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16. Abstract

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This report is part of Research Study 2039, "Investigation of Bonding Materials for Piezoelectric Traffic Monitoring Equipment," funded by the Texas Department of Transportation for the Center for Transportation Research (CTR) at The University of Texas at Austin. This volume is intended to assist TxDOT in the implementation of the findings of this project.

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IMPLEMENTATION MANUAL FOR THE USE OF BONDING MATERIALS FOR PIEZOELECTRIC TRAFFIC MONITORING SENSORS

by

Eric Joseph Ueber
David W. Fowler
Ramon L. Carrasquillo

Research Report Number 2039-2F

Research Project 1-2039
Investigation of Bonding Materials for Piezoelectric Traffic Monitoring Equipment

conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

by the

CENTER FOR TRANSPORTATION RESEARCH
Construction Materials Research Group
The University of Texas at Austin

November 1994

Implementation Statement

This document presents the procedures, equipment, and materials that should result in a functioning, long-lasting installation of piezoelectric classification sensors. The recommendations presented herein are already being implemented by the Texas Department of Transportation, and they should result in significant savings in money and time spent on these sensors.

Prepared in cooperation with the Texas Department of Transportation

Disclaimers

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List of Reports

Research Report 2039-1, "Investigation of Bonding Materials for Piezoelectric Traffic Monitoring Equipment," by Eric J. Ueber, David W. Fowler, and Ramon L. Carrasquillo, November 1994.

Research Report 2039-2F, "Implementation Manual for the Use of Bonding Materials for Piezoelectric Traffic Monitoring Sensors," by Eric J. Ueber, David W. Fowler, and Ramon L. Carrasquillo, November 1994.

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In order to properly design highway pavements, the Texas Department of Transportation (TxDOT) gathers traffic data with piezoelectric classification sensors. Use of these sensors includes the use of polymer binding materials to install the sensors in the pavement. In the past, the polymer being used by TxDOT proved to be inadequate. This project was undertaken to accomplish three goals: to select suitable polymer materials, to adjust the sensor installation design to make it more successful, and to develop a system for evaluating new materials as they become available.

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List of Notation

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BPO	benzoyl-peroxide, organic
CTR	Center for Transportation Research
DOT	Department of Transportation
DOTs	Departments of Transportation
G^*	complex shear modulus
G'	storage modulus
G''	loss modulus
L	length or span
P	load
SHRP	Strategic Highway Research Program
TxDOT	Texas Department of Transportation
UT	The University of Texas at Austin
WIM	weigh-in-motion (sensor)
δ	phase angle delta

Summary

Successful use of the piezoelectric classification sensors can be accomplished by using a well-trained installation crew, using an established and tested procedure, and using the appropriate materials. The procedure as recommended emphasizes proper care of the sensor, including storage, transport, and use. All successful materials found to date are acrylics. Tests that are to be used to evaluate other materials are viscosity, gel time, Vicat set time, compressive strength, flexural bond strength, complex shear modulus, and shrinkage.

This report is divided into five sections. The first chapter describes the background of the project. The second chapter describes the recommended installation procedure in detail. The evaluation criteria to be used on new materials are explained in the third chapter. The materials that successfully passed these criteria and are recommended for use are described in the fourth chapter. The last chapter gives a summary of the project's findings and recommendations.

Chapter One: Background

1.1 Background

Proper highway and road design requires the use of accurate traffic data which are collected by traffic monitoring equipment. In Texas, one important instrument is the 1.8-meter (6-foot) piezoelectric classification sensor. These sensors are installed in the wheel-paths of the roadway in small grooves cut into the pavement. The sensors are normally held in place by some type of polymer binder. In the past, the Texas Department of Transportation (TxDOT) has had difficulty in finding a sensor design and polymer binder combination that results in a successful, long-life installation. The Center for Transportation Research (CTR) of The University of Texas at Austin (UT) undertook a project to study this problem.

1.2 Objectives

This project was undertaken to help TxDOT solve its problems with piezoelectric classification sensors. The project objectives were to produce: (1) a recommendation regarding materials and sensors to use and (2) a procedure for evaluating new materials in the future. These recommendations were to be justified by a thorough laboratory and field testing program.

1.3 Scope

This implementation manual is divided into five parts. Chapter One, Background, describes the general background of the project and why it was undertaken. Chapter Two explains the basic installation procedure. The third chapter, Evaluation Criteria, lists the tests used to evaluate the materials and explains why these tests were chosen. Recommended Materials, the fourth chapter, describes the two materials recommended to TxDOT for use in this application, and explains why the bare cable sensors are recommended. The last chapter summarizes the major points of the report and presents the conclusions and recommendations.

Chapter Two: Installation Procedure

2.1 Site Preparation

The fist step of the installation procedure involves preparing the site. The site for the installation should be carefully chosen. It should be on level, straight road, and should not be close to a railroad (vibrations from the trains can cause signal noise). There should also be a power and phone line nearby, to power the signal processing equipment, and for use in remote monitoring. A cabinet must be installed to house the necessary electronic equipment, and a trench must be dug from this cabinet to the side of the roadway for the conduit which protects the sensors' signal wires.

Traffic control must be supplied, usually by the local DOT district office. Traffic handling depends on the specific installation. Traffic on multi-lane highways can be diverted to a single lane, which changes as the work progresses (the polymer binder must be completely set before allowing traffic over the installation). Two-way traffic on two-lane roads can be diverted to the shoulders, if they are wide enough, allowing all the lanes to be worked on at the same time. Otherwise, only one lane can be closed, and the traffic will have to be controlled carefully in the open lane.

The exact locations of the piezoelectric sensors and the wire-loop inductance sensors, as well as the signal wires from these sensors, must be marked on the pavement surface. The sensor configuration should be specified by the sensor manufacturer. The marks must be made with wax markers or paint, as shown in Figure 2.1, to ensure that they do not get washed away by the water used to lubricate and cool the pavement saw. All the marks for the lane (or lanes) being worked on should be made before beginning sawing, as the water from the saw can cause difficulties in marking the other sensor locations.

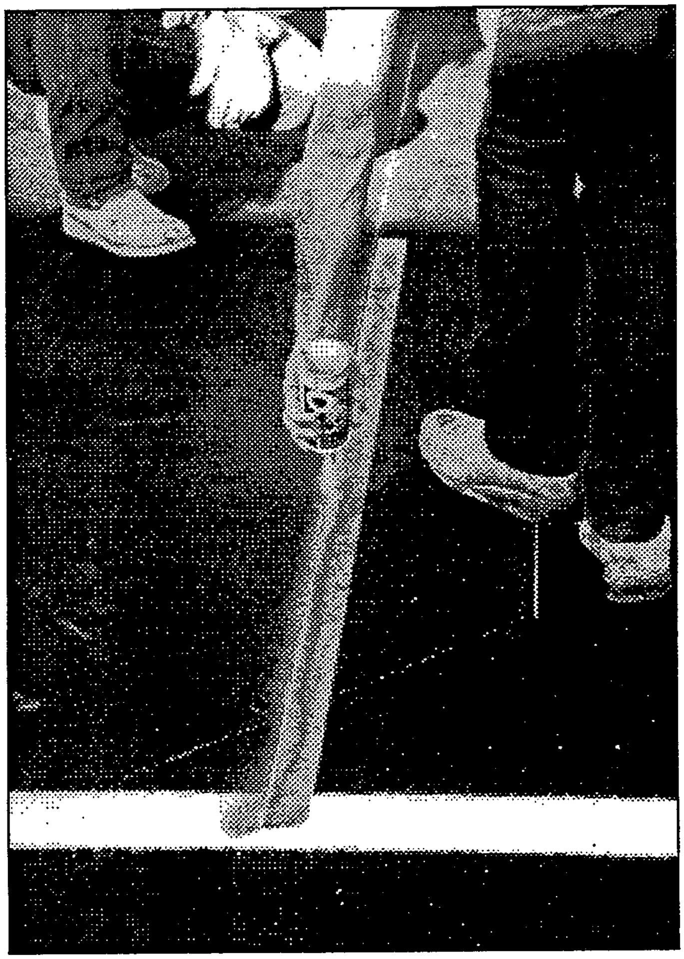

Figure 2.1: Marking the Sensor Location

2.2 Saw Work

The next step of the installation is to cut the grooves for the sensors and the signal wires. A water-cooled diamond-bit pavement saw should be used. A single blade is sufficient for the wire-loop and signal wire cuts. These cuts should be made about 20 mm ($^3/_4$ in.) deep.

After all the single-blade cuts are made, the grooves for the piezoelectric sensors can be made. These are made using a gang-blade of three 6-mm ($^1/_4$-in.) saw blades for a total cutting width of 20 mm ($^3/_4$ in.) or using a single 20-mm ($^3/_4$-in.)

saw blade. This groove is also cut to a depth of 20 mm ($^3/_4$ in.). The pavement saw should be modified by adding two depth-control wheels adjacent to the saw blade to provide better depth control on rutted pavement. Figure 2.2 shows this concept in a diagram, while Figure 2.3 shows a photograph of a modified saw (the saw blade has been removed in the photo).

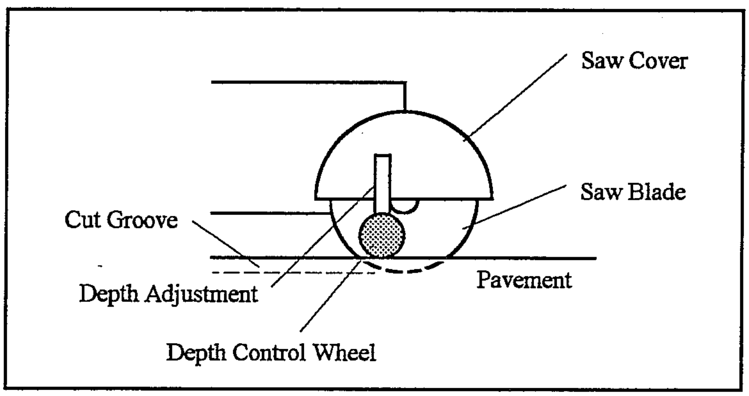

Figure 2.2: Pavement Saw Depth Control

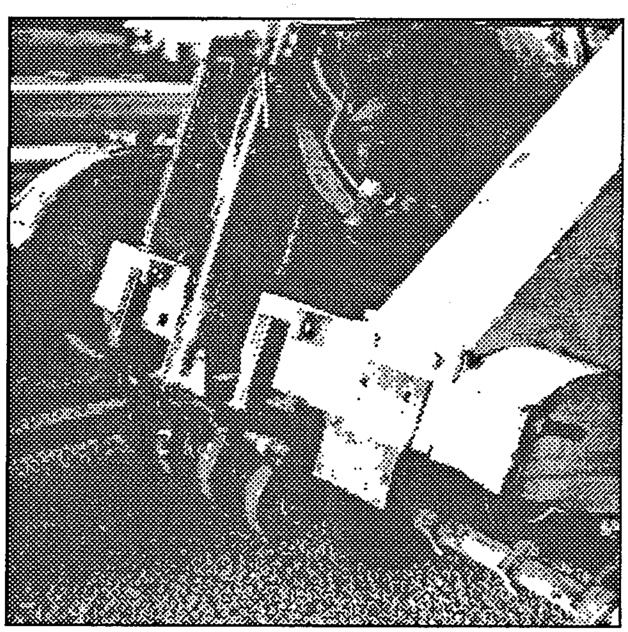

Figure 2.3: Modified Saw With Depth Control

It is important that the groove be cut in a single sawing operation, with no chipping or jack-hammering, to minimize damage to the pavement. After all cuts are complete, a water hose is used to clean out all debris. An air blower is then used to dry the cuts, especially the piezoelectric sensor groove. The grooved surfaces must be completely dry, or the polymer binder will not adhere to the pavement. Figure 2.4 shows workers using a water hose and an air blower.

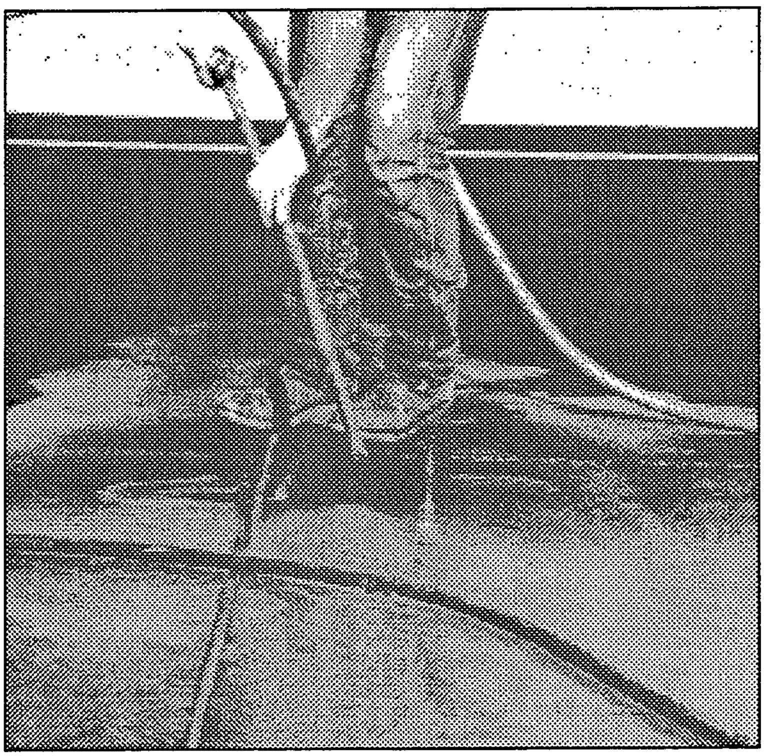

Figure 2.4: Cleaning and Drying the Cuts

2.3 Placing the Sensor

Placing the sensor can be the most critical part of the installation process. Proper handling of the bare cable sensor must be practiced at all times to ensure that it is not damaged. A well-trained, full-time installation crew should be used, not the general pavement maintenance crew. Extra care at this step can save money and time, as fewer sensors will fail.

After the sensor groove is completely dry, the specially modified plastic rebar chairs are placed. These chairs should be spaced at no more than 30-cm (1-foot) intervals to prevent sagging of the sensor. All the chairs should be placed in the groove before laying the sensor.

Once the chairs are in place, the sensor should be laid on top of them **while still in the protective PVC tube**. This is an extremely important part of the installation, as it prevents bending and damaging the sensor. The PVC tube is then pulled off of the sensor, leaving it lying on the chairs. Care should be taken not to pull on the coaxial signal cable, as this could damage the connection. Also, the sensor should not be forced out of the tube; any restraints holding the sensor should be carefully removed.

With the sensor lined up along the centers of the chairs, a screwdriver or other appropriate tool is used to press on one leg of each chair, opening the slot at the top. The sensor should then fall into the hole in the chair. Under no circumstance should the sensor be forced into the hole, as this could damage it. Figures 2.5 and 2.6 show this procedure.

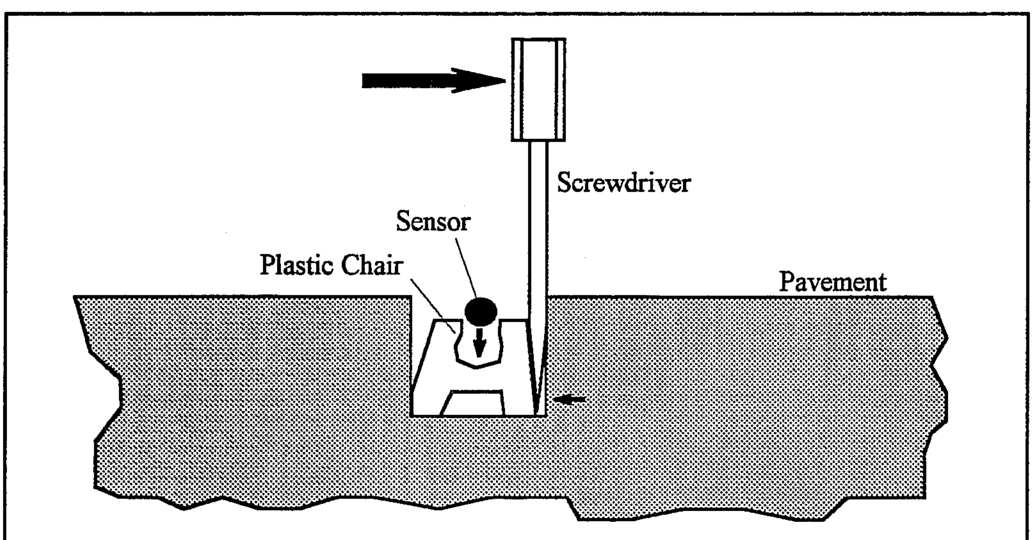

Figure 2.5: Opening the Plastic Rebar Chairs (diagram)

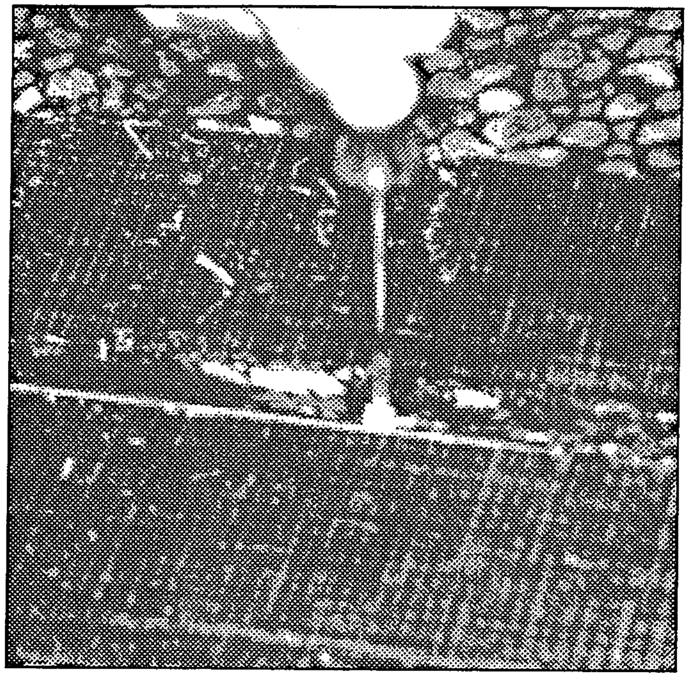

Figure 2.6: Opening the Plastic Rebar Chairs (photo)

2.4 Using the Binder

Once the sensor is properly placed in the plastic chairs, the polymer binder is used to adhere the installation to the pavement. The mixing directions supplied by the polymer binder manufacturer should be carefully followed. This will usually consist of mixing the resin and filler until it achieves a uniform consistency, and then adding the hardener and mixing again for a set amount of time, or until a certain condition, such as a uniform color, is reached.

While the polymer is being mixed, other workers should place tape, usually duct tape, along the sides of the sensor groove to catch any polymer that falls outside the groove. Some departments also use some type of thick tape, such as bituthane tape, to raise the sensor groove sides above the level of the pavement. This produces a raised installation, which may or may not be recommended by the sensor manufacturer.

After the polymer is thoroughly mixed, it is carefully poured into the sensor groove. Pour the polymer slowly, but steadily, to avoid creating large air voids. The polymer can be worked into the groove with a putty knife, but care should be taken not to hit the sensor. The top surface should be worked smooth, flush with the tape along the sides of the groove. After the polymer hardens, the tape is removed, leaving a clean installation. Figure 2.7 shows the polymer being poured and worked into the groove.

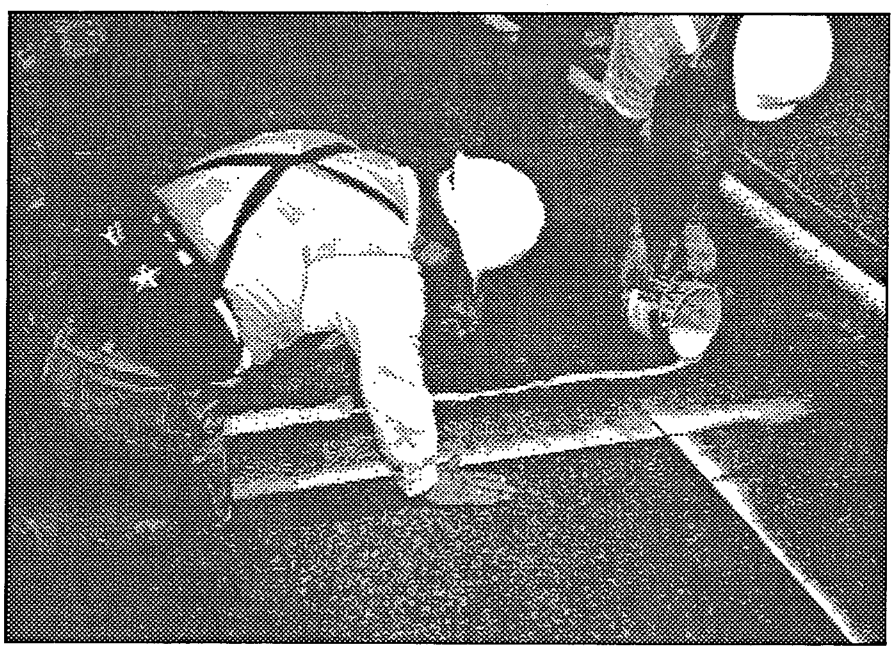

Figure 2.7: Pouring and Working the Polymer

During this last phase of the installation, the wire loops should also be installed and sealed. In addition, the signal cables from all the sensors should be laid in their cuts and sealed. A silicone loop sealant has proved to be the best material for this. The cuts should be wiped with the edge of a piece of cardboard to remove any extra sealant and to ensure a smooth surface.

2.5 Installation Concerns

There are a number of concerns that must be addressed to ensure a successful installation. The major concern is that **the installation must be performed by a well-trained installation crew.** The sensors being installed are very sensitive and fragile, and seemingly harmless treatment can damage them so that they no longer function. Owing to the nature of the sensor design, a bent sensor cannot be bent back to its original shape and still work. For this reason, careful handling of the sensors is required at all stages, including shipping, storage, and installation. For example, during transport to the installation site, the small PVC tubes containing the sensors should be left in the shipping box, or slipped inside the 50-mm (2-in.) PVC conduit tubes. This level of care is usually possible only with a well-trained, full-time installation crew.

Other concerns involve the polymer binding materials used to adhere the sensors to the pavement. Some of the materials may be toxic and/or flammable until cured, and must be handled in strict accordance with manufacturer's instructions. All these materials will be shipped with Material Safety Data Sheets (MSDS), as required by law. The instructions and information on these sheets must be observed not only by the shipping company, but also by the installation crew. Proper handling of these materials is essential to ensure safety and expected performance.

A final concern is sensor quality. Before the sensors are installed, they should be tested for acceptable performance. This is accomplished by using a standard LCR meter. The sensor's capacitance and dissipation are tested. The capacitance should be in the range of 17 to 20 nanofarads (the length of the signal cable has a major effect on the capacitance). The dissipation should be no greater than 0.1%. A dissipation of less than 0.01% is ideal. The sensors should be tested this way at least three times: 1) upon arrival, 2) after transport to the site but before installation, and 3) immediately after the polymer binder sets. Success at all three testing times indicates proper handling of the sensors. During the evaluation period for new polymers, the sensors should be checked this way on a regular basis (about once a month).

Figure 2.8 shows a site plan of the completed installation, and a photograph is shown in Figure 2.9. Figure 2.10 shows a cross-section of the finished sensor groove.

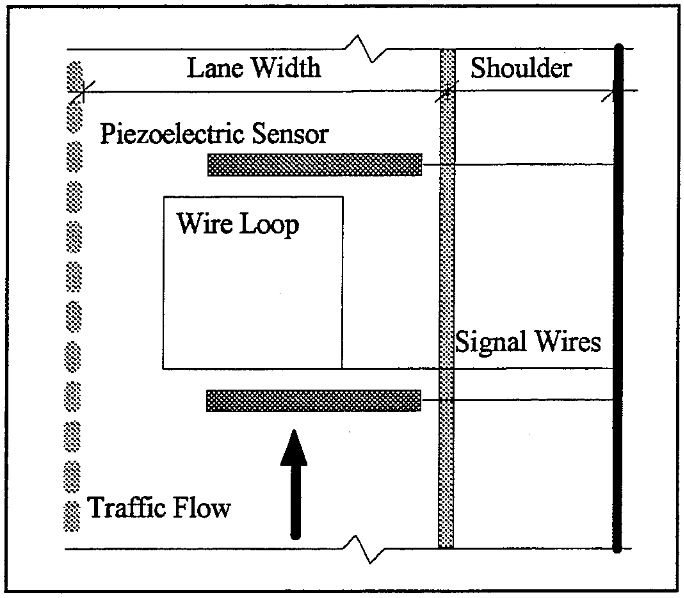

Figure 2.8: General Site Plan of Sensor Installation

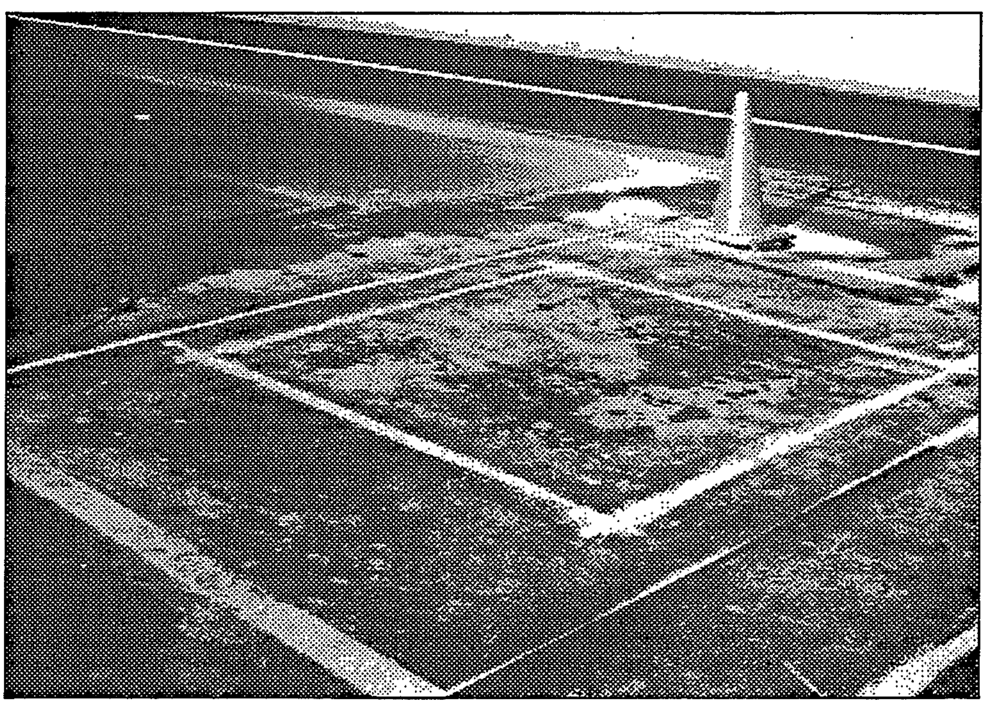

Figure 2.9: Photograph of Completed Site

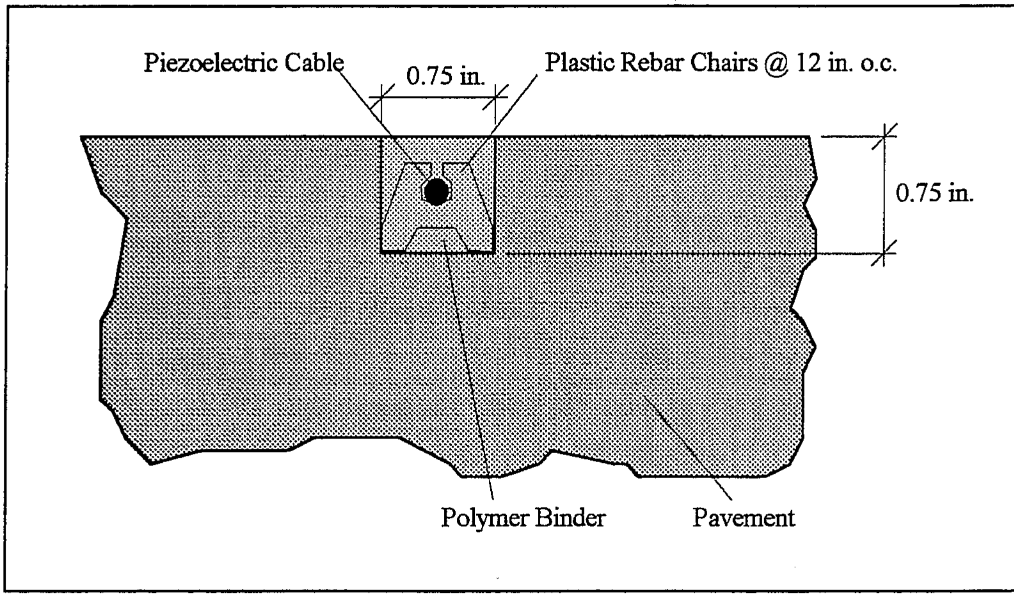

Figure 2.10: Bare Cable Sensor Installation (1 in. = 25.4 mm)

Chapter Three: Evaluation Criteria

3.1 Basic Laboratory Tests

Several basic laboratory tests were determined to be adequate for evaluating polymer materials for installing piezoelectric bare cable sensors. Most of these tests are standard ASTM tests. The following sections give brief descriptions of these tests. The referenced standard should be consulted for the complete details of each test.

3.1.1 Viscosity

The workability of the materials in their uncured state can be estimated by measuring their viscosities according to ASTM D 2393. This is a very simple test which consists of using a Brookfield viscometer to measure viscosity directly. A small sample of the mixed, but uncured, material is placed in a cup, then placed under the Brookfield viscometer. A small rotating spindle attached to the viscometer is lowered into the material. The viscometer compares the rotational speed of the spindle to the torsion required to maintain that speed and, from this information, it computes the viscosity. The required viscosity at 25° C (77° F) is in the range of 20 to 40 Pa-s.

3.1.2 Gel Time

As a measure of the working time available to use the materials, the gel time is measured based on ASTM C 881. For this test, small samples of the material are mixed and allowed to cure. The ASTM test method defines "gel time" as the time after mixing at which a standard amount of the material forms a gelatinous mass. For this project, gel time is defined as the time at which the peak temperature is achieved due to the exothermic reaction of the curing material. For most materials, this definition gives similar results similar to those of the ASTM definition, but times are easier to measure because the peak temperature is less subjective than the existence of a gelatinous mass. The desired gel time is anywhere from 5 to 15 minutes at 25° C (77° F). This test should also be run at other temperatures, such as 0° C (32° F) and

50° C (122° F), to determine the setting time for the extreme temperatures possible in the field.

3.1.3 Vicat Set Time

Gel time is used to estimate the working time available after mixing the materials. Testing to determine the final setting time (which determines when traffic can be allowed on the sensor) uses a Vicat needle, as described by ASTM C 191-92. This test uses a needle of standard dimensions and weight. The needle is dropped from a set height into the curing material at regular intervals. When the needle no longer penetrates the material, it is considered set, and this time is recorded as the Vicat setting time. Any result at 25° C (77° F) less than 30 minutes is acceptable. The test setup is shown in Figure 3.1.

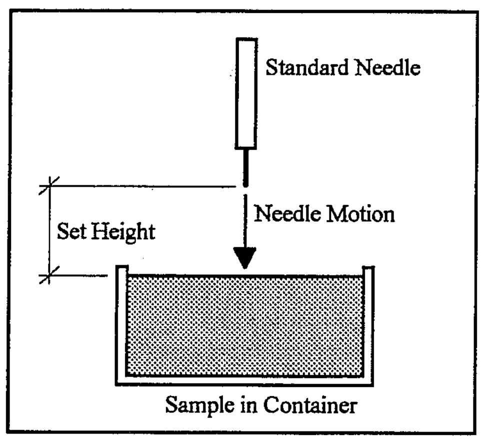

Figure 3.1: Vicat Needle Test Setup

3.1.4 Compressive Strength

A compression test is performed according to ASTM C 116-90. This test uses one-half of a 5-cm x 5-cm x 20-cm (2-in. x 2-in. x 8-in.) beam broken in a flexural-strength test. The half-beams are held in a support which properly seats the load onto the sample, as shown in Figure 3.2. The samples are then loaded to failure, at a constant strain rate. This test gives the ultimate compressive strength of the material by dividing the ultimate load by the loading area of 0.26 m^2 (4 in.^{2}). An acceptable result is any value above 6,900 kPa (1,000 psi) at 25° C (77° F).

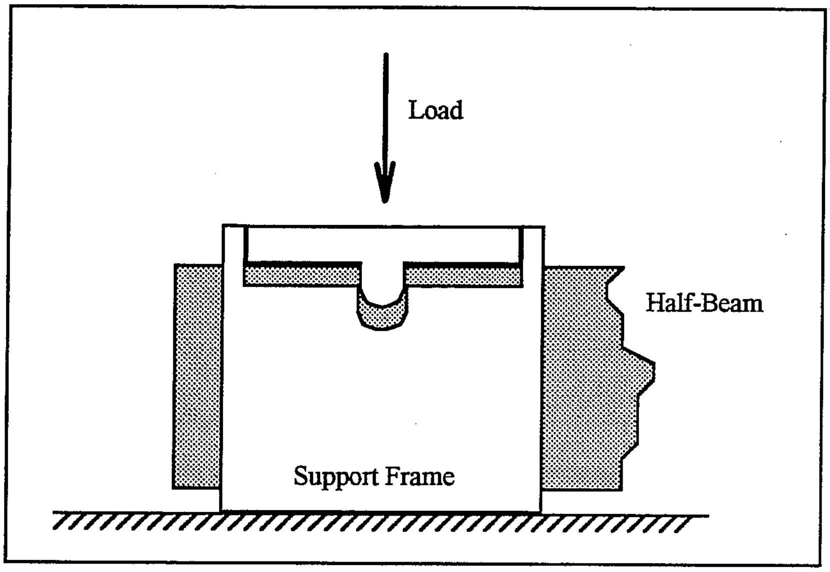

Figure 3.2: Compressive Test of Half-Beams

Obviously, other standard compressive tests could be used, such as the standard cylinder test described in ASTM C 39 (this will produce slightly lower strength values due to the effect of the aspect ratios of the samples). This test was used because, for this project, flexural tests were also run, and they provided specimens for compressive testing according to this standard, reducing the number of specimens that needed to be cast. In the tests recommended in this manual, the flexural bond test produces a half-beam of the appropriate dimensions for performing this test.

3.1.5 <u>Flexural Bond Strength</u>

The strength of the bond under flexural loading was tested according to ASTM C 78-84. This test uses third-point loading to produce a region of constant moment around the bond location. The strength is calculated by dividing the moment at rupture by the section modulus. The moment is calculated by PL/6, where P is the total load applied to the two loading points. The test setup is shown in Figure 3.3.

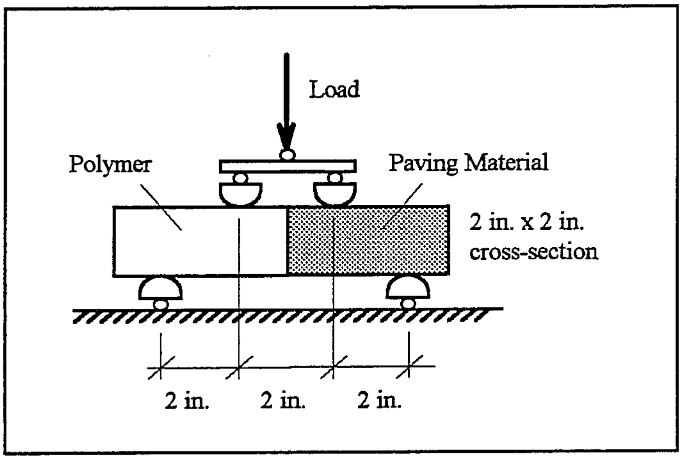

Figure 3.3: Flexural Bond Test Setup (1 in. = 25.4 mm)

Acceptable behavior is defined not only by the strength of the bond but also by the behavior of the bond. The desired bond strength at 25° C (77° F) is at least 690 kPa (100 psi) to asphalt or 2,070 kPa (300 psi) to concrete. In addition, at least half of the failure surface should be in the paving material, indicating that the bond is at least as strong as the original pavement, with failure completely in the paving material being the ideal behavior.

3.1.6 Complex Shear Modulus

In order to measure the flexibility of the materials, the complex shear modulus test is run according to AASHTO TP5. This test is meant to determine the complex shear modulus of asphalt samples at different temperatures, but it was decided that this test would work well for these materials, too, since they generally behave very similarly to asphalt pavement. The test uses standard equipment used in the design of asphalt pavement according to SHRP specifications. Therefore, the equipment was readily available for testing in this project, and should be available to TxDOT as well.

The test involves subjecting a small cylindrical sample about 6 mm ($^1/_4$ in.) in diameter and 2 mm ($^1/_{16}$ in.) thick to a cyclically applied torsional load. During the test, the load and deflection are monitored over time, with the offset in time between them measured as the phase angle δ, as shown in Figure 3.4. The equipment used gives this value directly, as well as the complex shear modulus G^*. The two values, δ

and G^*, can then be used to calculate other properties used for comparison with asphalt properties.

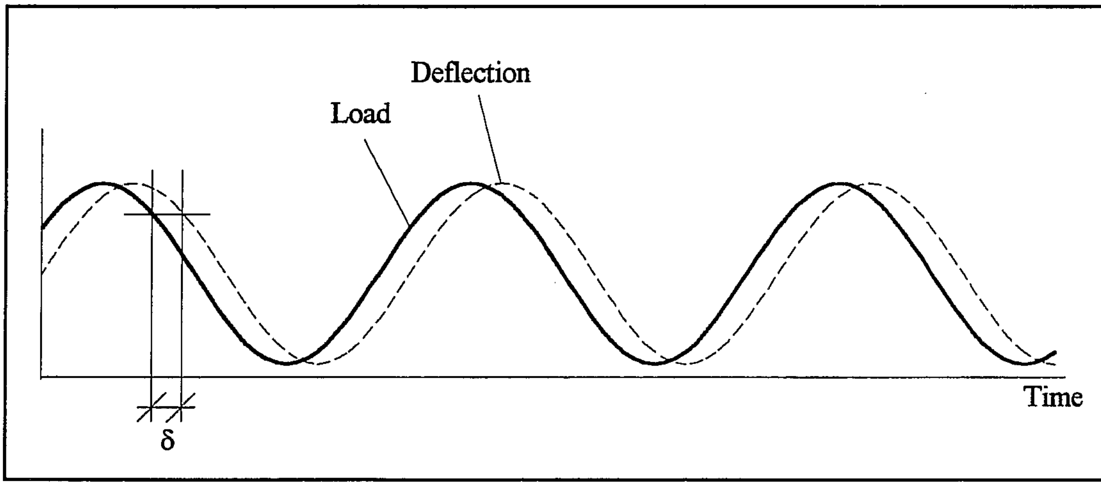

Figure 3.4: Definition of Phase Angle δ

With the phase angle δ and the complex shear modulus G^*, two other dynamic properties can be calculated. These are the storage modulus G', and the loss modulus G''. The storage modulus is analogous to the elastic modulus and is an indication of recoverable deformation. The loss modulus is analogous to viscosity and is an indication of unrecoverable deformation. These values are related as shown in Figure 3.5.

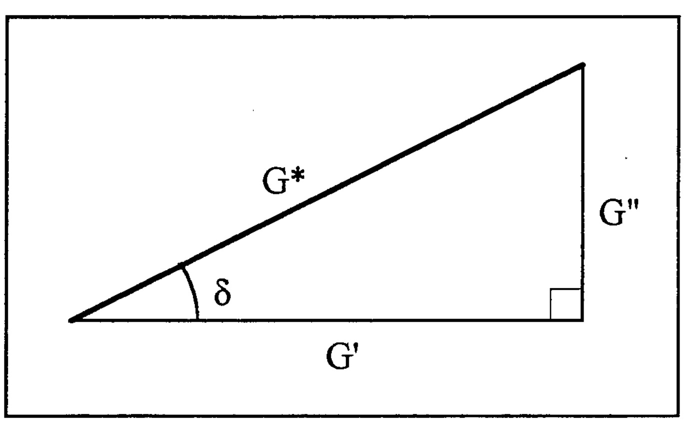

Figure 3.5: Definition of Storage Modulus G' and Loss Modulus G''

For evaluation of the materials, it is the storage modulus G' that is important. Because the loads to which the sensors are subjected are so transitory, there is not enough time to accumulate unrecoverable deformations. Since asphalt pavement changes properties with temperature, so should the binder material. Therefore, acceptable behavior is indicated by a storage modulus G' that decreases with increasing temperature. Also, at room temperature (25° C, or 77° F), the storage modulus should be in the range of 13,000 to 69,000 kPa (2,000 to 10,000 psi).

3.1.7 Shrinkage

Many polymer materials change density as they cure, due to chemical changes that occur during curing, that result in a change of size between the uncured mixture and the hardened material. In order to measure this change in size, which usually takes the form of shrinkage, a test developed by the DuPont Company (which is under review for ASTM C 9) is performed. The test consists of inserting two vertical angle legs at a set distance apart into the uncured mixture, then measuring the change in length over time. The test setup is shown in Figure 3.6. The shrinkage (or expansion) rate is expressed as a percentage of the original length. Acceptable shrinkage/expansion at 25° C (77° F) is in the range of 0.5% shrinkage to 1.0% expansion. The specimens for this test can also be used for the compressive strength test, as described earlier.

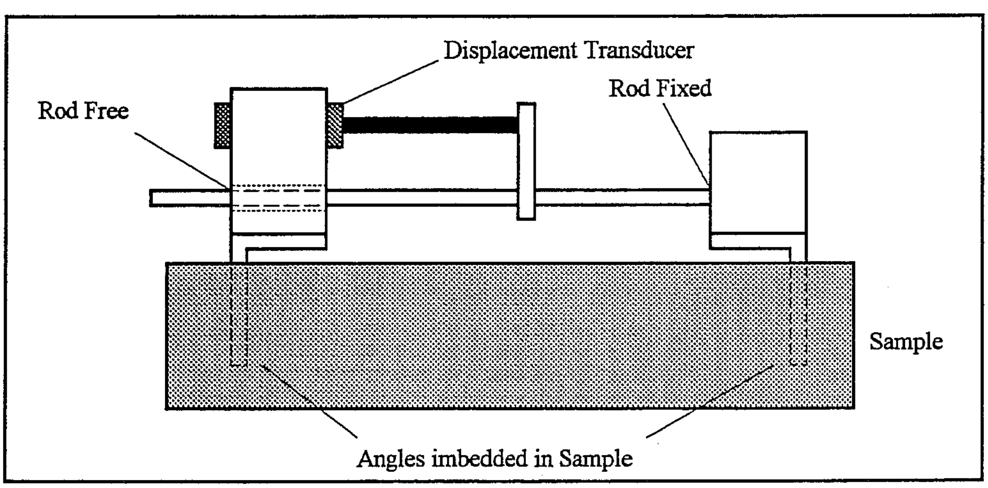

Figure 3.6: DuPont Shrinkage Test Setup

3.2 Field Trials

The most important method of testing potential materials for this application is the field trial. These trial installations give the installation crew a chance to work with the materials and make comments about their performance under installation conditions. In this way, the installation crew may determine that some materials are inappropriate, even if they performed well in the laboratory.

Field trial locations should be selected with care. The materials should be tested in each of the climate zones of the state (four in Texas). The material should experience the harshest weather cycle (summer to winter, or winter to summer) typical for each location, so field testing may take up to a year in order to subject the materials to extremes of temperature and humidity. These sites should also be located in significant traffic, but not at vital data collection sites, as some failures should be expected. The sites should be checked frequently during the evaluation period to determine the exact time of failure, if any. It is suggested that the data be remotely checked on a weekly basis to ensure that the sensors are still working, and the site should be visually inspected and the sensors' capacitance and dissipation checked once a month (this can be done by the local maintenance crew, who can take photographs of suspected troubles to send back to the central office).

3.3 Selection of Tests

The selection criteria described before were selected from a larger number of tests that were run as part of this project. These tests included the following:

- abrasion resistance
- compressive strength
- dynamic properties
- flexural strength
- gel time
- shrinkage
- thermal expansion
- Vicat set time
- viscosity

- bond flexural strength
- bond shear strength
- bond tensile strength
- temperature effects on bond strengths

Not all of these tests were appropriate for evaluating the materials. The following sections explain the tests that were chosen, and why. Each material was then ranked according to the tests that were selected. The rankings of each material for each test were then totaled, with the highest totals indicating the best materials. Some tests were given more importance by using a multiplier on the scores (the selection of multipliers was based on field observations; further experience may indicate a need to alter the multipliers). The interim project report, CTR Research Report 2039-1, describes all the tests tried and explains the ranking system in detail.

3.3.1 Viscosity

Viscosity was tested as a measure of the workability of the materials. Workability can be easily determined by having an installation crew member make a small sample installation, then rate the material by his own judgment. A more precise measurement is obtained with the viscosity test. Acceptable values of viscosity are in the range of 20 to 40 Pa-s.

3.3.2 Gel Time

This test is recommended, as it is a very simple test and it measures a very important property: working time. The working time should be at least 5 minutes and no more than 15 minutes. This gives ample time to perform the installation, but ensures that the final curing time will not be excessive. This test can be run at the same time as the Vicat test, and on the same samples, since all it requires is a thermocouple to monitor temperature.

3.3.3 Vicat Set Time

Since the Vicat test measures final curing time, this test is recommended. Along with the gel time, this test determines the time required to fully perform the installation. The time specified by TxDOT for final cure was 30 minutes. Therefore, this is also the maximum acceptable result for the Vicat test.

3.3.4 Compressive Strength

The compressive strength test is recommended. Some method should be used to determine the basic strength of the material. Compressive strength was chosen because it is easy to run, and, because it is the standard measure of strength used for paving materials, TxDOT personnel will be comfortable with the results. Although for this project the test was run on half-beams, TxDOT may perform the standard cylinder test, as described by ASTM C 39. Alternatively, the polymer half of the samples used for the flexural bond test could be used in this test (the cylinder test will produce slighlty lower strength results, due to the effect of the aspect ratio of the samples). The material being tested should have a strength of at least 6,900 kPa (1,000 psi), which was the lowest strength of any material that had acceptable field performance (IRD).

3.3.5 Flexural Bond Strength

The only bond strength test recommended is the flexural bond test. This is the easiest bond test to perform, as it requires no special equipment beyond beam molds. Also, the three bond tests gave similar results, in that, if a material performed well in one, it performed well in all three. Acceptable minimum flexural bond strength is defined as 690 kPa (100 psi) for asphalt or 2,070 kPa (300 psi) for concrete, with the failure at least half in the paving material.

3.3.6 Complex Shear Modulus

The complex shear modulus G^* test is recommended as a method for measuring flexibility. This test is required by the SHRP specifications for asphalt paving design, so TxDOT will have the equipment and the expertise to run this test. The results of interest for this test are the effect of temperature on the storage modulus G', and its value at room temperature (25° C or 77° F). The storage modulus should decrease with increasing temperature, and should have a value at room temperature in the range of 13 to 69 MPa (2 to 10 ksi).

3.3.7 Shrinkage

The shrinkage test is recommended. The shrinkage characteristics of the materials can have a very significant effect on the bond behavior. Excessive shrinkage will cause the material to pull away from the sides of the grooves, while expansion will improve the bond, and extreme expansion will damage the pavement. Therefore, the acceptable range of shrinkage results is from 0.5% shrinkage to 1.0% expansion, as based on field trial observations.

3.3.8 Field Trials

Field trials are always desirable, and they are recommended as the final step of the selection process. All materials under consideration should be used for at least one test installation per environmental area, and monitored for three months, including the period of the most severe weather for that location. This will identify any unforeseen problems or characteristics that laboratory testing might miss. In addition, this gives the installation crew a chance to work with the materials and make their recommendations about the ease of use. Obviously, it is the installation crew that ultimately determines which installations are successful, so their opinions should be held as the final word on the inappropriateness of a material for this application, even if laboratory test performance has been acceptable.

Chapter Four: Recommended Materials and Sensors

4.1 Bonding Agents

Two bonding agents were selected for recommendation on the basis of the evaluation criteria described in the previous chapter. These materials were the best two materials according to the ranking system used. The materials recommended are ECM P5G and IRD. The following sections describe these materials in detail.

4.1.1 ECM P5G

This material was already in use by the Texas Department of Transportation (TxDOT) on a trial basis. It is an acrylic with a fine mineral filler, designed for installing piezoelectric classification sensors. The product comes packaged in 6-kg (13.2-lb) units, with the resin and filler already mixed. The hardening agent is a small package of aromatic anhydride. ECM stands for Electronic Control Measurement, a company from France, with a local office in Pflugerville, Texas. "P5G" is the company's product designation for this material.

To use, the resin and filler must be thoroughly mixed with a drill-paddle, since the filler settles over time. Once the material is at a uniform consistency after about two minutes of mixing, the hardener is added. The combination should be mixed for about two minutes. The material is then poured into the application. The bucket is sufficiently oversized to allow easy mixing without spilling.

This material gave the best performance. It scored the highest in the ranking totals, with a total score of 118.5 (the lowest score was a 31.5). It was the best material in the gel and Vicat time tests, and passed all the other tests. It is extremely easy to work with, cures rapidly, and provides the optimum performance in terms of flexibility and compatibility with asphalt paving. All the ECM P5G field trial sensors are still working as of July 1994, with no signs of distress (during cold temperatures, the Amarillo sensors showed some minimal surface cracking, but the cracks have closed again with warmer temperatures).

4.1.2 IRD AS-475

IRD AS-475 is also an acrylic, similar in behavior to the ECM P5G, designed for installing piezoelectric classification sensors. It comes as black resin mixed with mineral filler in 5-, 15-, or 20-kg (11-, 33-, or 44-lb) pails , with small vials (17- or 33-g [0.5- or 1-oz]) of benzoyl peroxide organic hardener (BPO). The amount of BPO used depends on the mass of resin used and the ambient temperature at the application. More BPO is used for colder temperatures and larger masses.

Use of this material is also very similar to the use of the ECM P5G. The filler settles in the resin over time, so it must be mixed in its container until it reaches a uniform consistency (about two minutes). Then the BPO is added, with the amount determined by the ambient temperature, as indicated by the technical information provided by the manufacturer. Mixing takes about two minutes. The material is then ready to be placed into the application.

This was the second best material tested, with a total score of 102.5. It ranked third in the gel and Vicat times, and passed all the other tests. Generally, its performance was acceptable, showing no significant weaknesses in the field (except in Amarillo, where it exhibited cracking similar to that of the ECM P5G). All the IRD-installed sensors are still working as of July 1994.

4.2 Bare Cable Sensors

It was decided to try this type of sensor because some of the problems with the previous sensors were determined to be caused by the sensor design. The aluminum channel casing of the standard encapsulated design requires a fairly large groove to be cut into the pavement. This groove can adversely affect the pavement performance, especially when the paving is very thin (sometimes thinner than the groove is deep). Also, the shape of the channel gives it significant flexural and torsional stiffness. This stiffness can cause severe damage in asphalt pavements in warm weather when the asphalt becomes less stiff and the sensor installation causes stress concentrations. The stiffness also prevents conforming the sensor to the contours of the pavement surface, which may be uneven due to effects such as rutting. The smaller cross-section of the bare cable installation results in less damage to the pavement and uses less polymer binder. If a flexible polymer binder is used, the sensor causes less severe stress concentrations and may even change flexibility with changing temperature, like the asphalt pavement. Figure 4.1 shows a comparison of the two sensors as they are installed.

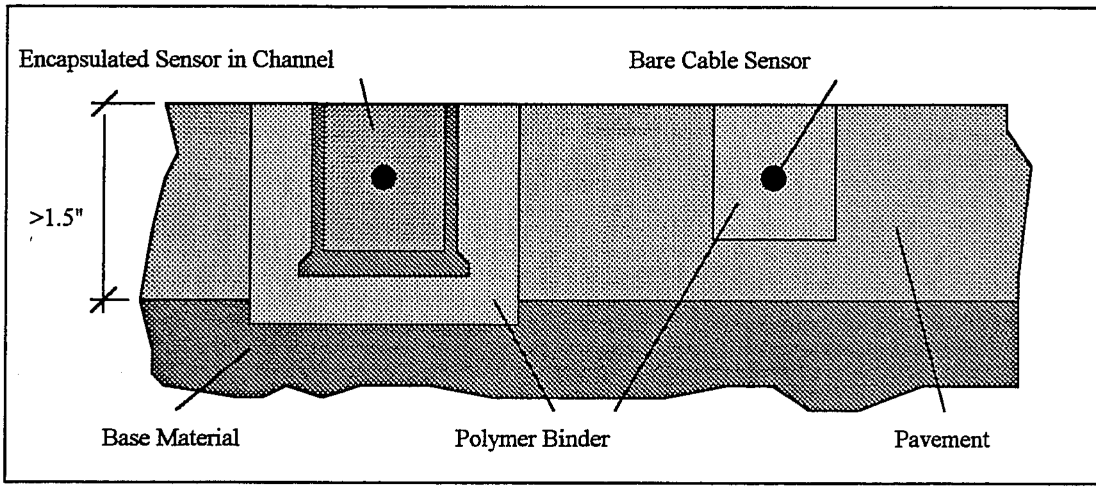

Figure 4.1: Comparison of Two Sensors As Installed (1 in. = 25.4 mm)

The sensors used in this project were Vibracoax Class II piezoelectric bare-cable classification sensors. They were purchased through two companies: Philips Electronic Instruments and ECM. This does not preclude the use of other sensors in the future if they should become available.

Chapter Five: Summary and Conclusions

5.1 Summary

In order to properly design highway and road pavements, the Texas Department of Transportation (TxDOT) needs accurate traffic flow data. To collect such data, piezoelectric classification and weigh-in-motion (WIM) sensors are used to monitor traffic at strategic locations throughout the state. In the past, keeping these sensors operational for more than about one year has proved to be very difficult. Therefore, TxDOT contacted the Center for Transportation Research (CTR) at The University of Texas at Austin (UT) to request a study to find a solution to the sensor problem. This study was to produce two results: recommended materials and sensors to be used, and a program of laboratory testing to use for evaluating new materials as they become available.

To achieve these objectives, three basic sources of information were used. Reports of previous research were obtained from published works in the UT and CTR library systems, and from other DOTs and material manufacturers by telephone survey. Laboratory tests were conducted to determine the basic material properties and the compatibility of the materials with typical paving materials. These tests measured the following properties: abrasion resistance, compressive strength, dynamic properties, flexural strength, gel time and temperature, shrinkage, thermal expansion, Vicat curing time, viscosity, bond strength under flexure, shear, and tension, and the effects of extreme temperatures on these properties. Finally, field trials were conducted in the form of three test installations at environmentally different sites in Texas.

5.2 Conclusions

From a comparison of the laboratory data and the field performance of the materials, a number of conclusions could be drawn. These conclusions can be divided into three basic groups, based on the objectives of the project: material acceptance criteria, acceptable materials, and sensor design to be used.

5.2.1 Selection Criteria (Tests to Use)

Comparing test performance to field experience revealed that the following properties correlate well with acceptable service performance:

- viscosity in proper range (optional)
- correct gel time, allowing adequate working time
- proper final curing time, as measured by the Vicat setting time test
- adequate strength in compression
- adequate bond flexural strength and behavior
- proper flexibility as described by the storage modulus G', with a proper relationship to temperature
- acceptable shrinkage, from some expansion to minimal shrinkage
- easy use at installation, as determined by installation crew

On the basis of these criteria, the materials were ranked, with some criteria having more influence than others. On that basis, the top two materials are recommended to TxDOT for use. The tests used to determine these properties are described in Chapter Three. Table 5.1 lists the properties to be tested, along with the acceptable ranges of results.

Table 5.1: Recommended Evaluation Criteria

Recommended Test	Required Result (1 psi = 6.9 kPa)
Viscosity	20 to 40 Pa-s
Gel Time	5 to 15 minutes
Vicat Set Time	≤ 30 minutes
Compressive Strength	≥ 1,000 psi
Bond Flexural Strength	≥ 100 psi (to asphalt) ≥ 300 psi (to concrete) Failure at least 50% in paving material
Complex Shear Modulus - Storage Modulus G'	2,000 - 10,000 psi at 25° C (77° F) Decrease with increasing temperature
Shrinkage	-1.0% to 0.5%
Field Trial (ease of use)	Acceptance by installation crew

5.2.2 Acceptable Materials

On the basis of the evaluation criteria described in Chapter Three, two materials are recommended for use. These materials are ECM P5G and IRD AS-475, both of which are acrylic materials with fine mineral fillers (IRD is a methyl methacrylate, a type of acrylic). These materials performed satisfactorily under all the tests that are being recommended as selection criteria. Limited field testing has also confirmed that these materials perform well in service, but further experience may yet alter these results. Finally, a couple of classes of materials have been eliminated from consideration for this application. These material classes are asphaltic materials, due to the need for compacting, and silicone-based materials, due to their extreme flexibility and long curing times. Table 5.2 lists the recommended materials.

Table 5.2: Recommended Materials

Recommended Material	Material Type
ECM P5G	Acrylic
IRD	Acrylic

5.2.3 Sensor Designs

On the basis of limited field testing, it was concluded that the use of the bare cable sensors is preferable to continued use of encapsulated sensors. The aluminum casing of the encapsulated sensors contributes many detrimental effects to the installation process, including larger volume of polymer used, more extensive damage to paving due to size of cut, and stress concentrations due to the rigidity of the casing design. The bare cable design eliminates all these problems, while the only problem it introduces is the need for more care in handling. Since the TxDOT installation crew has demonstrated ability in this area, it is recommended that the use of bare cable sensors be accepted as general policy.