ABSTRACT

Three applications of radio frequency identification (RFID) technology in pavement engineering are examined. The first follows previous work on tracking hot-mix asphalt (HMA) concrete using passive RFID tags. Some tags were observed on the surface of the compacted mat, raising questions about the local permeability and density of the pavement. In situ permeability and nuclear density tests confirmed that the surfaced tags are not detrimental to the pavement. The second application extended the HMA tracking scheme to Portland cement concrete (PCC). Extensive field and laboratory evaluations determined that the passive encapsulated RFID tags used successfully for HMA tracking cannot be read through concrete at depths sufficient for PCC tracking. Finally, the feasibility of RFID technology as a platform for a wireless reflection crack detection sensor was explored. Laboratory tests demonstrated that the sensor can detect a reflection crack well before it has propagated completely through an HMA overlay.
RADIO FREQUENCY IDENTIFICATION APPLICATIONS IN PAVEMENT ENGINEERING

By

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Chapter 1 Introduction

1.1 RFID Applications in Pavement Engineering

Radio frequency identification (RFID) technology encodes a digital identification number on a small silicon-based integrated circuit or “microchip” usually attached to a copper foil antenna; this unit is termed the RFID tag. The passive tag receives energy from radio waves transmitted by a reader; the tag then uses this energy to transmit back to the reader its encoded identification number. The RFID tags can be quite small, and they can be scanned from distances of up to several meters. The passive tags are also very inexpensive, at unit costs often less than 50 cents.

RFID is widely used today for supply chain inventory management (e.g., WalMart, Target), automatic toll collection (e.g., EZ Pass), access control (e.g., digital car keys), security, equipment tracking, livestock identification and tracking, and payment at gas pumps (Exxon/Mobil Speedpass). Construction-related applications of RFID technology include tracking of haul trucks and other heavy construction equipment (Naresh and Jahren, 1997; Peyret and Tasky, 2004; Violino, 2007), materials deliveries and storage at construction sites (Stone, Pfeffer, and Furlani, 2000; Collins, 2004; Song, Haas, and Caldas, 2006; Ergin and Hendrickson, 2007; Torrent and Caldas, 2007; Su and Liu, 2007), tracking usage of construction site tools and equipment (Goodrum, McLaren, and Durfee, 2006; Yabuki and Oyama, 2007), monitoring maturity of Portland cement concrete (O’Connor, 2006), identifying Portland cement cubes for QA testing (Anonymous, 2002), and monitoring of corrosion environment around bridge deck reinforcement (Johns Hopkins, 2005).
General surveys of RFID applications in construction are provided by Jaselskis et al. (1995), Jaselskis and El-Misalami (2003), and Sawyer (2004).

The two main RFID uses explored in this thesis are for tracking material placement and for providing a wireless interface for sensors. The first use is divided into two subtopics: further refinement of a previously-developed scheme for tracking hot-mix asphalt (HMA) placement, and adaptation of the HMA tracking scheme to Portland cement concrete (PCC).

1.1.1 Tracking of Material Placement (HMA, PCC)

It is very important to be able to correlate as-constructed properties of asphalt concrete and Portland cement concrete to their field performance in pavements. This would ensure and even improve the quality of flexible and rigid pavements. Hot mix asphalt and PCC are produced in the production facility and then transported to the highway. Samples are taken by the producers for running various tests to assure that the quality of the HMA and PCC is acceptable for quality control (QC) purposes. Quality assurance (QA) samples are also taken by the agency but with less frequency. These samples are taken at specified times of production. For instance, in Maryland HMA QC samples are taken every 1000 tons (approximately every 50 trucks) leaving the plant, whereas QA samples are taken for each day of production (usually corresponding to 4000 tons or more). The location where the sampled truckloads are deposited in the highway is not always recorded. It is necessary to develop a method of accurately relating the QC/QA data to a spatial location along the highway so that they can be correlated with pavement management data.
1.1.2 Wireless Interface for Sensors (Reflection Crack Detection)

One of the most common rehabilitation methods for a deteriorated pavement is an HMA overlay. It increases the structural capabilities of the pavement, inhibits water from penetrating in the subgrade, and gives the pavement adequate frictional resistance. HMA overlays are also beneficial because of the short time required to rehabilitate the pavement, decreasing delays for travelers.

One of the most common distresses in asphalt concrete is reflection cracking, the development of new cracks in the overlay over the existing cracks or joints in the deteriorated underlying pavement. Although reflection cracking can occur in HMA overlays over HMA pavements, it is most commonly experienced in HMA overlays on top of PCC pavements. The latter is the type of reflection cracking examined in this thesis. Such cracks start at the bottom of the HMA layer at the joint locations between slabs and then propagate to the top.

The two most critical movements of the concrete slabs are shown in Figure 1.1. The first movement is horizontal caused by changes in temperature; this corresponds to mode I cracking (opening mode). The second movement is vertical caused by wheel loading; this corresponds to mode II cracking (sliding mode). A good introduction to fracture mechanics can be found in the book by Broek (1982).

Once full depth cracks have developed, water can penetrate through the asphalt layer to the subgrade, decreasing its structural capabilities. During low temperature conditions, the entrapped water in the cracks expands due to freezing, which would expand the crack at the same time. As these cracks get wider, driving comfort decreases and damage to vehicles increases.

One of the objectives of this thesis is to develop a wireless sensor using RFID tags to detect reflection cracks before they reach the surface of the pavement and
become visible. The RFID-based crack detection sensor at the bottom of an HMA overlay would be able to detect early onset of reflection cracking; this would be especially valuable in assessing pavement performance in warranty construction projects. Because of the potentially very low cost of RFID crack detection systems, they could conceivably be placed at all potential reflection crack locations along an overlay rehabilitation project—i.e., at all joints in the underlying rigid pavement slabs.

![Diagram of concrete slabs](image1)

**Figure 1.1: Horizontal and Vertical Moving of Concrete Slabs Causing Mode I and Mode II Cracking**

1.2 Organization of Thesis

Earlier work on HMA tracking (Schwartz and Khan, 2009) showed that RFID tags could successfully trace loads of HMA as they were trucked from the plant, traveled through the paver, and compacted into the mat. Unexpectedly, some of the RFID tags rose to the surface of the compacted pavement. The impact of this on the durability of the pavement from locally increased water infiltration or decreased density was therefore evaluated.

In a related effort to expand the use of RFID tags for tracking purposes in rigid pavements, laboratory and field evaluations were undertaken to evaluate the
readability of RFID tags in PCC pavements. The tags were encapsulated in the same manner as for HMA tracking.

The last topic covered in this thesis deals with the development of an RFID-based wireless sensor for detecting reflection cracking before it reaches the pavement surface.

The following describes the organization of the chapters of this thesis.

Chapter 1 Introduction

This chapter states the objectives of this thesis and includes a brief summary of the three main topics: evaluation of surfaced tags in HMA pavements, tracking of Portland cement concrete, and development of a crack detection sensor.

Chapter 2 Literature Review

This chapter provides an overview of the RFID technology and previous works in which it has already been used. It also shows RFID being used as a wireless sensor interface for measuring temperature and detecting cracks. An introduction to fracture mechanics and a summary of works done in measuring crack mouth opening displacement in asphalt concrete is also included in this chapter.

Chapter 3 Surfaced RFID Tag Evaluation

This chapter includes an evaluation of the influence of the surfaced tags in the integrity of the pavement. The possibility of increased permeability at those locations that might reduce the durability of the pavement was evaluated based on density and permeability tests conducted in the field.

Chapter 4 Tracking PCC Placement
This chapter evaluates the possibility of using encapsulated passive RFID tags for tracking PCC. Results from field and laboratory evaluations are included.

**Chapter 5 Reflection Crack Detection Sensor**

This chapter explains the design of an RFID-based wireless sensor for reflection cracks. An introduction to antenna theory is given. Extensive evaluations of the best modified RFID tag configuration are shown. Design, fabrication, and survivability are some of the issues evaluated in the development of a crack sensor prototype.

**Chapter 6 Summary and Conclusions**

In this chapter a summary, conclusions, and recommendations when needed are provided for each of the three topics.
Chapter 2 Literature Review

Two RFID technologies are available, the Surface Acoustic Wave and low frequency, high frequency, ultra high frequency, and microwave frequency technology. These have been used in various applications in the construction industry, however they have yet to be implemented successfully in Portland cement concrete (PCC) tracking and pavement crack detection.

The concept of tracking Portland cement concrete and developing a crack sensor to detect reflection cracking would require the use of a large number of RFID tags. For this reason, the performance variability for different tags of the same model was researched. Although the performance variability tests were not run on the same model tag as were used in this thesis the work still provides a benchmark for possible variability.

In the development of a crack sensor, RFID tags would be required to be embedded in asphalt concrete. Because of the potential for attenuation of the RFID signal from the asphalt surrounding the tag, the dielectric constant of this material was evaluated, because it will affect the read range of the RFID tags.

There has been some research conducted involving the use of RFID tags to detect cracks, however this has not been explored beyond the theoretical stage. Morita and Noguchi (2006) propose the use of RFID technology to detect structural cracks in concrete. Wood and Neikirk (2001) work on developing a passive sensor that can give information about the condition of welded connections. Although both state that RFID technology could be used for these purposes, neither one explores the idea further to
test its practicality. Additionally, research on sensors is currently underway through
the Federal Highway Administration (FHWA).

An introduction to fracture theory is given. Currently the ground penetrating
radar system is used as a non-destructive method of evaluating pavements, however it
cannot detect small reflection cracks. To be able to develop a crack sensor, the strains
and the crack mouth opening displacement when cracks occur in asphalt overlays
need to be determined.

The use of RFID crack sensors in asphalt pavements would provide timely and
accurate information about the current condition of an asphalt overlay.

2.1 RFID Basics

2.1.1 Concept

Brown (2007) gives an introduction to the basics of the RFID technology and
its applications. A radio frequency identification system involves an RFID tag, a
reader, and a computer. The RFID tag, usually called a transponder, is composed of a
chip and an antenna. Information is stored in the chip, usually as a serial number. The
reader sends electromagnetic radio waves which power the RFID tag and the tag
sends a signal back to the reader, which is then decoded and sent to the host computer.
An illustration of how the RFID system works is shown in Figure 2.1.
Although both RFID tags and barcodes carry information, there are many advantages in using RFID tags including the following:

- Do not require manual scanning
- Can be scanned more than one time
- High speed reading
- Withstand harsh environments
- Ability to add more information to a tag
- Can be read even if not in line of view to the reader

RFID tags can be active, passive, or semipassive depending on the way they transmit information. Active tags have a battery to power them, so they require a much lower signal sent by the reader to exchange information compared to passive tags. Passive tags are powered only by the electromagnetic radio waves sent by the reader. They are much cheaper and have infinite lives. Semipassive tags transmit the same way as passive tags, but use a battery to power the chip’s circuit. Active tags have longer read capabilities and higher data capacity, but shorter life because of the battery.
RFID tags can be read through most non-conductive materials, like, plastics, wood, cloth and cardboard, but not through metals, graphite, sodium, and liquids. Some RFID tags come pre-encoded with a serial number, whereas others can be rewritten as many times as needed using an RFID reader. RFID systems can operate in low-frequency range, high-frequency range, ultra-high-frequency range, or microwave frequency range, depending on the application they are being used for. UHF technology operates in the 860 – 960 MHz frequency range and is the most widely used technology in the supply chain and for tracking purposes. A comparison between different RFID systems is shown in Table 2.

UHF tags can be read at a distance of up to 7 meters. They come in a wide range of sizes and configurations. Some of these tags are shown in Figure 2. The first three of them are the tags used to evaluate the feasibility of tracking Portland cement concrete in chapter 4.

Table 2.1: Characteristics of RFID Systems (Schwartz, 2007)

<table>
<thead>
<tr>
<th>Type</th>
<th>Frequency</th>
<th>Pros/Cons</th>
<th>Read Range (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Passive</td>
</tr>
<tr>
<td>LF</td>
<td>125 KHz</td>
<td>Require less power, better penetration of non-metallic and/or high water content substances</td>
<td>1</td>
</tr>
<tr>
<td>HF</td>
<td>13.56 MHz</td>
<td>Work well on metal objects</td>
<td>3</td>
</tr>
<tr>
<td>UHF</td>
<td>860-960 MHz</td>
<td>Better range, faster data transfer. Use more power. More “directed,” require a clear path between tag and reader. Largest application area, widest installed base in industry.</td>
<td>10-20</td>
</tr>
<tr>
<td>MW</td>
<td>2.45 GHz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Another growing technology is the Radio Frequency Surface Acoustic Wave, RF SAW (RF SAW, 2010). This system not only can acquire a digital signature from the RFID tag but it can also receive the temperature of the medium where the tag is placed. The interdigital transducer converts the radio wave pulse sent by the reader into a nanoscale surface acoustic wave. After the wave travels through some wave reflectors, it returns to the chip (interdigital transducer), which returns a radio wave signal back to the reader using the piezoelectric effect (Figure 2.3).
2.1.2 RFID Tags Variability

In his master’s thesis in 2005, Ramakrishnan conducted a series of tests to determine the performance of passive UHF RFID tags. For all the readings, the tags were aligned with the transmit antenna because that setup gave the best performance. Figure 2.4 shows the response rate of a Class 1 RFID tag at different power levels, simulating various distances. The response rate is defined as the ratio between the number of times a tag is read to the number of times the reader attempts to read the tag. One million read attempts were performed for 200 different power levels. Based on how fast the tag would respond to the reader they were separated in two groups; Class 1 fast and Class 1 Slow. There are three main parts in this graph corresponding to a strong field, weaker field, and out of field. This shows that up to a certain distance the tag always reads, and the farther away it goes from the reader the response rate drops dramatically, until it goes to zero.
More tests were conducted to determine the performance variability between different tags of the same model. About 100 tags of the same model were tested to determine the response rate as a function of attenuation. Nine models were tested but only the low variance model, high variance model, and the typical variance model were reported. The response rate ranges from 0% for the worst performing tag to 100% for the best performing tag. For all three graphs in Figure 2.5, Figure 2.6, and Figure 2.7, the dark line in the middle shows the median. The darkest color region corresponds to 40% of the tags in each model. The next three colors show 70, 87, and 98% of the tags. The lightest color covers all of the tags tested for each model.
Figure 2.5: Tag Model with a Typical Variance of Performance (Ramakrishnan, 2005)

Figure 2.6: Tag Model with the Lowest Variance of Performance (Ramakrishnan, 2005)
In this section the variability in performance of various RFID tags from the same model is evaluated. Different models have different levels of variability in their performance. Although the tags used in this study are not the same as the ones used in this thesis, an idea of what variances could be expected in the field for both the PCC tracking and reflection crack detection is provided. Looking at the worst case scenario, the highest variance of performance case, about 6.5% of the tags are going to read about 5 feet less than the median tag.

2.1.3 Dielectric Constant

The dielectric constant is the most important property of a material when trying to read an RFID tag through it. The dielectric constant is the ability of a material to store a charge from an applied electromagnetic field. Permittivity is the response of a material to an electrical field. Materials with a high dielectric constant are more opaque to RF transmission.
Jaselskis et al. (2003), gives a theoretical background on the interaction of electromagnetic waves with matter and continues into describing the dielectric properties of asphalt concrete. The dielectric constant, also referred to as relative permittivity, $\varepsilon_r$, is defined as the ratio between the permittivity of the material to that of vacuum, $\varepsilon_0 = 8.85 \times 10^{-12} \text{ F/m}$. As shown in Equation 2.1, it is composed of a real part, the polarization of the medium and an imaginary part, which is the energy loss, the energy absorbed from the medium.

$$\varepsilon^*(\omega) = \varepsilon'(\omega) - i\varepsilon''(\omega) \quad \text{Equation 2.1}$$

Jaselskis et al. measured both the real and imaginary components of the permittivity for various asphalt concrete mixes. Only the results for the mix made using sand as the aggregate and 8.4% binder at three different densities are shown here. Figure 2.8 shows the permittivity of the sample at various frequencies. Because the UHF RFID tags are read at a frequency of about 1 GHz, the permittivity of the asphalt mix is between 4.5 and 5.5. From Figure 2.9 it can be seen that the loss at about 1 GHz is between 0.2 and 0.3. When looking at Figure 2.10 for the whole temperature range at 1 MHz the permittivity is within the range from Figure 2.8 and the loss is from 0.02 to 0.22.
Figure 2.8: Asphalt Concrete Relative Permittivity at Various Frequency Levels (Jaselskis et al., 2003)

Figure 2.9: Asphalt Concrete Loss at Various Frequency Levels (Jaselskis et al., 2003)
The dielectric constant of asphalt concrete was determined to be in between 4.5 and 5.5. It is not clear if this is a high enough dielectric constant to attenuate the signal and make it hard for the tags to communicate with the antenna. However, as it will be described later on this chapter, successful work done in tracking asphalt concrete has shown that the attenuation through asphalt does not stop the electromagnetic waves from reaching the tag and powering it. This infers that UHF waves can go through a material with a dielectric constant of about 5.

2.2 RFID Applications

2.2.1 Material Tracking

Currently, RFID tags are used in the construction industry to improve collection of information, which is currently based in paper documentation and barcode use. Jaselskis et al. (1995) proposed the use of RFID technology in the construction industry. The idea of possibly using RFID tags for processing, handling, and quality control of concrete is addressed. Incorporating the tags in the employees
work card, which would be scanned at the entrance gate, would create a list of all the employees present at work and show the time they arrived. Also, the RFID tags could be used for tracking delivery vehicles and the materials they are transporting.

A similar idea is discussed in the paper by Jaselskis and El-Misalami (2003), looking at the use of RFID for locating pipe spools and recording information about certification for mechanical machinery.

Akinci et al. (2002) shows theoretically how an RFID system could be used for tracking precast components in a storage yard. This idea is taken a step further in the paper by Ergen et al. (2007) were the idea of using such a system is evaluated in a storage yard for precast concrete. The RFID reader was mounted in the crane cabin and turned on whenever the crane was operating, recording information about each precast piece as it was moved by reading the tags mounted on the surface. This allows for less time consuming inventory, making it easier for a piece to be located in the storage yard.

Another paper by Wang (2007), introduces RFID for quality inspection and management of concrete specimens. Instead of attaching the tags in the surface of the concrete specimens, in this study the idea of inserting them in the specimens is evaluated. Passive tags seemed to work well to satisfy the objective of this paper as long as they were not more than 3 cm deep from the surface of the concrete specimens.

2.2.2 HMA Tracking

The work conducted by Schwartz and Khan (2009) as part of an FHWA Phase II project (Schwartz, 2008) concentrated on finding a system to correlate as-constructed material properties of asphalt concrete with the field performance of the
pavement by tracking where a sampled truckload is deposited in the roadway. This system was developed using RFID technology. RFID tags were used to identify trucks leaving the plant by throwing them into the asphalt mix in the truck. These tags later went through the paver and ended up compacted in the mat. To be able to withstand the harsh construction environment, including high temperatures and large stresses during compaction, these tags were encapsulated in CPVC pipes filled with high temperature epoxy. Figure 2.11 shows two encapsulated tags before being compacted in the mat. After being compacted in the pavement, these tags were read at highway speeds with a 60-80% success rate. An unexpected finding was that after paving, some RFID tags surfaced on the top of the mat (Figure 2.12). A conceivable consequence of this may be accelerated local pavement damage caused by water ingress, durability/raveling, etc. around the surfaced tag. Determining whether the surfaced tags have a detrimental effect on the pavement area surrounding them, a series of in situ permeability and nuclear density tests were conducted in chapter 3.

Figure 2.11: Encapsulated RFID Tags During Paving (Schwartz, 2008)
MINDS, a Canadian company has developed a system called eRoutes (MINDS, 2010). The PaveTag application of eRoutes can successfully track trucks leaving the asphalt plant via RFID tags. In conjunction with IDENTEC SOLUTIONS (IDENTEC SOLUTIONS, 2010), they use intelligent long range (ILR) active tags for this operation. These tags can be read at a distance of up to 300 feet. Trucks are detected when they enter and exit the asphalt plant using RFID readers placed at the entrance. RFID readers are mounted in the pavers as well to detect the arrival time of the trucks and which of them is unloading the material. The entire information is sent to the eRoutes servers. A Geographic Information System is used to accurately locate trucks, pavers, and length of road paved.
2.2.3 Wireless Sensor Interface

On a recent study by Pfeiffer (2010), radio frequency surface acoustic wave (RF SAW) technology is used to measure the temperature of asphalt concrete pavements. This was done in an effort to field calibrate existing theoretical cooling models for flexible pavement mats. Similar to the work by Schwartz and Khan (2009), the RF SAW tags used in this study were encapsulated using high temperature epoxy to endure compaction stresses. Knowing how the temperature drops will help pavement compaction operations by allowing them to know whether the HMA temperature is high enough for compaction to be completed. Better compaction would result in a higher HMA stiffness.

Use of RFID in Detecting Cracks

Morita and Noguchi (2006) proposed the use of RFID tags to detect structural cracks. Electrically conductive paint or a printed sheet is to be placed in the structure and connected to the tag using copper wire. When a crack initiates, the conductive paint breaks, resulting in an increase in resistance. The crack width can be predicted based on the reader-tag communication, as the electrical resistance changes with varying crack width. However, Morita and Noguchi did not pursue this application any further than the theoretical stage. Rather than using an RFID tag and reader, they measured the resistance of the electrically conductive paint strip directly as the crack was propagating in the structure.

Wood and Neikirk (2001) worked on developing a passive sensor to provide information about the condition of welded connections in steel structures after earthquakes. They acknowledge the possibility of using RFID technology for this application, however they do not pursue this idea and continue in evaluating the use of Electronic Article Surveillance Stickers instead.
Neither of these works applies to the crack sensor to be developed in this thesis. Neither Morita and Noguchi or Wood and Neikirk went further than introducing the idea that RFID technology could work in detecting cracks in concrete or steel structures. One of the great advantages in trying to detect reflection cracking in pavements is that we can narrow down where the crack is going to occur as opposed to fatigue cracking, which is not as predictable.

Work Currently Underway at FHWA

As part of a Federal Highway Administration project, Intelligent Automation Incorporated has conducted work on integrating the temperature, humidity, and chemical sensors from Advanced Design Consulting, Inc. with their strain gauges and Zigbee platform to ultimately have a multi-sensor wireless network for road and bridge structures applications.

Advanced Design Consulting, Inc. is currently working on another FHWA sponsored project. They are working on developing a moisture, temperature, stress, and strain sensor to be embedded in asphalt or concrete.

Direct Measurements Inc. has developed SR-2, a wire free-embedded sensor for measuring strains and structural defects. It can determine the onset of cracks and crack growth in stress concentration areas like holes or fasteners.

2.3 Reflection Crack Detection

2.3.1 Fracture Mechanics Theory

Paris’ Law (Paris and Erdogan, 1963) is the most widely used theoretical way of looking at asphalt concrete fracture. It relates the rate of crack growth to repeated loading cycles. This relationship is given in the following equation:

\[
\frac{dC}{dN} = A \cdot (\Delta K)^n
\]  

Equation 2.2
where,

\[ C = \text{crack length} \]
\[ N = \text{number of loading cycles} \]
\[ A, n = \text{fracture properties of HMA} \]
\[ \Delta K = \text{change in stress intensity factor during loading and unloading} \]

The stress intensity factor is a measure of the crack resistance of the material and it depends on the geometry of pavement structure, fracture mode, and crack length, making it very difficult to measure. For this reason using this theoretical approach to determine the initiation of reflection cracking in an HMA overlay is not practical and not very accurate.

### 2.3.2 Available Instrumentation for Pavements

There are a number of different instruments being used in pavements nowadays. The main ones are used for measuring stresses (pressure cells), strains (strain gauges), deflections (geophones, deflectometer), temperature (thermocouples), and moisture (nuclear dual tube) (Sebaaly, 1992).

Another non-destructive technique used in pavements is the ground penetration radar. It works by sending electromagnetic waves through a pavement and determining the speed of the reflected signal based on the time it takes for the reflected signal to return. The ground penetrating radar can be used to measure the dielectric constant of the pavement structure (Al-Qadi et al., 2001), the thickness of the different layers up to 2.5% error accuracy (Lahouar and Al-Qadi, 2008), to detect voids underneath the pavement, and high moisture levels. However, the GPR is not able to detect reflection cracks, because of their small size.
2.3.3 Evaluation of Crack Mouth Opening Displacement

Lee et al. (2007) conducted some tests to determine the optimum rubblized depth for preventing reflection cracking. The tests conducted in mode I, bending tests, used 300x200x50 mm asphalt specimens. The asphalt slabs were attached on top of 2 PCC slabs separated by 10 mm to simulate a joint opening or crack. The concrete slabs were supported on an engineered synthetic rubber pad 3 cm thick, attached as shown in Figure 2.13. A crack gauge was used to measure the horizontal deformation at mid-depth of the asphalt slab. The results of the horizontal deformation and vertical propagation of the crack as a function of loading cycles are shown in Figure 2.14 and Figure 2.15.

Figure 2.13: Mode I Test Configuration for an HMA Overlay on Top of a Jointed PCC Slab (Lee et al., 2007)
Figure 2.14: Mid-depth Horizontal Deformation of the Asphalt Slab  
(Lee et al., 2007)

Figure 2.15: Crack Propagation through the Asphalt Slab Depth  
(Lee et al., 2007)
From Figure 2.15, it can be observed that the crack had propagated about 60% of the 50 mm overlay at about 200,000 cycles. This coincides with a horizontal deformation of about 0.45 mm. This information gives a basis to continue the work on the development of the crack sensor. Knowing the crack mouth opening displacement for a given vertical propagation of the crack is a very important aspect to be used in the design.

2.3.4 Warranty in Construction

A report by Cui et al. (2008), gives an overview on the implementation of warranties on highway projects. In 1990, FHWA initiated the Special Experiment Project Number 14, encouraging State DOTs to implement contracting techniques that would lower overall project costs. By 2004, more than 30 states had used warranties in some of their projects. The use of warranties helps reduce life-cycle cost, improve quality, and encourage contractor innovation. The use of crack sensors will give the State DOTs the ability to detect reflection cracking early on and hold the contractor responsible for either repairing the damage if still under warranty or allowing the DOT more time to set aside sufficient funds to cover damages.

As HMA overlays are not a new construction and their usual warranty period is between 2-4 years, cracks might have started before and not yet become visible. Unless a method to detect these cracks before reaching the surface is implemented, the state agencies will have to contract someone else and use more funds towards the roadway maintenance.
2.4 Summary

A basic RFID system consists of an RFID tag, an antenna, a reader, and a host computer. Passive Ultra High Frequency technology is widely used in the supply chain and for tracking purposes, because it has a read range of up to 20 feet and fast data transfer.

The dielectric constant of asphalt concrete for a frequency of about 1 GHz is between 4.5 and 5.5. Successful work done by Schwartz and Khan (2009) in tracking asphalt concrete with passive UHF RFID tags from the plant to the highway where the tags end up embedded in the mat, shows that asphalt concrete with a dielectric constant of about 5 does not pose a significant barrier to the electromagnetic waves when using Ultra High Frequency technology.

The use of RFID in detecting cracks has been researched but has not been taken to a practical stage so far. Morita and Noguchi (2006) state that structural cracks can be detected using electrically conductive paint and RFID technology, and they would be detected because the change in electrical conductivity with crack growth would be picked up by the reader-tag communication. However, they do not actually use an RFID tag and reader to show that it can be done in practice.

Wood and Neikirk (2001) try to implement a passive system for determining the condition of welded connections. Although, they state that RFID technology could be used for this application, in their paper only Electronic Article Surveillance Stickers are used, not RFID tags.

The Paris’ Law (Paris and Erdogan, 1963) gives a theoretical way of looking at asphalt concrete fracture. However, because the stress intensity factor in Equation 2.2 is very difficult to determine through many tests in the laboratory, this theoretical approach is not practical in determining crack initiation.
There are many instrumentations available for use in pavements, however none of them can wirelessly and non-destructively determine the occurrence of cracks in HMA overlays. Even the ground penetrating radar, a non-destructive device can only determine large size anomalies underneath the pavement surface and cannot detect reflection cracks because of their small size.

Lee, et al. (2007) worked on determining the optimum rubblized depth to prevent reflection cracks. Tests were also run for a zero rubblized depth for comparison. From the results of these tests, the crack mouth opening displacement in a 2 inch thick asphalt beam is about 0.45 mm for a crack that has propagated to about 60% of the height of the beam. This is an important finding that will be used when designing the reflection crack sensor to fail at a certain strain or CMOD.
Chapter 3 Evaluation of Surfaced Tags

Introduction

During field trials in Phase II (Schwartz, 2008) for tracking HMA placement, a small number of the RFID tags rose to the surface of the compacted pavement. This raised a question whether this would compromise the durability of the pavement by increasing water infiltration or decreasing density locally.

Measurements of in-place permeability and density in the local area surrounding surfaced RFID tags were obtained to answer this question. The assumption in this investigation is that if the permeability and density of the pavement around the surfaced tags are similar to that in other areas it can be assumed that the surfaced tags will not compromise the integrity of the pavement. All of the density and permeability tests were conducted in the UMD Parking Lot EE, where multiple tags surfaced in the 2 inch thick lift of 12.5 mm surface mix (see Figure 3.1).

Figure 3.1: Location of Permeability and Density Tests at Parking Lot EE at UMD
3.1 Density Testing

3.1.1 Methodology

In-place density measurements were obtained using the Troxler Model 3440 nuclear density gauge shown in Figure 3.2. Dr. Nelson Gibson and Mr. Dennis Sixbey of the FHWA Turner-Fairbanks Highway Research Laboratory provided the nuclear density gauge and performed the readings at the UMD campus. Mr. Sixbey is a certified nuclear gauge technician as well as the Radiation Safety Officer at the Turner-Fairbanks Laboratory. Testing was conducted on July 29, 2009 under generally clear weather conditions.

All nuclear density measurements were conducted in the backscatter mode. It was not possible to calibrate the nuclear gauge because the mix properties were unknown. As a consequence, the absolute density measurements are not accurate. However, since the main focus of these tests is the relative density near the surfaced tag relative to the density at some distance away, an absolute density reading is not
necessary. Two readings were recorded on top of each tag and four additional readings were recorded at distances of approximately 5 inches, 9 inches, and 16 inches away from the tag (see pattern in Figure 3.3) for a total of 98 readings. Another 8 readings were taken at random locations remote from any of the tags. All density measurements were based on one-minute readings. Care was taken to ensure that no vehicles, people, or other potential sources of interference were near the nuclear gauge during the readings. Some of the readings may have suffered some indeterminable loss of accuracy when the roughness of the asphalt surface made it difficult to completely stabilize the device.

Figure 3.3: Location of Tests Relative to Tag
3.1.2 Density Results

Figure 3.4 through Figure 3.10 summarize the full set of density readings taken on top of and around each tag. These graphs also indicate which readings might be compromised because of irregularities in the pavement surface.

A linear regression analysis of density vs. distance from the surfaced tag was performed for each set of test results. The results are shown as the trend lines in Figure 3.4 through Figure 3.10. The regression line was fit to the entire density data at each distance. However, the slopes of density trends vs. distance are the key indicator of interest. The slopes ranged from a minimum of 0.03 for Tag 6 (i.e., essentially no variation of density with distance) to a maximum of 0.18 for Tag 3 (i.e., modest variation of density with distance).

There are two reasons to suspect that the measurements directly on top of the tags (i.e., radial distance=0) may be biased: (1) the tags themselves have lower density than the HMA, so even if the HMA were completely uniform surrounding the tag the measurements directly on the tag would indicate a lower density for the zone; and (2) the surface irregularities directly surrounding the tag made it more difficult to place the nuclear gauge in a stable configuration directly on top of the tags than in locations away from the tags. To investigate this potential bias, the regression analyses were re-run with the points at r=0 removed. The slopes for the trend lines with the r=0 data retained and with the r=0 data removed are compared in Table 3.1. It is clear that removing the data at r=0 significantly reduces the slope of the density vs. distance trend, with some tags now even showing a decrease in density with increasing distance (i.e., Tags 5 and 7). The average slope of the trend lines across all tags drops from 0.09 when the r=0 data are retained to 0.03 when the r=0 data are
removed. In either case, these small slope values suggest very little impact of the tags on in-place density.

As a further check, t- and F-tests were conducted to determine whether there were any statistically significant differences in density at different distances from the tags. These tests also called the Hypothesis Tests, compare the variances (F-test) and the means (t-test) for two groups of data.

Data for all tags were combined for the purposes of performing the t- and F-tests. In order to compensate for normal spatial variability of in-place density, the measured density at each location for a given tag was normalized by the average of all density readings for that tag. Any remaining spatial variability after this normalization can then be attributed to distance from the tag. The t- and F-tests were conducted in pairs of data sets: r=0 (i.e., on top of the tag) and r=5 inches; r=0 and r=9; r=0 and r=16; and r=16 inches and random far-field readings. The results of the t- and F-tests are shown in Table 3.2. The $t_{crit}$ and $F_{crit}$ values in the table are for a significance level $\alpha=0.01$. In all but one case, both the t- and F-statistics are smaller than the critical values, indicating that the differences in the means and variances respectively of the two data sets in each pair are not statistically significant. The only exception is the 0 vs. 5 inch pair, where the F-test is satisfied but the t value slightly exceeds $t_{crit}$. The overall conclusion is that there is very little statistical difference between the density measurements at the various locations from the tag.
Figure 3.4: Density as a Function of Radial Distance for Tag 1 (Slope=0.12)

Figure 3.5: Density as a Function of Radial Distance for Tag 2 (Slope=0.04)
Figure 3.6: Density as a Function of Radial Distance for Tag 3 (Slope=0.18)

Figure 3.7: Density as a Function of Radial Distance for Tag 4 (Slope=0.11)
Figure 3.8: Density as a Function of Radial Distance for Tag 5 (Slope=0.04)

Figure 3.9: Density as a Function of Radial Distance for Tag 6 (Slope=0.03)
Figure 3.10: Density as a Function of Radial Distance for Tag 7 (Slope=0.08)

Table 3.1: Slopes of In-Place Density vs. Distance Trend Lines with and without Data at r=0

<table>
<thead>
<tr>
<th>Tag</th>
<th>Slope with r=0 data points</th>
<th>Slope without r=0 data points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.12</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>3</td>
<td>0.18</td>
<td>0.15</td>
</tr>
<tr>
<td>4</td>
<td>0.11</td>
<td>0.10</td>
</tr>
<tr>
<td>5</td>
<td>0.04</td>
<td>-0.08</td>
</tr>
<tr>
<td>6</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>7</td>
<td>0.08</td>
<td>-0.08</td>
</tr>
<tr>
<td>Average</td>
<td><strong>0.09</strong></td>
<td><strong>0.03</strong></td>
</tr>
</tbody>
</table>

Table 3.2: The t- and F-Test Results for In-Place Density Tests

<table>
<thead>
<tr>
<th>Combination</th>
<th>t</th>
<th>t_{crit}</th>
<th>F</th>
<th>F_{crit}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 vs. 5 inches</td>
<td>2.833</td>
<td>2.704</td>
<td>1.265</td>
<td>4.06</td>
</tr>
<tr>
<td>0 vs 9 inches</td>
<td>1.741</td>
<td>2.704</td>
<td>1.538</td>
<td>4.06</td>
</tr>
<tr>
<td>0 vs. 16 inches</td>
<td>2.173</td>
<td>2.704</td>
<td>3.417</td>
<td>4.06</td>
</tr>
<tr>
<td>16 vs. far field</td>
<td>0.465</td>
<td>2.727</td>
<td>1.049</td>
<td>3.86</td>
</tr>
</tbody>
</table>
3.1.3 Conclusions Regarding In-Place Density

The linear regression analyses of density vs. distance at each tag produced very small slope and $R^2$ values in nearly all cases. These both imply little or no relationship between density and distance from the RFID tag. In other words, there do not appear to be any localized variations in in-place density caused by the RFID tags.

The t-tests of the pooled in-place density measurements for all distance combinations except the 0 vs. 5 inch case found that any differences in the means were not statistically significant. Even for the 0 vs. 5 inch case, the t-statistic exceeded the $t_{\text{crit}}$ value at the 0.01 significance level by only a very small margin. The F values were smaller than $F_{\text{crit}}$ for all distance combinations, indicating that any differences in variance are not statistically significant. As with the linear regression results, the t- and F-test results suggest that there are no localized variations in in-place density caused by the RFID tags.

3.2 Permeability Testing

3.2.1 Methodology

In-place permeability tests were conducted on each of the seven surfaced tags using an NCAT field permeameter. The device is centered over the tag and measures the permeability over a diameter of approximately 5.75 inches. Seven additional tests were conducted at random locations in the parking lot far from any tags.

The procedure used to conduct the in-situ permeability tests followed the test protocol developed by the National Center for Asphalt Technology (Cooley, 1999). As shown in Figure 3.11, the permeameter consists of 4 tiers of different diameter cylinders separated in two sections. The sealant used for these tests was plumbset
putty from LA-CO. A small 1 foot square area is identified and brushed clear of debris. A 2 to 3 mm thick layer of the moldable sealant is applied to the rubber gasket on the base plate of the permeameter. Next, a uniform half-inch thick layer of moldable sealant is applied approximately three inches around the outside diameter on the base plate. Some sealant was re-used in other tests after slicing off the top part contaminated by debris. The permeameter is carefully placed on the asphalt test area so that the rubber gasket surrounds the outside diameter of the base plate. Uniform foot pressure is then applied around the perimeter of the base to create a watertight seal with the asphalt.

![Image of permeameter setup](image)

**Figure 3.11: In-place Permeability Test Setup**

Many tests were redone due to concern that water observed outside the test area was a leak in the sealant rather than lateral drainage through the HMA. It was sometimes difficult to create a watertight seal as the pavement was uneven. In an effort to improve the seal, four 5-lb weights were distributed on the base plate to
compensate for the head pressure from the water column. Extra weight was exerted by placing 4 bricks on the base plate as shown in Figure 3.11.

A thin layer of sealant was used to connect the two sections of the permeameter. The filling tube assembly was inserted all the way to the bottom and water was added at a steady rate while minimizing bubbles. Water was added until it filled a tier that made it possible for accurate observation head drop. The time required for the water to drop a given distance in the selected tier was recorded.

Using the measured time and distance for the water drop, the coefficient of permeability was calculated using the falling head permeability equation:

\[
k = \frac{aL}{A t} \ln \left( \frac{h_1}{h_2} \right)
\]

in which:

- \(k\) = coefficient of permeability
- \(a\) = inside area of standpipe (depends on tier used for testing)
- \(L\) = thickness of asphalt mat
- \(A\) = area of permeameter base through which water can flow into the pavement
- \(h_1\) = initial head
- \(h_2\) = final head
- \(t\) = elapsed time between \(h_1\) and \(h_2\)

### 3.2.2 Permeability Results

Figure 3.12 summarizes the results of the 14 permeability tests, which consisted of seven tests on top of the surfaced RFID tags and seven random readings far from the tags. Only the reading on top of Tag 1 showed a more permeable surface compared to all the other readings. This could be caused by segregation, as larger size aggregates were observed on the surface at this location only. Excluding this tag, the
readings on top of the RFID tags ranged from $12.5 \times 10^{-5}$ cm/s to $105.6 \times 10^{-5}$ cm/s, which is very similar to the random far-field readings which ranged between $12.1 \times 10^{-5}$ cm/s and $93.4 \times 10^{-5}$ cm/s.

To see if there was any significant difference between the means and standard deviations of these two sets of data, t- and F-tests were conducted. The t-test gave a value of $t=0.00813$ with $t_{crit}=3.055$ at a significance level $\alpha=0.01$. The F-test gave a value of $F=6.87$ and $F_{crit}=8.89$. In both cases, the test statistics were less than the critical values, implying no statistically significant differences in the means and variances for the in-place permeability values on top of the RFID tags vs. values at random far-field locations.

![Figure 3.12: Coefficient of Permeability on Top of the Tags and at Random Locations](image-url)
3.2.3 Conclusions Regarding In-Place Permeability

Based on the very similar ranges in measured permeabilities and the results from the t- and F-tests, it is concluded that there is no detrimental effect of the surfaced RFID tags on in-place permeability for the HMA.

3.3 Overall Conclusions

The test results show that there are no practical or statistical impacts on in-place density or permeability from the surfaced RFID tags. Consequently, the tags should not be causes of local damage due to reduced stiffness/strength (correlated with density) or water inflows (related to permeability). Other than aesthetic concerns, the surfaced RFID tags do not appear to have a detrimental effect on asphalt pavements.
Chapter 4 Tracking PCC Placement

In order to ensure and ideally to improve the performance of concrete pavements, it is vital that the influence of material properties on performance be clearly understood. Correlations between as-constructed properties of Portland Cement Concrete (PCC) in construction databases and field performance of pavements in pavement management systems can quantify the link between material quality and performance.

PCC is produced at a production facility and then trucked to the highway construction site for offloading. PCC producers sample their production periodically from delivery trucks as they leave the plant to perform various quality control (QC) tests to ensure that the mixture properties remain within acceptable limits. Agencies typically take additional samples for quality acceptance (QA) testing to corroborate the producer’s QC test results and to establish pay factors.

Knowledge of where the sampled truckload of material is deposited along the roadway is critical when attempting to correlate as-constructed material properties with measured performance from a pavement management system, since pavement management data is typically referenced to a specific spatial location (milepoint, latitude/longitude). Unless the PCC QC/QA data can also be tied to a spatial location along the pavement, it cannot be correlated accurately with pavement management data.

Similar to the HMA tracking application considered by Schwartz and Khan (2009), sensors based on radio frequency identification (RFID) technology could be used to tag truckloads of PCC as they left the production plant. The sensors would be cast into the slab during the concrete paving operation. After construction, a vehicle-
mounted scanner is used to electronically “read” the identity tags to link them to the material properties measured from samples obtained from the truck that brought the concrete to that location. The data can then be directly linked to future pavement performance data in the agency’s pavement management system, enabling robust statistical analyses of the correlations between material properties and actual performance.

4.1 Concrete Cylinder Laboratory Evaluation

A preliminary laboratory evaluation of read range was conducted after embedding encapsulated tags in 4 inch diameter, 12 inch high concrete cylinders. Two type of tags including the Alien Gen 2 2”x2” and Alien Gen 2 1”x1” were embedded in the middle of the cylinders in the upward position. Two replicates of each tag type were embedded in a one tag per cylinder base. After the tags were embedded, read ranges were measured periodically as the cylinders were curing. All the readings in this section and the rest of this chapter were conducted using the Mercury 5 ThingMagic reader. No connection between the curing of the cylinders and the read range of the RFID tags was observed. To determine the orientation effect on the readings, the read range was recorded for the cylinders being in vertical and horizontal position. The results are shown in Table 4.1 and Table 4.2 for readings taken after 13 days of curing at 20 second intervals. The best read range results obtained when the RFID tags where in front of the transmit side of the antenna are given.
Table 4.1: Read Range for Vertically Positioned Cylinders

<table>
<thead>
<tr>
<th>Size</th>
<th>Maximum Distance</th>
<th>Number of Readings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x2</td>
<td>3 ft</td>
<td>12</td>
</tr>
<tr>
<td>2x2</td>
<td>4 ft</td>
<td>2</td>
</tr>
<tr>
<td>1x1</td>
<td>1 ft</td>
<td>5</td>
</tr>
<tr>
<td>1x1</td>
<td>1.5 ft</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 4.2: Read Range for Horizontally Positioned Cylinders

<table>
<thead>
<tr>
<th>Size</th>
<th>Maximum Distance</th>
<th>Number of Readings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x2</td>
<td>5 ft</td>
<td>26</td>
</tr>
<tr>
<td>2x2</td>
<td>1 ft</td>
<td>215</td>
</tr>
<tr>
<td>1x1</td>
<td>1 ft</td>
<td>5</td>
</tr>
<tr>
<td>1x1</td>
<td>0</td>
<td>0</td>
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</tbody>
</table>

Based on these results, it can be seen that the bigger format of the tags, the 2"x2" tags, have much longer read range through concrete compared to the 1"x1" tags. Also, orientation is a very important factor in the consistency of the readings. The read range for the second replicate of the 2"x2" tags in the horizontal position is only 1 foot. Because in the field the orientation of the tags is purely random, it should be anticipated that some of the tags could end up in the worst orientation and may not be read as it happened for one of the 1"x1" tags. However, overall these preliminary results show the potential of this application in PCC tracking.

4.2 Field Evaluation

The concept of PCC tracking was evaluated in the field in conjunction with the reconstruction of a section of the New York State Thruway I-90 outside Syracuse, NY. The Syracuse Project was located between exits 39 and 40 on I-90 as shown in Figure 4.1. Three different types of tags all encapsulated including Alien Gen 2
Higgs2 2”x2”, Alien Gen 2 1”x1”, and Gen 2 Titan tags were placed into four different trucks as they left the batch plant. A total of 80 tags were used in this project, with seven 2”x2”, seven 1”x1”, and six Titan tags in each truck.

4.2.1 Methodology

The Syracuse field trial was done in two steps. The first was the embedment of the RFID tags in the concrete pavement, which took place on October 8, 2009. Four sets of tags, each consisting of 3 different types of tag, were used for this project. The Alien Gen 2 Higgs2 2”x”2 and 1”x1” were pre-encapsulated in CPVC pipes with high temperature epoxy following the procedure explained in the work by Schwartz and Khan (2009). They were curled inside of the CPVC pipes in an effort to keep the final product in the size and shape of an aggregate, thus maintaining the strength of the concrete. The third type used was the Titan tags, which were already encapsulated by the manufacturer to endure high humidity and pressure.

The first three sets of tags, each including 7 Alien Gen 2 2”x2” tags, 7 Alien Gen 2 1”x1” tags, and 6 Gen 2 Titan tags, were thrown in three consecutive trucks as they were being loaded with concrete at the plant. These were the last trucks to unload before the bridge. After unloading, the tags in the concrete mix went through the slipform paver and were finished into the 13 inch slab. Some concern was raised whether the concrete unloaded from these three trucks would be cut and replaced with manually finished concrete next to the bridge, as bridge obstacles might interfere with the slipform paver’s progress. However, it was later confirmed that there was no slipform concrete removed from in front of the bridge. The fourth set of tags was thrown in the sixth truck after the bridge. The finished pavement with the tags embedded is shown in Figure 4.2.
The second step was to read the embedded tags after the concrete had cured for 24 days. Two antennas were connected to the reader and mounted in the outside of a cargo van at a height of approximately 6 inches from the pavement (Figure 4.3). The antennas consist of the receive side and the transmit side. Because as mentioned earlier the best readings were received when tags were in front of the transmit side of the antenna, in order to cover the pavement area where the tags were embedded in the most efficient way the antenna sequence across the width was T/Transmit-R/Receive-T/R. Overlapping passes at very low speeds were performed to cover the whole width of the pavement. The overlapping passes were repeated three times. Next, the pavement area was checked for tags by manually moving the antenna over the area of the pavement where the trucks carrying the tags were unloaded.
4.2.2 Field Test Results

None of the embedded tags were read in any of the passes. This was not unexpected for the Alien Gen 2 1”x1” tags because as shown in Table 4.1 and
Table 4.2 their read range was much lower than that of the Alien 2”x2” tags. However, the inability to read any of the Alien Gen 2 2”x2” or the Titan tags was a surprise. The Titan tags could be read up to 6 feet in air.

It is unlikely that the failure to read any tags was due to equipment malfunction. The reader was checked and worked in the laboratory the day before and after the test and it passed all diagnostics in the field on the day of the test. There is a remote but unlikely possibility that all of the tags ended up in the bottom of the 13 inch slab and could not be read because of severe attenuation.

The inability to read any of the tags in the field was particularly surprising because RFID tags have been used successfully in tracking precast concrete. Trackcon, a division of International Coding Technologies, uses passive UHF tags to track precast concrete components. The tags are UPM Raflatac, Dogbone tags incorporating the Monza 3 chip, which is the newest chip from Impinj, Inc. They are molded into the surface of precast concrete components. Trackcon has also tried to embed them in concrete and according to Tom Tilson, CEO of International Coding Technologies, the tags can be read through 6 inches of concrete and sporadically even through 12 inches of concrete. For these tags to be read the reader (9090 Motorola handheld reader) has to be no further than 3 or 4 inches away.

Another commercial system using RFID in precast concrete manufacturing is the Falken Secure Networks. They confirm reading through precast concrete of thicknesses of 6-8 inches using the latest generation tags such as Alien Higgs3 or UPM Raflatac Dogbone Monza 3 with the 9090 Motorola handheld reader.

There are two possible reasons to why these two companies were able to read tags through concrete:
• The tags used have the newest chip available like Monza 3 and Higgs-3
• The tags are encapsulated flat instead of curled like the ones used for PCC tracking in this thesis

Even though ICT was able to read some tags through concrete, they are not pursuing the idea of inserting passive tags in concrete, because they determined that the read ranges and read success are not good enough to pursue this application. ICT continues to place RFID tags only on the surface of precast components. Based on the new insights, a laboratory evaluation took place to determine the reason why these tags read through HMA but not through PCC.

### 4.3 Laboratory Evaluation

To simulate the field conditions in the lab, encapsulated RFID tags were embedded in a concrete block. Only the Alien Gen 2 2”x2” tags were used for the laboratory evaluation as they had the best read range in air. An 8 cubic foot wooden box was built for the laboratory evaluation.

Because the coarse aggregate is the largest component of concrete and often has a high dielectric constant, 12 tags were first placed in known positions inside the box as the box was filled with coarse aggregate. The coarse aggregate was limestone from Millville quarry with an estimated dielectric constant of 7 (dry) or 8 (wet) (Ho and Li, 2003). The RFID tags were placed in three layers as shown in Figure 4.4, Figure 4.5, and Figure 4.6. The box was then read with the antenna positioned at the mid-height of the box at a distance of 1 and 2 feet away from the box. The antenna was positioned horizontally with the transmitter on the right side. Readings were taken for the middle of the antenna being located 24 inches on the left of the box to 24
inches in the right of the box in 4 inch intervals for all four sides. All the read ranges were conducted in the laboratory, so there was the inevitable random interference due to metal objects.

Because the box is symmetric the readings on each side should have theoretically been identical. However, due to interferences and possible inconsistencies when placing the tags in the box filled with aggregate there was slight variations in reading from one side to the other with a maximum difference of three tags at a particular offset.

The number of tags read at each offset averaged for each side is shown in Figure 4.8. It can be seen that the number of tags read is skewed with more tags being read in the left side of the box corresponding to the negative values for distance. From previous read ranges it was determined that the RFID tags read the best if they are closer or in front of the T (transmit) side of the antenna. Because the T side of the antenna was on the right, the more it was offset in the right side, the further away the T side was from the tags, which explains the skewed readings.

Another important fact is that although the antenna is placed only 1 or 2 feet away from the box, that is not the actual antenna to tag distance. For both cases there were tags being read through an extra 4 to 20 inches of coarse aggregate based on their position inside the box.

The maximum distance any of the tags read was generally on the order of 6 feet.
Figure 4.4: Tags Located 8 Inches from the Bottom and 4 Inches from the Sides

Figure 4.5: Located 12 Inches from the Bottom and 12 Inches from the Sides
Figure 4.6: Tags Located 8 Inches from the Top and 8 Inches from the Sides

Figure 4.7: Box Filled with Aggregate and 12 RFID Tags
Next, the same tags were placed in the same locations as in the aggregate tests as the box was filled with concrete. None of the tags could be read after encapsulation in concrete, even after the concrete had been curing for one month. To check the survivability of the tags, they were extracted from the concrete block during demolition. The tags could be read after extraction, so survivability was not an issue.

Additional tests were performed in an effort to determine the reason why these passive RFID tags could not be read through concrete. Since the tags read through the coarse aggregate, the next logical step was to determine if the moisture present in the concrete attenuated the electromagnetic waves enough so that the chip could not be activated. The dielectric constant of water is about 80, which makes it one of the most difficult mediums for the RF waves to penetrate.

A 32-gallon bucket was filled with sand at about 9.5% water content, which was similar to the water content for the concrete mixture. Sixteen tags were embedded at various depths in the sand at a maximum of seven inches deep from the sides of the bucket. All of these tags were read successfully from at least two feet away. This
finding shows that moisture by itself was not the reason why there were no readings through concrete.

As a final test, 6 tags were embedded at three different depths in a 5-gallon bucket of cement paste prepared at a water to cement ratio of 0.4. The tags closest to the surface were embedded only to about 3.5 to 4 inches. None of these tags could be read even after 12 days of hydration. These findings clearly indicated that the cement paste was the reason for the unsuccessful readings through concrete.

**The Dielectric Constant of Cement Paste**

Using mixture theory the dielectric constant of concrete is approximately 11, which by itself would not account for the poor read performance. Therefore, in an effort to try to determine the reasons why the RFID tags did not give readings through the cement paste and ultimately through the concrete block, a thorough literature review was performed on the dielectric constant of cement.

Zhang *et al.* (1996) used a microwave technique to determine the dielectric constant of cement pastes with different water to cement ratios at frequencies between 8.2-12.4 GHz for up to 30 hours of hydration. The w/c ratio of 0.4 is the closest to the one used in the present study. Because attempts to read the tags embedded in the concrete block were made even one month of hydration—i.e., after most of the water was hydrated—the dielectric constant of interest from Zhang *et al.*’s study is the latest one after 30 hours of hydration. As can be seen in Figure 4.9, the dielectric constant of the cement paste was about 20 at 8.5 GHz, which is the closest frequency to the 915 MHz UHF frequency used in the present study. Other results by Zhang *et al.* show that the dielectric constant increases as frequency decreases, which means that the dielectric constant will be greater than 20 for frequencies close to 1 GHz.
Wen and Chang (2001) examined the dielectric constant of cement pastes with different admixtures. Table 4.3 summarizes their key results. The first row gives the dielectric constant of Portland cement mixed only with water, which is the value of interest for the present study. At 1 MHz, this value is $23.7 \pm 2.8$. For frequencies of about 1 GHz, the dielectric constant would be slightly lower, approaching perhaps 20.

From these two papers, it is seen that the dielectric constant of cement is much higher than that of the coarse aggregate and coarse aggregate and water as estimated using mixture theory. Although the coarse aggregate is the main component of concrete, the cement paste covers all of the aggregate. The electromagnetic waves coming from the antenna have to first go through the cement paste, which would strongly attenuate the signal due to its high dielectric constant. After that, the EM waves still have to go through more attenuation from the aggregate, making it hard for the signal to reach the RFID tags and power the chip.
Figure 4.9: Dielectric Constant of OPC with w/c=0.4 at 8.5, 9.5, and 12 GHz (Zhang et al., 1996)

Table 4.3: Dielectric Constant for Various Cement Pastes (Wen and Chung, 2001)

<table>
<thead>
<tr>
<th>Paste no.</th>
<th>Fiber type</th>
<th>% by mass of cement</th>
<th>vol.%</th>
<th>Admixture</th>
<th>Relative dielectric constant @ 10 kHz</th>
<th>100 kHz</th>
<th>1 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i)</td>
<td>–</td>
<td>0</td>
<td>0</td>
<td>–</td>
<td>28.6±3.4</td>
<td>24.8±3.6</td>
<td>23.7±2.8</td>
</tr>
<tr>
<td>(ii)</td>
<td>–</td>
<td>0</td>
<td>0</td>
<td>SF</td>
<td>20.8±3.4</td>
<td>19.6±3.2</td>
<td>16.5±0.8</td>
</tr>
<tr>
<td>(iii)</td>
<td>–</td>
<td>0</td>
<td>0</td>
<td>L</td>
<td>34.9±4.5</td>
<td>31.5±2.9</td>
<td>24.3±2.9</td>
</tr>
<tr>
<td>(iv)</td>
<td>Carbon</td>
<td>0.5</td>
<td>0.48</td>
<td>SF</td>
<td>53.7±7.0</td>
<td>38.3±4.8</td>
<td>28.1±2.9</td>
</tr>
<tr>
<td>(v)</td>
<td>Carbon</td>
<td>0.5</td>
<td>0.41</td>
<td>L</td>
<td>63.2±5.2</td>
<td>40.4±5.9</td>
<td>33.2±6.8</td>
</tr>
<tr>
<td>(vi)</td>
<td>Carbon</td>
<td>1.0</td>
<td>0.95</td>
<td>SF</td>
<td>48.7±4.8</td>
<td>29.6±5.0</td>
<td>25.9±5.0</td>
</tr>
<tr>
<td>(vii)</td>
<td>Steel</td>
<td>0.5</td>
<td>0.10</td>
<td>–</td>
<td>19.6±4.8</td>
<td>19.0±1.0</td>
<td>13.7±2.4</td>
</tr>
</tbody>
</table>

SF: silica fume, L: latex.

4.4 Conclusions

Through the preliminary laboratory evaluation of the concrete cylinders it was determined that Alien Gen 2 2”x2” tags can read through about 2 inches of concrete at
a distance of up to 5 feet. Although, this suggests a potential positive outcome on the PCC tracking, negative results were obtained during the Syracuse project field trials. None of the encapsulated RFID tags which were embedded in the concrete pavement were read even after 24 days of concrete curing.

In an effort to determine the reason of such results an extensive laboratory evaluation took place. Twelve encapsulated RFID tags were embedded in three layers of an eight cubic foot box filled with coarse aggregate and they were all read when the antenna was moved around all sides of the box. This concluded that although the coarse aggregate is the main component of concrete, it is not the reason why the tags do not give a signal through concrete.

Next, the same configuration as for the aggregate box was applied to the box filled with concrete. In this case even after one month of curing none of the tags read, although four of them were only four inches deep from one of the sides.

The next test consisted of inserting sixteen tags in a bucket filled with sand and water. All of the tags read from at least two feet away. As a final test, six RFID tags were embedded at different depths in a 5-gallon bucket of cement paste. None of the tags read even after 12 days of hydration. This determines that the cement paste, which has a dielectric constant of about 20, is the main factor in attenuating the electromagnetic waves coming from the antenna.

On the light of these results, it can be said that passive RFID tags although successful in tracking HMA are not suitable for tracking Portland cement concrete. Active tags could possibly work for this application, however because they are needed in large quantities, their high price makes them unsuitable for the PCC tracking application.
Chapter 5 Reflection Crack Detection Sensor

Reflection cracking is one of the most common distresses in an HMA overlay on top of a PCC slab. These cracks start at the joints in the bottom of the HMA layer and continue their way to the top. It would be highly beneficial for state DOTs to develop a sensor that would detect such cracks before they reach the surface. This would ensure the contractor is kept responsible provided these cracks start during the warranty period or at least would warn the state agencies about problems in the future.

This chapter focuses on developing an RFID-based wireless sensor to detect reflection cracking before it propagates to the surface. One of the biggest challenges in developing a crack sensor was configuring the tag so the circuit would be broken and the tag would stop reading when a crack had initiated. Two possibilities where explored, a conductive paint that would crack at a certain strain, and an overlapped copper antenna that would disconnect for a certain crack mouth opening displacement.

Another important factor in developing this sensor was the read range. In the field the sensor would have to be read through 2 inches of an asphalt overlay from at least 1-2 feet of air. Also, the sensor must not read from that same distance once the crack has formed and the sensor is disabled.

Finally, the sensor must be able to survive the paving operations. The easiest and most cost effective way to achieve this was to encase the tag in a Lexan polycarbonate sheet.
5.1 Design Concept

The concept for early detection of reflection cracks is to adapt an RFID tag to “fail” in the sense that it can no longer be read once a significant crack initiates. To achieve this, a short section of the antenna link is replaced with a conductive but frangible link. The modified RFID tag is placed above a joint in an existing PCC pavement layer before paving the HMA overlay. When the frangible antenna link fails at a prescribed strain level, the RFID tag stops working, indicating the initiation of a reflection crack. RFID tags could be placed in pairs at the bottom of the HMA overlay, one crossing the joint in the underlying PCC slab and one parallel and slightly away from the joint. Failure of the tag crossing the joint while the companion tag remains readable would be a clear indicator of early reflection crack formation.

The RFID tags used for this project are the Avery Dennison AD-223 shown in Figure 5.1. These are ultra high frequency (UHF) Gen 2 tags with the Monza 3 chip, the newest chip developed from Impinj. The chip is cut from the tag, leaving about 2 mm of the original antenna as shown in Figure 5.2. The modified antenna is then connected to the 2 mm of the existing antenna. The reader used for all of the tests in this chapter is the Mercury 5 Thingmagic reader.

Figure 5.1: RFID Tag AD-223
5.2 Antenna Investigations

5.2.1 Antenna Theory

Reactance is a measure of the effect of capacitance and inductance on a time varying current. The reactance of a very thin dipole antenna as a function of its length is given in Figure 5.3. It can be seen that a half-wave dipole has a reactance of zero. A shorter than half-wave antenna has a capacitive reactance and a longer one has inductive reactance. In this chapter all the read range tests have been conducted for a half-wave dipole and shorter.

When shortening the tag from the half-wave dipole, capacitive reactance is introduced, which would cause the tag to start losing its best performance. This is caused because part of the signal is “wasted” as some electromagnetic energy is stored in the reactive capacitance. The resistor dissipates power that is applied to the circuit. Also, another way the circuit loses power is by radiating it. For the tag to perform the best, most of the power would have to be lost due to radiation. This occurs when the radiation resistance is equal to the internal resistance.

However, in the case of developing a crack sensor, it could be that the best performing tag does not fit the application well, because as mentioned earlier, the tag once disconnected should not give a signal at large distances.
5.2.2 Frangible Antenna Link

Two ways of modifying an existing RFID tag to include a frangible antenna link are described. The first one is based on electrically conductive paint that would break at a critical strain. The second uses slightly overlapped metal strips to form a microswitch in the antenna that opens—i.e., breaks the antenna connection—at a critical crack mouth opening displacement (CMOD). For either case the modified RFID tag is required to work/give a readable signal from a given distance before a crack has initiated and give no readable signal from the same distance after a crack has initiated but not yet appeared on the surface of the pavement. Another consideration of this section is to determine the type of antenna to be used and the way to create a frangible link that will fail once there is a crack in the pavement.
5.2.2.1 Conductive Paints

A conductive paint was thought to be the best choice for the frangible link, in large part because of the ease and flexibility of its application. Three possible antenna configurations were evaluated in this section: a loop antenna, a dipole antenna, and a C-shaped antenna.

Read Range

As a first attempt, Aquadag E, a conductive carbon paint from M.E. Taylor Engineering, Inc., was used to paint a 5 mm wide loop antennae connected to the RFID chip from the Avery Dennison tags. Small dabs of a thicker silver conductive paint were use to create better connections between the Aquadag E paint and the chip. Three tags were made with loop antennae of one wavelength, two wavelengths, and three wavelengths as shown in Figure 5.4 through Figure 5.6. The loop antennas were 5 mm wide and 32.8 cm, 65.6 cm, and 98.4 cm in total length based on the
calculation shown below:

\[
\lambda = \frac{c}{\nu} = \frac{3 \cdot 10^8 \text{m}}{915 \cdot 10^6 \text{Hz}} = 0.328 \text{m}
\]

Equation 5.1

where,

\(\lambda = \text{wavelength}\)
\(c = \text{speed of light} = 3 \times 10^8 \text{ m/sec}\)
\(\nu = \text{frequency} = 915 \text{ MHz for UHF tags}\)

The maximum read distance was evaluated for all tags, with results shown in Table 5.1. All the readings were taken in 20 second intervals on the T (transmit) side of the antenna.
Figure 5.4: One Wavelength Loop Antenna

Figure 5.5: Two Wavelengths Loop Antenna
Table 5.1: Read Range for the Carbon Paint Loop Antenna Tags

<table>
<thead>
<tr>
<th>Number of Wavelengths</th>
<th>Maximum Read Distance (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>44.45</td>
</tr>
</tbody>
</table>

The maximum read range for the loop antennae was 50 cm, which might not be sufficient to give a signal in the field when the tag is placed at the bottom of the HMA overlay. In an effort to extend the read range, the loop antennae were replaced with dipole antennae. Typically, dipole antennae are created by two quarter wavelength conductors next to each other; this was done using the conductive paint. As with the loop antennae, silver paint was used to create better connections between the Aquadag E paint and the chip. Figure 5.7 illustrates one of the fabricated dipole antennae and RFID chip. The maximum read distance for the dipole tag was approximately 120 cm.

The read performance of the half wavelength dipole tag was evaluated as one of the antenna legs was shortened to simulate breakage by a reflection crack. A series
of 5mm cuts were made on one side of the dipole antenna and the effect on maximum read range was evaluated. The results are shown in Table 5.2. It can be seen that the maximum read distance starts dropping significantly after the antenna is shortened to about half of its original length. If the antenna is cut at about 1 cm away from the chip, the tag cannot be read a distance beyond around 40 cm. This would imply that if the antenna is kept at a distance of 50 cm away from the embedded tag, the reader would be able to detect that the antenna had broken as a result of reflection cracking. A second dipole tag fabricated and tested in the same manner showed very consistent results.

Figure 5.7: Dipole Carbon Paint Antenna
Table 5.2: Read Range for the Carbon Dipole Tag with One Side Shortened

<table>
<thead>
<tr>
<th>Antenna Length (cm)</th>
<th>Maximum Read Distance (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.2</td>
<td>122</td>
</tr>
<tr>
<td>7.7</td>
<td>122</td>
</tr>
<tr>
<td>7.2</td>
<td>122</td>
</tr>
<tr>
<td>6.7</td>
<td>122</td>
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<td>64</td>
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<tr>
<td>0.7</td>
<td>38</td>
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<tr>
<td>0.2</td>
<td>20</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Close examination of the read ranges for the modified tag after cutting one side of the antenna (Table 5.2) shows that the read range did not drop as precipitously as expected as the antenna length was shortened. Even when there was only about 2 cm left on one side of the tag, it could still be read from about 60 to 80 cm. The smaller the read range after the antenna is broken, the easier it will be to detect if a crack has initiated. For this reason, additional tests were conducted in which one side of the dipole antenna was already snipped at 2 cm as shown in Figure 5.8. Read range was then measured as the other side of the antenna was progressively shortened. The antenna for these tests was made out of silver conductive paint from Engineered Conductive Materials. The reason the tests were not continued with the carbon paint is because when one side of the antenna is only about 2 cm, in the half wavelength carbon dipole, the maximum read distance is approximately 70 cm. This particular
silver paint was used because it was thought that it would give better read ranges, as it is usually used in RFID applications.

The results from these tests are summarized in Table 5.3. These results show that it would be best to have both sides of the antenna break at a distance of 2 cm or less from the chip. Before failure, this tag could be detectable at a read range of about 127 cm. Another similar test with the same silver paint was conducted for another possible configuration, a C-shaped antenna instead of a straight dipole as shown in Figure 5.9. The maximum read range for this tag with no cuts to the antenna was about 2.5 meters. When one side of the antenna was trimmed to within 6 mm of the chip, the read range for the tag dropped to only 1.5 feet. When both sides of the antenna were trimmed to within 6 mm of the chip, the tag could not be read at any distance. The motivation for the C-shaped configuration was that the antenna would break simultaneously on both sides, which would give a much lower read range once the crack has initiated than if it broke only on one side. However, the C-shaped antenna also keeps the size of the tag very small, raising the concern that it cannot cover the entire area where a reflective crack might occur. This does not make it a good candidate for the crack sensor application.
Figure 5.8: Silver Dipole Antenna with One Side Snipped at 2 cm

Table 5.3: Read Range for the Silver Dipole Antenna with One Side Fixed at 2 cm Length while the Other Side is Progressively Shortened

<table>
<thead>
<tr>
<th>Left Side Antenna Length (cm)</th>
<th>Maximum Read Distance (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.2</td>
<td>127</td>
</tr>
<tr>
<td>7.7</td>
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<tr>
<td>7.2</td>
<td>116</td>
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</tbody>
</table>
The high conductivity of the silver paint allows evaluation of antenna effects for the “best case”—i.e., longest read range—conditions. However, as will be shown in a later section, the carbon paint was the only coating that broke anywhere near the target strain level and as a consequence it is the coating that must ultimately be used to modify the RFID tag. For this reason, more modified tags having carbon paint dipole antennae were constructed and tested. As expected, the read ranges of the tags with the carbon paint were not as long as for the silver dipole antennae because of the lower conductivity of the carbon compared to the silver. The maximum read range of the tags with the carbon dipole antennae in these new tests was only about 50 cm as compared to about 120 cm for the silver. Although in earlier tests (Table 5.2) the carbon paint dipole also read up to 120 cm, because of variations from tag to tag it would be more cautious to base the decisions on the worst results. To capitalize on the properties of both materials, tags having hybrid dipole antennae combining both silver and carbon paint were fabricated. The 2 cm of the antenna closest to the RFID chip was painted with carbon and the rest of the dipole length was painted with silver.
paint, as shown in Figure 5.10. It was expected that this tag would have a maximum read range close to that of the pure silver dipole while at the same time having a link at the critical location close to the chip that would fail at the target strain level. Read range test results for this hybrid silver and carbon dipole antenna tag are shown in Table 5.4. The maximum read range before trimming the antenna length was 180 cm, comparable to the pure silver dipole antenna. The read range of the tag dropped by approximately 40% to 1 meter or less as the remaining dipole leg is shortened to 2 cm.

Figure 5.10: Silver and Carbon Dipole Antenna
Table 5.4: Read Range for the Silver and Carbon Dipole Antenna as one Side is Shortened

<table>
<thead>
<tr>
<th>Antenna Length (cm)</th>
<th>Maximum Read Distance (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.2</td>
<td>175</td>
</tr>
<tr>
<td>7.7</td>
<td>175</td>
</tr>
<tr>
<td>7.2</td>
<td>175</td>
</tr>
<tr>
<td>6.7</td>
<td>175</td>
</tr>
<tr>
<td>6.2</td>
<td>163</td>
</tr>
<tr>
<td>5.7</td>
<td>135</td>
</tr>
<tr>
<td>5.2</td>
<td>135</td>
</tr>
<tr>
<td>4.7</td>
<td>127</td>
</tr>
<tr>
<td>4.2</td>
<td>122</td>
</tr>
<tr>
<td>3.7</td>
<td>122</td>
</tr>
<tr>
<td>3.2</td>
<td>122</td>
</tr>
<tr>
<td>2.7</td>
<td>122</td>
</tr>
<tr>
<td>2.2</td>
<td>119</td>
</tr>
<tr>
<td>1.7</td>
<td>89</td>
</tr>
<tr>
<td>1.2</td>
<td>84</td>
</tr>
<tr>
<td>0.7</td>
<td>64</td>
</tr>
<tr>
<td>0.2</td>
<td>39</td>
</tr>
<tr>
<td>0</td>
<td>13</td>
</tr>
</tbody>
</table>

The conclusion from these read range tests is that the dipole configuration is best for the crack sensor. Also, because of its higher initial read range before breakage and low read distance after the carbon paint is broken, the hybrid dipole antenna provides the best design for the reflection crack sensor.

**Fracture Strains**

Initially the targeted critical strain at which the conductive paint was to break at was estimated to be around 1000µε based on elastic strain distributions at the bottom of an asphalt layer. Consequently, tests were conducted to find a conductive paint that breaks around that strain level. Two carbon conductive paints, two conductive silver paints, and one conductive silver epoxy were tested in the lab to
Table 5.5: Description of the Conductive Paints Tested to Determine their Failure Strains

<table>
<thead>
<tr>
<th>Name</th>
<th>Composition</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquadag E</td>
<td>Water based colloidal graphite</td>
<td>M.E. Taylor Engineering, Inc.</td>
</tr>
<tr>
<td>Conductive Shielding Paint</td>
<td>Carbon paint</td>
<td>Stewart-MacDonald</td>
</tr>
<tr>
<td>Conductive Silver Paint</td>
<td>18% silver</td>
<td>M.E. Taylor Engineering, Inc.</td>
</tr>
<tr>
<td>Conductive Silver Pen</td>
<td>45-50% silver</td>
<td>M.E. Taylor Engineering, Inc.</td>
</tr>
<tr>
<td>Conductive Silver Epoxy</td>
<td>Two part electrically conductive silver epoxy</td>
<td>M.E. Taylor Engineering, Inc.</td>
</tr>
</tbody>
</table>

Determine the strain at which they would break. More details about these paints are given in Table 5.5. They were strained in a four point bending test using an Instron Model 1331 compression machine. A strip of each of the paints was painted on a plastic film. The film with the paint was then glued to the bottom of the beam to be bent using SG496, a methyl-based cyanoacrylate, 1-part glue commonly used for strain gages purchased from Omega Engineering Inc. A beam was fabricated from 7075-T6 aluminum, a material that remains in the elastic region at strains up to 4600µε. The calculated beam dimensions to reach the target strain of 1000µε under reasonable applied load levels are shown in Figure 5.11. An ohmmeter was used to measure the resistance in the painted strip of conductive paint to check for breakage. The complete test setup is shown in Figure 5.12. Although the required critical strain was 1000µε, the tests were run to the elastic limit of 4600µε. Unfortunately, none of the cured conductive paints broke at this strain level.
Figure 5.11: Beam Dimensions for the Four Point Bending Test

Figure 5.12: Thin Film Test Setup
As a next step, another set of tests were developed to localize the strains similar to what occurs across the mouth of a fracture. Two plexiglass sheets were attached along the bottom of the beam; the sheets just touched each other, simulating the joints in the PCC slab in a pavement. This test setup is shown in Figure 5.13 and Figure 5.14. Thin strips of the conductive paints were then painted across the simulated joint. The 18% silver conductive paint did not break. The carbon Aquadag E conductive paint broke at about 300 microstrains. Because the Aquadag E paint actually broke, albeit at strain levels below the target, it was selected for the tag antenna studies described in the previous section.

Figure 5.13: Painted Aquadag E on the Two Abutting Plexiglass Sheets
Based on the read range tests from the previous sections, it was determined that the antenna needs to break at a short distance close to the chip for the read distance to shorten significantly. In the plexiglass plate setup the antenna would fail wherever needed because of the “pre-cracked” plexiglass plates. However, painting on top of the plexiglass plates would imply that you need to paint directly on the top of PCC slabs or underside the overlay, which is not possible. A carrier for the paint would be needed that will force the maximum strains to occur right next to the chip. For these reasons a new test configuration was developed. A 10 x 23 cm Lexan polycarbonate sheet was fabricated with a 9 cm diameter hole in its center to act as a stress/strain raiser. The 9 cm diameter hole in the 10 cm wide Lexan sheet causes the elastic stresses and strains to increase by a factor of 10 in the ligaments at the edges of
the hole. The plate length was chosen as 23 cm so that the Lexan sheet would fit between the middle rollers where the bending strain is constant in the four point aluminum beam loading system. A continuous 5 mm strip of Aquadag E was painted along one edge of the plate (including over the ligament on one side of the hole) and a dipole tag with a 5 mm wide antenna strip of Aquadag E was painted along the other, as shown in Figure 5.15. The test setup is shown in Figure 5.16. The dipole tag was painted so that the chip was slightly offset from the highest strain location in the ligament at the edge of the hole in order to break the antenna close to the chip. Two ohmmeters were used to monitor the conductivity in the painted strips to determine breakage. The antenna of the dipole tag broke about 5 mm away from the thinnest part of the ligament at a strain of about 12000µε (after adjustment for strain magnification effects). The antenna broke very close to the chip as expected, after which the tag could not read at long range. The continuous strip of paint on the other side of the plate did not break during the test.
Figure 5.15: Painted Dipole Tag on One Side and Painted Aquadag E Only on Other Side of Lexan Polycarbonate Sheet

Figure 5.16: Lexan Polycarbonate Sheet Test Setup
Based on insights from an additional literature search on measurement of crack mouth opening displacement (CMOD), it is a reasonable ballpark assumption that a reflection crack will have initiated and grown partially (but not completely) through an overlay at a CMOD on the order of 1 mm. A CMOD of 1 mm over a gauge length of 10 cm corresponds to a strain of $10000\mu\varepsilon$. These strain levels cannot be achieved with the bending beam apparatus except when using the Lexan sheet with the hole for concentrating and magnifying the stress and strain levels. However, this apparatus is problematic in practice because of difficulties in getting an appropriate attachment at the bottom of the aluminum beam. For these reasons, a set of direct tension tests to determine the failure strains of the paints was conducted. Direct tension dogbone specimens were fabricated out of Lexan with dimensions as shown in Figure 5.17. Two tests can be conducted simultaneously on the same specimen by coating each side of the specimen. The test setup is shown in Figure 5.18 and Figure 5.19. The tests were run in displacement control mode at a rate of 0.005 inches per minute. Adhesion problems between the paint and the Lexan were observed in some of the previous bending tests; the paint in some occasions would just fall off the Lexan sheet. To remedy this, the Aquadag E carbon conductive paint was painted on a strip of watercolor art paper that had been glued to the Lexan specimen using strain gauge adhesive. The strips of paint were 5 mm wide. Figure 5.20 shows a typical strip of conductive paint on the Lexan specimen with wires connected to the ohmmeters.
The test was continued to a strain of 26000µε, well above the strain at which reflection cracks would initiate in an HMA overlay. The carbon paint did not break.
There was some concern that the watercolor paper might be creeping and that therefore the carbon paint was not experiencing the true applied strains. To account for this, the test was repeated with two strips of carbon paint applied directly on the Lexan specimen after its surface had been roughed with extra-fine sand paper to enhance adhesion. The painted strips were 5 mm wide, similar to the first test. This test was continued to a strain of 25000µε and the carbon paint still did not break, although some small cracks were visible.

One last tension test was conducted for the Aquadag E carbon paint and the 18% silver conductive paint. The width of the painted strips narrowed to 2 mm for this test on the assumption that a crack would propagate easier over the narrower width. The test was run to 30000µε without any breakage/conductivity fault in either the carbon or the silver paint.

The overall conclusion from all these tests is that while the carbon and the silver conductive paints can be used to make suitable antennae for the RFID chip, none was sufficiently brittle to serve as a frangible link. Therefore the approach was changed from a strain-based brittle material concept to a simple displacement-based “microswitch” scheme for interrupting the antenna circuit, as explained in the following section.
Figure 5.19: Tension Test Specimen Attachment

Figure 5.20: Conductive Paint on the Dogbone Specimen
5.2.2.2 Metal Antenna with Mechanical Link

The final crack sensor design was based on modifying the antenna of an existing RFID tag using electrically conductive metal strips that overlap just enough to disconnect when a crack occurs. Essentially, the RFID crack sensor will behave like a switch, so when a crack occurs the antenna circuit is broken and the tag turns off and gives no signal.

Existing Antenna – Copper Overlap

It was decided that the crack sensor should be developed so that it detects cracks that have propagated through 60% of the overlay. One of the main reasons for this decision was to try to keep the crack sensor manufacturing as simple as possible. From the literature review (Lee et al., 2005), in order to detect cracks at an earlier stage a smaller than 0.45 mm overlap would be required, which is not very practical and would make the design more complicated and difficult to fabricate.

Read Range

A 36 gauge (0.125 mm) copper sheet was cut into strips about 2 to 3 mm wide for creating the dipole antenna of the RFID tag. One side of the dipole was connected to the 2 mm stub of the original antenna using the 2 part, electrically conductive silver epoxy from M.E. Taylor Engineering, Inc., to assure a good connection. The other side of the dipole was fabricated to have a 0.45 mm overlap of the thin copper sheet over the stub of the original antenna.

To determine the best configuration of the dipole, read range studies were conducted for different antenna lengths as was done earlier with the conductive paint antenna. These tests were initially conducted in the civil engineering laboratory at University of Maryland. Because of inconsistencies in the indoor readings, it was determined that the read range studies be conducted outdoors in parking lot E at
University of Maryland in order to minimize any interference from metal objects in
the laboratory (Figure 5.21). It was expected that the results would be less variable
and more reliable, and in addition the outdoor conditions better represent the actual
field scenario.

The first set of tests was done for a symmetric antenna, starting with a half-
wave length dipole, consisting of two sides of 8.2 cm each and then continuing by
shortening each side of the dipole.

For each length readings were taken with one side being connected and
disconnected. The dipole tag was put in between two thin Lexan pieces to keep it in
place and to simulate the expected encapsulation of the sensor in the field. To create a
good connection at the mechanical overlap, a wooden toothpick was sandwiched
between the Lexan pieces (Figure 5.22). The readings were taken in four directions,
North, South, East, and West. The tag was optimally placed in front of the transmit
side of the antenna.

The results for the symmetric dipole read range are shown in Figure 5.23. The
maximum read distance are very similar in all four directions. Except for a slight
anomaly at 17 cm, the maximum read distance consistently decreases as the total
dipole length gets shorter. Some possible suitable configurations chosen from these
results were:

- 10 cm dipole length
  
  Connected read at 231 cm
  
  Disconnected read at 50 cm

- 9 cm dipole length
  
  Connected read at 160 cm
  
  Disconnected read at 39 cm
- 8 cm dipole length

  Connected read at 135 cm

 Disconnected read at 30 cm

Figure 5.21: Read Range Tests in Lot E

Figure 5.22: Symmetric Dipole Used in the Read Range Study
Next, a read range study was conducted with one side of the dipole fixed at 8.2 cm and the other starting at 5 cm and progressively shortened. The longer 8.2 cm antenna leg contained the overlapped microswitch. The same testing method as for the symmetric antenna readings was followed. Readings were taken with the short side connected and disconnected. The dipole tag was put in between two thin Lexan pieces and a toothpick was used as well (Figure 5.24). The readings were taken in four directions, North, South, East, and West and for two replicates of the tag to evaluate reproducibility. Again, the tag was placed in front of the transmit side of the antenna for all the readings.

![Read Range Starting with a Half-Wave Length Dipole and Shortening Each Side by 1 cm](image)

*Figure 5.23: Read Range for the Symmetric Dipole in Each Direction Connected and Disconnected*
Figure 5.24: Asymmetric Dipole Used in the Read Range Study

The results of these tests are shown in Figure 5.25 through Figure 5.28. The read ranges for the two different tags and in the four different directions are very similar. Looking at these results it was decided that the best dipole length for this application is 8.2 cm on one side and 1.5 cm on the other. This configuration when disconnected could be read at only 27 cm and when connected it could be read at 211 cm. This discrepancy in read ranges is large enough for the antennas to be read from a moving vehicle when connected and not read from that same distance when disconnected. The 211 cm read range when connected is actually greater than required in the field; however, this will ensure that the tag will be able to be read even after possible signal attenuation through several inches of HMA.
Figure 5.25: Read Range for Both Tags Disconnected and Connected in the North Direction

Figure 5.26: Read Range for Both Tags Disconnected and Connected in the South Direction
Figure 5.27: Read Range for Both Tags Disconnected and Connected in the East Direction

Figure 5.28: Read Range for Both Tags Disconnected and Connected in the West Direction
5.3 Prototype Design

5.3.1 Fabrication

Because the sensor must be placed on the surface of the existing layer prior to the overlay, for practical field applications the RFID tag needs to be encapsulated, so that the sensor is protected from stresses and high temperatures during paving operations. However, the encapsulation used should transmit displacements to the antenna so that eventually the overlapped microswitch can disconnect. The following are the considerations for the copper modified dipole encapsulation:

- Resist compaction stresses
- Endure high paving temperatures
- Encapsulate the tag in a way that the strains when the crack occurs will be transmitted to the RFID tag and the overlapped antenna will disconnect

For the encapsulation, Lexan (polycarbonate) was used. Its melting temperature is 267°C and its glass transition temperature is 150°C, which make it a good candidate for protecting the tag. The glue used for attaching the RFID tag to the Lexan and to connect Lexan on Lexan parts was the SG496 strain gauge adhesive used previously in the laboratory studies.

The different parts used for encapsulating the tag are shown in Figure 5.29 and the actual encapsulated tag is shown in Figure 5.30. A 1 cm wide piece of 0.093 inches thick Lexan was used as the top mounting plate for the RFID tag. This part would experience the displacement first and transmit it to the antenna. The mounting plate is about 30 cm to cover most of the area where the reflection crack could initiate. A longitudinal groove deep enough to fit the RFID tag is cut and the dipole ends are glued in the groove. Two small 1.5 cm x 5 cm cross pieces of 0.177 inches thick Lexan are glued to the end of the top mounting plate. The grooved Lexan
bottom protection piece covers the dipole and the mounting plate and is about 3 cm shorter than the top mounting plate. The bottom cover is glued only in one place to the top piece; the bottom cover provides a protection cover but does not interfere with the stress and strains in the top piece and the sensor. Only the two side pieces of the assembled sensor are to be affixed to the underside of the asphalt overlay. Once a crack initiates, these side pieces begin to spread, putting the sensor into tension and decreasing the overlap in the microswitch until the RFID tag stops giving a readable signal.

**Figure 5.29: Parts for Encapsulating the RFID Tag**

**Figure 5.30: H-Sensor**
5.3.2 Survivability

Field tests were conducted to determine the survivability of these tags when subjected to high compaction stresses and temperatures during paving. Another objective of the field tests was to finalize the length of the antenna by evaluating read ranges of various length tags through the 2 inch asphalt overlay. This would give a better understanding how the tags perform through HMA as opposed to just air.

Eighteen RFID tags were prepared for the field tests. Two of them were encapsulated in the H-sensor configuration (Figure 5.30). The other 16, however, were just sandwiched between two 1 cm wide Lexan pieces, one of which was grooved so that the chip would not be damaged. In order to determine which antenna length would be the best for the crack sensor design, the maximum read distances for the connected case and disconnected case must be evaluated. The 16 tags were therefore paired in groups of two, where one tag was in the connected condition and the other disconnected. For simplicity, in the connected case the copper in either side of the chip was attached using conductive silver epoxy instead of overlapping one side. Six different lengths as listed in Table 5.6 were evaluated. A 2 inch HMA overlay with milling project on Campus Drive at the University of Maryland was selected for the field trials. The encapsulated tags were placed longitudinally at a two foot spacing, as shown in Figure 5.31. To make sure the tags would not be displaced during the paving operations, quick set epoxy putty was used to keep them in place (Figure 5.32 and Figure 5.33).

Two days after the paving was completed a read range study of the tags compacted in the mat was conducted (Figure 5.35). The number of successful reads over a 20 second interval was recorded. Although some tags were run over by
equipment during the paving operations, only one tag out of 18 failed to give any readings. The results for the maximum read distances for the tags are given in Table 5.6. The 156 cm height entries do not necessarily represent the maximum distance at which the tags could read; 156 cm was just the highest distance above the pavement that could be achieved in the field. Establishing the actual maximum read distance beyond 156 cm was not necessary, as the reader antenna would not be placed in a vehicle at a higher distance than this above the pavement. Based on the results, the symmetric dipole with a 4 cm antenna on each side of the chip was determined to be the best configuration. When connected it read at least 156 cm and when disconnected it read only about 18 cm. If the reader antenna were mounted anywhere from 2-5 feet above the pavement, the tag would give a signal when there is no crack and would not read once there is a crack in the pavement.

![Figure 5.31: Encapsulated Tags Placed in the Roadway Prior to Paving](image-url)
Figure 5.32: A Close View of One of the Encapsulated Tags

Figure 5.33: Two H-Sensors in the Pavement Prior to Paving
Figure 5.34: Paving in Progress

Figure 5.35: Read Range Setup
Table 5.6: Field Tests Results

<table>
<thead>
<tr>
<th>RFID Tag</th>
<th>Maximum Read Distance (cm)</th>
<th>Number of Readings</th>
</tr>
</thead>
<tbody>
<tr>
<td>8x8 C</td>
<td>31</td>
<td>14</td>
</tr>
<tr>
<td>8x8 D</td>
<td>66</td>
<td>9</td>
</tr>
<tr>
<td>6x6 D</td>
<td>72</td>
<td>4</td>
</tr>
<tr>
<td>8x8 C</td>
<td>156</td>
<td>9</td>
</tr>
<tr>
<td>8x8 D</td>
<td>101</td>
<td>9</td>
</tr>
<tr>
<td>6x6 C</td>
<td>127</td>
<td>12</td>
</tr>
<tr>
<td>6x6 D</td>
<td>96</td>
<td>9</td>
</tr>
<tr>
<td>5x5 C</td>
<td>156</td>
<td>16</td>
</tr>
<tr>
<td>5x5 D</td>
<td>47</td>
<td>15</td>
</tr>
<tr>
<td>4.5x4.5 C</td>
<td>156</td>
<td>16</td>
</tr>
<tr>
<td>4.5x4.5 D</td>
<td>34</td>
<td>12</td>
</tr>
<tr>
<td>4x4 C</td>
<td>156</td>
<td>17</td>
</tr>
<tr>
<td>4x4 D</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td>8x1.5 C</td>
<td>107</td>
<td>16</td>
</tr>
<tr>
<td>8x1.5 D</td>
<td>33</td>
<td>16</td>
</tr>
</tbody>
</table>

5.4 Laboratory Evaluation

A laboratory evaluation was undertaken to demonstrate that the crack sensor design can detect cracks in a 2 inch thick asphalt overlay. The end cross pieces of the encapsulated RFID tags were glued to the bottom of asphalt beams. The idea was that when the beam experienced a crack during three point bending, the crack sensor microswitch would disconnect when the crack had reached about 50% or more of the height of the beam.

The asphalt specimens were prepared at the standard fatigue tests size of 380 mm in length, 63 mm in width, and 50 mm in height. The sides of the asphalt beams where painted white to make it easier to observe cracking. The ends of the copper antenna where glued to the grooved Lexan piece as shown in Figure 5.36. Copper wires were glued to each side of the RFID tag antenna using conductive silver epoxy and then connected to an ohmmeter in order to measure resistance and determine at
what point the conductivity was lost. The Lexan piece where the RFID tag was glued was kept at a length equal to the effective length of the beam during bending. For the laboratory tests, the protective top cover for the tag was not used; it is not necessary for the laboratory testing, and it would fall off since it is not glued with the top part. However, to make sure the antenna overlap remained in place with a good connection, small pieces of Lexan were glued across the groove over the microswitch.

The specimens were then bent in three point bending using the Instron compression machine. The test setup is shown in Figure 5.37. The tests were run in displacement controlled mode at a rate of 5 mm/min. For the first three tests the overlap of the copper antenna to the existing antenna was kept at about 0.5 mm as discussed previously in the literature review chapter. However, in all three instances the disconnection occurred prior to a crack initiating. This could have been due to several factors including the slow loading rate used during the three point bending, the mix properties of the beam, and other details of the test setup. For this reason, the third test was continued until the crack propagated 50% through the beam thickness even though the antenna was disconnected. This was done in order to determine that about an overlap of about 1.5 mm was required.

The next step was to run a test which would more closely represent the use of the crack sensor in the field. Instead of measuring resistance, the reader and antenna were positioned close to the bending machine. Although even in air the 4x4 cm RFID tag did not read further than 150 cm, in the lab during the test it read at a distance more than 180 cm. This was most probably due to wave reflections coming from the metal machines surrounding the antenna. The antenna was placed 180 cm away from the RFID tag, as shown in Figure 5.39. The connection was lost at a vertical displacement of the asphalt beam of about 2 cm. At this point the crack had
propagated about 50% through the 2 inch beam thickness at a CMOD of between 2 to 3 mm (Figure 5.38).

Figure 5.36: RFID Tag Glued on the Asphalt Slab

Figure 5.37: Crack Sensor Test Setup
5.5 Conclusions

Two designs were considered for the crack detection sensor, one using conductive paint and the other the idea of overlapped metals which would disconnect at a certain crack mouth opening displacement. The conductive paint dipoles had
good read ranges especially when the silver conductive paint was used to paint the antenna of the tag reaching about 180 cm. However, the drawback with the conductive paint was that none of the evaluated paints broke at the desired strain. The Aquadag E carbon paint and the 18% silver one were strained up to $25000 \mu \varepsilon$ and did not break.

The second design was based on the use of copper as the antenna of each side, with one side having an overlapping with the existing antenna cut from the original AD-223 RFID tags. The idea was that when a crack occurs the antenna will be pulled in tension and the disconnection of the overlap would occur.

To survive field conditions the RFID tag was encapsulated in between Lexan pieces. The ends of the copper modified antenna were glued on a Lexan mounting plate, which would be right beneath the asphalt overlay. This plate would serve two purposes simultaneously: protect the tag and transmit displacements to the tag.

A survivability check of the encapsulated tags was conducted by embedding them in a 2 inch thick overlay and with the exception of one tag, the other seventeen all survived. A laboratory testing procedure was followed and the idea of overlapping the copper with the existing antenna worked successfully.

In conclusion, it was determined that a crack sensor can be developed when using the idea of an antenna overlap, which would disconnect once a crack has grown to the desired depth. A dipole copper modified RFID tag encapsulated in between Lexan pieces at a length of about 9 cm including the chip was used for this purpose.
Chapter 6 Summary and Conclusions

6.1 Evaluation of Surfaced Tags

During the Phase II project (Schwartz, 2008), field trials were conducted to evaluate a system for tracking hot mix asphalt (HMA). Encapsulated RFID tags were thrown into trucks at the asphalt plant, which then ended up in the HMA pavement. During the trials, some of the tags rose to the surface of the pavement. A possible consequence of this could be compromised durability of the pavement because of increased water ingress and decreased density around the surfaced tags.

In-place permeability and density tests were conducted at the area close to the surfaced tags. The permeability and density next to the tags were similar to the results at random locations away from the tags. A linear regression analysis and a statistical analysis concluded that the surfaced tags would not cause local damage to the pavement. Other than aesthetic concerns, the surfaced RFID tags do not appear to have any detrimental effect on the pavement properties.

6.2 Tracking of PCC Placement

Based on the successful work by Schwartz (2008) in tracking HMA from the plant to its place of deposition on the highway, a laboratory evaluation was conducted to determine if this same method could be applied to Portland cement concrete tracking. Encapsulated passive tags placed in 4 inch diameter cylinders and at the best orientation in the horizontal position could be read at distances up to 5 feet. Next, a field evaluation of the encapsulated tags embedded in a 13 inch thick asphalt
pavement was conducted. The field trials were done in conjunction with the reconstruction of a section of the New York State Thruway I-90 outside Syracuse, NY. The results from this evaluation were surprising as none of the tags gave any readings. This suggested that the positive results obtained in the laboratory with the concrete cylinders occurred because the tags were only embedded in 2 inches of concrete.

In an effort to explain why RFID tags read through HMA but not through concrete, further laboratory evaluation was necessary. RFID tags were embedded in an eight cubic foot box filled with coarse aggregate, which is the main component of concrete. All of the tags, including the ones 12 inches deep from any side, could be read. The coarse aggregate was limestone, which has a dielectric constant of 7 when dry and 8 when wet. Because the coarse aggregate is the main component of concrete, the dielectric constant of the concrete mix based on mixture theory is about 11. Even though this value is not much higher than that of the coarse aggregate, when the RFID tags were embedded in the eight cubic feet of concrete, none of them could be read, not even the ones located only four inches from one of the sides.

Because the tags read through coarse aggregate but not through concrete, another test with tags embedded in wet sand was performed to determine if the moisture was the reason the tags could not be read in concrete. However, all of the tags could be read in this case, which left the actual cement paste as the only possible reason for the lack of readings. Six encapsulated tags were embedded in a 5-gallon bucket of cement paste and, even after 12 days of hydration, none of the tags gave any readings.

In conclusion, the idea of expanding the wireless tracking of pavement materials in PCC does not appear to work using encapsulated passive RFID tags.
Using active RFID tags this application could be successful, however their higher price makes them unsuitable for PCC tracking.

Recommendations

Additional investigations should be pursued to identify the reason for the very high apparent dielectric constant of hydrated cement paste. One hypothesis is that hydrated water molecules in the cement paste may retain dielectric properties that are as high if not higher than free water. The interactions between the chemistry of hydrated cement paste and dielectric properties should be evaluated in fundamental chemical terms. This might then point to alternative RFID technologies (e.g., different frequency ranges, different tag designs) that might be more successful for the PCC tracking application.

6.3 Reflection Crack Sensor

HMA overlays are the most common rehabilitation methods for deteriorated pavements. The most common distresses in these pavements are reflection cracks. The development of a crack sensor for detecting early onset of reflection cracks would be beneficial to state DOTs so that they can hold the contractor responsible for repairs and to help them plan for future problems.

The reflection crack sensor idea acts like a switch: when there is no crack the RFID tag gives a signal, and when a crack forms, the tag stops reading. Two possible designs were evaluated for developing the reflection crack sensor. The first one was based on electrically conductive paint used to modify an RFID tag. When cracks occur the conductive paint would be strained to failure. Read range studies of loop antennas, dipole antennas, and a C-shaped antenna were conducted. It was determined that a dipole antenna mostly made out of silver conductive paint gives very good
reads at up to 175 cm. Several tests in different configurations were conducted to try to determine the strain at which the conductive paints purchased for this study would break. None of the conductive paints showed a consistent failure strain in these tests. Two of the paints, the Aquadag E carbon paint and the 18% silver conductive paint were strained to levels of 25000 µε and higher.

The failure with the conductive paint idea was the reason for developing the second design, which used thin copper strips as the antenna of the RFID tag. The scheme was to overlap the copper on one side to the existing antenna right next to the chip. When a crack occurs the tag would be exposed to tension in the bottom of the overlay and the overlap would get smaller until a disconnection would occur and the tag would not give as strong of a signal. Read range studies in air were conducted to determine the best dipole configuration. To determine the optimal configuration more accurately, a read range study was also conducted for some RFID tags embedded in a 2 inch thick HMA overlay. From these sets of data, the dipole with an antenna 4 cm long on each side of the chip was determined to be the best for this application. The main factor when determining the length of the dipole was that the RFID tag should read from at least 1 or 2 feet from the pavement surface when there are no cracks in the overlay and should give no readings when the crack has initiated.

When the read range was measured for the tags through the 2 inch thick overlay, a survivability check of these tags to the high compaction stresses and high temperature was done simultaneously. Only one out of 18 tags could not be read; the other 17 tags survived the overlay construction.

As a final evaluation of the crack sensor, a three point bending test was configured. The crack sensor was glued in the bottom of an asphalt beam 2 inches high and then the beam was bent by applying a static load. When a crack started and
grew to about 50% of the height of the beam the sensor stopped giving readings, successfully detecting the crack.

**Recommendations**

The tests to determine the amount of the overlap were conducted in a three point bending configuration with a static load applied in the middle of the beam. Future tests should be conducted using a Texas Overlay Tester so that the beam fails in a way more similar to how the pavement would fail. Through these tests the CMOD as a function of vertical crack propagation can be determined more accurately, and the overlap can be adjusted as needed. The flexibility of the design presented in this chapter allows one to use the sensor to detect small cracks or strains (less overlap) or detect larger cracks or strains (more overlap). The laboratory testing using the Texas Overlay Tester should then be followed by field trials on in-service pavements.
References


Ho, K. K. S. and Li, K. S., (2003), Geotechnical Engineering, Lisse: Swets and Zeitlinger B. V.


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