-channel strain modules (used for input from both SG and VDT sensors), and one 14-channel thermocouple module, controlled from a Panasonic Toughbook™ rugged laptop computer. The laptop and DAQ system can be run from direct current (DC) battery power, eliminating the need to obtain alternating current (AC) electrical service from the airport. In order to keep the batteries charged, a self-contained power supply was designed, consisting of an array of solar panels combined with a wind generator. When fully operational, it is estimated that the solar panels and wind generator will generate sufficient power to acquire data once per hour continually for the life of the system.

Because the permanent data collection system was not assembled in time for the concrete placement, the initial data were acquired using a portable DAQ system manufactured by National Instruments. Data were acquired from the time of concrete placement, for 48 hours after placement, and at specific intervals thereafter. After activation of the permanent DAQ system, the data collected using the portable National Instruments system will be available to establish continuity with the early-age responses.

CONSTRUCTION ACTIVITIES

The construction and installation had to be coordinated with the fast track replacement of Runway 8R-26L and the adjacent Taxiway E. The existing slabs were being used as the main construction entrance for all materials and equipment entering and exiting the job site. Consequently, coordination with the construction contractor was vital, so that the installation would not be damaged by construction operations, and so that FAA activities would not interfere with the construction, causing the contractor to experience delays (and possibly liquidated damages).

Installation of the instrumentation, weatherproof enclosure and underground conduit was accomplished entirely by FAA and FAA support contractor personnel. A small FAA-owned Bobcat™ utility machine and all materials were transported to the site on September 13, 2006, to coordinate with the planned slab replacement date of October 1. Shortly after arrival the FAA learned that the slabs would not be replaced as originally scheduled for October 1. The new placement date would be determined by other project considerations, as the contractor needed to utilize the existing slabs as the construction entrance until new slabs placed earlier had achieved sufficient strength to support the construction vehicles. The decision was made to accomplish as much work as possible on site in preparation for the placement and, if necessary, to return to the FAA Technical Center until the slabs were ready to be placed. The preparatory work included installation of electrical conduits and the data collection enclosure on its pad.

Three 3-inch (7.6 cm) diameter conduits were installed underground running from the shoulder of the taxiway to the location of the data collection equipment enclosure. The weatherproof enclosure was mounted on four galvanized steel legs. The legs were Schedule 40 2-in. (5.1 cm) diameter pipe placed in concrete. The conduit was then routed up from the ground and into the sides of the cabinet. The final step for this trip was the placement of an 8 × 8 ft. (2.4 × 2.4 m) concrete slab around the cabinet. The slab was placed on September 21.

On October 12, FAA personnel returned to Atlanta to complete the installation. The slabs were rescheduled to be placed on October 16. The instrumentation wires were pulled through the conduit on October 15 with the assistance of Atlanta DOA's electrical contractor. After several long days, the instrumentation was in position and ready for concrete. The concrete was eventually placed on the night of October 17-18 due to rain the previous days. The first data were collected during and immediately after placement of the concrete. Figure 5 shows the site of the instrumented slabs prior to concrete placement, and figure 6 shows the completed pad and instrumentation enclosure.

Figure 5. Instrumentation and Cabling Installed Prior to Concrete Placement.

Figure 6. FAA Data Equipment Enclosure.

EARLY AGE RESPONSES

As of this writing, the only data available for analysis are the early-age responses collected using the portable data acquisition equipment. Nevertheless, these data are significant since they include the slab responses during the hardening phase of the concrete and establish a baseline for later measurements.

Figures 7 through 10 contain plots of selected early-age response data. Data were acquired manually for three separate time periods: (1) October 18-19, (2) October 31 - November 5, and (3) December 5-8. During the first time period, readings were taken approximately once per hour over the 48-hour period immediately following concrete placement. This was done in order to capture the rapid changes in temperature and strain that accompany concrete hardening, and in order to locate the minimum deflectometer reading to which subsequent readings can be referenced. During the second and third time periods, readings were taken twice daily, in the early morning and mid-afternoon, when temperatures are expected to be near their daily minimum and maximum values. No data readings were taken for the period October 20-30, or for the period November 5 - December 4, hence there are gaps in the recorded data. Responses have been plotted as a function of time along with available temperature data, in order to better show the variation of the response with temperature. Figure 7 shows the response of deflection sensor VDT-13, which is located along the free edge of slab 2, as shown in figure 3. For clarity, vertical deflections shown in the figure are all referenced to the minimum sensor reading, which occurred for VDT-13 on October 18 at 10:01 PM, about 24 hours after placement, and is assumed to represent the “zero” deflection point. The adjusted VDT-13 response has been superimposed on three temperature plots: (1) the reading from temperature gage T-2A (top of slab), (2) the reading from temperature gage T-2G (bottom of slab), and (3) the minimum and maximum daily temperatures reported at Atlanta HJIA from the National Weather Service (NWS). It is clear from this figure that the response of VDT-13 generally tracks the concrete surface temperature, but trends in the opposite direction. That is, a decrease in the temperature at the surface of the slab corresponds to an increase in the recorded deflection. For the time period observed, the maximum deflection was on the order of 12 mils (0.3 mm) relative to the assumed zero. It remains to be seen whether, as the concrete ages and the slab is subjected to further daily and seasonal temperature cycles, the vertical deflections along the free edge of the slab will increase significantly.

By contrast, the response of sensor VDT-16, located at a corner of slab 3 (figure 8), shows little or no variation in response to temperature changes following the initial set. The deflection remains nearly constant at approximately 6 mils (0.15 mm).

Sample responses from a pair of strain gages, SG-5 and SG-6, are shown in figures 9 and 10. From figure 3, these strain gages are located at the center of slab 1, near the top and bottom of the slab, respectively. Figure 9 pertains to strains collected during the period October 31 - November 1, while figure 10 pertains to the period December 5-8. For convenience, the plotted strain is the difference between the absolute strain gage output (in microstrains) and the mean value of the strain over the period for which measurements were taken. Thus, it is possible to compare strain readings for different gages. It can be seen that the paired strain gages respond differently to the diurnal temperature cycles, with the top gage (SG-5) output in phase with the temperature, and the bottom gage (SG-6) 180 degrees out of phase. Since an increase in temperature causes the concrete material to expand (resulting in positive strain) it might be expected that the SG-5 output would be in phase with the concrete temperature. This is not the case, however, because the CTL strain gages are designed to be temperature-compensating. Disregarding the component of strain due to moisture gradients, which is assumed to be small, the strain gage outputs in figures 9 and 10 represent only the load-induced component of strain arising from the self-weight of the slab. As the temperature falls, and the top surface contracts, the tendency of the slab is to curl upward. However, the slab self-weight counteracts the tendency to curl, inducing a tensile (positive) strain at the top of the slab. This load-induced strain is primarily responsible for the strain gage behavior seen in figures 9 and 10. In addition, it is observed that the response of the gage closer to the surface (SG-5) is significantly more pronounced. The higher amplitude of the top gage relative to the bottom gage is an indication that the neutral plane of the slab is not at mid-slab, but is actually closer to the bottom (due to traction between the concrete slab and the asphalt base).

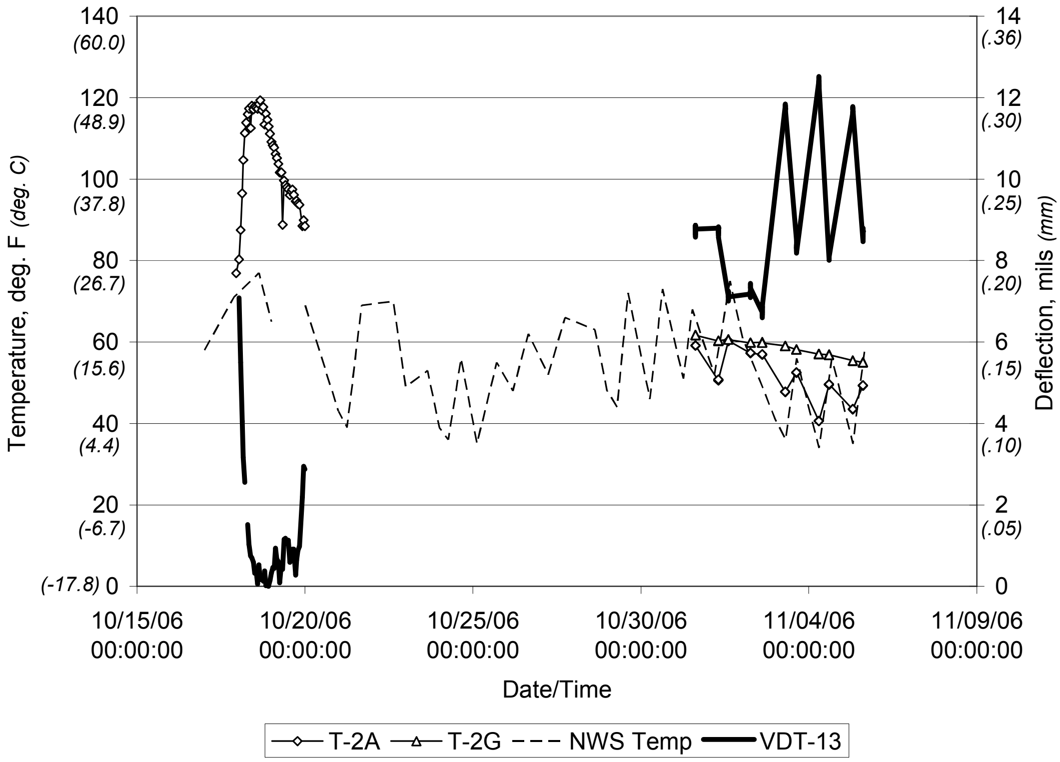


Figure 7. Plot of VDT-13 Response with Temperature.

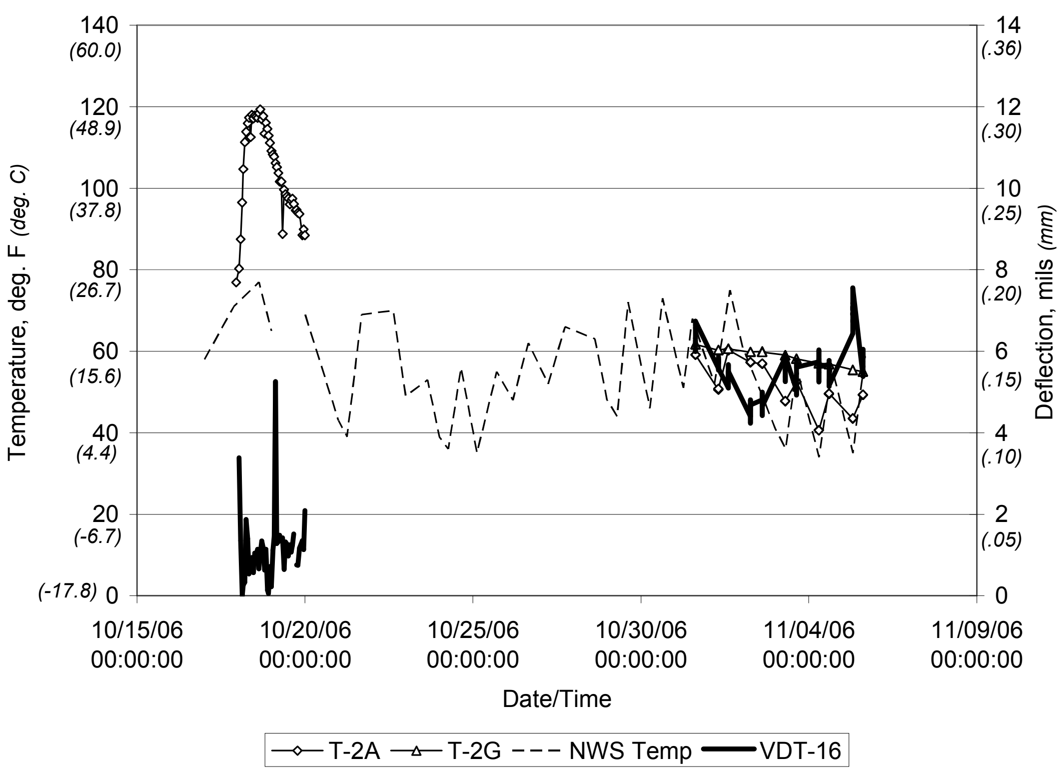


Figure 8. Plot of VDT-16 Response with Temperature.

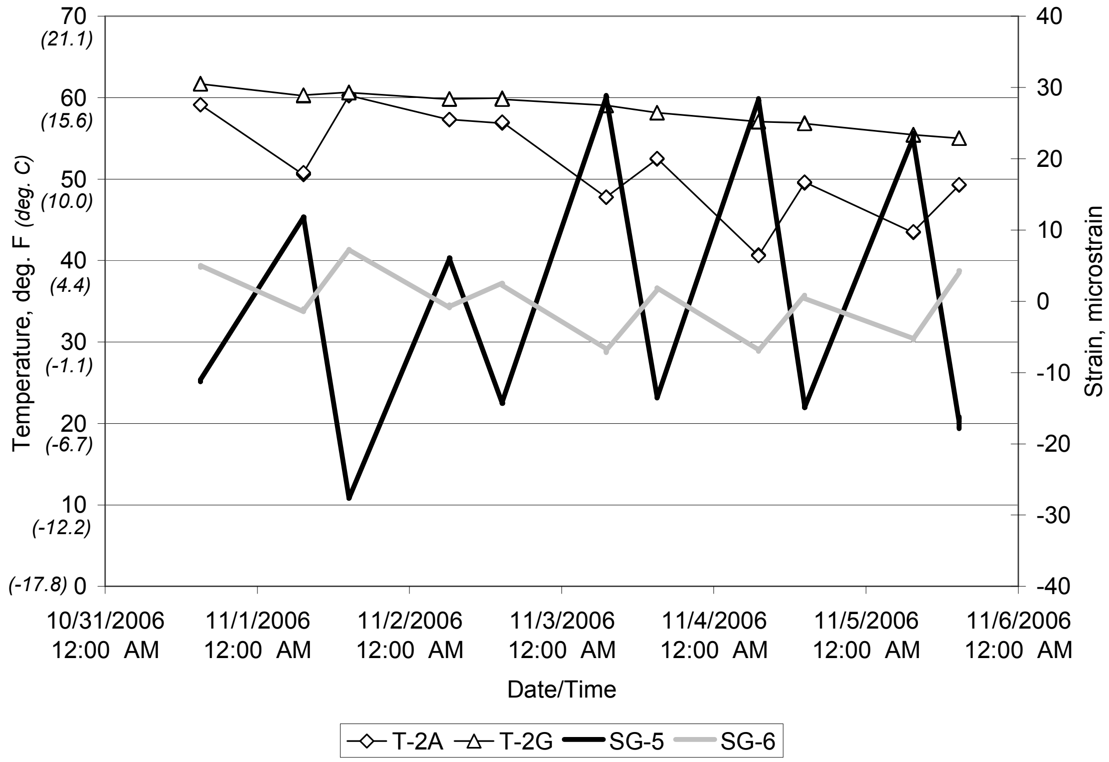


Figure 9. Plot of SG-5 and SG-6 Responses with Temperature (Oct. 31 - Nov. 5).

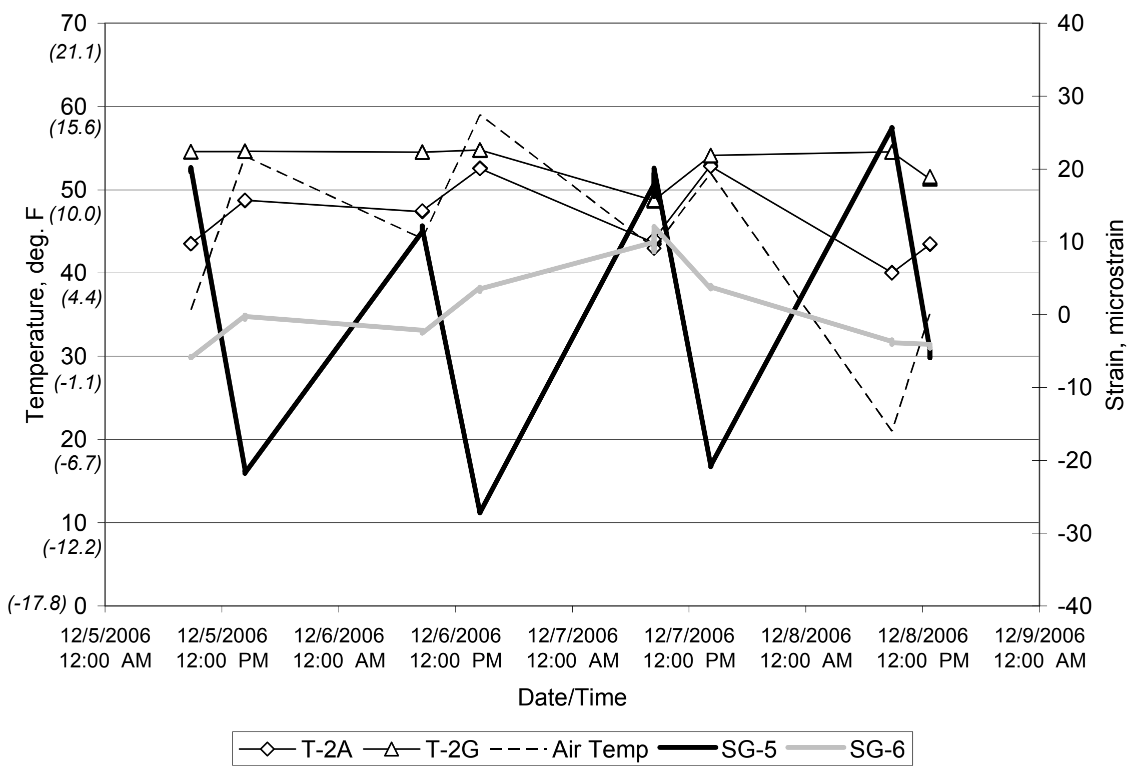


Figure 10. Plot of SG-5 and SG-6 Responses with Temperature (Dec. 5-8).

PROJECT DATABASE

The FAA is preparing an internet-accessible database that will contain data collected by the instruments in Taxiway E, as well as information, such as sensor coordinates, that will enable users to interpret the data. Prior to being uploaded to the database, the sensor data are screened for null or erroneous readings, damaged sensors, etc., but are not otherwise filtered or analyzed. The FAA plans to make this database available to the public on the FAA Airport Technology R&D Branch web site: www.airporttech.tc.faa.gov.

CONCLUSIONS

In cooperation with the Atlanta DOA, the FAA Airport Technology R&D Branch instrumented three new rigid pavement slabs in a reconstructed portion of Taxiway E at Atlanta Harsfield-Jackson International Airport. In total, 64 gages were installed in the three slabs during construction of the taxiway, which took place in October 2006. The first data were collected simultaneously with concrete placement on October 18, 2006. Sensors included vertical displacement transducers, strain gages and thermocouples. The object of this instrumentation project is to monitor the long-term behavior of the slabs in response to environmental loads, paying particular attention to slab warping and curling. Slabs were selected to provide different loading conditions, from no anticipated vehicle traffic to frequent wheel loading.

Initial data collected using portable data acquisition equipment over limited periods of time indicate some measurable vertical slab displacement at the free edge of slab 2 (adjacent to the shoulder) and maximum strain variations in response to daily temperature cycling on the order of 30 microstrains. These data are preliminary and subject to further analysis. A permanent data acquisition system powered by solar and wind generation is planned for the site and will be installed in early 2007.

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