A Synthesis of Practical and Appropriate Instrumentation Use for Accelerated Pavement Testing in the United States

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ABSTRACT
Pavement testing facilities can be utilized to help with the integration of the new *Mechanistic-Empirical Pavement Design Guide* (MEPDG). One way test facilities are doing this is by embedding instrumentation, such as strain gauges and pressure plates, in pavement structures to measure pavement responses under loading. As new facilities are being constructed or reconstructed, it is important that the instrumentation chosen for research at the facility is appropriate and reliable. Accelerated Pavement Testing (APT) facilities have come together through the Consortium of Accelerated Pavement Testers (CAPT) to help develop practical and appropriate instrumentation uses based upon positive and negative experiences at the various facilities. Using this insight, a facility undergoing redesign or a new facility might be able to answer some of the following questions before designing its instrumentation scheme. What types of strain gauges are appropriate for what we are trying to determine? What gauges are other facilities using so our results might be comparable to theirs? If a facility were determining whether thermistors are advantageous over thermocouples, it would be important to realize it is difficult to install thermistors horizontally pre-construction; however, these instruments can be installed post-construction vertically in the pavement. The difficulty with this scenario is determining the tip depth of the device. Using experiences from other successful APT facilities to bolster success at other facilities will only increase the amount of valuable findings and help make APTs more profitable.

INTRODUCTION

Mechanistic-empirical (M-E) design is currently in a stage of progression. As states march toward this design methodology, the need for model calibration and verification will continue to expand. While some organizations consider full-scale testing on actual in-service roads, completing such research can be severely limited by the following factors: (1) testing could take many (15-20) years to complete, (2) it is often difficult and unsafe to close lanes on in-service roads for inspection, (3) Departments of Transportation tend to be reluctant to leave roads in-service until failure, and (4) the public can be intolerant to traffic delays due to road closures (*1*).

To overcome the setbacks involved in testing in-service roadways, a new type of testing facility was developed. Accelerated pavement testing (APT) facilities were first developed when new design and analysis techniques for pavements needed to be related to actual performance. This new type of facility allowed for empirical data to be bridged with actual pavement performance under traffic (*2*).

An APT is defined as a "controlled application of wheel loading to pavement structures for the purpose of simulating the effects of long-term in service loading conditions in a compressed period of time" (*3*). Under this definition, experimental setups such as test roads, circular tracks, and heavy vehicle simulators all contribute to expanding the knowledge of the pavement community (*2*).

APT History

APTs were first introduced to the world in 1912 when the United Kingdom created the "Road Machine" (*4*). The idea soon infiltrated the United States in 1919 with the construction of the Arlington Test Road where concrete pavement designs were tested by loaded truck traffic. Over time, facilities like the Bates experimental road, Maryland Test Road, and the Western Association of State Highway Officials Road Test began to test pavements using simulated or actual traffic on test roads (*5*).

While the aforementioned experiments paved the way for future APTs , the front-runner to modern APT facilities was the American Association of State Highway Officials (AASHO) Road test. This experiment began to elevate the rationality behind road construction and pavement design by developing empirical equations for design from the experiment's results (*2*).

While APT programs were developed globally over the next thirty years (*3*), APT usage came to the forefront of pavement design in the 1990s (*6*). In 1996, 28 APT experiments were located globally (*5*); however, by 2002, this number had grown to 45, 14 being inside the United States (*7*).

M-E Design

Mechanistic-empirical design has recently made great strides towards widespread implementation in the United States. States such as Illinois, Kentucky, and Washington, along with countries such as the United Kingdom, Spain, and South Africa have developed M-E design methodologies (e.g., *8-12*). As the new M-E Pavement Design Guide (MEPDG) is being completed and implemented, more time is being spent on determining material properties and pavement response characteristics under traffic loadings (*13*).

Mechanistic design relies on fundamental models that relate vehicular loading, materials, and structural design to fundamental pavement responses (*12*). These responses are coupled with transfer functions to predict pavement life using Miner's Hypothesis (*14*). Transfer functions rely on theoretical strains and pressures to estimate the design life of pavement structures. If these responses are accurately estimated, the transfer functions will return a pavement design of appropriate thickness.

The recent advancements in instrumentation and computing technology have allowed proponents of M-E design to go from estimating to measuring pavement responses such as stress, strain, deflection, moisture, and temperature (*15*). Today, embedded pavement instrumentation is used in analyzing pavement responses at APT facilities and in-service roadways (*16*).

Pavement Instrumentation Potential Pitfalls

Embedding pavements with instrumentation should not be taken lightly as this can add complexity and cost to any project due to delays in construction and additional equipment cost (*17*). In order for accelerated pavement experiments to be successful, the measurements made by pavement instrumentation must be accurate (*17*) and precise (*18*). This might appear to be simple on the surface, but variability is inherent in all pavement measurements. This variability might come from wheel wander (under live traffic), the precision of the instrument itself, material variability (stiffness, thickness), gauge alignment, and vehicle bounce. These issues should be addressed and quantified at each experiment to ensure reliable data are being used for modeling and research (*18*).

While variability is a problem with pavement instrumentation, it is not the only liability to a project's success. Using pavement instrumentation adds complexity during the construction process most contractors are not used to encountering such as time delays, gauge placement, and additional difficulty in quality control (*6*). Failure to achieve proper compaction near instrumentation has led to premature failure at APT facilities (*19*). However, if care is taken during the design and construction phases of a project where pavement instrumentation is being used, measurement variability and premature failures can become negligible through proper quality control practices. Proper gauge calibration and installation are the two most profitable ways to minimize instrumentation pitfalls.

INSTRUMENTATION BASICS

Pavement instrumentation has been used extensively at APTs to validate fatigue and rutting models for states and agencies (*16*). However, every experiment is set up by a different organization with its own objectives. These subtle nuances cause each experiment to judge for itself what pavement responses to measure and where to measure them.

Four of the most critical pavement responses to measure are strain, pressure, temperature, and moisture. However, if an experiment uses live traffic as opposed to a linear heavy vehicle simulator, one should consider capturing wheel wander data. If concrete pavements are being considered, curling and warping measurements are important to consider. Once the facility has chosen which pavement responses to measure, six considerations have been presented for gauge selection (*6, 20)*.

1. Ability to measure the desired response (strain, pressure, etc…)

2. Suitability to the project (cost)
3. Availability (delivery time)
4. Reputation for performance and reliability
5. Compatibility with existing equipment and continuity with previous research
6. Availability of vendor for extended service and guarantee.

One reason for pavement instrumentation's high cost is the robust nature of the gauge. Pavement instrumentation must be able to withstand the trials of construction as gauges and wires are subjected to high temperatures and compaction strains. While proper installation practices are vital for gauge survivable, some gauges seem more durable than others (*17*).

Gauge reputation and quality should be heavily researched before use. This can be done by contacting facilities that have experience with the exact gauge for similar research. An unwieldy quantity of data should not be preferred to high quality data. It is better to use fewer gauges of better quality than multiple gauges that have no track record of use in similar environments (*17*).

Developing Instrumentation Arrays

Gauge arrays will vary depending on the facility and experiment being conducted. A gauge array could be as simple as a straight line of four strain gauges; however, it can become much more complicated depending on the pavement response and purpose of the study.

If a pavement is subjected to loading at a specified location, gauges can aligned under the load path. However, given complexities (such as wheel wander due to live traffic), larger gauge arrays might need to be designed. The NCAT Pavement Test Track gauge array (Figure 1) is one such example. In this case, asphalt strain gauges placed at the bottom of the hot mix asphalt layer spaced 0.67 meters on center in three columns to capture wheel wander (*20*). When designing the instrumentation array at the Virginia SmartRoad, load associated instruments were located at 0.5, 1.0, and 1.5 meters from the shoulder. Gauges need to be located far enough apart to as not to interfere with each other's readings, but they should also be close enough to adequately capture wheel wander (*12*).

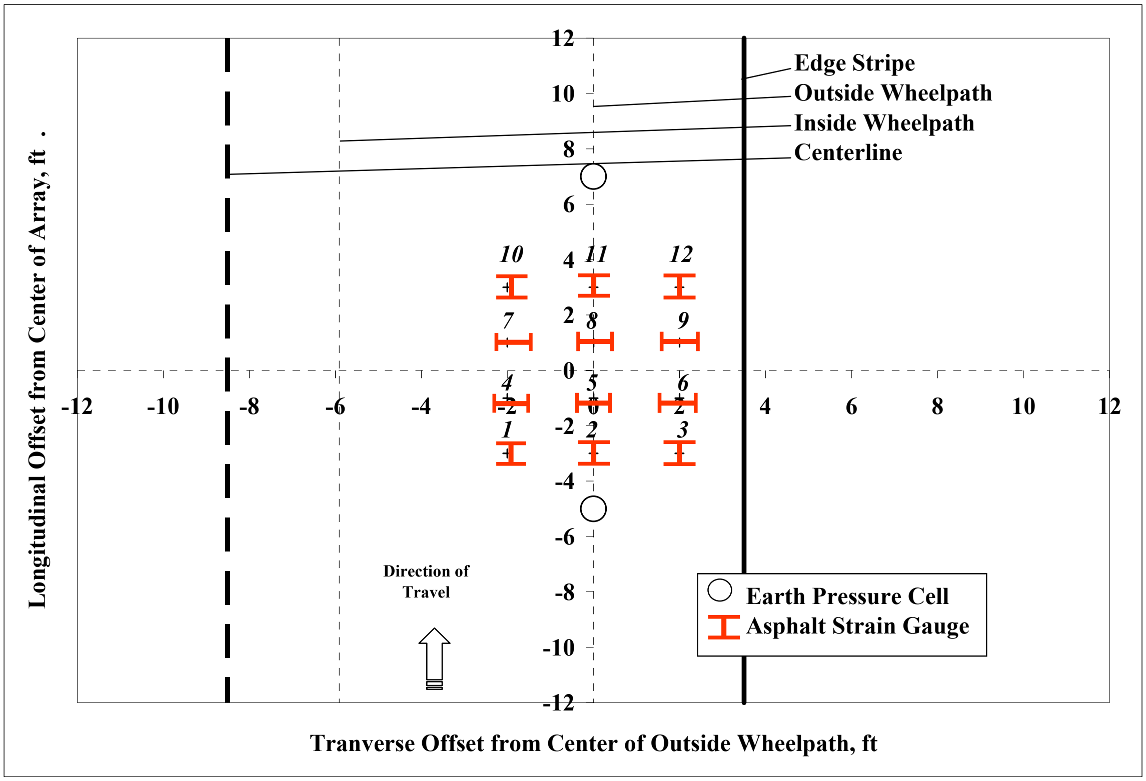

Figure 1. NCAT Pavement Test Track Gauge Array.

When designing a gauge array, facilities should incorporate redundant gauges in their design. Redundant gauges are gauges with the same orientation to the wheelpath (transverse or longitudinal), lateral offset from the shoulder, and depth. Gauges can cause interference, fail during installation, or read erroneously (*6, 17*). Redundancy, such as seen in Figure 1, is advantageous for two reasons (*18*):

1. If one gauge fails, another gauge is reading the theoretically same pavement response.
2. Functionality checks can be made to ensure reliable data.

Scope

The Consortium of Accelerated Pavement Testers (CAPT) is a pooled-fund organization in the United States of America designed to bring together leaders from APT facilities or states interested in APT research to share knowledge and experiences so APT research can become more profitable to the pavement community.

Using web-based surveys and interviews, CAPT has collected data on specific instrumentation experiences and the lessons learned from the following APT facilities in the United States: the National Center for Asphalt Technology, the Ohio Research Institute, Florida Department of Transportations, Louisiana Transportation Research Center, MnRoad, the Kansas State Civil Infrastructure Laboratory, and CalTrans. An extensive literature review was also conducted to supplement the surveys.

While there are many types of pavement instrumentation in use today, this report will focus on four of the devices used most extensively in the pavement community: strain gauges, pressure cells, temperature devices, and moisture technology. During a

2007 meeting of the CAPT group, these gauges were chosen as the most important to research at that time.

Objectives

The measurements coming from APT experiments are only as good as the instrumentation measuring the pavement response. While vast amounts of research have been published on the results of pavement instrumentation, little has been produced detailing the successes and failures of previously instrumented experiments. The objectives of this paper are two-fold.

1. To synthesize the surveyed instrumentation usage at seven APT facilities in the United States.
2. To illustrate successes and challenges at APT facilities in the United States to improve future APT research using pavement instrumentation.

FACILITIES

The following data are the results of web surveys completed by seven different APT experiments. It should be noted that each APT experiment comes with its own unique set of challenges, and there is no "one size fits all" pattern for the construction of APT facilities. Table 1 provides basic information about the seven facilities that were willing to share instrumentation experiences for its work. This information includes the following: facility name, type, and what governs the research design (sponsor, industry, etc . . .).

Table 1. APT Facility Information.

Facility	**Type**	**Needs-Based**
NCAT Pavement Test Track	Closed Loop	Sponsor (mostly DOTs, but also FHWA and private industry)
Ohio Research Institute	HVS	Sponsor
Florida DOT	HVS	Research
Louisiana Transportation Research Center (LTRC)	ALF	Research
MnRoad	Test Road	Research (main goal), sponsor, industry (depending on project/scope)
Kansas State	HVS	Research
CalTrans	HVS	Sponsor

Some experiments may have their projects controlled by governing or sponsoring agencies. This, along with the type of facility, should be considered before implementing any instrumentation scheme. Table 2 lists the surveyed measurements taken at each of the included facilities. Other measurements are taken, such as permanent deformation, rutting, and cracking; however, these phenomenons were not included in the questionnaires and study. Further research should be conducted which includes these parameters.

Table 2. Pavement Responses Measured.

Facility	Horizontal Strain	Vertical Strain	Pressure	Temperature	Moisture
NCAT Pavement Test Track	X	X*	X	X	X*
Ohio Research Institute	X		X	X	X
Florida DOT	X		X	X	X
MnRoad	X	X**	X	X	X
LTRC	X		X	X	X
Kansas State	X	X	X	X	X
CalTrans				X	X

*Experimented with this measurement, but no longer uses it.
**Experimenting with this measurement in the future.

STRAIN

Strain is can be measured either horizontally (parallel to the surface of the pavement) or vertically (perpendicular to the pavement surface). While strain can be measured in different directions, the devices incorporated in capturing these pavement responses vary drastically.

Horizontal Strain

Of the seven facilities surveyed, 85.7% of them measure horizontal strain. This has increased from 50% in 2003 (*7*). Horizontal strain has been important to quantify because of its relationship to bottom-up fatigue cracking in HMA (*16*). For this reason, most facilities quantify fatigue life by measuring horizontal strain at the bottom of the HMA in the center of the wheelpath (*6, 16*). As seen previously, gauges can be offset from the wheelpath to capture the effects of wheel wander, and the NCAT Pavement Test Track has even placed gauges at non-conventional locations (between HMA lifts) to study the effect of strain with depth (*21*). For Portland cement concrete (PCC), strain gauges are typically located at the center and edges of the slabs. Non-conventional locations include slab joints at the top, middle, and bottom of the PCC slab. These locations are chosen because these are the critical design points for concrete design (*6*).

While there are many different types of strain gauges, three basic design principals used in their construction: foil gauges, strip gauges, and strain coils. Foil gauges, which are used in Florida's research, have been used to measure both horizontal and vertical strain in bituminous materials, but on a limited basis. One drawback to using foil gauges is they must be cemented to a carrier block. This block is set so the gauge is flush with the bottom of the HMA; however, it intrudes into other layers of the structure (*17*).

Another type of strain gauge is the strain coil. These gauges can be placed at the bottom of a bituminous layer; however, they have also been used for studying strain in intermediate layers of a pavement structure. These gauges are either cemented into place using a tack coat, or they can be cemented to carrier blocks similar to the foil gauges (*17*).

The most common of the three strain gauges is the strip gauge. Also known as an "H" gauge, strip gauges have been shown to perform well if the bond between the gauge and the bituminous material is strong. These instruments have strain gauges enclosed in a plastic strip which are connected to two brass anchors, locking the gauge into place in the layer being studied. Another type of strip gauge can be cemented to an aluminum plate with a resin coating on it. If this strip gauge is used, one should be careful not to reinforce the pavement structure by choosing a plate with a high modulus (*5*).

Six gauges have seen the most use at US pavement facilities: Kyowa, Dynatest, Tokyo Sokki, Texas Measurements (TMK), Vishay, and Construction Technology Laboratories (CTL). Table 3 shows which facilities use which gauges.

Table 3. Strain Gauge Usage.

Facility	**Kyowa**	**Dynatest**	**Tokyo Sokki**	**CTL**	**TMK**	**Vishay**
Ohio		X				
Florida			X			X
NCAT				X		
MnRoad		X	X	*		
Kansas State					X	
LTRC			X			
VA SmartRoad	X	X				

*Will use on next construction cycle.

The Kyowa strain gauges have seen little use at APT facilities in the United States with the exception of the Virginia SmartRoad project. In this one case, temperature susceptibility caused some challenges with this gauge (*12*).

Two of the six surveyed (SmartRoad not being surveyed) APT facilities use gauges produced by Dynatest. The most common gauge in use is the Dynatest FTC II A (Past II-AC). This gauge has seen use in Ohio and MnRoad and the Marquette Interchange reconstruction project (*16*). This gauge operates as a 120 ohm ¼ bridge epoxy based sensor with a modulus of about 320,000 psi. A casual examination found the gauge to be well-constructed (*16*), but not without concern in its design. The lack of a "wing" structure might not allow the gauge to lock into place as well as a typical "H" gauge, and the quarter bridge, as opposed to a full bridge structure, requires complex and costly precision bridge completion resistors (*16*).

Results from this gauge have been typically positive. Ohio and Virginia SmartRoad were both pleased with the results returned from the Dynatest gauges. Cost and accuracy appear to be balanced, and Ohio even plans to continue their use in the future. MnRoad used the Dynatest gauges in its project due to their availability. While they gauges have provided good data, MnRoad has had issues with gauge durability over time as gauge failure has occurred in 2-3 years. Forensics has shown that these failures are not due to lead wire or installation errors; therefore, this experiment is changing gauges for future research cycles.

Tokyo Sokki produces the KM-100HAS strain gauge, a 350 ohm full-bridge strain gauge which is temperature compensated. Like the Dynatest gauge, on a visual inspection, it appeared to be well-constructed as it has been modified from its counterpart PCC gauge to work in bituminous materials. The only questionable design parameter is the anchorage (*16*). Both Florida and LTRC have had very good results with these gauges as they are durable and very rugged in relationship to their cost. MnRoad has also had mostly positive results with these gauges with limited gauge failures. Unlike the Dynatest gauges, forensics has shown these shortcomings were due to lead and installation problems.

The CTL ASG-152 is a 350 ohm full-bridge 6/6 nylon based "H" gauge. These gauges have been known to have misaligned wings at times which prevent the gauge from lying flush with the HMA; however, they do perform as advertised. The full-bridge component eliminates the cost and complications of having to add complex resistors, and if they are installed correctly, they have been known to be very rugged (*16*). The NCAT Pavement Test Track has had the most extensive experience using these strain gauges. They were originally chosen because their short delivery time and reasonable price, but the gauges have been shown to be reliable in the field (*18*). MnRoad plans on using CTL gauges in its next cycle of testing, and the Marquette Interchange reconstruction project was pleased with the CTL gauges finding them more reliable than others (*16*).

Little is known about the inner workings of the Vishay and TMK gauges. Both Florida and Kansas State have been satisfied with these gauges and plan on using them in future work. The TMK Model PML-60-2L gauges are used by Kansas State. The inexpensive nature of these gauges makes them very affordable for measuring horizontal strain; however, gauge durability is a concern. Many of these gauges have been crushed by the roller during the compaction process impeding the results of the project.

Vertical Strain

Little research is currently conducted using vertical strain measurements. In the 2003 cycle of the NCAT Pavement Test Track, CTL designed a strain gauge which could be mounted vertically in the pavement structure (*20*); however, these gauges were difficult to install and provided little meaningful information to the study.

Today, vertical strain is measured indirectly through either pressure or deformation. While pressure will be discussed later, linear variable displacement transducers (LVDT) and deflectometers are sometimes used to measure vertical strain. These deflections have been used to estimate rutting in roadways (*22*).

LVDTs use electromechanical transducers to convert motion into an electrical response. In turn, strains in small layers of pavement can be determined by comparing a measured displacement to the original length of the gauge (*23, 26*). An LVDT can either be used by itself or in conjunction with other LVTDs to measure deflection under a load which will help engineers estimate the material properties of the layers (*24*). LVDTs can also be used to measure permanent deformation and surface deformation. These measurements can be taken either in-depth or at the surface. Gauges installed in-depth can quantify the non-recoverable plastic strain of the pavements by measuring their permanent deformation; however, LVDTs can also measure the vertical elastic recoverable strain by measuring in-depth deflection.

Kansas State and MnRoad have both used LVDTs in their research. Kansas State has developed their own in-house LVDTs to monitor deflection in a single layer; however, if these gauges are not installed correctly, they have been known to report bad data. On the other hand, MnRoad used LVDTs due to their availability and has had success measuring deflections. The one drawback to using LVDTs is that they work well as long the gauge is maintained and regularly inspected which can prove to be extensive.

Ohio has used single-depth deflectometers for its research while MnRoad, LTRC, and CalTrans have all used multi-depth deflectometers (MDD). MDDs have been used exclusively by CalTrans because their ease of use, cost, reliability, and their compatibility with the South African HVS studies being conducted. They have allowed researchers at APT facilities to measure pavement deformation and gaps between concrete slabs and their subgrade support (*26*).

The LTRC, on the other hand, has merely used their MDD experience as an experiment for possible future use. CalTrans has found its MDD data to be reliable barring improper installation or anchoring the device in wet material. Ohio has also noticed that MDD anchorage can slip if the anchor location is not chosen carefully. To remedy this, this experiment has moved to using single-depth deflectometers with much success. If moisture is present, these devices are susceptible to condensation problems, and in colder climates, MnRoad has even experienced freezing of MDD instrumentation.

PRESSURE

While there are many types and brands of pressure cells in existence today, most behave on similar principles. Two steel plates are welded together with a de-aired fluid such as oil between the plates. Loading the cell causes an increase to the fluid pressure which is converted through a semi-conductor transducer or a strain gauge to an electrical voltage. Gauge calibration constants are used in conjunction with software to interpret pressure measurements (*16, 17, 20*).

Of the seven surveyed facilities, six measure pressure. This, again, is an increase from three measuring pressure in previous research (*7*). Virginia SmartRoad and the Marquette Interchange reconstruction project also have incorporated pressure measurements in their research (*12, 16*). Table 4 describes the typical gauges used to measure pressure at APT facilities.

Table 4. Pressure Cells.

Facility	Geokon	RST	Dynatest
Ohio	X		
Florida	X	X	
NCAT	X		
MnRoad	X		X
Kansas State	X		
LTRC	X		

The most common gauge in pressure measurement is produced by Geokon. All six of the experiments measuring pressure have incorporated this device into their data analysis. Most facilities use the Geokon 3500 due to its ability to capture appropriate ranges of pressures for pavements, but smaller gauges can suffice if less intense pressures are expected.

Previous research shows the most common locations for pressure cells to be placed is at the top of the subgrade and/or base material (*6, 12, 16, 20*). The Geokon pressure cell has a proven reliability in measuring pressure in soils with extensive use in APT research. Another positive aspect of this gauge is its ruggedness as Kansas State has been able to recover used gauges for further research.

One challenge seen in both the Geokon and Dynatest cells has been inconsistent data. Both Kansas State and MnRoad have reported erratic pressure readings from duplicate gauges with some gauges reading double its redundant gauge. Both facilities feel this could possibly due to installation procedures. When installing pressure cells, it is critical that they be level, and the surrounding material be well-compacted. If the gauges are not level or if the gauge can move in its hole, invalid pressure measurements might be noticed.

While the Geokon gauge is appropriate for measuring pressures in soils, Florida and the Virginia SmartRoad project have tried to measure pressures in the HMA lifts of the pavement with much success. When considering gauges placed in HMA, a high temperature rating is required due to heat expended during the construction process. Florida used a gauge produced by RST Instruments for this reason and has been very satisfied with its results.

TEMPERATURE

Since HMA is a thermo-visco-elasto-plastic material, correctly quantifying temperature is critical to studying pavement responses. Responses, such as strains and pressure, react to temperatures change because HMA pavements soften as they are heated and harden as they cool (*25*).

The two most common methods for measuring pavement temperatures are thermocouples and thermistors. Table 5 presents the usage of each at APT facilities.

Table 5. Temperature Measuring Devices.

Facility	Thermistor	Thermocouple	Temperature Button
Ohio	X	X	
Florida		X	
NCAT	X		
CalTrans		X	X
MnRoad	X	X	
Kansas State		X	
Louisiana		X	

Thermocouples are the most commonly used temperature measuring device at APT facilities today and are typically fashioned from two different metals where a measured temperature induces temperature dependant voltages at the metallic joint. Type K and Type T thermocouples are most often used for temperature measurements in pavements due to their ability to measure a broad spectrum of temperatures (*26*). Facilities have had success installing thermocouples during construction which gives them the advantage of less pavement intrusion (*17*).

Five surveyed experiments have had positive experiences with them. These gauges have proven to be reliable, cost effective, and corrosion-resistant. Kansas State has even been able to go as far as fabricating thermocouples in-house to reduce instrumentation costs. The LTRC experimented with thermocouples and had a less than favorable experience. In the future, this facility is going to move away from their use.

Thermistors are resistors constructed with temperature sensitive metal. Thermistors are also cost efficient, simple, and adaptable (*26*). While some consider thermistors less robust than thermocouples (*5*), thermistors have the advantage of having a larger voltage output; therefore, they require less sensitive measuring equipment (*26*). They can also require fewer datalogger channels to operate.

Thermistors have been used at the NCAT Pavement Test Track and Ohio to measure temperature with much positive success. MnRoad's use of thermistors has been limited to thermistors attached to vibrating wire strain gauges. These devices have proven to be durable as many have survived multiple testing cycles at the NCAT Pavement Test Track. While thermocouples can be installed during construction, thermistor data have proven to be more useful if they are installed post-construction. NCAT experimented with positioning its thermistors horizontally during construction; however, this proved to be ineffective. More success has come through retrofitting the gauges by drilling holes into the pavement shoulder and installing the thermistors vertically. While this does damage the shoulder of the pavement, NCAT has been pleased with the data returned. Its only concern is knowing the exact depth of the thermistor tip during installation.

MOISTURE

Moisture content in soils and unbound granular materials can be important for understanding drainage and soil strength (*27, 28*). For this reason, most APT facilities attempt to measure moisture using technology such as time domain reflectometers (TDR), environmental sensors, and moisture blocks.

Moisture content is related to the dielectric properties of a soil. If one were to average the dielectric properties of the air, soil, bound water, and free water in the soil, the dielectric constant for the soil could be determined (*29*). TDRs analyzes high frequency electronic signals to indirectly measure a soil's moisture content (*26, 30*). This is the most popular moisture responsive technology used at the surveyed APT experiments; however, though recommended by SHRP, TDRs have returned mixed results.

Kansas State has had some success in achieving reliable data, but other experiments such as Ohio, Louisiana, MnRoad, CalTrans, and NCAT have had less than desirable results. Some TDR setbacks have been small such as noise in the signal or minor failures at MnRoad and in Ohio. However, CalTrans and NCAT both have had TDRs produce invalid long-term data. When the 2003 cycle of the NCAT Pavement Test Track was being constructed, TDRs were used to measure moisture content. Laboratory calibrations and early field testing proved to be positive, but after time, the TDRs began to return very high water contents. Forensics proved that these values were indeed erroneous.

MnRoad and Florida are two APT experiments that have experimented with non-TDR moisture technology. Florida has had success with their environmental sensors. They have proven to be easy to use as they can be installed vertically into the structure to return moisture gradients.

Moisture blocks are similar to thermocouples in that they measure electronic resistance to measure moisture content. MnRoad was the only surveyed experiment using moisture blocks and has found that the data is very subjective and requires significant amounts of soil disturbance during installation (*31*). While moisture blocks have not proven efficient at measuring moisture content, they have been reliable at estimating frost depth.

CONCLUSIONS

It is imperative that facilities choose instrumentation properly when beginning instrumented APT or in-service roadway research. One of the most beneficial ways to determine appropriate instrumentation practices is to look at the successes and challenges of other research experiments to benefit from lessons learned . Based upon previous literature and survey results, the following conclusions can be gathered about pavement instrumentation in the United States:

1. Horizontal strain gauges can be used to quantify pavement responses which predict pavement fatigue life. Dynatest and CTL produce the most commonly used devices for capturing this pavement response.
2. Vertical strain is very rarely measured; however, LVDTs can be used to measure pavement deflection and return similar results.
3. Pressure cells are being more commonly incorporated into pavement research with the Geokon pressure cell being the most commonly used gauge.
4. Thermocouples are more commonly used to measure temperature at APT facilities; however, while not as commonly used, thermistors have returned reliable data to researchers.
5. Installation of gauges is one of the most important factors in determining if a gauge is going to behave correctly.

Recommendations

Based upon this research, the following recommendations can be made to further advance the field of research involving instrumented pavements.

1. Sensors need to be compared to determine the working ranges and qualities of the various gauges. CAPT plans to conduct a sensor rodeo where gauge comparisons can be investigated.
2. Gauges should be calibrated and checked before being installed in pavements for research. This will ensure gauges are behaving properly.
3. Duplication of gauges allows researchers to check the quality of the data. In HMA pavements, at least two strain gauges should be placed in the transverse and longitudinal direction to allow for functionality checks. If wheel wander is present and uncontrolled, additional gauges should be considered to accurately quantify this phenomenon.
4. Further research needs to be conducted on developing accurate and reliable devices for measuring the moisture contents of soils.
5. Further research also should be conducted into the data acquisition systems, signal processing programs, and in-situ accuracy verification programs used at APT facilities. Currently, a study is being conducted at the NCAT Pavement Test

Track to determine the precision of their strain gauges (*18*). Other studies should be conducted to determine appropriate working ranges for gauges in question.

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REFERENCES

1. Brown, R.E. and R.B. Powell. "A general overview of research efforts at the NCAT pavement test track." *Proceedings, 2nd International Symposium on Maintenance and Rehabilitation of Pavements and Technological Control*. Auburn, AL, 2001.
2. du Plesis, L., N.F. Coetzee, T.P. Hoover, J.T. Harvey, and C.L. Monismith. "Three decades of development and achievements: The Heavy Vehicle Simulator in accelerated pavement testing." *Proceedings of Sessions of GeoShangai*. American Society of Civil Engineers: 2006, pp. 45-54.
3. Hugo, F., and A.L. Epps. "NCHRP synthesis 325: Significant Findings from Full-Scale Accelerated Pavement Testing." *National Cooperative Highway Research Program*. Transportation Research Board, Washington, DC: 2004.
4. Powell, R.B. *A History of Modern Accelerated Performance Testing of Pavement Structures*. NCAT Document (in-press), 2006.
5. Metcalf, J.B. "NCHRP Synthesis 235: Application of Full-Scale Accelerated Pavement Testing." *National Cooperative Highway Research Program*, Transportation Research Board. Washington, DC: 1996.
6. Llenin, J.A, T.K. Pellinen, and D.M. Abraham. "Construction Management of a Small-Scale Accelerated Pavement Testing Facility." *Journal of Performance of Constructed Facilities*, Volume 20:3, August 2006, pp. 229-236.
7. Saeed, A. and J.W. Hall. "NCHRP Report 512: Accelerated Pavement Testing Data Guidelines." *National Highway Cooperative Research Program*. Transportation Research Board, Washington, DC: 2003.
8. Monismith, C.L. Analytically Based Asphalt Pavement Design and Rehabilitation: Theory in Practice, 1962-1992. *Transportation Research Record: Journal of the Transportation Research Board, No. 1354*, TRB, National Research Council, Washington, D.C., 1992, pp. 5-26.
9. Kentucky Transportation Cabinet. *Pavement Design Guide (2007 Revision) for Projects off the National Highway System less than 20,000,000 ESALs, less than 15,000 AADT, and less than 20% trucks*. Kentucky Transportation Cabinet Division of Highway Design, Lexington, KY, 2007.
10. Timm, D.H., D. E. Newcomb, and B. Birgisson. Development of Mechanistic-Empirical Design for Minnesota. *Transportation Research Record: Journal of the Transportation Research Board, No. 1629*, TRB, National Research Council, Washington, D.C., 1998, pp.181-188.
11. *Thickness Design, Asphalt Pavements for Highways and Streets.* Report MS-1, The Asphalt Institute, 1982.

12. Loulizi, A., I.L. Al-Qadi, and M. Elseifi. "Difference between In Situ Flexible Pavement Measured and Calculated Stresses and Strains." *Journal of Transportation Engineering*, Vol. 132:7, July 2006, pp. 574-579.
13. Timm, D.H. and A.L. Priest. *Material Properties of the 2003 NCAT Test Track Structural Study*. Report No 06-01, National Center for Asphalt Technology, Auburn University, 2006.
14. Miner, M.A. Estimation of Fatigue Life with Emphasis on Cumulative Damage. *Metal Fatigue*, edited by Sines and Wiseman, McGraw Hill, 1959, pp 278-89.
15. Al-Qadi, I., A Loulizi, M. Elseifi, and S. Lahouar. The Virginia Smart Road: The Impact of Pavement Instrumentation on Understanding Pavement Performance. *Journal of the Association of Asphalt Paving Technologists*, Vol. 73, 2004, pp. 427-466.
16. Hornyak, N.J., J.A. Crovetti, D.E. Newman, and J.P. Shabelski. *Perpetual Pavement Instrumentation for the Marquette Interchange Project – Phase 1*. SPR #0092-06-01. Transportation Research Center, Marquette University, August 2007.
17. Brown, S.F. "State-of-the-Art Report on Field Instrumentation for Pavement Experiments." *Transportation Research Record: Journal of the Transportation Research Board, No. 640*, TRB, National Research Council, Washington, D.C., 1977, pp. 13-28.
18. Willis, J.R. and D.H. Timm. "Repeatability of Asphalt Strain Measurements under Full-Scale Dynamic Loading." *Journal of the Transportation Research Board*, 2008 (in-press).
19. Hugo, F., T. Scullion, N. Lee, K. Fults, and T. Visser. "A Rational Evaluation of Pavement Performance Using the Texas Mobile Load Simulator." *Proceedings of the 8th International Conference on Asphalt Pavements*, Seattle, Washington, 1997, Volume II, pp. 1125-1243.
20. Timm, D.H., A.L. Priest, and T.V. McEwen. "Design and Instrumentation of the Structural Pavement Experiment at the NCAT Test Track." NCAT Report 04-01. April 2004.
21. Willis, J.R. and D.H. Timm. "A Forensic Investigation of Debonding in a Rich-bottom Pavement." *Journal of the Transportation Research Board, TRB, 2007,* (in-press).
22. Chen, D. and F. Hugo. "Full-scale Accelerated Pavement Testing of Texas Mobile Load Simulator." *Journal of Transportation Engineering*, Vol. 124:5, September/October 1996, pp. 479-490.
23. Chehab, G.R., Y. Seo, and Y.R. Kim. "Viscoelastoplastic Damage Characterization of Asphalt-Aggregate Mixtures Using Digital Image Correlation." *International Journal of Geomechanics*. March/April 2007, pp. 111-118.
24. Oh, J., R.L. Lytton, and E.G. Fernando. "Modeling of Pavement Response Using Nonlinear Cross-Anisotropy Approach." *Journal of Transportation Engineering*. 132:6, 2006, pp. 458-468.
25. Marotta, T.W. *Basic Construction Materials*. Prentice-Hall: New Jersey, 2005.
26. Hammons, M.I., D.H. Timm, and J. Greene. *Instrumentation Data Interpretation*. State of Florida, Contract PR490902, September 2007.

27. Huang, Yang H. *Pavement Analysis and Design*. Englewood Cliffs, New Jersey: 1993.
28. Holtz, R.D. and W.D. Kovac. *An Introduction to Geotechnical Engineering*. Prentice-Hall, New Jersey, 1981.
29. Nasser, W. *Utilization of Instrumentation Response of SuperPave Mixes at the Virginia SmartRoad to Calibrate Laboratory Developed Fatigue Equations*, Ph.D. Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA.
30. Wright, W.C., R.E. Yoder, N.R. Rainwater, and E.C. Drumm. "Testing and Performance Evaluation of Ultrathin Whitetopping Pavements at Spirit of St. Louis Airport." *Journal of the Transportation Research Board: Transportation Research Record 1809.* Transportation Research Board, National Research Council, Washington, DC.
31. Robertson, R. and J. Siekmeier. *Instrumentation for Improved Pavement Design*. <http://www.mnroad.dot.state.mn.us/research/mnroad_project/m-e_group?instrumentation_for_improved_pavement_design.pdf>, 29 February 2008.