Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TX-95+2039-1		

4. Title and Subtitle *INVESTIGATION OF BONDING MATERIALS FOR PIEZOELECTRIC TRAFFIC MONITORING EQUIPMENT*	5. Report Date *November 1994* 6. Performing Organization Code
7. Author(s) *Eric J. Ueber, David W. Fowler, and Ramon L. Carrasquillo*	8. Performing Organization Report No. *Research Report 2039-1*
9. Performing Organization Name and Address *Center for Transportation Research* *The University of Texas at Austin* *3208 Red River, Suite 200* *Austin, Texas 78705-2650*	10. Work Unit No. (TRAIS) 11. Contract or Grant No. *Research Study 1-2039*
12. Sponsoring Agency Name and Address *Texas Department of Transportation* *Research and Technology Transfer Office* *P. O. Box 5080* *Austin, Texas 78763-5080*	13. Type of Report and Period Covered *Interim* 14. Sponsoring Agency Code

15. Supplementary Notes

Study conducted in cooperation with the Texas Department of Transportation
Research Study Title: "Investigation of Bonding Materials for Piezoelectric Traffic Monitoring Equipment"

16. Abstract

Proper highway design requires the use of accurate traffic data. Such data are collected by traffic monitoring equipment installed in the road surface. This equipment usually consists of piezoelectric sensors, either 1.8 meters or 3.6 meters long (6 or 12 feet long), installed in a groove cut into the pavement, and held in place by a bonding agent. This study was undertaken at the request of the Texas Department of Transportation (TxDOT), in an effort to find bonding agents applicable to this use. Preliminary research consisted of a literature search, DOT survey, and manufacturers' survey to determine the current practice. Materials were selected and screened with some basic laboratory tests to determine their basic physical and material properties. Compatibility tests were conducted to determine the bond characteristics. Field tests were also conducted to determine the installation parameters of the materials. Finally, the test results were analyzed to determine which materials would perform satisfactorily in actual use. Recommendations are made, listing the most promising materials and the selection criteria to be used in future evaluations.

17. Key Words	18. Distribution Statement
traffic monitoring equipment, road surface, piezoelectric sensors, groove, pavement, bonding agent, materials, laboratory tests, physical and material properties, bond characteristics, installation parameters, performance, selection criteria	*No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.*

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	*Unclassified*	*122*	

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INVESTIGATION OF BONDING MATERIALS FOR PIEZOELECTRIC TRAFFIC MONITORING EQUIPMENT

by

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Research Report Number 2039-1

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 working, long-lasting installation of piezoelectric classification sensors. The recommendations presented herein are already being implemented by the Texas Department of Transportation, and should result in significant savings in money and time spent on these sensors.

Prepared in cooperation with the Texas Department of Transportation

Disclaimers

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily represent the official views or policies of the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

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BIDDING, OR PERMIT PURPOSES

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Preface

This is the first report in a pair of reports describing an investigation of polymer binding materials for use with piezoelectric classification sensors.

The authors wish to thank the personnel from the Texas Department of Transportation who assisted in this project: Dean Barrett, Brian St. John, and Dayton Grumbles. Special thanks are given to Willard Peavy and the other members of the installation crews, without whom this project would not have been successful.

The authors also wish to express their appreciation for the help of David Whitney and Agata Wiackowska in the laboratory. Their experience and advice made the project run all the more smoothly.

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.

Abstract

Proper highway design requires the use of accurate traffic data. Such data are collected by traffic monitoring equipment installed in the road surface. This equipment usually consists of piezoelectric sensors, either 1.8 meters or 3.6 meters long (6 or 12 feet long), installed in a groove cut into the pavement, and held in place by a bonding agent. This study was undertaken at the request of the Texas Department of Transportation (TxDOT), in an effort to find bonding agents applicable to this use. Preliminary research consisted of a literature search, DOT survey, and manufacturers' survey to determine the current practice. Materials were selected and screened with some basic laboratory tests to determine their basic physical and material properties. Compatibility tests were conducted to determine the bond characteristics. Field tests were also conducted to determine the installation parameters of the materials. Finally, the tests results were analyzed to determine which materials would perform satisfactorily in actual use. Recommendations are made, listing the most promising materials and the selection criteria to be used in future evaluations.

Table of Contents

List of Figures

List of Tables

List of Notation

A	area
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BPO	benzoyl-peroxide, organic
CMRG	Construction Materials Research Group
CTR	Center for Transportation Research
d	diameter
DOT	Department of Transportation
DOTs	Departments of Transportation
E^*	complex modulus
f_r	flexural stress or strength
G^*	complex shear modulus
G'	storage modulus
G"	loss modulus
h	height or depth
L	length or span
M	moment
NAFTA	North American Free Trade Agreement
P	load
S	section modulus
SHRP	Strategic Highway Research Program
T_g	glass transition temperature
TTI	Texas Transportation Institute
TxDOT	Texas Department of Transportation
UT	The University of Texas at Austin
WIM	weigh-in-motion (sensor)
α	coefficient of thermal expansion alpha
δ	phase angle delta

Summary

This report is divided into eight chapters, each dealing with a major step of the project. The first chapter gives a brief background of the project, including the reasons why it was undertaken and the goals it was to acheive. The second chapter details the previous research performed by others in this field. It includes the results of a library search, a telephone survey of the procedures used by other states' Departments of Transportation, and a telephone survey of polymer manufacturers. From this research it was possible to make initial selections of materials and tests. The third chapter describes the materials and sensors used in this project. The fourth chapter details the laboratory tests used to evaluate the polymer materials. These tests included abrasion resistance, compressive strength, dynamic properties, flexural strength, gel time, shrinkage, thermal expansion, Vicat setting time, viscosity, bond tests, and extreme temperature tests. The fifth chapter describes the field trial installation performed. The sixth chapter presents the results of the laboratory and field tests. The seventh chapter analyzes these results to determine which materials performed well and which tests could accurately determine acceptable material performance. The eigth chapter summarizes the findings of the project and makes recommendations for use.

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, such equipment usually consists of 1.8-meter (6-foot) piezoelectric classification sensors and 3.6-meter (12-foot) piezoelectric weigh-in-motion (WIM) sensors. These sensors are installed in the roadway, in the wheel-paths, in small grooves cut into the pavement. The sensors are 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. Therefore, TxDOT contacted the Center for Transportation Research (CTR) of The University of Texas at Austin (UT) to undertake a project to study this problem.

1.2 Objectives

This project was undertaken to help TxDOT to solve its problems with piezoelectric classification and WIM 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 Relevance of Project

The significance of this project can be appreciated when it is noted that TxDOT has hundreds of these sensors already installed and plans to vastly increase the number of such installations. TxDOT also intends to upgrade the existing sites based on the recommendations from this study, as the old sites require reworking. With the adoption of the North American Free Trade Agreement (NAFTA), traffic along the Texas-Mexico border is expected to increase dramatically, requiring even more sensor sites, as TxDOT evaluates the traffic flow.

Since this project began, several other state DOTs have contacted TxDOT, requesting copies of the project report. This project will, therefore, have far-reaching application in much of the United States. The improved traffic data obtained with sensors installed with this project's recommendations will coordinate well with that of the Strategic Highway Research Program (SHRP). This combination of results could lead to a significant improvement of America's vast highway infrastructure.

1.4 Scope

The study was divided into eight parts, which also provide the organization of this report. Chapter One, Background, describes the basic background of the project and why it was undertaken. Chapter Two, Previous Research, summarizes the first steps of the project, including a literature review and surveys of other DOTs and binder manufacturers. The third chapter, Materials and Sensors, describes the materials selected on the basis of the preliminary research and the different sensor types used in this project. Laboratory Program, the next chapter, explains the tests used to evaluate the materials, including screening tests and compatibility tests, while Field Trials describes the field installations used to evaluate the materials; Chapter Six, Test Results, summarizes the results of these laboratory tests and field trials. Chapter Seven presents the recommendations made to TxDOT and the justifications for each. The last chapter, Summary, Conclusions, and Recommendations, summarizes the major points of the report and presents the conclusions. It also contains a summary of the recommendations made to TxDOT and suggested future work.

Chapter Two: Previous Research

2.1 Introduction

In order to begin the project, a review of existing information was required. This research was conducted in order to better use existing information for the selection of more appropriate materials. The information sought was in three forms: published literature, experience of other state Departments of Transportation (DOTs), and experience of the materials suppliers. Published literature was found using The University of Texas library system and the library of the Center for Transportation Research (CTR). The experience of DOTs and suppliers was obtained through the use of telephone surveys.

2.2 Literature Search

Two library systems were utilized to determine the current state of traffic monitoring equipment and polymer usage. Specifically, information was sought regarding traffic monitoring equipment, piezoelectric sensors, general polymer chemistry, general usage of polymer materials, roadway applications of polymers, and the effect of fillers on polymer behavior.

Published information concerning traffic monitoring equipment was out of date. The sensors described were bending-plate weigh-in-motion (WIM) sensors, pneumatic tube detectors, and wire-loop inductance sensors. There was little information available on piezoelectric traffic sensors. However, there was plenty of information on general piezoelectric sensors; nevertheless, such information was of limited use for this project.

Many textbooks were available on the general chemistry of polymer materials. These books also gave general physical properties of these materials. Several books, articles, and journals were identified which described the use of polymers, particularly for transportation applications. From this information, a preliminary list of materials was formed. The materials under consideration were epoxies, acrylics, and urethanes. These materials have seen successful use in many roadway applications, such as crack and joint sealing, waterproof overlays, and adhering traffic buttons. Silicon-based materials were not considered due to their long curing times and high flexibility when cured.[1-19]

2.3 Departments of Transportation (DOT) Survey

Many other states use piezoelectric classification sensors to collect traffic data. These states have had varying success with their installation methods and materials. Numerous state DOTs were contacted during the summer of 1992, and a phone survey was conducted (Appendix A contains the telephone questionnaire). Originally, the Traffic Engineering Divisions of the state DOTs were called, but they referred these questions to their Planning Divisions. After the first few states, the Planning Divisions were contacted directly. The individuals questioned from each DOT are listed in Table 2.1.

Table 2.1: DOT Phone Survey Contacts

State	Contact
Arizona	Ed Green
Arkansas	Tom Black
California	Craig Copeland
Colorado	Bob Sakaguchi
Florida	Mulder Brown
Idaho	John Hamerick
Iowa	Don Miller Steve Highland
Kansas	Dennis Brooks Bill Hughes
Louisiana	Ed Wagner
Nebraska	Terry Guy
New Mexico	John Grey
Oklahoma	Kenny Beard
South Dakota	Dave Huft
Utah	Marty Cutler

The survey included questions concerning which sensors were used, which bonding agents were used, and the details of the installation process. Each of these topics is covered in the following sections, followed by a summary of other problems encountered.

2.3.1 Sensors

There are two basic types of piezoelectric classification sensors available: film and cable. DOTs can use one or both types. There are about four different distributors of these sensors. The survey results are shown in Table 2.2 and are summarized in Table 2.3.

Table 2.2: DOT Phone Survey Results - Sensors

State	Brand of Sensor	Sensor Types
Arizona	Philips	cables only
Arkansas	Peak, Philips, Atochem	both films & cables
California	Philips, IRD	both films & cables
Colorado	IRD	cables only
Florida	Atochem, Philips, IRD	both films & cables
Idaho	Atochem	films only
Iowa	Atochem, Saratec, GK	both films & cables
Kansas	Peak	cables only
Louisiana	Atochem, Philips	both films & cables
Nebraska	–	cables only
New Mexico	Peak, Atochem	both films & cables
Oklahoma	IRD, Peak	cables only
South Dakota	Atochem	films only
Utah	Peak	cables only

(NOTE: Peak is the present name for GK and Saratec)

Table 2.3: Sensor Use by Type and Brand

Sensor Type	Percent Using
cable	42.86
film	14.28
both	42.86

Sensor Brand	Percent Using
Atochem	50.00
IRD	28.57
Peak	42.86
Philips	35.71
unknown	07.14

(NOTE: Brand percentages do not add up to 100.00: some states use more than one brand)

2.3.2 Bonding Agents

The use of bonding agents was much more variable. A summary of usage is found in Table 2.4. Florida and Arkansas use a modified version of the Texas specification G-100 epoxy. The modifications result in a faster cure, more flexibility, and greater resistance to water on the bonding surface. The manufacturer, E-Bond Chemical, was unable to provide details of the modifications, but indicated that the modified epoxy does not qualify under the present Texas specification. However, according to the DOTs, this new epoxy has performed well in Florida and Arkansas, and would probably work well in Texas, too.

Colorado, Kansas, Louisiana, and Utah use epoxies supplied by the sensor manufacturers. Colorado uses an epoxy from 3M, supplied by IRD. For Louisiana, both Atochem and Philips suggested an E-Bond epoxy, as did Peak for Utah. New Mexico also selected an E-Bond epoxy after contacting other states. Kansas uses a hermatite epoxy supplied by Peak and used E-Bond for a short trial period, but decided not to continue with it.

Arkansas also uses a hermatite epoxy, which was specified by GK Instruments for their sensors. However, Arkansas has since shifted to E-Bond, because Florida has had good experience with it and it was available for only 25% of the cost of the hermatite. Iowa uses only a hermatite epoxy, as recommended by their sensor manufacturer and a consultant. Neither state has had any significant problems with the hermatite bonding agent.

Table 2.4: DOT Phone Survey Results - Bonding Agents

State	Type of Binder	Source of Binder Suggestion
Arizona	Filled epoxy (from IRD)	Other application
Arkansas	G-100*, hermatite epoxy	Other state, sensor supplier (GK)
California	Epoxy	Other application
Colorado	Epoxy (from 3M)	Sensor supplier (IRD)
Florida	G-100*	Other state
Idaho	Silicon loop sealant	Other application
Iowa	Hermatite epoxy	Sensor supplier
Kansas	Hermatite epoxy	Sensor supplier (Peak)
Louisiana	Epoxy (from E-Bond)	Sensor supplier (Atochem, Philips)
Nebraska	Loop sealant (Bondo)	Other application
New Mexico	Epoxy (from E-Bond)	Other states
Oklahoma	unknown	Sensor supplier (IRD, Peak)
South Dakota	Epoxy (from Sylvax)	Other application
Utah	Epoxy (from E-Bond)	Sensor supplier (Peak)

*Modified version from E-Bond

Oklahoma, too, uses the bonding agent supplied with the sensors they use. These agents, which differ for each company, have worked adequately. Oklahoma was also the only state contacted that used different agents for concrete and asphalt (but still supplied by the sensor manufacturer).

California, Idaho, Nebraska, and South Dakota all use a bonding agent that was readily available. California uses the same epoxy they use for crack sealing, concrete repairs, and other applications (and only one sensor out of about 130 has failed). Idaho used a silicone loop-sealant for their two sites (which were supposed to be temporary). Nebraska also uses their loop-sealant, called Bondo, and only 4 out of

25 sensors have come loose. South Dakota experimented with a number of their available polymers, and they settled on an epoxy from Sylvax due to its useful curing time and wide temperature range.

Arizona has only one piezoelectric site. For that site, they used the same epoxy they had been using to attach raised centerline markers and reflectors, with sand added as a filler. They used this epoxy because IRD had good experience with it at a large project in Phoenix. The site has been installed for about three months, and has had no problems despite local weather extremes including large amounts of rain and temperature swings of 55° Fahrenheit or more in 24 hours (112° F ambient dropped to 55° F that night).

2.3.3 Installation

Most of the states contacted use the same basic installation process, which differs slightly from the method previously used by TxDOT. The difference involves the application of the bonding agent. In these states, the bonding agent is poured into the sensor slot before the sensor is placed. The slot is filled about half full, then the sensor is pressed into the binder. This forces binder up around the sides of the sensor. Additional binder is added as needed to fill the remaining space. (TxDOT modified its installation to match those of these other states after this survey was conducted.)

This process is used to ensure that the binder makes a good bond with the bottom and sides of the sensor. Pouring the binder over the in-place sensor was found to leave air pockets underneath. Some states work the binder with trowels to ensure that all the air has been removed. This simple modification to Texas' method would seem to be worth the improved performance. This method also tends to be cleaner, with less wasted binder outside the sensor slot.

Most DOTs also emphasized the need to completely dry the slot surfaces before applying the bonding agent. Any water present tends to degrade the bond quality. Two states (Arkansas and Oklahoma) use heated drying (blower heaters or torches) in cold weather to speed up the curing time. Drying is a factor in most states, as all but Florida use water-lubricated diamond-bit saws (Oklahoma uses dry saws in asphalt).

Two states, Idaho and South Dakota, use different installation methods. Idaho was using a portable temporary sensor from Atochem that was merely taped down in a 6-mm (1/4-in.) groove. Additional adhesion was supplied by silicone loop-sealant. The sensors were also covered with a bituthane tape (usually used for crack sealing). Idaho is also studying, with Texas Transportation Institute (TTI), a method of installing WIMs sideways in the pavement. These would detect the pressure wave preceding the tires instead of detecting the weight of the tires directly. Sensors used this way would be completely encapsulated in the bonding agent, at about the mid-depth of the slab.

South Dakota was the only state contacted that routed sensor slots instead of sawing them. The routing seemed to provide a better bonding surface for the epoxy. However, South Dakota is using flat sensors, only 4 mm (3/16 in.) thick, so routing is feasible. Sawing is preferable for deeper slots due to improved efficiency.

2.3.4 Problems

Almost all the states contacted had problems, similar to those in Texas, with keeping the sensors installed. Some of the problems are:

- the sensor becomes partially loose, causing vibrations that degrade the accuracy of the sensor reading.
- sensors that protrude above the level of the pavement can be pulled out (especially in areas that use snow plows).
- the binder-pavement bond fails, causing the sensor to come out of the pavement (this is very rare, but most states cited at least one occurrence).
- extreme temperatures at installation cause problems:
  - if too hot, the binder sets too quickly and the low workability causes poor bonding;
  - if too cold, the binder takes a long time to set, causing traffic to be delayed excessively (or if traffic is returned too soon, poor bonds develop).

Excessive rutting in poor asphalt is the most common reason cited for the above problems. The uneven surface results in a poor installation, because the sensor cannot conform to the ruts. Therefore, parts of the sensor are above the pavement, where they receive extra punishment from vehicles, and parts of the sensor are below the surface, resulting in loss of accuracy.

2.4 Binder Supplier Survey

The last step of the preliminary research was to contact suppliers of the bonding agents. Information gathered in the survey of DOTs identified major suppliers of polymers. The companies that supplied the sensors to the various state DOTs were also consulted to determine the materials they recommend for their sensors. A program book for an industry conference was also used to locate companies that supply appropriate polymer products.[20] This produced a significant list of potential suppliers, as shown in Table 2.5. A complete list, with names and phone numbers, of the companies that supplied the test materials is in Appendix B.

Table 2.5: Potential Material Suppliers

Material	Supplier
Acrylic	Electronic Control Measurement, Inc. International Road Dynamics, Inc. Philips Electronics Instruments Company
Epoxy (Flexible)	E-Poxy Industries, Inc. Poly Carb Tamms Industries Company Transpo Industries, Inc.
Epoxy (Rigid)	E-Bond Epoxies, Inc. Sika Corporation Schul International Company
Urethane	Azon, Inc. Euclid Chemical Company

Each of these companies' technical sales department was contacted, and the project was described to them. Quick curing time was stressed, as was the need to function in both portland cement concrete and asphalt concrete pavements. Most of the companies contacted had products they recommended for this application, and they provided small quantities, free of charge, for testing. Those companies that did not have appropriate products provided the name of a company that did. From this information, a list of materials to be subjected to the screening tests was formed. These materials are covered in Chapter Three: Materials and Sensors. The screening tests are described in Chapter Four: Laboratory Program.

Chapter Three: Materials and Sensors

3.1 Materials

Several materials were selected on the basis of the previous research, as described in Chapter Two. This research indicated that epoxies, acrylics, and urethanes would be appropriate. Silicon-based materials are usually described as having very long curing times and are very flexible when cured. So-called "high-end" asphalt materials were also considered, but were rejected due to the sensitivity of the sensors, which makes compacting the asphalt impossible.

Most of these materials were selected after discussion with polymer product suppliers. A few were selected on the recommendation of the sensor manufacturer. One material tested was developed by a visiting researcher at the UT Construction Materials Research Group (CMRG). Each material is described below, under the designation used for this project. Appendix B lists the products' names with the suppliers' names and phone numbers. Table 3.1 at the end of this section gives a summary of the material components.

3.1.1 ECM P5G

This material was already in use by the Texas Department of Transportation (TxDOT) on a trial basis. It is a methyl methacrylate (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 peroxide. 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 peroxide 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.

3.1.2 Flexbond #11

This product from E-Poxy is a flexible epoxy coal-tar. It is usually used for sealing cracks and joints with a maximum width of 2.54 cm (1 in.). It comes in two parts, a straw-colored resin and a black hardener (with the coal-tar). Each of the two parts comes in a 4-liter (1-gallon) can. There is no aggregate included.

Using this material requires mixing equal parts by volume of the resin and hardener. Mixing should be done in a larger container, such as a 20-liter (5-gallon) bucket (which is not provided). The components should be mixed until the material attains a uniform color, which takes about two minutes. The material is then ready for use in the application. A fine mineral aggregate could be added, such as #1 blasting sand, with three parts of aggregate to one part of mixed epoxy, by volume. No aggregate was used for this project.

3.1.3 Flexolith

Flexolith is a flexible epoxy from Tamms, Inc., intended for making waterproof bridge-deck overlays and sealing joints. It comes in two packages, marked "A" (base) and "B" (hardener), with one gallon of "A" and two gallons of "B." There is no filler included in the package.

To use, the contents of the cans must be poured into another bucket (a 5-gallon (20-liter) bucket works well, but is not provided), with one part "A" and two parts "B" by volume. For this application, a filler consisting of silica fume and fine sand is also added, with a ratio of 3:1 by volume (aggregate to mixed binder). The exact gradation of the filler was developed by another researcher on the project and is described in an internal UT report.[21] The liquid parts are mixed thoroughly for about one minute, and then the filler is added, followed by about two more minutes of mixing. When the entire mass is at a uniform consistency, the mix is poured into the application.

3.1.4 HMMUP

"HMMUP" stands for *H*igh *M*olecular-weight *M*ethacrylate and recycled *U*nsaturated *P*olyester. This material was developed at the Construction Materials

Research Group by Yinhong Bao, a visiting researcher from China, as a way to recycle waste or scrap polyester materials. The formulation is complex, consisting of eight separate materials in varying amounts. A mineral filler was developed for this material along with the filler for Flexolith.[21]

Since this material is composed of so many parts, using it requires a careful system of mixing. The components are poured into a large container (such as a 20-liter (5-gallon) bucket) one at a time, with each addition followed by about 30 seconds of thorough mixing. After all the liquid parts are mixed, the aggregate is added, and the total material is mixed for about two minutes, until it achieves a uniform consistency. The HMMUP is then poured into the application groove.

3.1.5 IRD

This material is product AS-475 from International Road Dynamics, Inc. It is methyl methacrylate based, similar to ECM P5G, designed for installing piezoelectric classification sensors. It comes as black resin mixed with mineral filler in 5-, 15-, or 20-kg pails, with small vials (17- or 33-g) 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 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.

3.1.6 Masterfill CJ

Master Builders, Inc., makes this product for joint filling and sealing. It comes in two parts, a 1-gallon can of gray resin marked "A" and a 4-liter (1-gallon) can of clear-amber hardener marked "B." There is no aggregate, and no mixing container is provided.

To use this material, the components are poured into a large container (such as a 20-liter (5-gallon) bucket) in equal parts by volume. The material should be mixed until it attains a uniform color, which takes about two minutes, after which it is poured into the application. Fine aggregate could be added, but the manufacturer would have to be contacted to determine an appropriate gradation and mixing ratio. No aggregate was used for this project.

3.1.7 Schul

Schul International provided its Ready-Set Pavement Grout, a rigid epoxy designed for installing piezoelectric classification sensors. It comes in a complete application kit, which includes a 7.5-liter (2-gallon) bucket for mixing. Inside the bucket are two 0.95-liter (1-quart) cans, one each of resin and hardener, a bag of sand, and a mixing stick.

The application kit provided makes using this material a simple process. First, all the contents of the bucket are removed. The two 0.95-liter (1-quart) cans are emptied into the 7.5-liter (2-gallon) bucket and mixed thoroughly. The mixing stick can be used, but an electric drill and a mixing paddle work better. After the resin and hardener are mixed for about a minute, the sand filler is added. The combination is mixed until it achieves a uniform consistency (about two minutes with the drill). The material is then poured into the application.

3.1.8 Transpo T46

Transpo Industries provided its product T46, an epoxy coal-tar designed for joint filling and sealing. It is packaged in two 3.6-kg (8-lb), or about 3.8-liter (1-gallon), cans, one of clear resin and one of black hardener (with the coal-tar). There is no aggregate provided.

Using this material requires mixing the resin and hardener in equal parts by volume (or by weight, since the components have the same specific gravity). There is no mixing container provided, but a 20-liter (5-gallon) bucket works well. The components are mixed until they attain a uniform color. The material is then poured into the application. A fine mineral aggregate, such as #1 blasting sand, can be added, with three parts aggregate to one part mixed epoxy, by volume. No aggregate was used for this project.

3.1.9 TxDOT G-100

The TxDOT specification G-100 epoxy was the material being used by TxDOT before this project began. It is available from a number of companies around the country. The material is packaged in two cans, consisting of 13 parts of "A" (resin with filler) and 1 part "B" (hardener) by volume (25:1 by weight), for a total application mass of 5.2 kg (11.5 lb). The can containing part "A" is sufficiently oversized to accept part "B" and allow mixing without spilling.

To use, the resin and filler must be mixed, as the filler settles over time. Mixing should continue until part "A" is of a uniform consistency (about two minutes). The small can of hardener (part "B") is then poured into the larger can. This should then be mixed until it achieves a uniform color (also about two minutes). The material is then poured into the application.

Table 3.1: Summary of Material Parts

Material	Parts	Mixing Ratio
ECM P5G	Resin w/ Filler & BPO	1 pkg. BPO : 6 kg resin
Flexbond #11	Resin & Hardener	1 : 1 by volume
Flexolith	Base & Hardener	1 : 2 by volume 3 : 1 by volume Filler : Binder
HMMUP	Total of 8 various parts, plus Aggregate	Complex formulation 3 : 1 by volume Filler : Binder
IRD	Resin w/ Filler & BPO	Depends on temperature
Masterfill CJ	Resin & Hardener	1 : 1 by volume
Schul	Resin, Hardener, & Filler	1 : 1 by volume, plus Filler as provided
Transpo T46	Resin & Hardener	1 : 1 by volume
TxDOT G-100	Resin w/ Filler & Hardener	13 : 1 by volume

3.2 Sensors

A variety of sensors were used for this project. This section will describe the sensors used, beginning with the encapsulated film sensors that TxDOT was using before this project began. The bare cable sensors that were investigated are then described, with an explanation of the reasons TxDOT decided to try bare cable sensors instead of the encapsulated film sensors they used previously.

3.2.1. Encapsulated Film

The sensors used by TxDOT prior to this project were encapsulated film sensors. These consist of a piezoelectric film embedded in a flexible encapsulating material, encased in an aluminum channel. A cross-sectional diagram of this type of sensor in its installed configuration is shown in Figure 3.1.

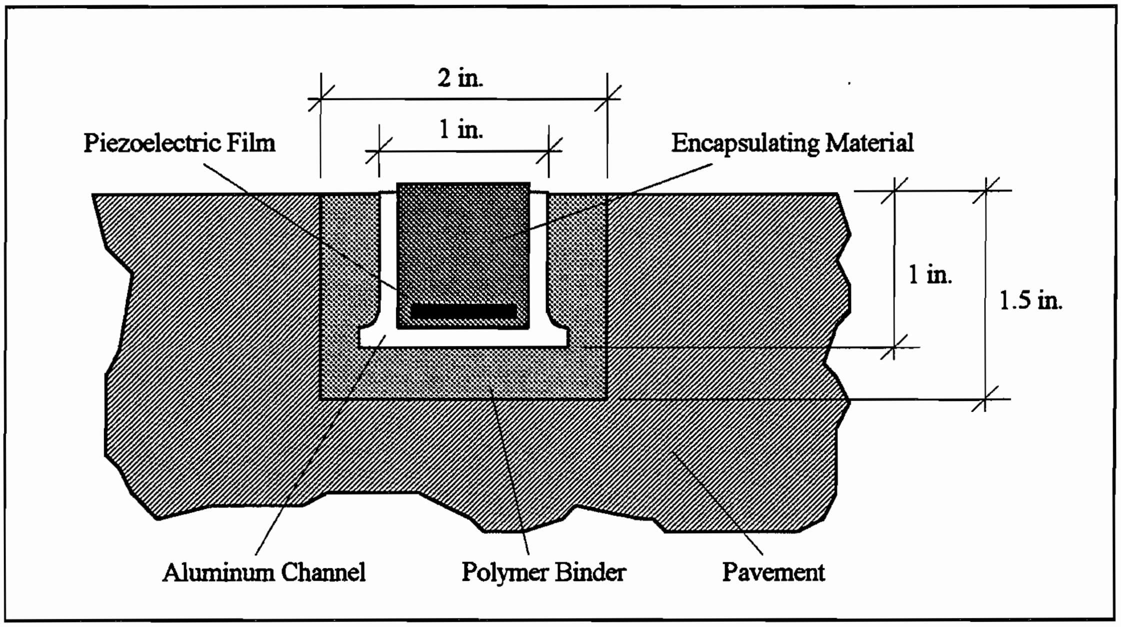


Figure 3.1: Encapsulated Film Sensor (Installed) (1 in. = 25.4 mm)

As shown in the figure, these sensors are installed so that the aluminum channel is flush with the pavement, but the encapsulating material extends slightly above the pavement to ensure contact with the tires of monitored traffic. This is achieved at installation by hanging the channel from cross-supports which are placed on bituthane tape to raise the sensor to the proper level. The cross-supports are cut off after the polymer binder sets. The flanges at the bottom of the aluminum channel were not part of the original design, but were later added to the design to help improve the mechanical bond between the channel and the polymer binder.

3.2.2. Bare Cable

As part of this project, TxDOT decided to try using bare cable sensors. These consist of the bare piezoelectric cable installed directly into the road, with no factory-made casing and encapsulating material. The sensor is supported in the slot by plastic chairs, usually used for supporting reinforcement bars, spaced at 30.5-cm (1-foot) intervals along the length of the sensor. A cross-section of this type of sensor installation is shown in Figure 3.2. The cable is placed approximately in the center of the groove, and the polymer binder is extended slightly above the pavement to ensure good contact with vehicle tires. Bituthane tape is used to contain the polymer above the pavement surface while it sets.

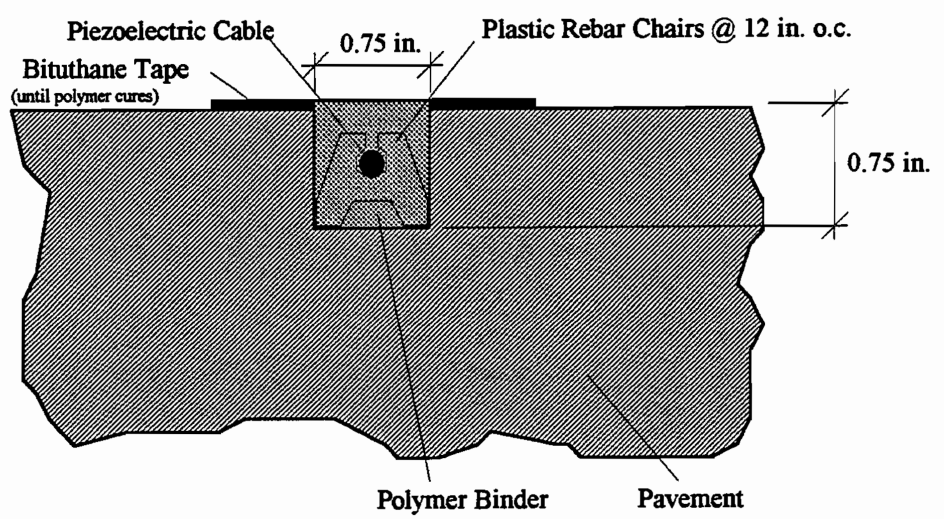


Figure 3.2: Bare Cable Sensor (Installed) (1 in. = 25.4 mm)

TxDOT 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 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 and the cut extends into the base. 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 the sensor from conforming 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.

Chapter Four: Laboratory Test Program

4.1 Screening Tests

The materials selected for this project were subjected to laboratory tests in order to determine their general material properties. The properties tested were selected on the basis of their presumed influence on the behavior of the material at installation and during in-service conditions. Most of the tests performed were American Society for Testing and Materials (ASTM) tests, as described below.[22]

4.1.1 Abrasion

The abrasion test was performed to determine the resistance of the material to wear by traffic. The testing procedure is fully described by ASTM C 944. The test consists of subjecting a flat sample of the material to an abrasion spindle rotating at 100 rpm under a constant load of 10 kg (22 lb). The sample is weighed before and after the abrasion, which lasts for two minutes. The weight in grams lost due to the abrasion is recorded as the result. The test setup is shown in Figure 4.1.

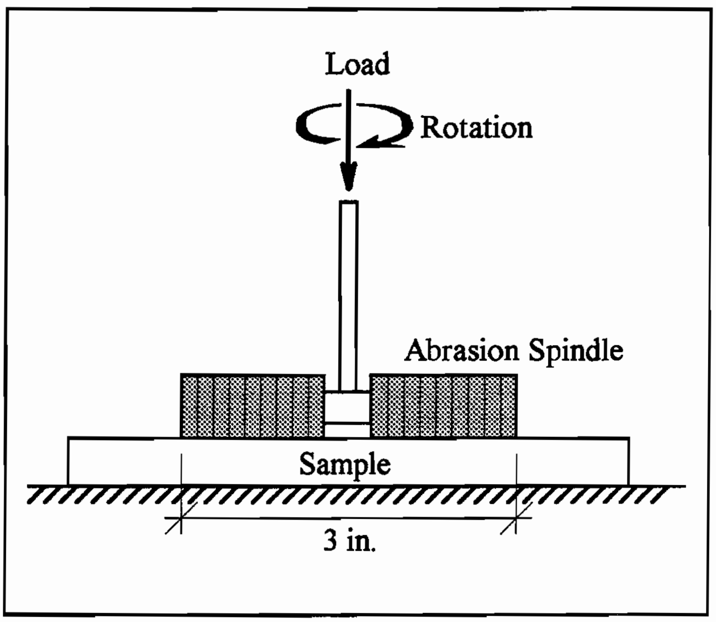


Figure 4.1: Abrasion Test Setup (1 in. = 25.4 mm)

4.1.2 Compressive Strength

A compression test was performed according to ASTM C 116-90. This test uses one-half of a 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 4.2. 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 $in.^2$).

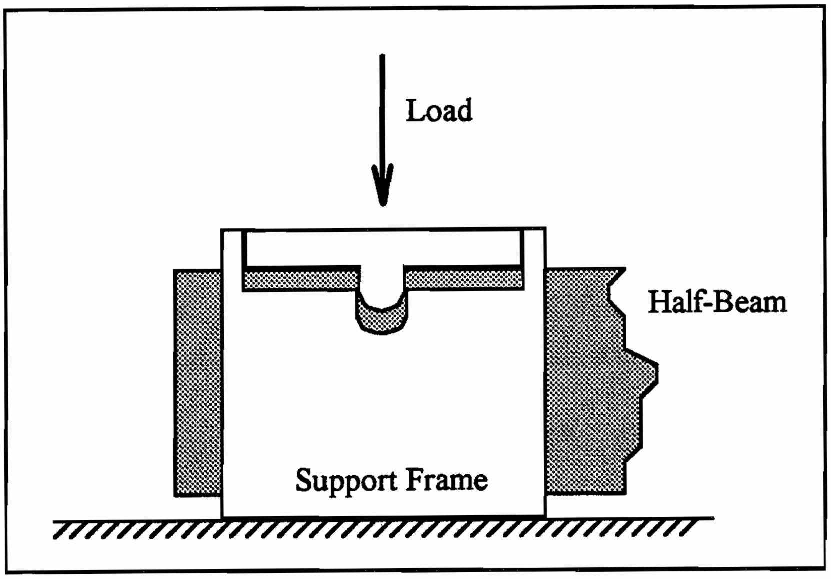


Figure 4.2: Compressive Test of Half-Beams

4.1.3 Dynamic Properties

The complex modulus, a dynamic property, was measured according to ASTM D 5023. The complex modulus, which is the ratio of stress to strain in a viscoelastic material, was measured instead of the modulus of elasticity because it was felt that this dynamic test would more accurately reflect the loading pattern caused by traffic flow over a sensor. The test involved cyclically loading a beam in flexure (to about 40% of its ultimate flexural capacity) and then monitoring the load and the deflection over time. The basic test setup is shown in Figure 4.3. The deflection pattern matches the loading pattern, in this case a sine-wave, with a slight shift in the pattern, called the phase angle, denoted as "δ," as shown in Figure 4.4. The phase angle is then used to calculate E^*, the complex modulus.

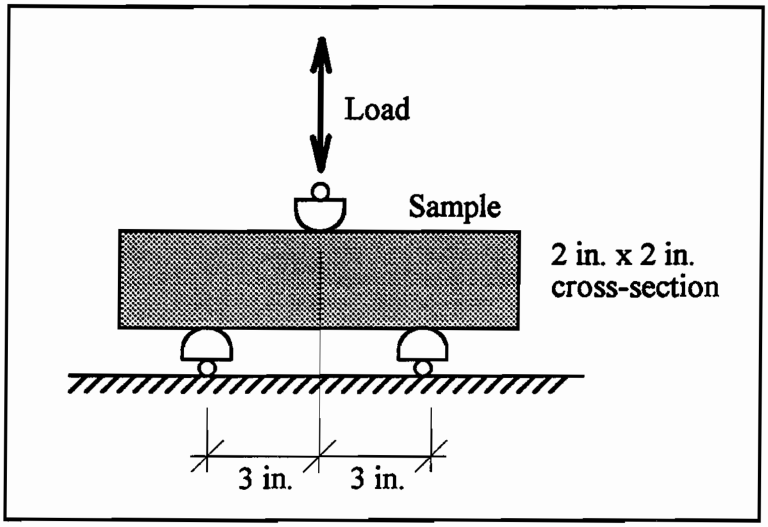


Figure 4.3: Complex Modulus Test Setup (1 in. = 25.4 mm)

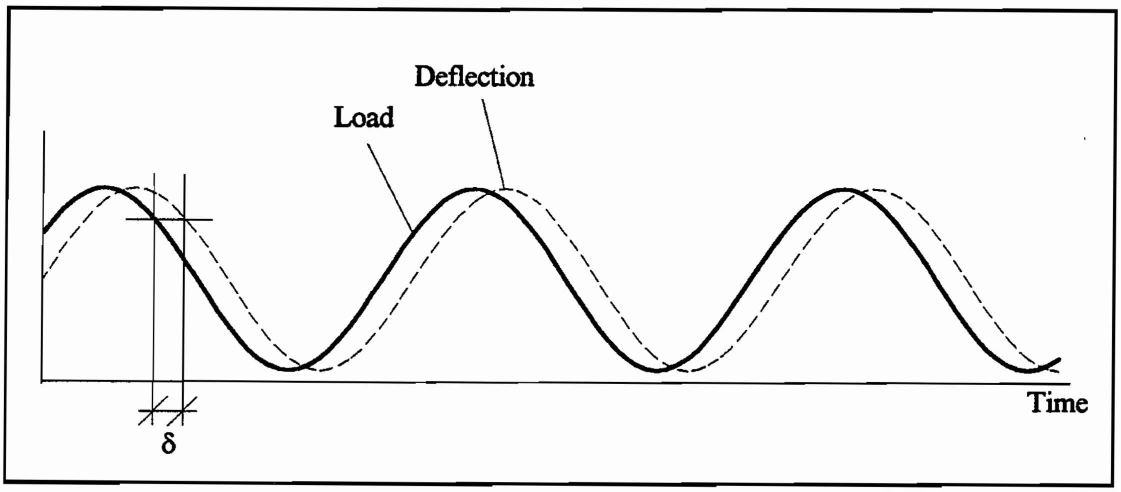


Figure 4.4: Definition of Phase Angle δ

After the complex modulus test was run, it was discovered that the results were not very accurate. In order to obtain a more accurate measure of the flexibility of the materials, the complex shear modulus test was run according to AASHTO TP5. This test is used 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, 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. Like the complex modulus, the load and deflection are monitored over time, with the offset in time between them measured as the phase angle δ. The equipment used gives this value directly, so there is no need to plot graphs, then visually measure the offset. The equipment also gives the complex shear modulus G^* directly. The two values, δ and G^*, can then be used to calculate other properties for the purpose of comparing them with asphalt properties. This method was seen to give much more accurate results.

4.1.4 Flexural Strength

A standard flexural strength test was performed according to ASTM C 293-79. The beam was tested with single point loading, like the complex modulus test shown in Figure 4.3, except that the load was applied at a constant strain rate until failure. The flexural strength is then calculated by the following formulas:

$$f_r = M/S$$

$$M = PL/4$$

where f_r is the flexural stress at rupture, M is the moment at rupture, S is the section modulus, P is the load at rupture, and L is the span of 15 cm (6 in.).

4.1.5 Gel Time

As a measure of the working time available in which to use the materials, the gel time was 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 temperature was defined as the peak temperature achieved due to the exothermic reaction of the curing material. Gel time is the time at which this peak exothermic temperature is reached. For most materials, these definitions gave similar results to those of the ASTM definition, but were easier to measure because the peak temperature is less subjective than the existence of a gelatinous mass.

4.1.6 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) was 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 4.5. The shrinkage (or expansion) rate is expressed as a percentage.

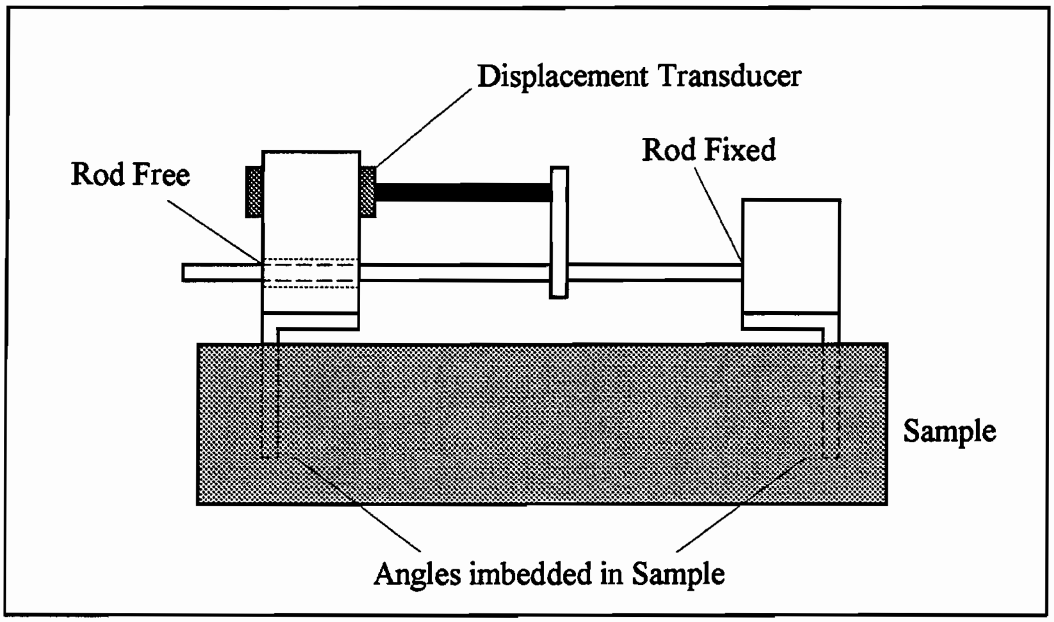


Figure 4.5: DuPont Shrinkage Test Setup

4.1.7 Thermal Expansion

Paving materials can expand significantly with rising temperatures, so it is important to attempt to match this thermal expansion with the materials used to install the sensors, to minimize stress concentrations. To this end, the coefficient of thermal expansion, α, was measured using ASTM E 831. This test uses small cylindrical samples 13 mm (0.5 in.) in diameter and 25 mm (1 in.) long. The samples are placed in a fused-quartz tube which is immersed in a temperature-controlled water-bath. A fused-quartz rod is placed on top of the sample (fused quartz is used due to its small α), extending out of the tube to a point at which the movement caused by changes in length of the sample can be measured with an electronic displacement transducer. The water bath is brought down to 0° C (32° F) with ice, then heated at a constant rate to about 50° C (122° F). The bath is then allowed to cool back down to room temperature. The displacement of the sample is monitored over time, to generate a temperature vs. displacement curve. The slope of this curve is α. Figure 4.6 shows the test setup.

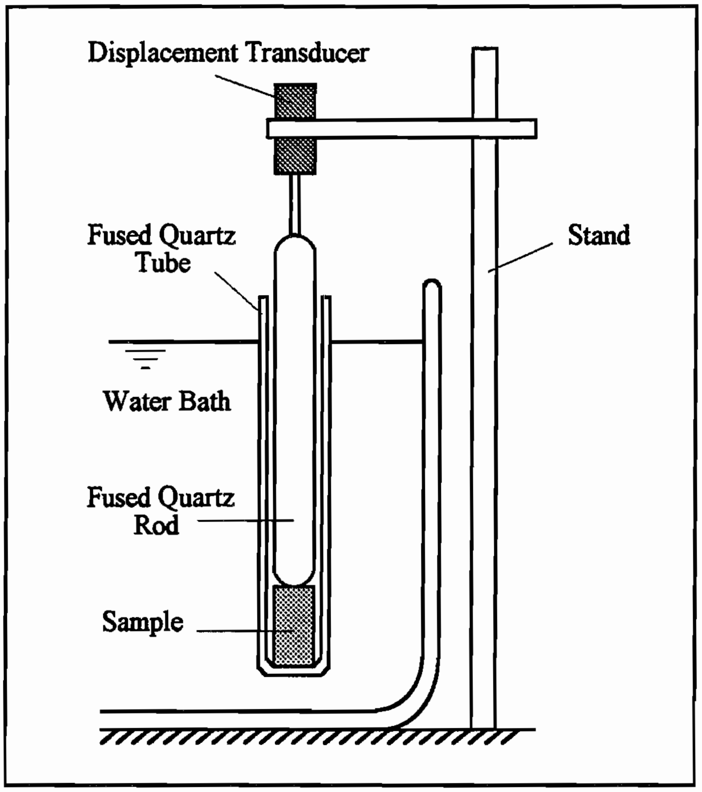


Figure 4.6: Thermal Expansion Test Setup

4.1.8 Vicat Set Time

Gel time was used to estimate the working time available after mixing the materials. Testing to determine the setting time 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. The test setup is shown in Figure 4.7.

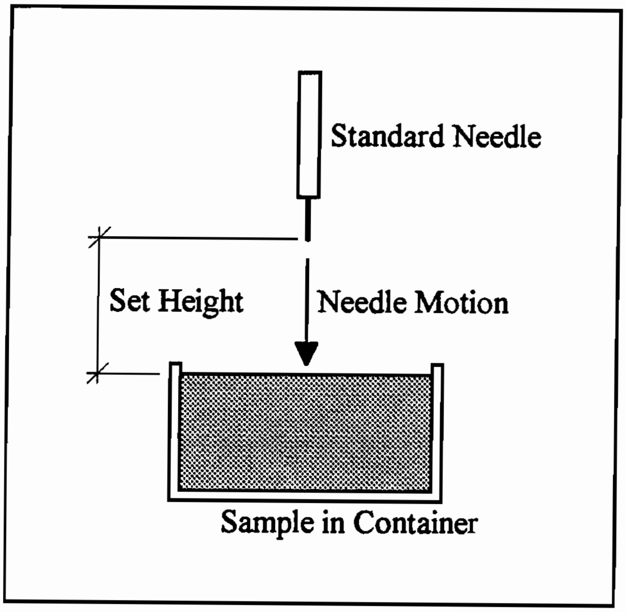


Figure 4.7: Vicat Needle Test Setup

4.1.9 Viscosity

The workability of the materials in their uncured state was estimated by measuring their viscosity 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.

4.2 Compatibility Tests

In addition to determining the basic physical properties of the materials, this project also determined the compatibility of these materials with portland cement concrete and asphalt paving. This compatibility testing consisted mainly of studying the bond behavior of these materials. The most promising materials had their bond characteristics tested at the extreme temperatures likely in the field, 0° C (32° F) and 50° C (122° F).

4.2.1 Bond Strength

The bond strength of these materials was tested under flexure, shear, and pure tension. The concrete used for these tests was cast in the lab, then cut to the appropriate size with a diamond-bit saw. The asphalt samples were cut from asphalt paving that had been removed from the roadway. All bond surfaces were cleaned before the polymer materials were cast against them.

4.2.1.1 Flexural Bond Test

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. As in the simple flexural test (4.1.4 above), 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 4.8.

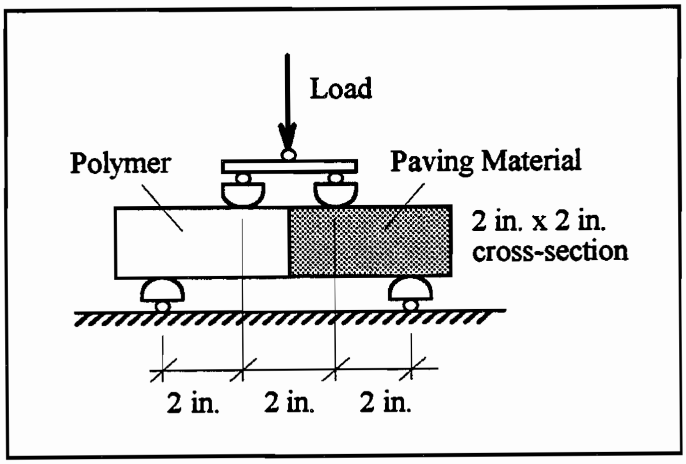


Figure 4.8: Flexural Bond Test Setup (1 in. = 25.4 mm)

4.2.1.2 Shear Bond Test (Pull-out)

The shear-strength of the bond was measured using a pull-out test developed for this project. The samples are prepared by drilling a 76-mm- (3-in.-) diameter hole in the paving material, about 76 mm (3 in.) deep. An aluminum plate with a 50-mm (2-in.) U-bolt attached is placed so that its top surface is 50 mm (2 in.) deep in the hole. The space between the plate and the side of the hole is sealed with a silicon sealant, and then the hole is filled with the test material. After the material cures (at least 24 hours), the sample is placed in a loading rig set for a tensile load, the U-bolt is attached, and the material is pulled out. The ultimate load required to pull out the polymer plug is then divided by the shear area. The shear area is found by the formula $A = \pi hd$ where A is the shear area, h is the depth of the sample material above the plate, and d is the diameter of the hole. The test setup is shown in Figure 4.9.

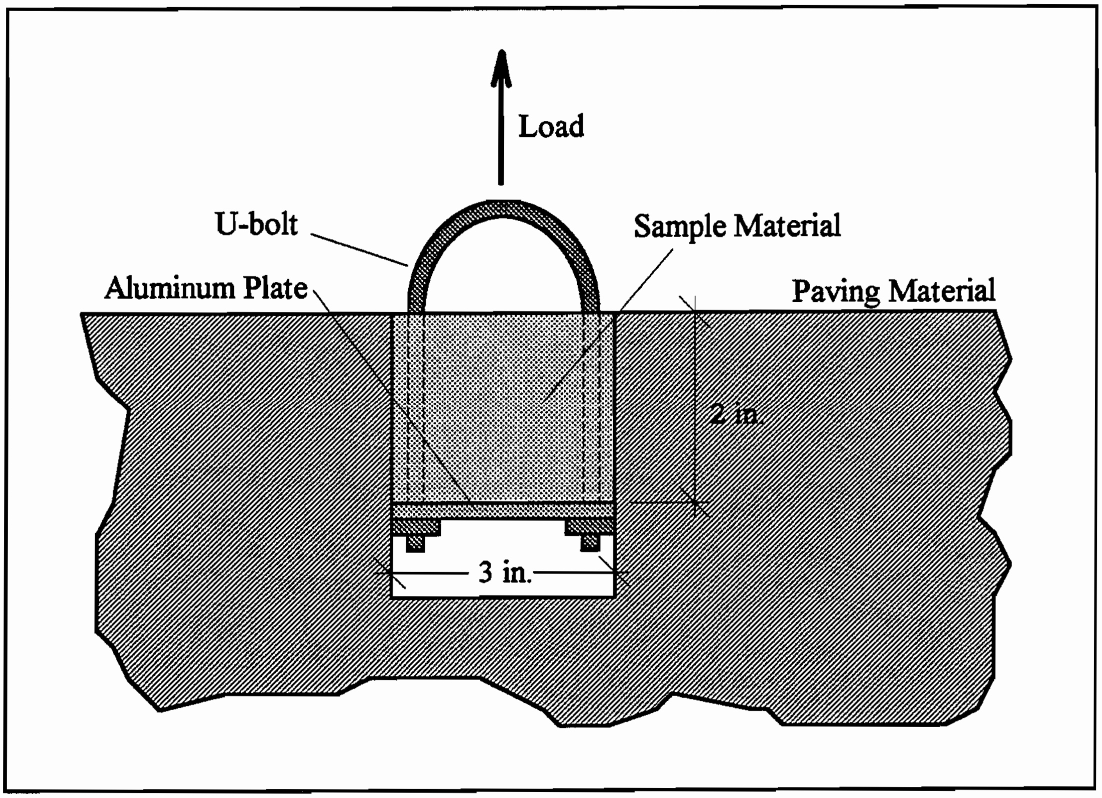


Figure 4.9: Shear Bond Pull-out Test Setup (1 in. = 25.4 mm)

4.2.1.3 Tension Bond Test (Pull-up)

The tensile strength of the bond was tested using a pull-up test according to ACI 503R. To run this test, a 13-mm (0.5-in.) layer of the material being tested is poured onto the top of a slab of paving material. After it cures, a coring machine is used to core through the polymer material into the paving substrate. A steel disk is then bonded to the top of the polymer with a high-strength, fast-setting epoxy designed for this test. The plate is then pulled up, and the ultimate force required to break the sample is divided by the tensile area (the cored area). Figure 4.10 shows the test setup.

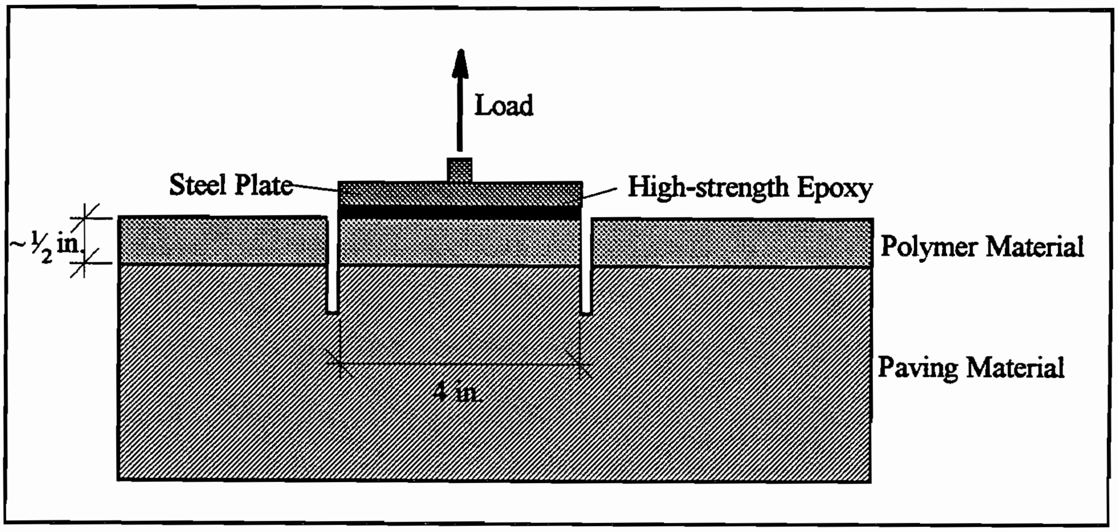


Figure 4.10: Tension Bond Pull-up Test Setup (1 in. = 25.4 mm)

4.2.2 Freeze/Thaw Tension (Pull-up)

To determine the effect of changing temperature on the bond strength, pull-up samples were subjected to cycles of freezing and thawing according to ASTM C 884-87. The samples were cycled between -15° C (5° F) and 25° C (77° F) (room temperature) for a total of 8 cycles. The pull-up test was then run on these samples and the results were compared to the results from testing samples kept at room temperature.

4.2.3 Extreme Temperature Tests

The flexure and shear bond strength was also determined for samples at the likely extreme service conditions of 0° C (32° F) and 50° C (122° F). Screening tests were also run at these temperatures. These tests should show significant changes from those at room temperature, as the materials under consideration are meant to be similar to asphalt in their response to temperature changes.

Chapter Five: Field Trials

5.1 Installation Procedure

The materials under consideration for this project were also tested in the field in trial installations. Before the trial installations could be made, the installation procedure in use by TxDOT had to be observed. To this end, two installations were monitored, one in San Angelo and one in Tilden. Both of these installations were in asphalt pavement, and at that time TxDOT was still using the encapsulated film sensors. The installation consisted of the following steps:

- General site preparation is performed, such as digging a trench from the road to the signal box for the conduit carrying the signal wires from the sensors. If necessary, a new signal box is installed and prepared to accept the new lines.
- The exact position of the sensors and wire loops is located, using tape measures and straight-edges, and the location is marked with chalk line, wax markers, and spray paint.
- A water-cooled diamond-bit concrete saw is used to make the wire-loop and signal-wire cuts. These cuts are made about 20 mm ($^3/_4$ in.) deep and 3 mm ($^1/_8$ in.) wide, which is the width of the saw blade. A gang-blade consisting of three normal saw blades is used to cut the groove for the sensor, which takes two passes. The groove is cut about 50 mm (2 in.) wide and 40 mm (1.5 in.) deep.
- The cuts and the groove are cleaned with pressurized water. This drives out any debris left over from cutting.
- The cuts and the groove are dried with air-blowers. The pressurized air forces out the water and dries the surface. Some water is invariably left in the groove, as it is very difficult to completely dry it in a reasonable amount of time.
- The piezoelectric sensors are installed into the groove. The groove is filled about half full with polymer binder, and then the sensor is forced down into the polymer. The sensor is held in place at the correct depth in

the groove by temporary cross-bars. Next, the rest of the groove is filled with more polymer. The polymer is then tooled to ensure that there are no air pockets around the sensor.

- The wire loop inductance sensors, which consist simply of insulated wire laid into rectangular cuts in the pavement, are installed. The cuts are then sealed with silicon loop sealant. The signal wires for the piezoelectric sensors are also sealed in this step.
- The installation is cleaned when the polymer gels by cutting off the cross-bars and removing the tape laid next to the sensor groove. This tape is used to control overflow of polymer from the sensor groove and to properly locate the cross-bars. When it is removed, it leaves a clean installation with no cured polymer bumps near the sensor which could affect the accuracy of the sensor readings.

Figure 5.1 shows a site plan of a sensor installation. Figures 3.1 and 3.2 show cross-sectional views of the sensor groove.

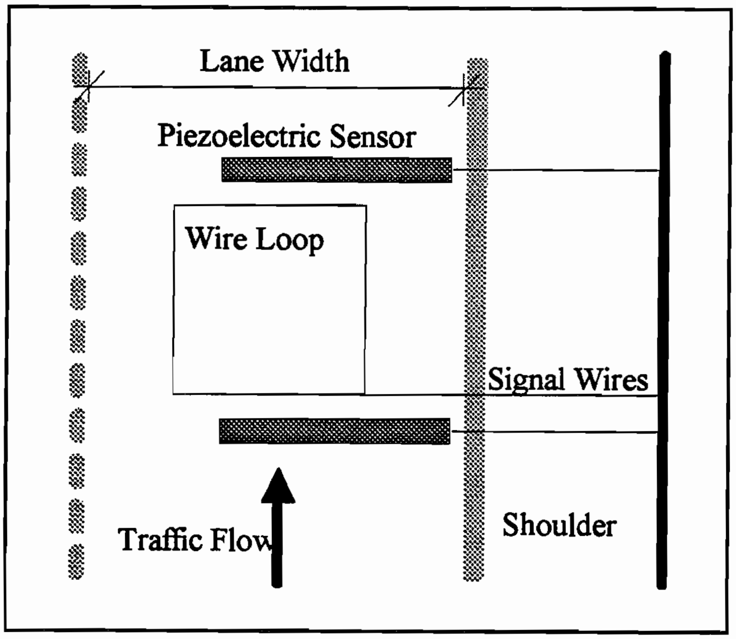


Figure 5.1: General Site Plan of Sensor Installation

The rest of the field installations used the bare cable sensor design. The installation process differed from that described earlier since the groove is now much smaller. A single pass with the gang blade is sufficient to cut the groove. Also, cross-bars are no longer used; instead, the bare cable is supported by plastic chairs placed in the groove before adding any polymer. After the cable is seated in the chairs, the polymer is used to fill the groove. Three bare cable installations are described in the following sections. The site locations were chosen to allow testing in the widest range of the environmental factors temperature and humidity.

5.2 San Angelo

The first installation using the bare cable sensor design was near San Angelo, on U.S. Highway 67, 10 miles south of San Angelo Loop 360, for testing in a hot and dry climate. The site was installed on June 2, 1993, beginning at 8:30 AM. It has two lanes, one each for north-bound and south-bound traffic, for a total of four piezoelectric sensors. The paving material at this site is asphalt. Four materials were used, one for each sensor. The materials used were ECM P5G, Flexolith, IRD, and Schul. A site plan of the installation is shown in Figure 5.2.

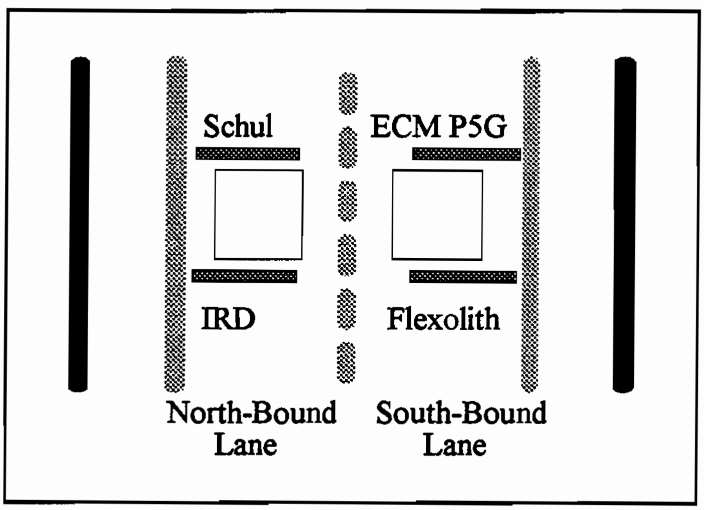


Figure 5.2: San Angelo Installation Site Plan

5.3 Amarillo

The second field test installation of the bare sensor cables was near Amarillo, on IH-40. This site was selected for testing materials in a cold and dry climate. This site has four lanes of asphalt pavement, so there are eight sensors. The installation was made on June 8, 1993, beginning at 8:00 AM. Four materials were used at this site, one for each lane, meaning that two sensors were installed with each material. The four materials used were ECM P5G, IRD, Masterfill CJ, and a product from Poly Carb called M-266. The Poly Carb M-266 is very similar to Flexolith, but it was later dropped as a candidate owing to difficulty in obtaining the material from the manufacturer. Figure 5.3 shows a site plan of the installation, with the signal box to the left (not shown).

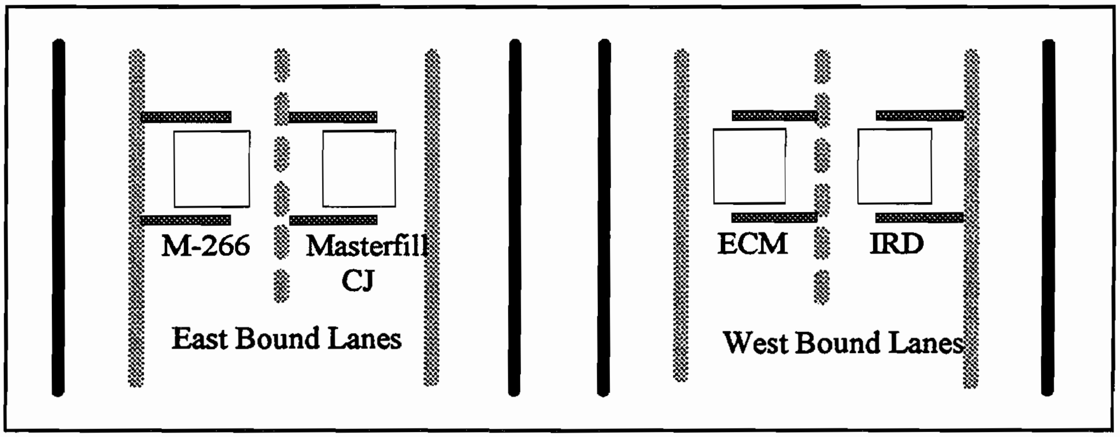


Figure 5.3: Amarillo Installation Site Plan

5.4 Laredo

The final field trial was installed near Laredo, on IH-35, just south of U.S. Highway 83, on August 18 and 19, 1993, beginning at 7:00 AM. each day, with work continuing until about 2:00 PM. This location tests the materials under hot and humid conditions. The roadway is four lanes of asphalt paving. Six materials were used to install the eight sensors. The materials used were ECM P5G, Flexbond #11, IRD, Transpo T46, Schul, and another product from Poly Carb called M-163. The ECM P5G and the IRD were each used for two sensors, while the other materials were each used for one sensor. Again, the Poly Carb material used was very similar to Flexolith, but had to be dropped as a candidate because it was difficult to obtain. Figure 5.4 shows the site plan of this installation, with the signal box to the left (not shown).

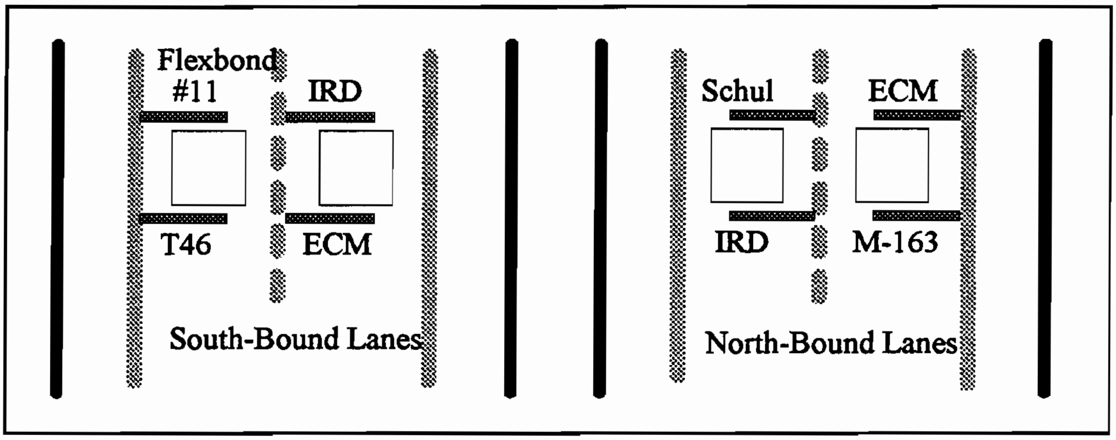


Figure 5.4: Laredo Installation Site Plan

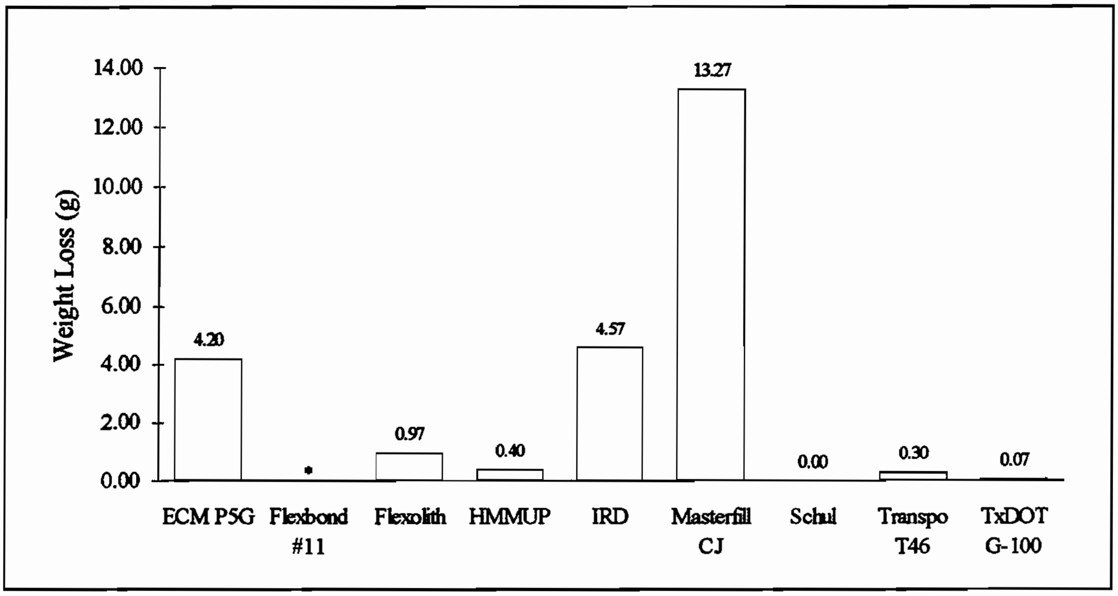
Chapter Six: Test Results

6.1 Screening Tests

The materials selected for this project were subjected to basic materials tests in order to determine their physical properties. The materials and tests are described in Chapters Three and Four, with the results described in this chapter. The bar graphs used in this chapter include numerical values indicating the average value. No bar and no numerical value indicates that the property could not be measured, usually because of extreme flexibility in the tested material. Appendix C shows the raw data as collected.

6.1.1 Abrasion

The abrasion test was run on three samples of each material, with the average weight loss reported as the result. The results are shown in Figure 6.1.



* could not be measured

Figure 6.1: Abrasion Test Results (1 oz = 28.4 g)

As shown in the figure, most materials had very little weight loss. The exceptions were ECM P5G, IRD, and Masterfill CJ (the test could not be run on

Flexbond #11 due to its extreme flexibility). Generally, the more flexible the polymer, the more it was abraded. The weight lost from Flexolith, HMMUP, and TxDOT G-100 was mostly in the form of aggregate particles that were pulled out of the polymer matrix. The abrasion of Schul was negligible.

6.1.2 Compressive Strength

Compression tests were run on half-beams broken in the flexural strength test. The test was run on about three samples of each material; then the values obtained were averaged to get the results shown in Figure 6.2.

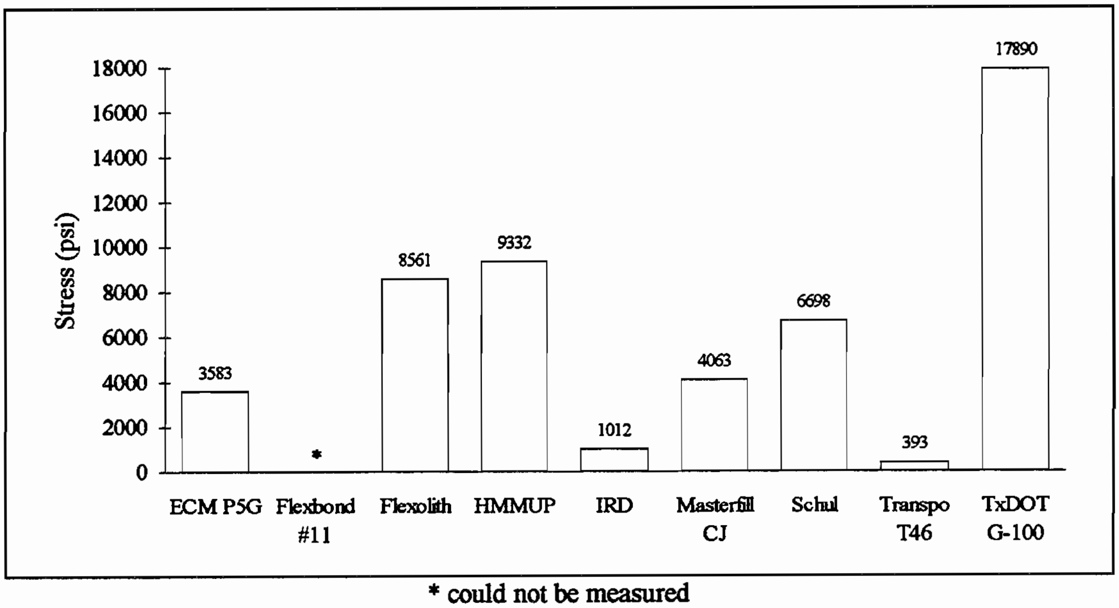


Figure 6.2: Compressive Strength Test Results (1 psi = 6.9 kPa)

Generally, the more flexible the material, the lower its ultimate compressive strength. Many of the more flexible materials had poorly defined ultimate strengths, as they did not crush. Instead, these materials eventually required less load to produce additional deflection. The peak load applied was then used to calculate the compressive strength. The materials that behaved this way were ECM P5G, IRD, Masterfill CJ, and Transpo T46. The results for Flexbond #11 were inconclusive, as the material was too flexible and deformed under very little load, with no observed peak load.

6.1.3 Dynamic Properties

Because of the service loading pattern expected for this application (that of transitory loads quickly applied and removed), it was decided to measure the complex modulus E^* instead of the static modulus of elasticity E. The results of this test at three temperatures are shown in Figure 6.3.

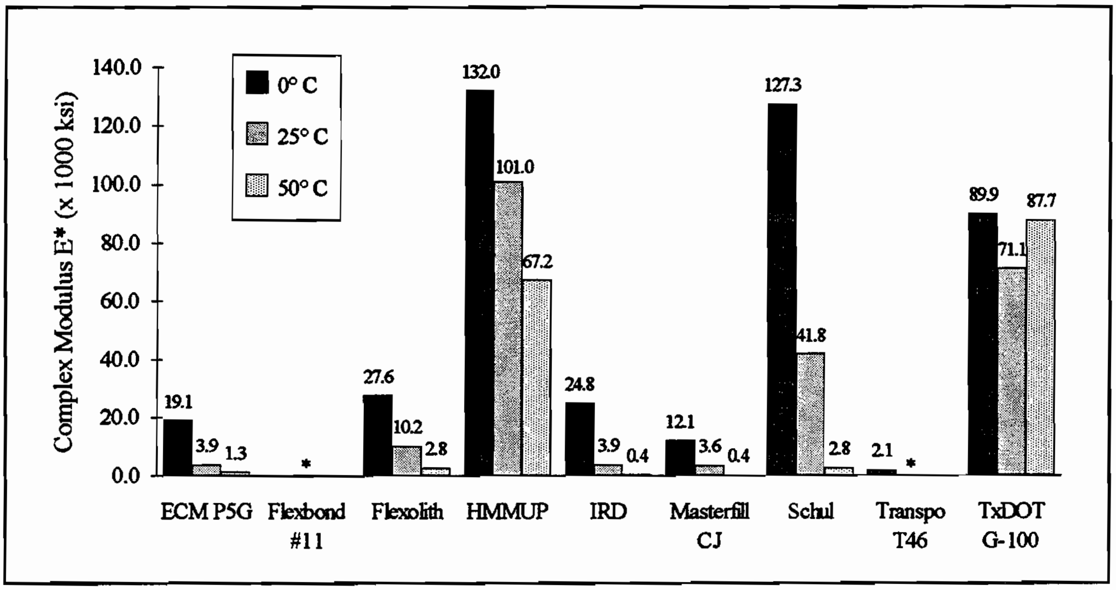


Figure 6.3: Complex Modulus E^* Test Results (1 ksi = 6.9 MPa)

Calculating the results for this test was very difficult, as the phase angle δ had to be measured visually from plots of the load and deflection. Also, many of the materials were so flexible that they made contact with the support frame at times during the loading cycle, thus further reducing the accuracy of the test. Averaging the results of three samples for each material reduced the error to a slight degree.

Owing to the problems in measuring the complex modulus, it was decided to measure the complex shear modulus, G^*. This test was much easier to run, as the equipment used is fully automated. The load and deflection curves are monitored by a computer which then calculates the phase angle for each cycle, then averages them over many cycles while checking for acceptable variability. The equipment also directly measures the complex shear modulus, G*. The average results of this test on three samples of each material are shown in Figures 6.4. and 6.5.

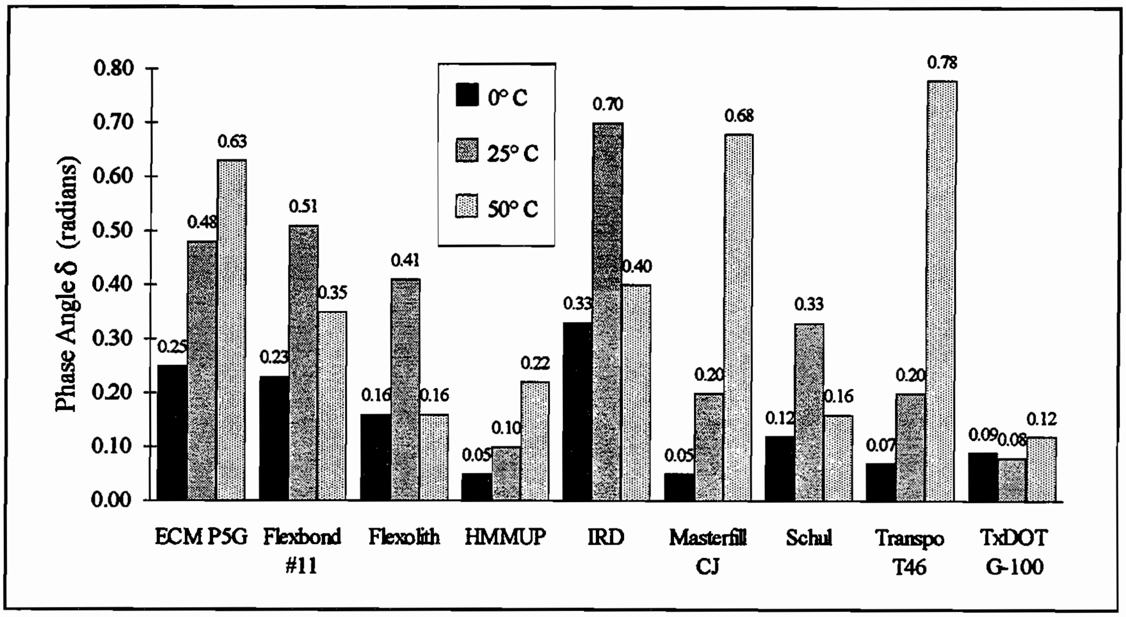


Figure 6.4: Complex Shear Modulus Test Phase Angle δ Results

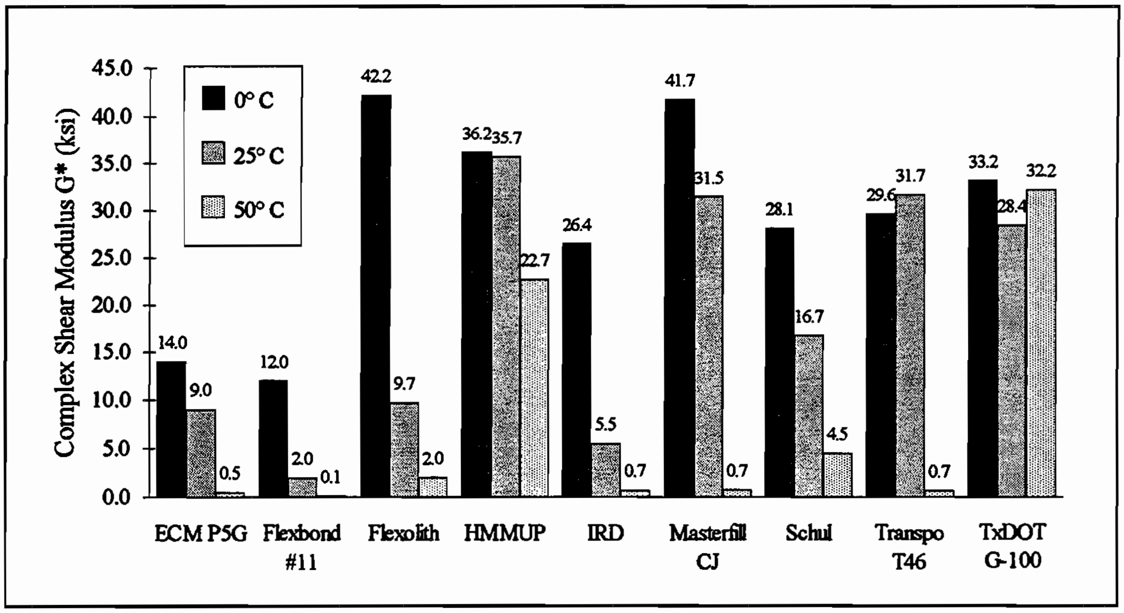


Figure 6.5: Complex Shear Modulus Test G* Results (1 ksi = 6.9 MPa)

The complex shear modulus G* and the phase angle δ are used to define a material's viscoelastic properties, specifically the storage modulus G' and the loss modulus G". The storage modulus is analogous to the modulus of elasticity and represents recoverable deformations. The loss modulus is analogous to viscosity and represents unrecoverable deformations. Figure 6.6 shows how these values are defined.

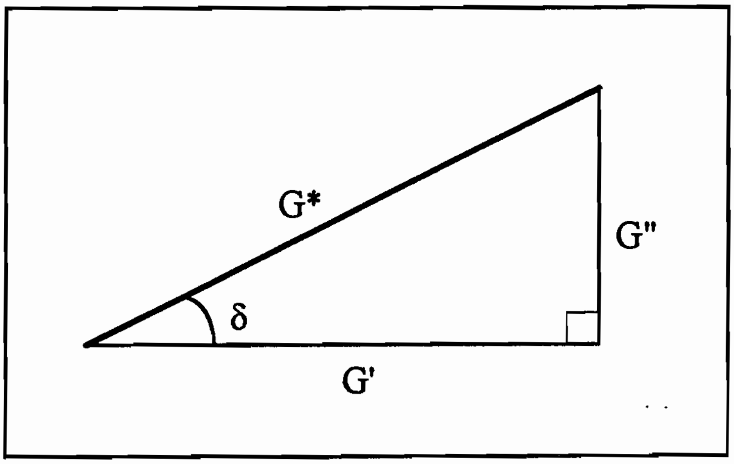


Figure 6.6: Definition of Storage Modulus G' and Loss Modulus G"

As shown in Figure 6.6, if G* remains constant as δ increases, G' decreases and G" increases. Thus, a material with δ = 0° would be perfectly elastic, and a material with δ = 90° would be perfectly viscous. Obviously, the materials under consideration lie between these extremes, and are thus viscoelastic materials, like asphalt.

Asphalt pavements behave less elastically and more viscously with rising temperatures, indicating that the δ of asphalt increases with rising temperature. Therefore, qualitatively, materials that increase δ with increases in temperature behave similarly to asphalt and are therefore compatible with asphalt. ECM, HMMUP, Masterfill CJ, and Transpo T46 are the materials that behave this way.

The complex shear modulus G* determines the magnitude of G' and G", but may increase or decrease with temperature. For this application, however, only the storage modulus G' matters, as the loads applied are too transitory to create any viscous effects. Generally, G' should decrease with temperature, similarly to asphalt, as the material becomes softer. Figure 6.7 shows the G' values at the three temperatures.

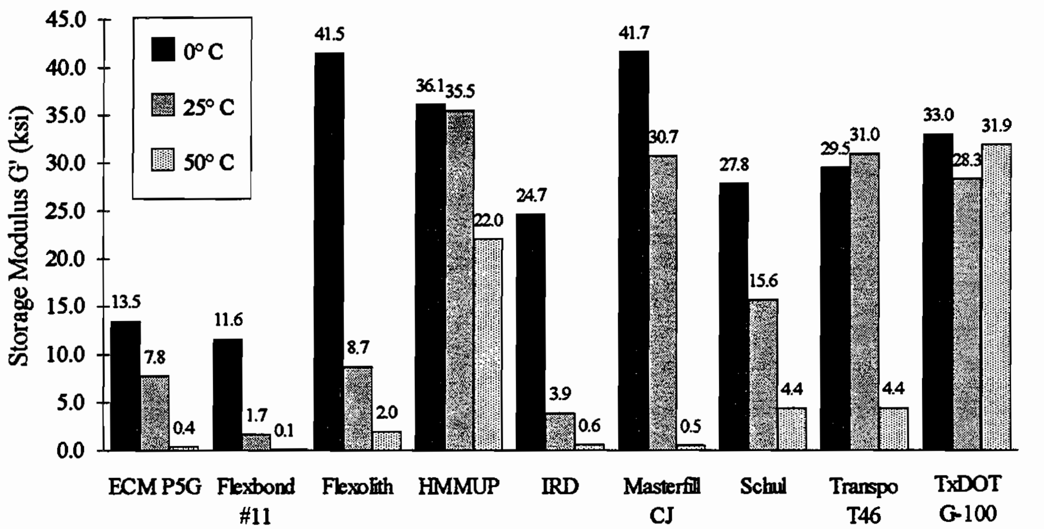
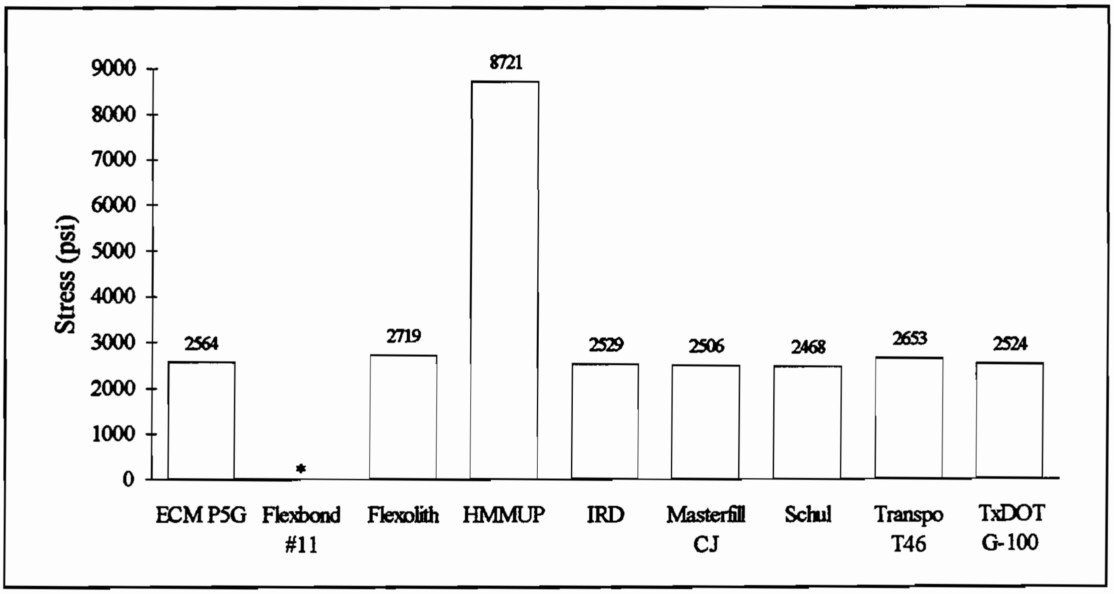


Figure 6.7: Complex Shear Modulus Test Storage Modulus G' Results
(1 ksi = 6.9 MPa)

6.1.4 Flexural Strength

The flexural strengths of the materials were found with simply supported beams loaded at midspan. The beams were loaded to failure to determine the ultimate flexural strength. Unfortunately, some materials were too flexible to fail by rupture. These materials attained a peak load, then required less load to continue deflecting. For these materials, the maximum load attained was used to calculate the flexural strength. The test produced no useful results for Flexbond #11, as the load continued to increase until the beam had deflected so much that its midspan was resting on the testing machine table between the supports. The test was run on about three samples of each material, and then the average of these results was found. The results of this test are shown in Figure 6.8.



* could not be measured

Figure 6.8: Flexural Strength Test Results (1 psi = 6.9 kPa)

As shown in the figure, most of the materials had essentially the same flexural strength. The only exception was HMMUP, for which there was no apparent explanation.

6.1.5 Gel Time

This simple test was used to estimate the working time available after each material was mixed. The temperature of the materials was monitored over time. The time the peak temperature was reached was recorded as the gel time, with the temperature recorded as the gel temperature. Samples were used at each of three temperatures. The gel time for each material at each temperature is shown in Figure 6.9.

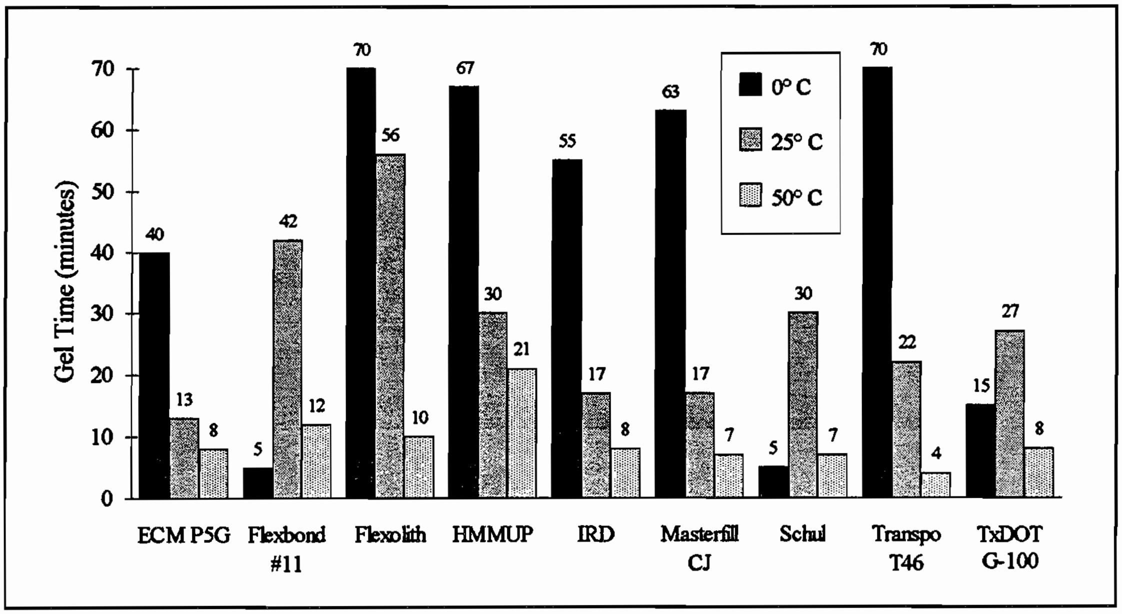


Figure 6.9: Gel Time Test Results

The results at low temperatures are somewhat misleading, as some materials gained very little heat from the exothermic curing reaction, and the time reported was the time at which that temperature was first attained. These materials maintained that temperature for extended periods of time and were probably still workable for some time after attaining the peak temperature.

6.1.6 Shrinkage

The shrinkage of the materials was measured using the DuPont shrinkage device. This test measures shrinkage as a percentage reduction in the length of a sample from the original length. Obviously, negative shrinkage is expansion. The results are shown in Figure 6.10.

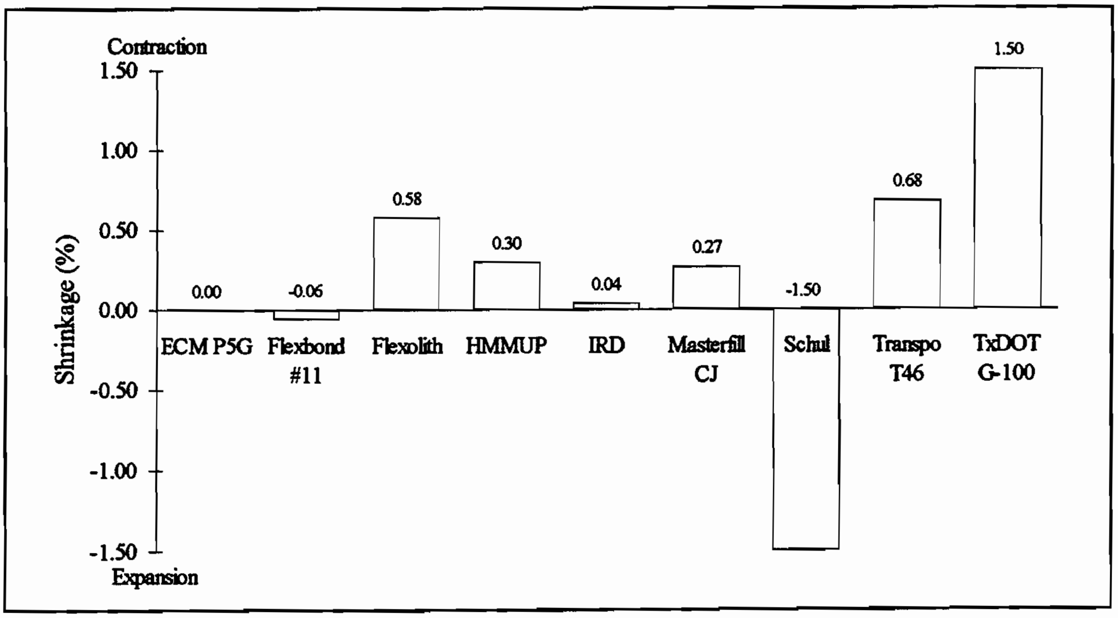


Figure 6.10: DuPont Shrinkage Test Results

The results show that most materials have very little shrinkage. The relatively high shrinkage of TxDOT G-100 could be one reason that material performed poorly in the past, as the material pulled away from the sides of the sensor groove (the contraction would be even greater in the larger grooves previously used for this application, due to the larger original dimensions). A couple of materials, Flexbond #11 and Schul, actually expanded while curing. In the field, the high expansion of Schul could produce a superior bond strength. However, if the expansion is too great, it could actually damage the asphalt in the vicinity of the sensor groove.

6.1.7 Thermal Expansion

Measuring the coefficient of thermal expansion, α, involves plotting a displacement versus temperature curve and finding its slope. This measurement is complicated, however, by the fact that most materials behave differently above and below their glass transition temperature, T_g. This property of the material is easily measured, as the change in α at that temperature is reflected as a change in slope of the displacement-temperature curve. Figure 6.11 shows an example of this effect. Figure 6.12 shows the average transition temperatures for the materials.

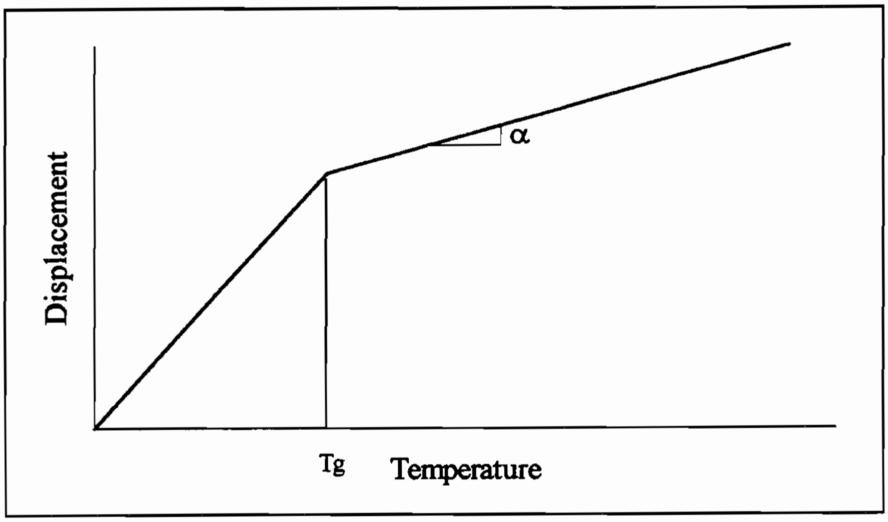
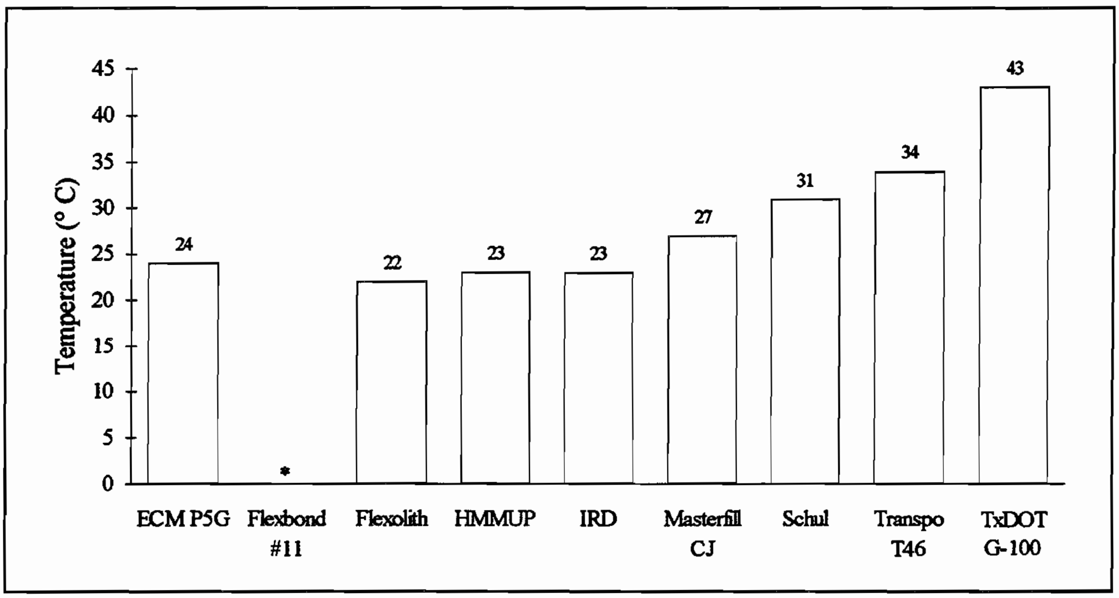


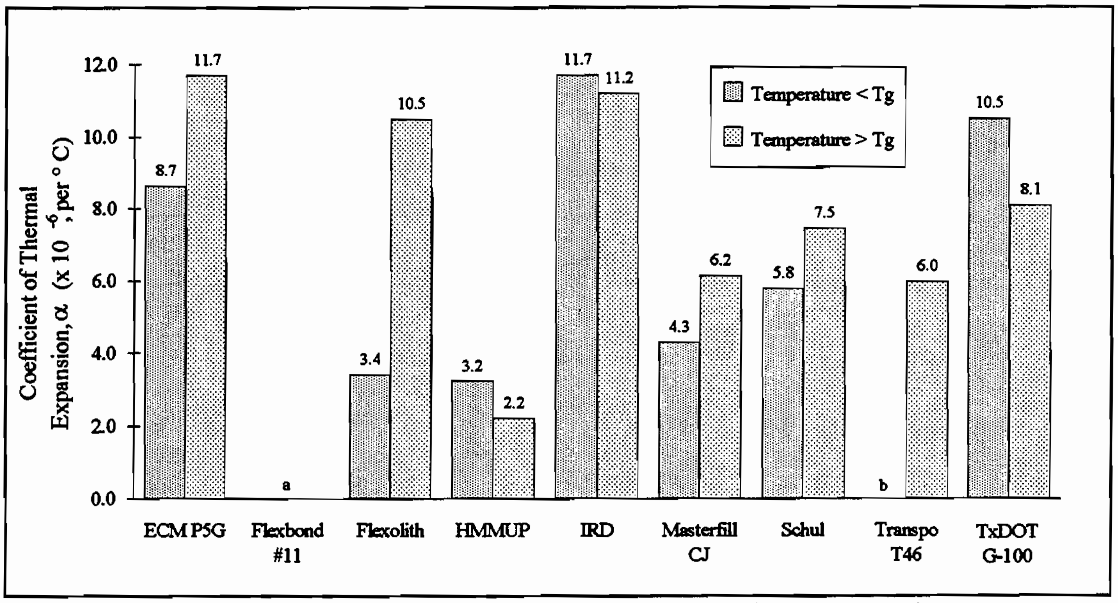
Figure 6.11: T_g Determined from Displacement Versus Temperature Response



* could not be measured

Figure 6.12: Glass Transition Temperatures

The maximum expected temperature range for these materials in the field is 0° to 50° C (32° to 122° F). Since all the materials tested had transition temperatures within this range, it was necessary to determine α above and below T_g for each material. Each material was tested with three samples, and the slope of the curve was determined during the cooling and heating stages, above and below T_g, then averaged. The results are shown in Figure 6.13.



NOTES: a - test sample could not be made b - results too scattered

All values shown above should be multiplied by 5/9 to get the thermal expansion per degree Fahrenheit

Figure 6.13: Coefficient of Thermal Expansion, α, Test Results

The test could not be run on Flexbond #11 because it proved impossible to make the samples, due to the material's extreme flexibility. The results for Transpo T46 below T_g were too scattered to produce any meaningful value. The significance of these values when compared to the α of asphalt is explained in Chapter Seven: Recommendations for Use.

6.1.8 Vicat Set Time

The Vicat test is used to determine the setting time of the materials. The test was run on samples of each material at 25° C (77° F). The results are shown in Figure 6.14.

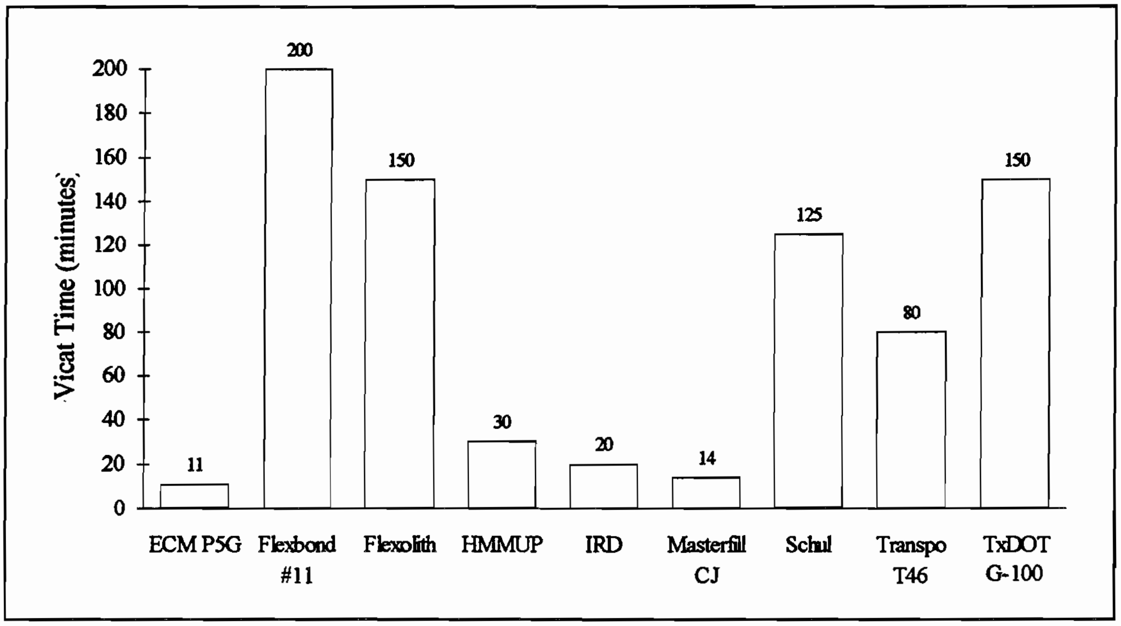


Figure 6.14: Vicat Test Results

Generally, the fastest curing time is desirable. However, any value under one half hour is acceptable. Under that criterion, ECM P5G, HMMUP, IRD, and Masterfill CJ have acceptable performances. The other materials take too long to cure.

6.1.9 Viscosity

Viscosity was measured as a means to estimate the workability of the materials after mixing. Materials that are too viscous do not pour well and can leave air pockets in the installation. Materials that are not viscous enough flow too easily and are hard to work with. The average viscosity of three samples of each material at 25° C (77° F) are shown in Figure 6.15.

The acceptable range of viscosity values was unknown before the tests began. Field trials indicated that Flexbond #11 and Schul were too thick and Masterfill CJ was too thin to work with easily. Therefore, the range of acceptable viscosity values appears to be 20 to 40 Pa-s. However, it should be emphasized that use in the field should be the most important measure of workability.

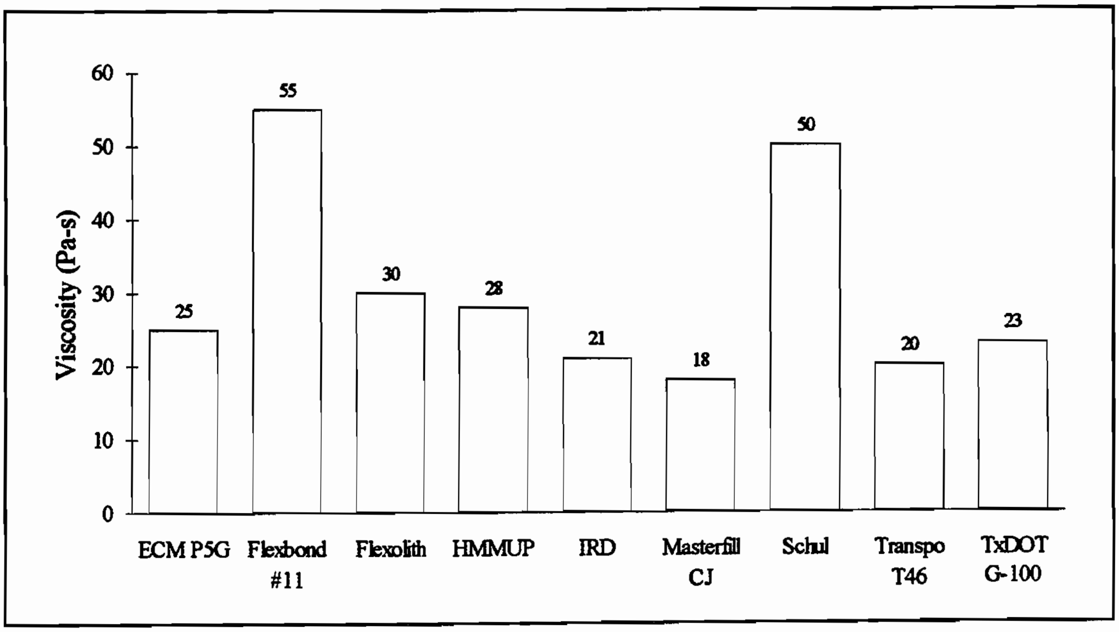


Figure 6.15: Viscosity Test Results (1 psf-s = 48 Pa-s)

6.2 Compatibility Tests

The materials used in this project were also subjected to tests to measure their performance when bonded to paving materials, specifically concrete and asphalt. In compatibility testing, failures can occur in one of three places: the polymer, the bond, or the paving material. Good bond performance is indicated by failure in the paving material, unless other factors such as rigidity or thermal expansion are more dominant.

6.2.1 Bond Strength

The strength of the bond between these materials and paving materials was measured under three types of loading: flexure, shear, and pure tension. The test procedures are described in Chapter 4: Laboratory Test Program.

6.2.1.1 Flexural Bond

The flexural bond test used a region of constant moment around the bond location. Therefore, the failure could take place in one of three locations: in the polymer, in the bond, or in the paving material. Table 6.1 summarizes the failure modes, while Figure 6.16 shows the average results of three samples of each material with each paving material.

Table 6.1: Bond Flexural Strength Test Failure Modes

	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD
Asphalt	50/50	bond	asphalt	asphalt	50/50
Concrete	50/50	deflection	50/50	bond	50/50

	Masterfill CJ	Schul	Transpo T46	TxDOT G-100
Asphalt	asphalt	asphalt	asphalt	asphalt
Concrete	50/50	concrete	concrete	concrete

NOTE: Refer to text for explanation of modes.

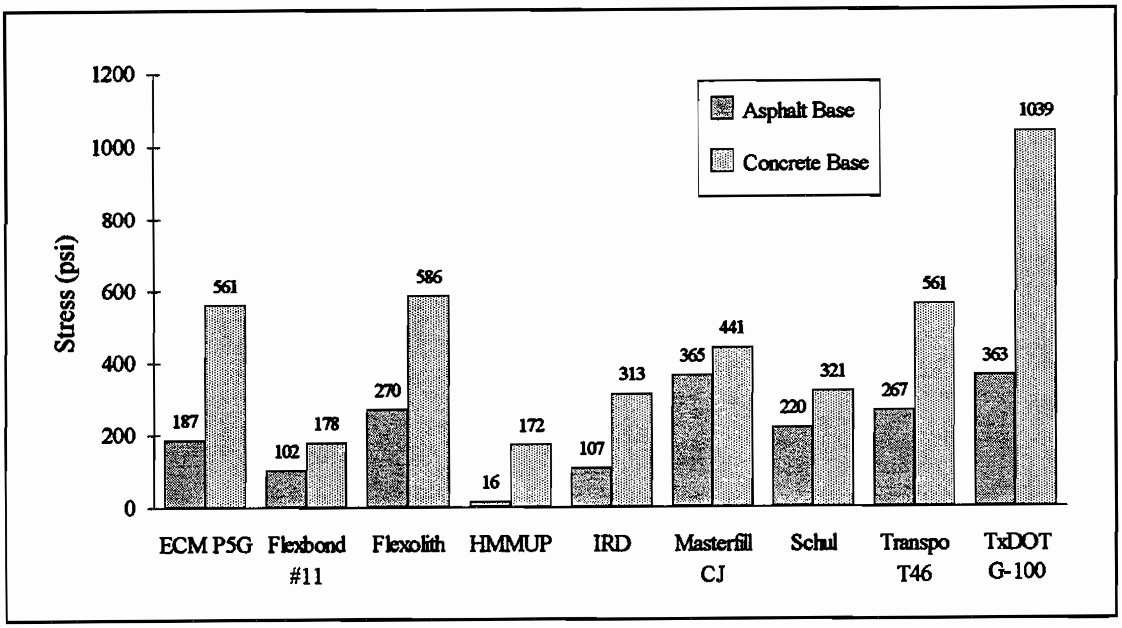


Figure 6.16: Bond Flexural Strength Test Results (1 psi = 6.9 kPa)

The columns in the table correspond to the materials tested. The rows correspond with the type of paving material. An entry of "50/50" means the failure was half in the bond and half in the paving material. An entry of "asphalt" or "concrete" indicates that the failure was strictly in the paving material. An entry of "bond" indicates that the bond failed. An entry of "deflection" indicates that the sample deflected until it contacted the testing surface and there was no cracking observed.

Most of the materials had sufficient bond strength to ensure that the paving material failed first, or at the same time as the bond. The exceptions are Flexbond #11 and HMMUP. In all cases, the results were greater with concrete than with asphalt, but this is due to the higher strength of the concrete (since most of the samples failed in the paving material). The low strength of the HMMUP to asphalt bond is due to solvents in the HMMUP that dissolve the asphalt, thus making it weaker.

6.2.1.2 Shear Bond

The shear bond pull-out test was used to determine the strength of the bond under shear conditions. This test was run on two samples of each material with each paving material. Table 6.2 lists the failure modes, and Figure 6.17 shows the average results.

Table 6.2: Bond Shear Strength Test Failure Modes

	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD
Asphalt	50/50	50/50	asphalt	asphalt	bond
Concrete	bond	bond	50/50	bond	bond

	Masterfill CJ	Schul	Transpo T46	TxDOT G-100
Asphalt	asphalt	asphalt	asphalt	asphalt
Concrete	50/50	bond	50/50	U-bolt

NOTE: Refer to text for explanation of modes.

Again, "asphalt" and "concrete" indicate that the sample failed in the paving material. "Bond" indicates a bond failure, while "50/50" indicates a failure of both the bond and the paving material. The "U-bolt" entry indicates a test in which the strength of the sample exceeded the strength of the U-bolt used to apply the load (Figure 4.8).

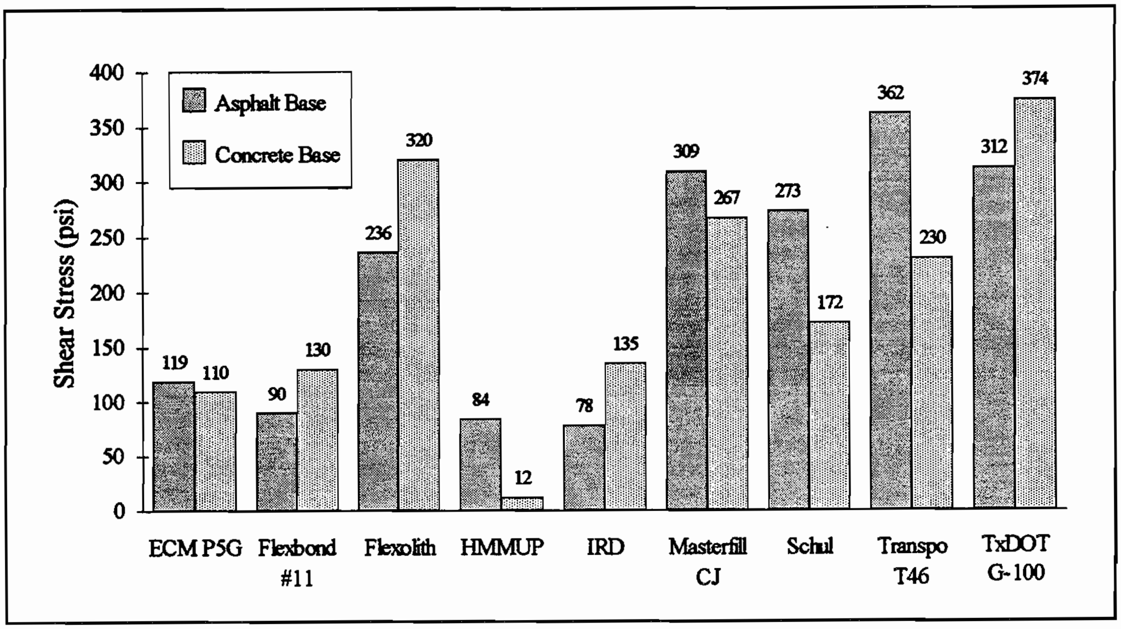


Figure 6.17: Bond Shear Strength Test Results (1 psi = 6.9 kPa)

Generally, the bond of the concrete samples was stronger than that of the asphalt samples. There were some exceptions for this test, however, probably due to the nature of the bond surface. The holes in the asphalt samples were drilled, while the holes in the concrete samples were formed when the concrete was poured. Because of this, the asphalt samples had exposed aggregate particle surfaces while the concrete did not. The exposed aggregate surfaces provided a better bond than that to the smooth cement surface, as evidenced by the large number of bond failures for the concrete samples. Also, the materials that performed better with asphalt were generally the low-viscosity materials, indicating that these materials were probably able to flow into cracks and voids in the asphalt surface, providing a better mechanical bond. It is felt that if the holes in the concrete were drilled, thus providing exposed aggregate surfaces, then the materials would consistently perform better with concrete.

6.2.1.3 Tension Bond

The tension pull-up test was used to measure the bond strength under pure tension. Two samples were prepared for each material for each paving material. Table 6.3 identifies the failure modes. Figure 6.18 shows the results.

Table 6.3: Bond Tensile Strength Test Failure Modes

	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD
Asphalt	asphalt	asphalt	asphalt	asphalt	asphalt
Concrete	concrete	steel bond	concrete	polymer	bond

	Masterfill CJ	Schul	Transpo T46	TxDOT G-100
Asphalt	asphalt	asphalt	asphalt	asphalt
Concrete	bond	concrete	concrete	concrete

NOTE: Refer to text for explanation of modes.

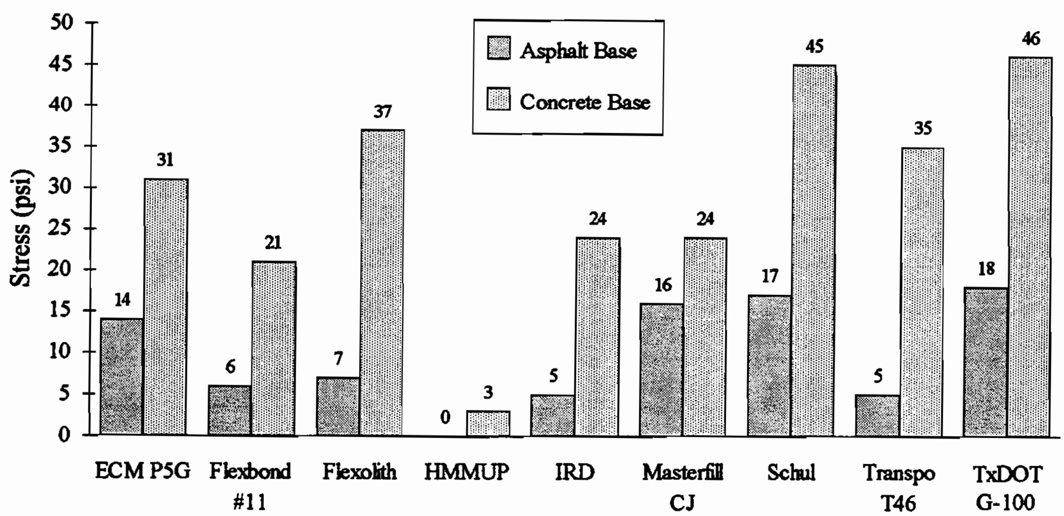


Figure 6.18: Bond Tensile Strength Test Results (1 psi = 6.9 kPa)

The "steel bond" entry on the table indicates that the bond between the high-strength epoxy and the steel plate failed (Figure 4.9). As shown in the table, the asphalt samples all failed in the paving material. Most of the concrete samples failed this way, too, with only Masterfill CJ and IRD failing at the bond, and HMMUP failing in the polymer. Also, for all of these materials, the concrete samples were stronger than the asphalt samples. As with the flexural bond test, this is probably due to the fact that the concrete bases were stronger than the asphalt bases. The zero value for HMMUP with asphalt was due to the solvent attack, as described earlier.

6.2.2 Freeze/Thaw Tension Bond

The tensile bond strength was also tested after subjecting samples to cycles of freezing and thawing. This test was to determine the detrimental effect, if any, of temperature cycling, which would decrease the bond strength resulting from differences in thermal expansion between the polymers and the paving materials. Two samples of each material combination were subjected to temperature cycles. The standard tensile bond pull-up test was then run on the samples. The failure modes are listed in Table 6.4, and the average test results are shown in Figure 6.19.

Table 6.4: Freeze/Thaw Bond Tensile Strength Test Failure Modes

	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD
Asphalt	asphalt	asphalt	asphalt	asphalt	asphalt
Concrete	50/50	equipment	concrete	polymer	polymer

	Masterfill CJ	Schul	Transpo T46	TxDOT G-100
Asphalt	asphalt	asphalt	asphalt	asphalt
Concrete	concrete	concrete	concrete	concrete

NOTE: Refer to text for explanation of modes.

The results in the figure are expressed as a percentage reduction from the tests run on samples kept at room temperature. Most materials were actually stronger after freezing and thawing. This indicates that most materials were largely unaffected, and that the increases in strength were probably due to the longer curing times allowed between pouring and testing (all samples were poured at the same time and the constant temperature samples were tested while the freeze/thaw samples were cycling, and therefore cured for almost ten days more). The modes of failure were also unchanged, as most samples failed in the paving material. The solvent action of HMMUP on asphalt was not affected by the temperature cycling, so the strength was again zero, which was reported as zero reduction in this test.

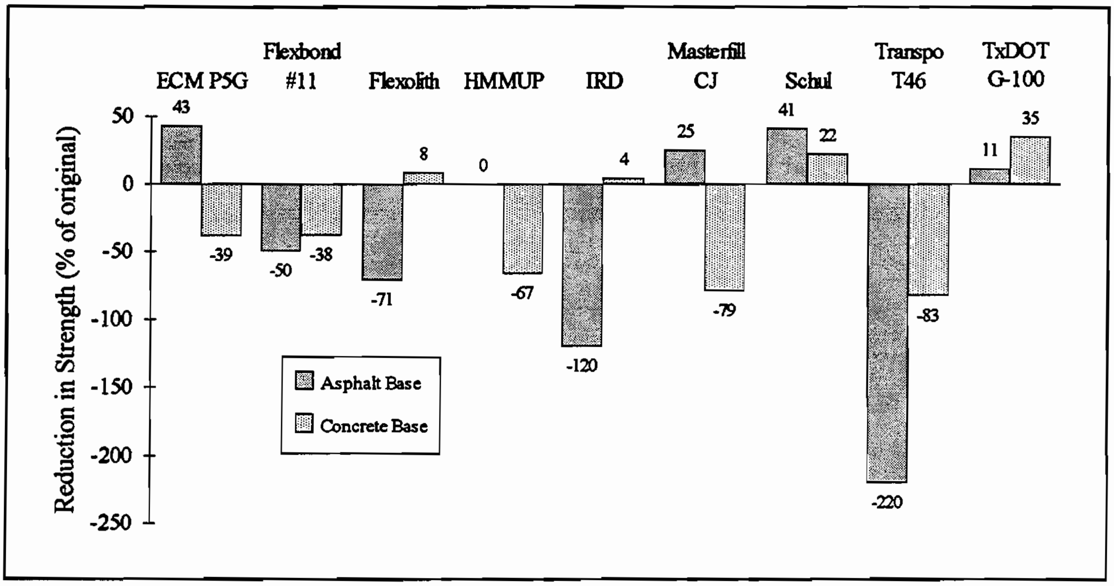


Figure 6.19: Freeze/Thaw Bond Tensile Strength Test Results

6.2.3 Extreme Temperature Tests

The other two compatibility tests, flexural and shear bond strength, were run on the two most promising materials at the extreme temperatures expected in the field, 0° and 50° C (32° and 122° F). The two materials tested were ECM P5G and IRD, since these materials had been performing the best in the field and had the best general performance in the lab.

The standard bond flexural strength and bond shear strength tests were run on samples that had been conditioned for at least 24 hours at the testing temperature. Three samples of each material combination were used for the flexural tests, and two of each were used for the shear tests. The results for each test were then averaged. A comparison of the results at all three testing temperatures (including room temperature of 25° C [77° F]) is shown in Figure 6.20. The failure modes are listed in Table 6.5.

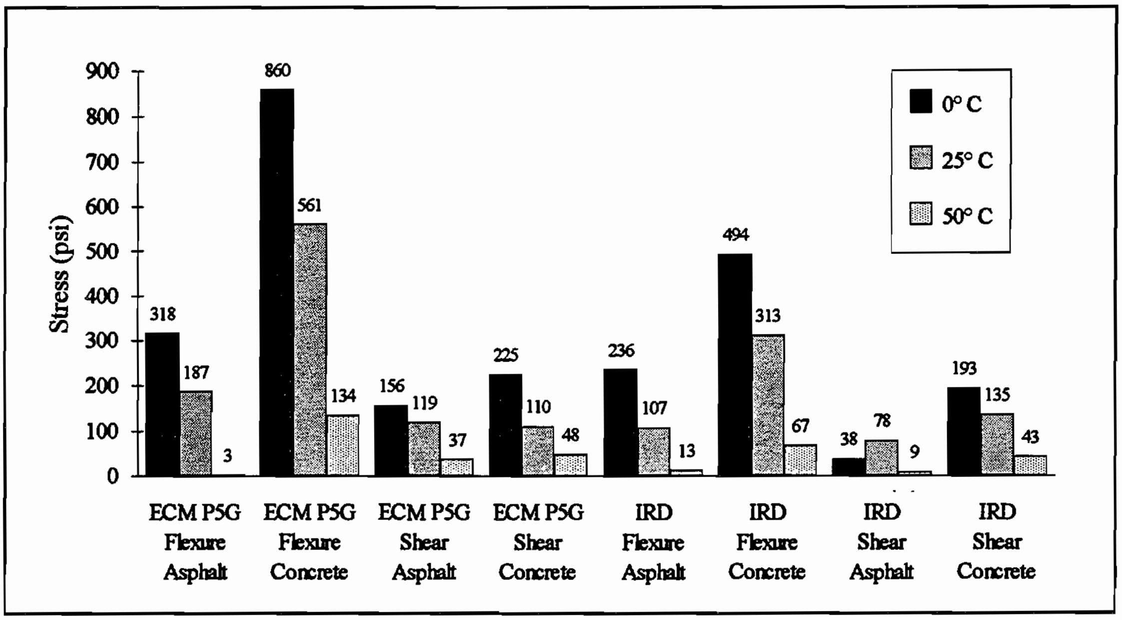


Figure 6.20: Extreme Temperature Bond Strength Test Results (1 psi = 6.9 kPa)

Table 6.5: Extreme Temperature Bond Strength Test Failure Modes

	ECM P5G Flexure		ECM P5G Shear	
	Asphalt	Concrete	Asphalt	Concrete
0° C	asphalt	bond	bond	50/50
25° C	50/50	50/50	50/50	bond
50° C	asphalt	bond	50/50	bond

	IRD Flexure		IRD Shear	
	Asphalt	Concrete	Asphalt	Concrete
0° C	bond	bond	bond	50/50
25° C	50/50	50/50	bond	bond
50° C	50/50	50/50	bond	bond

NOTE: Refer to text for explanation of modes.
0° C = 32° F; 25° C = 77° F; 50° C = 122° F

The data show that, in general, the bond strengths decreased as the temperature increased. This is probably due to softening in the materials with temperature and a similar response in the paving materials. Note that with these materials, almost all failures are at least half in the bond. The only exception was ECM P5G when bonded to asphalt.

6.3 Field Trials

Field installations were made using the candidate materials to determine their performance under service conditions. The performance of each material in the field can then be used to determine which materials are generally acceptable, and from that information, which tests give a good indication of adequate performance. For example, the viscosity test was run without knowing the acceptable range of values. The results of the field trials made it possible to match viscosity values with the materials that were easy to work with, producing a range of acceptable viscosity of 20 to 40 Pa-s. The relevant observations from each of the final three bare cable installations are described in the following sections. Two materials were not tested at a field installation. The HMMUP was not used because of its complex preparation, which TxDOT indicated made it inappropriate. Also, the TxDOT G-100 was not used, as TxDOT already had years of experience with it.

6.3.1 San Angelo

San Angelo was the first site to use the new bare cable sensor design. It was also the first site to use the new materials under consideration for this project. The materials used were ECM P5G, Flexolith, IRD, and Schul. The ECM P5G and the IRD were both very easy to work with, as they flowed easily into the groove and around the sensor, but they were not so low in viscosity as to cause problems such as spilling and flowing out of the groove through the signal wire cuts. The Flexolith was also easy to work with, but it took over an hour to cure. The Schul was too viscous and had to be worked into the groove and around the sensor with putty knives. Also, after about three weeks, the sensor installed with the Schul was no longer working, and it had to be replaced (ECM P5G was used for the replacement). All the other sensors (and the replacement) were still functioning adequately as of April 1994.

The bare cable sensor design worked well in a number of respects. The smaller groove made cutting easier, as only one pass was needed from the saw. Also, the sensor was very easy to locate within the groove, using the plastic reinforcing bar chairs. Finally, a smaller amount of polymer was needed, which was easier to work with than the quantities required for the encapsulated sensors.

Thermocouples were installed in each material as it cured, as well as on the pavement and in the air. The temperatures were then monitored in the same manner as was done in the gel time test. These data confirmed the curing times of the materials as consistent with those measured in the lab. Also, it was noted that the peak temperature reached was not significantly higher, even though the ambient temperature was higher.

6.3.2 Amarillo

The Amarillo site also used four materials: ECM P5G, IRD, Masterfill CJ, and the M-266 from Poly Carb. The ECM P5G and IRD continued to perform very well, and the TxDOT personnel at the installation preferred working with these materials. The Masterfill CJ proved to be too low in viscosity which made it difficult to work with. In addition, when it cured, it stiffened very rapidly, changing from a liquid to a solid almost instantaneously, giving no warning that this was about to happen. The Poly Carb M-266 was very similar to Flexolith in all respects. Using the bare cable sensors again proved to be more acceptable than using the encapsulated film sensors.

After the winter of 1993-94, the ECM P5G and the IRD have shown some signs of deterioration as a result of cold temperatures. Both of these materials have exhibited some minor cracking on the surface at the end of the sensor that is placed in the center of the traffic lane. These cracks were probably formed during the coldest temperatures when the material was the most brittle. The cracking has so far not had any effect on the performance of the sensors. All sensors at this installation were still functioning adequately as of April 1994.

6.3.3 Laredo

Laredo was the last site in this study to use the bare cable sensors. The materials used at this site were ECM P5G, Flexbond #11, IRD, Schul, Transpo T46, and another Poly Carb product, M-163. Again, the ECM P5G and IRD performed the best, with good workability and quick curing.

The Schul, in addition to being too pasty, seemed to be too rigid as well, as cracks formed in the asphalt along the installation on the down-stream side after only one day. These cracks were probably formed by the combination of the polymer expansion and the stress concentrations caused by its rigid nature. The Flexbond #11 and the Transpo T46 were both easy to work with, but took well over an hour to cure. Also, the TxDOT personnel expressed concern that the coal-tar component of those materials might become too soft during extremely hot weather. Blasting sand was used as an aggregate in these materials, which may have contributed to the slow cure, as the aggregate particles may have acted like a heat-sink (which would slow down the curing reaction as exothermic heat could not increase). The Poly Carb M-163 was very similar to M-266, taking about an hour to cure.

By the time this installation was performed, the TxDOT crew had perfected the use of the bare cable sensors. Obviously, if these installations continue to perform well, this is the installation method of choice. All the sensors at the Laredo site were still functional as of April 1994.

Chapter Seven: Recommendations for Use

7.1 Recommended Materials

The first objective of this project was to recommend appropriate materials for installing piezoelectric sensors. To this end, the materials tested in this project were evaluated on the basis of the laboratory tests and field trials. In this section, the significance of the tests results is discussed, and then the materials are ranked by their performance in each test.

7.1.1 Ranking System

The ranking system is based on a simple point system, with the best materials assigned 9 points; the next best material is given 8 points, and so on, until all materials are ranked. If two materials tie for the same ranking, they are both given the average point value of the two rankings. For example, if two materials can be considered the best, they would both be given 8.5 points, as this is the average point value of first and second place. This average point system is also used when more than two materials have the same rank.

At the end of this section, the points each material scored are totaled, and the materials are ranked for overall performance, with all tests assumed to be of equal importance. The materials are also ranked according to only those tests which are recommended in the second section of this chapter, with adjustments for the importance of the test.

7.1.1.1 Abrasion

The abrasion test results are very straightforward. The materials that lost the least weight to abrasion had the best performance. Table 7.1 shows the rankings and the points scored by each material.

Table 7.1: Abrasion Test Rankings

	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD
Ranking	6	9	5	4	7
Points	4	1	5	6	3

	Masterfill CJ	Schul	Transpo T46	TxDOT G-100
Ranking	8	1	3	2
Points	2	9	7	8

7.1.1.2 Compressive Strength

Interpreting the compressive strength results is also very simple. The material with the highest strength had the best performance. The material rankings and points are shown in Table 7.2.

Table 7.2: Compressive Strength Rankings

	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD
Ranking	6	9	3	2	7
Points	4	1	7	8	3

	Masterfill CJ	Schul	Transpo T46	TxDOT G-100
Ranking	5	4	8	1
Points	5	6	2	9

7.1.1.3 Dynamic Properties

The dynamic properties of the materials were fairly difficult to interpret. The results of the complex modulus E^* were determined to be highly inaccurate due to difficulties in testing as well as in calculating the phase angle from the plotted graphs. Since the results are considered unreliable, these results are not used to rank the materials.

The complex shear modulus G^* test gave much more accurate results. A property that is indicative of acceptable performance is the phase angle, δ. As explained before, changes in the phase angle indicate that the material shifts from elastic behavior to viscous behavior. Asphalt pavement becomes less elastic as temperatures rise, so acceptable material performance is indicated by similar behavior, which would manifest as an increase in δ as temperature rises. Since this is only a qualitative analysis, each material will be ranked as "pass," indicating acceptable behavior, or "fail," indicating unacceptable behavior. All materials that rate "pass" are considered tied for first place, while those that "fail" are tied for last place, for purposes of assigning points. Table 7.3 shows the material ratings and points.

Table 7.3: Complex Shear Modulus Phase Angle, δ, Rankings

	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD
Ranking	pass	fail	fail	pass	fail
Points	7.5	3	3	7.5	3

	Masterfill CJ	Schul	Transpo T46	TxDOT G-100
Ranking	pass	fail	pass	fail
Points	7.5	3	7.5	3

Another property measured by this test that is of importance is the storage modulus, G'. This property is analogous to the modulus of elasticity, and is an indication of the rigidity of the material. An acceptable range of values for this property was unknown before testing began. Therefore, the range had to be determined by comparing the test results to field performance and observations of the effect of rigidity on other tests. Also, changes of this property with temperature should be similar to those of asphalt, which becomes more flexible with heat. From these criteria, the acceptable performance was determined to be a value in the range of 2 to 10 ksi (13.8 to 69 MPa), with colder temperatures giving a higher value and hotter temperatures giving a lower value. By these criteria, the materials either pass or fail, as indicated in Table 7.4, which also shows the points earned.

Table 7.4: Storage Modulus G' Rankings

	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD	Masterfill CJ	Schul	Transpo T46	TxDOT G-100
Ranking	pass	fail	pass	fail	pass	fail	fail	fail	fail
Points	8	3.5	8	3.5	8	3.5	3.5	3.5	3.5

7.1.1.4 Flexural Strength

As with the compressive strength results, the flexural strength test results are ranked simply according to magnitude. The materials with the highest strengths are considered the best. However, this test revealed that almost all the materials had the same flexural strength (within 6%). For this reason, the best material, HMMUP, is ranked first and Flexbond #11 is ranked last. All the other materials are considered equal, so their rankings are averaged. Table 7.5 shows the points for this test.

Table 7.5: Flexural Strength Rankings

	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD	Masterfill CJ	Schul	Transpo T46	TxDOT G-100
Ranking	5	9	5	1	5	5	5	5	5
Points	5	1	5	9	5	5	5	5	5

7.1.1.5 Gel Time

The gel time is a measure of working time, but it also indicates curing time. Therefore, values that are too short would give insufficient time for a proper installation, while too great a value indicates a material that takes too long to cure. The minimum time would be about 5 minutes with a maximum of 15 minutes. All the materials had gel times of over 5 minutes, so they all allowed ample working time. Accordingly, the materials are ranked by time, with the lowest value considered best. Table 7.6 shows the rankings and points scored for this test at 25° C (77° F). Longer times should be expected at lower temperatures.

Table 7.6: Gel Time Rankings

	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD
Ranking	1	8	9	7	3
Points	9	2	1	3.5	7.5

	Masterfill CJ	Schul	Transpo T46	TxDOT G-100
Ranking	3	7	4	5
Points	7.5	3.5	6	5

7.1.1.6 Shrinkage

The DuPont shrinkage test determined the extent of changes in volume with curing. Ideally, a minimal expansion (negative shrinkage) is desired. Minimal shrinkage is also acceptable. Excessive shrinkage or expansion is considered a failure. For purposes of this project, the acceptable shrinkage is 0.5%, based on field observations and observed shrinkage effects on other tests. Allowable expansion is 1.0%, also based on observation. Any material in this range is rated as "pass," while any material outside this range is rated as "fail." All passing materials are considered tied for first place, while all failing materials are tied for last place. Table 7.7 shows the ratings and point values for the test materials.

Table 7.7: Shrinkage Rankings

	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD
Ranking	pass	pass	fail	pass	pass
Points	7	7	2.5	7	7

	Masterfill CJ	Schul	Transpo T46	TxDOT G-100
Ranking	pass	fail	fail	fail
Points	7	2.5	2.5	2.5

7.1.1.7 Thermal Expansion

The coefficient of thermal expansion, α, of the materials was to be compared to that of asphalt to determine acceptable behavior. Those materials with α values similar to that of asphalt were to be considered as passing this test. Also of consideration was the glass transition temperature, T_g, of each material, as α changes as the temperature rises above (or falls below) T_g. The glass transition temperature of asphalt depends on the specific grade used, but generally falls below 0° C (32° F).[23] Therefore, there is only one value of α for asphalt to be used for comparison, which is generally around 6 x 10^{-4} per degree Celsius (3.3 x 10^{-4} / 1° F).[24] The test data for all materials gave values of α well below the average asphalt value (by at least an order of magnitude), above and below each material's T_g. Therefore, it was concluded that the thermal expansion of the binding material does not have a significant effect on the material's performance. For this reason the materials were not ranked according to this test. (Thermal expansion could become a factor if a material's α was actually greater than asphalt's.)

7.1.1.8 Vicat Set Time

The Vicat set time is strictly a measure of curing time. Assuming all the materials tested had sufficient working time, the lowest Vicat time is considered the best. This was indeed the case for the materials tested. The rankings and points of the materials according to this test are shown in Table 7.8.

Table 7.8: Vicat Time Rankings

	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD
Ranking	1	9	7.5	4	3
Points	9	1	2.5	6	7

	Masterfill CJ	Schul	Transpo T46	TxDOT G-100
Ranking	2	6	5	7.5
Points	8	4	5	2.5

7.1.1.9 Viscosity

Viscosity was measured to provide an estimate of workability. As indicated in Chapter Six, the acceptable range of viscosity was unknown before testing. Field installations indicated which materials were easy to work with. These materials were then assumed to have an acceptable viscosity, while the other materials were not. Under this criterion, the acceptable range of viscosity is 20 to 40 Pa-s. Table 7.9 lists each material's rank and points.

Table 7.9: Viscosity Rankings

	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD
Ranking	pass	fail	pass	pass	pass
Points	6.5	2	6.5	6.5	6.5

	Masterfill CJ	Schul	Transpo T46	TxDOT G-100
Ranking	fail	fail	pass	pass
Points	2	2	6.5	6.5

7.1.1.10 Bond Strength

The bond strength test results are difficult to rank, due to the variability of the paving material which makes up half of the beam. Generally, acceptable performance is indicated by failure in the paving materials, not in the bond or the polymer. In the flexural bond test, most materials had failures at least partly in the paving material. These materials can therefore be considered acceptable, according to this test. With the other tests, however, there were some difficulties which prevented such simple ranking. The bond shear strength was adversely affected by the fact that the concrete surface at the bond was smooth, with no exposed aggregate surfaces. The bond tension test was adversely affected by the fact that the bond was to the top (wearing) surface of the paving material, not a cut surface with exposed aggregate surfaces.

For these reasons, the materials are ranked only according to the failure type of the flexural bond test. The lowest acceptable magnitude of the flexural bond is then set to the lowest value of any material considered to have acceptable field performance and failure type. Table 7.10 shows the rankings and points according to the flexural failure type. If the material is given a failure rating, the letter in parentheses, either "a" for asphalt or "c" for concrete, indicates which paving material was used in the failed sample.

Table 7.10: Bond Flexural Strength Rankings

	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD
Ranking	pass	fail (a,c)*	pass	fail (c)*	pass
Points	6	2.5	6	2.5	6

	Masterfill CJ	Schul	Transpo T46	TxDOT G-100
Ranking	pass	pass	pass	pass
Points	6	6	6	6

* a - indicates failure with asphalt sample c - indicates failure with concrete sample

The lowest value of a passing material was 107 psi (747 kPa) for IRD. The acceptable bond flexural strength performance is therefore defined as at least 100 psi (690 kPa) to asphalt or 300 psi (2,070 kPa) to concrete, with at least half of the failure in the paving material and the rest in the bond.

7.1.1.11 Temperature Effects

Temperature effects can be divided into two basic categories: freeze/thaw effects and behavior at extreme temperatures. The freeze/thaw effects were measured with the bond tension pull-up test, which demonstrated no significant strength reduction. The extreme temperature effects were used only on the two most promising materials (according to field observations and screening tests). Therefore, those tests are not used to rank the materials. The extreme temperature tests were used to verify that the materials will function adequately under service conditions.

7.1.1.12 Field Trials

The field trials were used to monitor the materials under service conditions. They were also useful for obtaining the opinions of the installation crew on the performance of the materials during installation. Finally, the field trials were used to calibrate the acceptable results of tests such as viscosity and gel time.

For purposes of ranking the materials, one last property of the materials was considered, based on the comments of the installation crew. This property is ease of use, which is determined mainly by the number of components and the packaging. The best material would be a single component in a package that is sufficiently oversized to allow mixing without spilling. The material that comes the closest to this objective is ECM P5G, which is basically a single component with a small amount of hardener additive, in a bucket with enough extra room for mixing. The IRD and the TxDOT G-100 are almost as easy, but are complicated by such factors as the dependence on temperature (for IRD) or the use of messy fluid additives (for TxDOT G-100). The Schul is the next easiest material to use, due largely to its excellent packaging. Most of the other materials would tie for the next place, as they are all two component materials that require a third container for mixing. Finally, the HMMUP ranks last, as it contains many parts and a complex mixing schedule. Table 7.11 summarizes these rankings and shows the points earned by each material.

Table 7.11: Field Trial Ease of Use Rankings

	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD	Masterfill CJ	Schul	Transpo T46	TxDOT G-100
Ranking	1	6.5	6.5	9	2.5	6.5	4	6.5	2.5
Points	9	3.5	3.5	1	7.5	3.5	6	3.5	7.5

7.1.2 Total Rankings

The best material can be determined by totaling the points earned by each material for all the tests, as described above. The material with the most points is designated the best material. This ranking system assumes that all the tests are of equal importance and does not consider the cost of the material. Figure 7.1 shows the point totals as a bar graph so that the highest total can be easily seen.

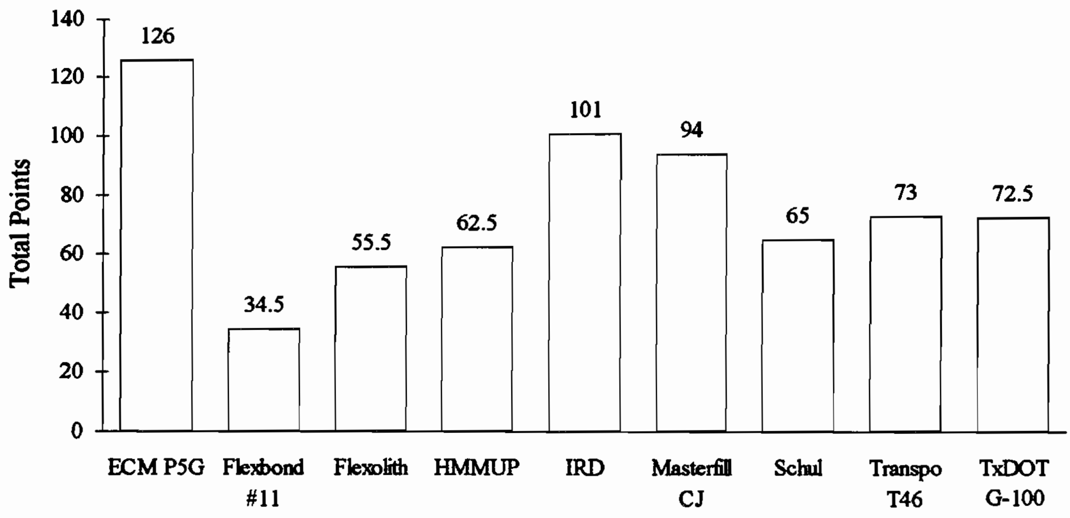


Figure 7.1: Preliminary Material Total Ranking Points

According to these totals, ECM P5G is the best material, followed by IRD. However, as shown on the chart, TxDOT G-100, a material known to be inappropriate for this installation, also scored fairly well. This is so because the tests are all treated equally, while some are actually more important than others. Also, not all the tests used to rank the materials are recommended to TxDOT for use in its evaluations. The next section explains which tests were chosen and the rationale. Table 7.12 shows the importance of each test recommended for TxDOT. The importance is indicated by a multiplier that is applied to the points scored by that test. These adjusted scores are modified so that a score of 1 remains 1 using the formula:

$$[(\text{points} - 1) \times \text{multiplier}] + 1$$

The points scored for tests that are not recommended were not included in these totals. Figure 7.2 shows the point totals scored under this system.

Table 7.12: Ranking of Tests by Importance

Test	Multiplier
Compressive Strength	1
Complex Shear Modulus - G'	2
Gel Time	3
Shrinkage	1
Vicat Set Time	3
Viscosity	1
Bond Flexural Strength	2
Field Trial (ease of use)	3

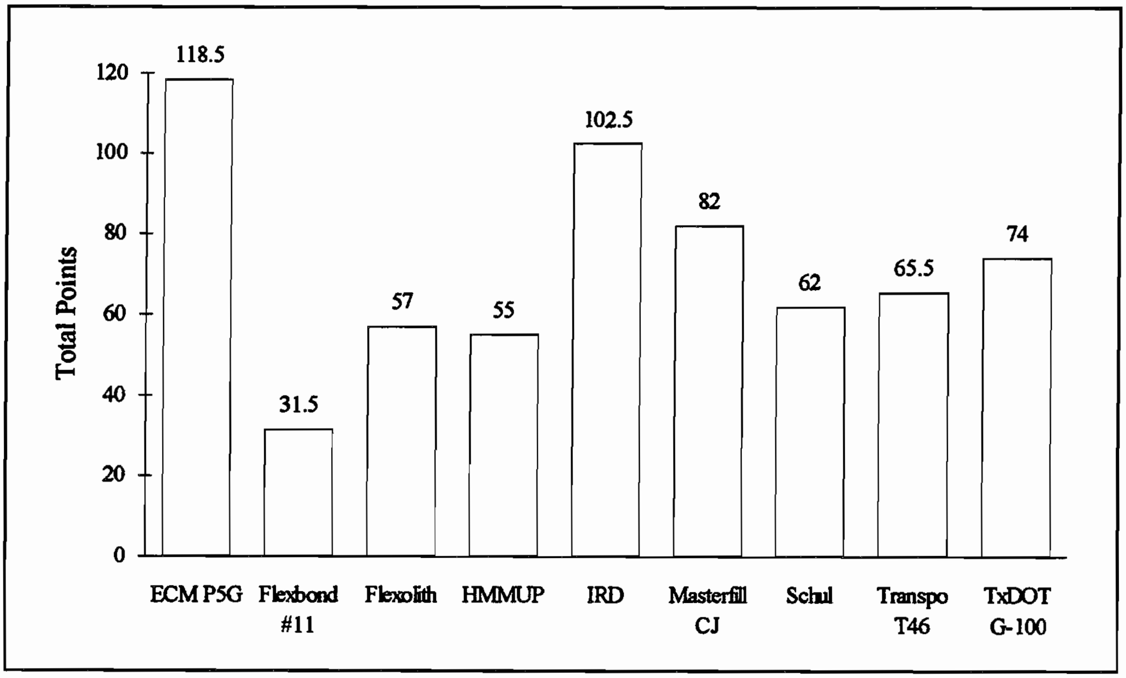


Figure 7.2: Final Material Total Ranking Points

Table 7.13 summarizes the point scores for each test, before and after adjusting for importance. The main numbers in the chart are those before adjusting, while the numbers in parentheses are those after adjusting.

Table 7.13: Summary of Test Points

Test	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD	Masterfill CJ	Schul	Transpo T46	TxDOT G-100
Abrasion	4	1	5	6	3	2	9	7	8
Compressive Strength	4 (4)	1 (1)	7 (7)	8 (8)	3 (3)	5 (5)	6 (6)	2 (2)	9 (9)
Phase Angle	7.5	3	3	7.5	3	7.5	3	7.5	3
Storage Modulus	8 (15)	3.5 (6)	8 (15)	3.5 (6)	8 (15)	3.5 (6)	3.5 (6)	3.5 (6)	3.5 (6)
Flexural Strength	5	1	5	9	5	5	5	5	5
Gel Time	9 (25)	2 (4)	1 (1)	3.5 (8.5)	7.5 (20.5)	7.5 (20.5)	3.5 (8.5)	6 (16)	5 (13)
Shrinkage	7 (7)	7 (7)	2.5 (2.5)	7 (7)	7 (7)	7 (7)	2.5 (2.5)	2.5 (2.5)	2.5 (2.5)
Vicat Set Time	9 (25)	1 (1)	2.5 (5.5)	6 (16)	7 (19)	8 (22)	4 (10)	5 (13)	2.5 (5.5)
Viscosity	6.5 (6.5)	2 (2)	6.5 (6.5)	6.5 (6.5)	6.5 (6.5)	2 (2)	2 (2)	6.5 (6.5)	6.5 (6.5)
Bond Flexural Strength	6 (11)	1.5 (2)	6 (11)	1.5 (2)	6 (11)	6 (11)	6 (11)	6 (11)	6 (11)
Ease of Use	9 (25)	3.5 (8.5)	3.5 (8.5)	1 (1)	7.5 (20.5)	3.5 (8.5)	6 (16)	3.5 (8.5)	7.5 (20.5)
Totals	75 (118.5)	26.5 (31.5)	50 (57)	59.5 (55)	63.5 (102.5)	57 (82)	50.5 (62)	54.5 (65.5)	58.5 (74)

- raw data (#) - data adjusted by importance of test

From the final ranking, it is obvious that ECM P5G is the best material. IRD is the next best material, followed closely by Masterfill CJ. Masterfill CJ is a good example of the importance of the field trial, as the difficulties in working with it (due to its low viscosity and sudden curing) eliminate it as a useful material, even though it scored fairly well in the laboratory tests.

7.2 Recommended Tests

The second objective of this project was to recommend a series of tests that TxDOT could use to perform its own evaluations of potential materials. Obviously, not all the tests used in this project can be recommended. Some tests were too inaccurate, such as the complex modulus E^*. Other tests gave inconclusive results, such as the flexural strength test, which gave almost the same result for almost all the materials. This section explains for each test why it is, or is not, recommended for use by TxDOT.

7.2.1 Abrasion

The abrasion test is not recommended, mainly as a result of field observations. The few materials that do abrade, abrade only to the level of the pavement. After the material is reduced to that level, there is no further significant wear, and the accuracy of the sensor is still acceptable.

7.2.2 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 the test is easy to run, and because compressive strength is the standard measure of strength used for paving materials, so 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, samples cut from the shrinkage test samples could be used in place of half-beams in the test used for this project. The material being tested should have a strength of at least 1,000 psi (6,900 kPa), which was the lowest strength of any material that had acceptable field performance (IRD).

7.2.3 Dynamic Properties

The complex modulus E^* test is not recommended, due to difficulties in running the test and interpreting the results. However, the complex shear modulus G^* test is recommended. 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. As this test is intended to determine the flexibility of the material, it is the storage modulus G' that is of interest. The material should become more flexible with rising temperatures, as indicated by a decrease in the storage modulus with an increase in temperature. Also, the value of G' at room temperature should fall in the range of 2 to 10 ksi (13.8 to 69 kPa).

7.2.4 Flexural Strength

The flexural strength test is not recommended. Since almost all the results were basically the same, this test is useless for comparison purposes. A material that would fail this test would almost certainly fail some other test, such as compressive strength or complex shear modulus.

7.2.5 Gel Time

This test is recommended, as it is a very simple test and it measures a very important quality: working time. The working time available should be at least 5 minutes and no more than 15 minutes. This allows 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 the temperature.

7.2.6 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.

7.2.7 Thermal Expansion

The coefficient of thermal expansion α is not an important property, and therefore this test is not recommended. All the materials under consideration had α values at least one magnitude less than that of asphalt pavement. Assuming that the storage modulus is in the correct range, acceptable materials will be flexible enough to adjust to the changes in shape induced by expanding or contracting asphalt.

7.2.8 Vicat Set Time

Since the Vicat test measures curing time, this test is recommended. Along with the test for 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.

7.2.9 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.

7.2.10 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 100 psi (690 kPa) for asphalt or 300 psi (2,070 kPa) for concrete, with the failure at least half in the paving material.

7.2.11 Temperature Effects

No temperature effect tests are recommended, other than the use of the three temperatures for the complex shear modulus test and the gel time test. All other temperature effects are largely due to changes in the flexibility of the material, as indicated by the complex shear modulus. Therefore, there is no need to test further for such effects.

7.2.12 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, and monitored for one month (4 weeks). 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 material 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 if laboratory test performance has been acceptable.

7.3 Summary of Recommendations

The final recommendations, as discussed in the previous sections, are summarized in Tables 7.14 and 7.15. Also, continued use of the bare piezoelectric cable sensors is recommended, based on their acceptable performance in the field and positive influence on the installation procedure. As additional experience is gained with the bare sensors and the accompanying smaller volumes of materials, it may be necessary to revise the material selection criteria.

Table 7.14: Recommended Materials

Recommended Material	Ranking
ECM P5G	1^{st}
IRD	2^{nd}

Table 7.15: Recommended Selection Criteria

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

Chapter Eight: Summary, Conclusions, and Recommendations

8.1 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 to evaluate new materials as they become available.

To achieve these objectives, three basic sources of information were used. Previous research was 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.

8.2 Conclusions

By comparing 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: acceptable materials, material acceptance criteria, and sensor design to be used.

8.2.1 Acceptable Materials

On the basis of the tests used for this project, weighted in importance as explained in Chapter Seven, two materials are recommended for use. These materials are ECM P5G and IRD AS-475, both of which are methyl methacrylate materials with fine mineral fillers. 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 8.1 lists the recommended materials.

Table 8.1: Recommended Materials

Recommended Material	Material Type
ECM P5G IRD	Acrylic Acrylic

8.2.2 Selection Criteria (Tests to Use)

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

- adequate strength in compression
- proper relationship between phase angle δ and temperature
- proper flexibility as described by the storage modulus G', with a proper relationship to temperature
- correct gel time, allowing adequate working time
- shrinkage in the acceptable range, from some expansion to minimal shrinkage
- proper final curing time, as measured by the Vicat test
- adequate bond flexural strength and behavior
- 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 Four. The results are described in Chapter Six, while the analysis that led to the final test selections is described in Chapter Seven. Table 8.2 lists the properties to be tested, along with the acceptable ranges of results.

Table 8.2: Recommended Selection Criteria

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

8.2.3 <u>Sensor Designs</u>

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 films. 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.

8.3 Recommendations

To conclude this report are some recommendations for future work. One environmental zone of Texas was not tested, which is the cold and humid region of east Texas. A test site should be set up in this region in the near future. In addition, none of the field trials was installed in portland cement concrete. While the behavior of asphalt pavement is probably more influential on the installation than concrete, some field testing in concrete should be done. Also, further testing of the effects of extreme temperatures, both hot and cold, would be useful in verifying that the gel time and the complex shear modulus tests are adequate to determine acceptable behavior at these temperatures. Finally, laboratory testing should be conducted on the bare cable sensors. Such tests could include quality control, determining ranges of deformation before significant reduction in sensor accuracy, and the effect of extreme temperatures on sensor accuracy.

Further testing may indicate that some of the conclusions of this project need revision. As more information is collected, the selection criteria, as well as the other recommendations of this project, may need to be altered. Such adjustments should be viewed as necessary growth and refinement of TxDOT policy, not as an invalidation of the results of this study.

APPENDICES AND BIBLIOGRAPHY

Appendix A: DOT Phone Survey Questionnaire

(Note the state and the name of the person contacted, and the date.)

Does your department use electronic traffic monitoring equipment, such as classification devices or weigh-in-motion instruments?

Are the piezoelectric sensors you use films or cables?

What are the brand names of the equipment you have been using?

Please describe the sensors':

intended use,

size and shape,

casing material.

Please describe the installation procedure.

What equipment is used to perform the installation (dry saw, water lubricated saw, air hammer, gang saw, combinations)?

What special precautions are taken with the signal wires?

What kind of bonding agent is used to attach the instruments to the pavement for:

asphalt?

concrete?

How do you select the bonding agent (how do you screen possible bonding agents and determine the best one)?

How do you apply the bonding agent?

Do you have specifications for bonding agents? Are there different specs for concrete and asphalt pavements?

Do you cover the sensors with anything (such as bituminous tape)? Why?

What is your success record (how long do the sensors stay functional)?

What other problems have you encountered (specifically, any problems with potholes around the sensors)?

What combination of materials and methods works best?

Please explain what factors make that procedure work better than others.

Please describe the types of failures that have occurred and what caused them.

Could you send us information, such as specifications or sales brochures, about the materials and methods that you use?

Appendix B: Material Suppliers List

Material	Company	Contact	Phone Number
ECM P5G	Electronic Control Measurement, Inc.	Ron White	(512) 990-3773
Flexbond #11	E-Poxy Industries, Inc.	—	1-800-833-3400
Flexolith	Tamms Industries Company	—	1-800-624-1438
HMMUP	CMRG, UT	Dr. David Fowler	(512) 471-4498
IRD AS-475	International Road Dynamics, Inc.	Douglas Pratt	(306) 653-6616
Masterfill CJ	Master Builders, Inc.	Bud Shipman	1-800-221-7549
Schul	Schul International Company	—	(404) 441-0588
Transpo T46	Transpo Industries, Inc.	Ron Brennan	(914) 636-1000
TxDOT G-100	Texas Department of Transportation	Dean Barrett	(512) 465-7545

Appendix C: Project Data Table

The following pages show the complete table of all data collected for this project. An entry of "- - -" indicates no data. The first four pages (92-95) show the raw data as collected. The next four pages (96-99) show the average, maximum, and minimum values collected.

Appendix C: Project Data Table — Raw Data

Test or Property	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD	Masterfill	Schul	Transpo T46	TxDOT G-100
Abrasion	2.4	---	1.4	0.6	2.4	12.2	0.0	0.0	0.1
(g)	6.0	---	1.1	0.2	4.5	14.9	0.0	0.9	0.0
	---	---	0.4	---	6.8	12.7	0.0	0.0	0.1
Compressive Strength	3178	---	8603	9349	961	3789	6662	330	16382
(psi)	3988	---	8632	9315	1123	4248	6734	457	22997
	---	---	8448	---	---	4150	---	---	17209
E*	19.1	---	18.6	132.0	24.8	8.8	127.3	2.1	107.1
0° C	---	---	36.1	---	---	14.7	---	---	142.7
(ksi)	---	---	---	---	---	---	---	---	19.8
E*	3.9	---	12.4	101.0	3.9	3.1	41.8	---	105.5
25° C	---	---	7.9	---	---	4.1	---	---	71.3
(ksi)	---	---	---	---	---	---	---	---	140.6
E*	1.3	---	0.3	67.2	0.4	0.4	2.8	---	71.4
50° C	---	---	2.0	---	---	---	---	---	105.3
(ksi)	---	---	6.0	---	---	---	---	---	74.2
G* - Phase Angle	0.25	0.22	0.09	0.04	0.27	0.03	0.08	0.09	0.18
0° C	---	0.23	0.27	0.07	0.45	0.06	0.17	0.05	0.23
(radians)	---	---	---	0.05	0.28	0.04	0.11	---	---
G* - Phase Angle	0.48	0.53	0.38	0.09	0.63	0.16	0.32	0.20	0.05
25° C	---	0.49	0.45	0.10	0.75	0.23	0.32	0.20	0.09
(radians)	---	0.50	0.38	0.09	0.70	0.20	0.33	0.18	0.10
G* - Phase Angle	0.63	0.33	0.16	0.22	0.37	0.67	0.16	0.78	0.19
50° C	---	0.37	0.17	0.19	0.41	0.67	0.17	0.79	0.19
(radians)	---	---	0.17	0.23	0.41	0.68	0.15	---	---
G*	14.0	13.0	66.2	31.7	45.4	55.2	46.1	23.0	3.8
0° C	---	10.9	17.1	45.1	24.2	43.2	20.3	32.5	3.3
(ksi)	---	---	---	31.7	45.2	26.7	17.8	---	---
G*	9.0	1.8	11.0	29.7	7.2	32.6	16.1	32.0	36.4
25° C	---	2.3	7.5	44.1	3.0	32.2	15.4	25.1	31.4
(ksi)	---	2.0	10.5	33.3	6.2	29.6	18.7	38.0	10.2
G*	0.5	0.1	2.1	17.4	0.9	0.7	4.7	0.8	41.6
50° C	---	0.1	2.3	30.0	0.5	0.7	4.8	0.5	3.4
(ksi)	---	---	1.7	20.6	0.6	0.7	3.9	---	---
G'	13.6	12.7	66.0	31.7	43.7	55.2	46.0	22.9	3.7
0° C	---	10.6	16.5	45.0	21.8	43.1	20.0	32.5	3.2
(ksi)	---	---	---	31.7	43.5	26.6	17.7	---	---

Appendix C: Project Data Table — Raw Data (continued)

Test or Property	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD	Masterfill	Schul	Transpo T46	TxDOT G-100
G'	8.0	1.5	10.2	29.6	5.8	32.2	15.3	31.4	36.3
25° C	---	2.1	6.8	43.8	2.2	31.3	14.6	24.6	31.3
(ksi)	---	1.7	9.7	33.2	4.7	29.0	17.7	37.4	10.1
G'	0.4	0.1	2.1	17.0	0.8	0.6	4.7	0.6	40.9
50° C	---	0.1	2.2	29.4	0.5	0.6	4.7	0.4	3.3
(ksi)	---	---	1.6	20.0	0.6	0.5	3.9	---	---
Flexural Strength	2482	---	2727		2463	2482	2468	2653	2499
(psi)	2529	---	2724		2529	2529	---	---	2657
	---	---	2713		---	---	---	---	2416
Gel Time	40	5	70	67	55	63	5	70	15
0° C	---	---	---	---	---	---	---	---	---
(minutes)	---	---	---	---	---	---	---	---	---
Gel Time	13	42	56	30	17	17	30	22	27
25° C	---	---	---	---	---	---	---	---	---
(minutes)	---	---	---	---	---	---	---	---	---
Gel Time	8	12	10	21	8	7	7	4	8
50° C	---	---	---	---	---	---	---	---	---
(minutes)	---	---	---	---	---	---	---	---	---
Shrinkage	0.00	-0.06	0.58	0.30	0.04	0.27	-1.50	0.68	1.50
(%)	---	---	---	---	---	---	---	---	---
	---	---	---	---	---	---	---	---	---
Tg	20	---	23	26	32	32	30	22	43
(° C)	25	---	22	20	36	36	36	24	45
	23	---	27	24	28	28	28	21	40
Alpha (T<Tg)	1.43E-05	---	1.01E-06	2.36E-06	1.17E-05	6.33E-06	1.68E-05	---	9.90E-06
(x10^6 / ° C)	4.78E-06	---	4.10E-06	---	---	---	7.62E-06	---	8.48E-06
	6.87E-06	---	5.13E-06	3.80E-06	---	2.25E-06	4.17E-06	---	8.25E-06
Alpha (T>Tg)	1.57E-05	---	1.05E-05	4.10E-06	6.82E-06	8.38E-06	1.12E-05	6.33E-06	7.57E-06
(x10^6 / ° C)	8.98E-06	---	1.08E-05	4.29E-06	1.61E-05	3.48E-06	1.05E-05	5.10E-06	1.11E-05
	1.03E-05	---	1.02E-05	2.09E-06	1.07E-05	3.91E-06	4.35E-06	6.55E-06	6.15E-06
Vicat	11	200	150	30	20	14	125	80	150
(minutes)	---	---	---	---	---	---	---	---	---
	---	---	---	---	---	---	---	---	---
Viscosity	25	55	30	28	21	18	50	20	23
(Pa-s)	---	---	---	---	---	---	---	---	---
	---	---	---	---	---	---	---	---	---

Appendix C: Project Data Table — Raw Data (continued)

Test or Property	ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD	Masterfill	Schul	Transpo T46	TxDOT G-100
Flexural Bond	192	102	276	15	140	399	206	263	390
Asphalt Base	50/50	bond	asphalt	asphalt	50/50	asphalt	asphalt	asphalt	asphalt
(psi)	199	108	267	15	86	332	188	253	336
(failure mode)	50/50	bond	asphalt	asphalt	50/50	asphalt	asphalt	asphalt	asphalt
	169	97	266	19	96	---	266	285	---
	50/50	bond	asphalt	asphalt	50/50	---	asphalt	asphalt	---
Flexural Bond	521	165	466	183	262	545	272	380	1103
Concrete Base	50/50	deflection	bond	bond	50/50	polymer	50/50	concrete	concrete
(psi)	565	191	707	120	290	445	369	654	976
(failure mode)	50/50	deflection	concrete	bond	50/50	concrete	50/50	concrete	concrete
	598	---	---	212	388	333	---	648	---
	50/50	---	---	bond	50/50	bond	---	concrete	---
Shear Bond	110	92	201	92	58	293	290	365	295
Asphalt Base	50/50	50/50	asphalt	asphalt	bond	asphalt	asphalt	asphalt	asphalt
(psi)	128	89	270	76	98	303	279	360	328
(failure mode)	50/50	asphalt	asphalt	asphalt	bond	asphalt	asphalt	asphalt	U-bolt
	---	---	---	---	---	331	251	---	---
	---	---	---	---	---	asphalt	asphalt	---	---
Shear Bond	0	136	327	3	160	272	186	227	342
Concrete Base	bond	bond	50/50	bond	bond	50/50	bond	50/50	U-bolt
(psi)	220	124	314	22	111	262	159	233	406
(failure mode)	bond	bond	50/50	bond	bond	50/50	bond	50/50	U-bolt
Tension Bond	15	6	11	0	4	16	18	6	16
Asphalt Base	asphalt	asphalt	asphalt	asphat	asphalt	asphalt	asphalt	asphalt	asphalt
(psi)	13	7	4	0	6	16	16	4	20
(failure mode)	asphalt	steel bond	asphalt	asphalt	asphalt	asphalt	asphalt	asphalt	asphalt
Tension Bond	27	23	33	4	24	16	52	35	49
Concrete Base	50/50	steel bond	concrete	polymer	steel bond	50/50	concrete	concrete	concrete
(psi)	35	18	41	1	24	33	37	35	43
(failure mode)	concrete	steel bond	concrete	polymer	bond	bond	concrete	50/50	concrete
Freeze/Thaw Bond	10	10	10	0	10	12	11	14	16
Asphalt Base	asphalt	asphalt	asphalt	asphalt	asphalt	asphalt	asphalt	asphalt	asphalt
(psi)	6	9	14	0	12	13	8	17	16
(failure mode)	asphalt	asphalt	asphalt	asphalt	asphalt	asphalt	asphalt	asphalt	asphalt
Freeze/Thaw Bond	35	27	45	4	22	32	40	60	27
Concrete Base	50/50	epoxy bond	concrete	polymer	polymer	concrete	50/50	concrete	concrete
(psi)	50	30	---	5	25	53	41	68	33
(failure mode)	bond	epoxy bond	---	polymer	polymer	concrete	concrete	concrete	concrete

Appendix C: Project Data Table — Raw Data (continued)

Extreme Temperature Tests

Test or Property	ECM P5G			IRD		
	0° C	25° C	50° C	0° C	25° C	50° C
Flexural Bond	264	192	0	208	399	8
Asphalt Base	50/50	50/50	asphalt	bond	asphalt	50/50
(psi)	344	199	0	251	332	16
(failure mode)	asphalt	50/50	asphalt	bond	asphalt	50/50
	345	169	8	248	- - -	14
	bond	50/50	asphalt	bond	- - -	50/50
Flexural Bond	1069	521	116	489	545	68
Concrete Base	bond	50/50	bond	bond	polymer	50/50
(psi)	649	565	150	472	445	62
(failure mode)	bond	50/50	bond	bond	concrete	50/50
	863	598	135	521	333	70
	bond	50/50	bond	bond	bond	50/50
Shear Bond	156	110	42	42	58	8
Asphalt Base	bond	50/50	50/50	bond	bond	bond
(psi)	156	128	32	34	98	10
(failure mode)	bond	50/50	50/50	bond	bond	bond
Shear Bond	195	0	48	184	160	41
Concrete Base	50/50	bond	bond	50/50	bond	bond
(psi)	254	220	- - -	202	111	45
(failure mode)	50/50	bond	- - -	50/50	bond	bond

Appendix C: Project Data Table — Processed Data

Test or Property		ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD	Masterfill	Schul	Transpo T46	TxDOT G-100
Abrasion	avg	4.2	---	1.0	0.4	4.6	13.3	0.0	0.3	0.1
(g)	max	6.0	---	1.4	0.6	6.8	14.9	0.0	0.9	0.1
	min	2.4	---	0.4	0.2	2.4	12.2	0.0	0.0	0.0
Compressive Strength	avg	3583	---	8561	9332	1042	4062	6698	394	18863
(psi)	max	3988	---	8632	9349	1123	4248	6734	457	22997
	min	3178	---	8448	9315	961	3789	6662	330	16382
E*	avg	19.1	---	27.4	132.0	24.8	7.8	63.7	1.1	89.9
0° C	max	19.1	---	36.1	132.0	24.8	14.7	127.3	2.1	142.7
(ksi)	min	19.1	---	18.6	132.0	24.8	8.8	127.3	2.1	19.8
E*	avg	3.9	---	10.2	101.0	3.9	2.4	20.9	---	105.8
25° C	max	3.9	---	12.4	101.0	3.9	4.1	41.8	---	140.6
(ksi)	min	3.9	---	7.9	101.0	3.9	3.1	41.8	---	71.3
E*	avg	1.3	---	2.8	67.2	0.4	0.1	2.8	---	83.6
50° C	max	1.3	---	6.0	67.2	0.4	0.4	2.8	---	105.3
(ksi)	min	1.3	---	0.3	67.2	0.4	0.4	2.8	---	71.4
G* - Phase Angle	avg	0.25	0.23	0.18	0.05	0.33	0.05	0.12	0.07	0.21
0° C	max	0.25	0.23	0.27	0.07	0.45	0.06	0.17	0.09	0.23
(radians)	min	0.25	0.22	0.09	0.04	0.27	0.03	0.08	0.05	0.18
G* - Phase Angle	avg	0.48	0.51	0.41	0.10	0.70	0.20	0.33	0.20	0.08
25° C	max	0.48	0.53	0.45	0.10	0.75	0.23	0.33	0.20	0.10
(radians)	min	0.48	0.49	0.38	0.09	0.63	0.16	0.32	0.18	0.05
G* - Phase Angle	avg	0.63	0.35	0.16	0.22	0.40	0.68	0.16	0.78	0.19
50° C	max	0.63	0.37	0.17	0.23	0.41	0.68	0.17	0.79	0.19
(radians)	min	0.63	0.33	0.16	0.19	0.37	0.67	0.15	0.78	0.19
G*	avg	14.0	12.0	41.7	36.2	38.3	41.7	28.1	27.8	3.6
0° C	max	14.0	13.0	66.2	45.1	45.4	55.2	46.1	32.5	3.8
(ksi)	min	14.0	10.9	17.1	31.7	24.2	26.7	17.8	23.0	3.3
G*	avg	9.0	2.0	9.7	35.7	5.5	31.4	16.7	31.7	26.0
25° C	max	9.0	2.3	11.0	44.1	7.2	32.6	18.7	38.0	36.4
(ksi)	min	9.0	1.8	7.5	29.7	3.0	29.6	15.4	25.1	10.2
G*	avg	0.5	0.1	2.0	22.7	0.7	0.7	4.5	0.7	22.5
50° C	max	0.5	0.1	2.3	30.0	0.9	0.7	4.8	0.8	41.6
(ksi)	min	0.5	0.1	1.7	17.4	0.5	0.7	3.9	0.5	3.4
G'	avg	13.6	11.6	41.2	36.1	36.3	41.6	27.9	27.7	3.5
0° C	max	13.6	12.7	66.0	45.0	43.7	55.2	46.0	32.5	3.7
(ksi)	min	13.6	10.6	16.5	31.7	21.8	26.6	17.7	22.9	3.2

Appendix C: Project Data Table — Processed Data (continued)

Test or Property		ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD	Masterfill	Schul	Transpo T46	TxDOT G-100
G'	avg	8.0	1.8	8.9	35.5	4.2	30.8	15.8	31.1	25.9
25° C	max	8.0	2.1	10.2	43.8	5.8	32.2	17.7	37.4	36.3
(ksi)	min	8.0	1.5	6.8	29.6	2.2	29.0	14.6	24.6	10.1
G'	avg	0.4	0.1	2.0	22.1	0.6	0.6	4.4	0.5	22.1
50° C	max	0.4	0.1	2.2	29.4	0.8	0.6	4.7	0.6	40.9
(ksi)	min	0.4	0.1	1.6	17.0	0.5	0.5	3.9	0.4	3.3
Flexural Strength	avg	2506	---	2721	0	2496	2506	2468	2653	2524
(psi)	max	2529	---	2727	0	2529	2529	2468	2653	2657
	min	2482	---	2713	0	2463	2482	2468	2653	2416
Gel Time	avg	40	5	70	67	55	63	5	70	15
0° C	max	40	5	70	67	55	63	5	70	15
(minutes)	min	40	5	70	67	55	63	5	70	15
Gel Time	avg	13	42	56	30	17	17	30	22	27
25° C	max	13	42	56	30	17	17	30	22	27
(minutes)	min	13	42	56	30	17	17	30	22	27
Gel Time	avg	8	12	10	21	8	7	7	4	8
50° C	max	8	12	10	21	8	7	7	4	8
(minutes)	min	8	12	10	21	8	7	7	4	8
Shrinkage	avg	0	-0.06	0.58	0.3	0.04	0.27	-1.5	0.68	1.5
(%)	max	0	-0.06	0.58	0.3	0.04	0.27	-1.5	0.68	1.5
	min	0	-0.06	0.58	0.3	0.04	0.27	-1.5	0.68	1.5
Tg	avg	23	---	24	23	32	32	31	22	43
(° C)	max	25	---	27	26	36	36	36	24	45
	min	20	---	22	20	28	28	28	21	40
Alpha (T<Tg)	avg	8.65E-06	---	3.41E-06	3.08E-06	1.17E-05	4.29E-06	9.53E-06	---	8.88E-06
(x10^6 / ° C)	max	1.43E-05	---	5.13E-06	1.43E-05	1.17E-05	6.33E-06	1.68E-05	---	9.90E-06
	min	4.78E-06	---	1.01E-06	2.36E-06	1.17E-05	2.25E-06	4.17E-06	---	8.25E-06
Alpha (T>Tg)	avg	1.17E-05	---	1.05E-05	3.49E-06	1.12E-05	5.26E-06	8.68E-06	5.99E-06	8.27E-06
(x10^6 / ° C)	max	1.57E-05	---	1.08E-05	4.29E-06	1.61E-05	8.38E-06	1.12E-05	6.55E-06	1.11E-05
	min	8.98E-06	---	1.02E-05	2.09E-06	6.82E-06	3.48E-06	4.35E-06	5.10E-06	6.15E-06
Vicat	avg	11	200	150	30	20	14	125	80	150
(minutes)	max	11	200	150	30	20	14	125	80	150
	min	11	200	150	30	20	14	125	80	150
Viscosity	avg	25	55	30	28	21	18	50	20	23
(Pa-s)	max	25	55	30	28	21	18	50	20	23
	min	25	55	30	28	21	18	50	20	23

Appendix C: Project Data Table — Processed Data (continued)

Test or Property		ECM P5G	Flexbond #11	Flexolith	HMMUP	IRD	Masterfill	Schul	Transpo T46	TxDOT G-100
Flexural Bond	avg	187	102	270	16	107	366	220	267	363
Asphalt Base	max	199	108	276	19	140	399	266	285	390
(psi)	min	169	97	266	15	86	332	188	253	336
(failure mode)										
Flexural Bond	avg	561	178	587	172	313	441	321	561	1040
Concrete Base	max	598	191	707	212	388	545	369	654	1103
(psi)	min	521	165	466	120	262	333	272	380	976
(failure mode)										
Shear Bond	avg	119	91	236	84	78	309	273	363	312
Asphalt Base	max	128	92	270	92	98	331	290	365	328
(psi)	min	110	89	201	76	58	293	251	360	295
(failure mode)										
Shear Bond	avg	110	130	321	13	136	267	173	230	374
Concrete Base	max	220	136	327	22	160	272	186	233	406
(psi)	min	0	124	314	3	111	262	159	227	342
(failure mode)										
Tension Bond	avg	14	7	8	0	5	16	17	5	18
Asphalt Base	max	15	7	11	0	6	16	18	6	20
(psi)	min	13	6	4	0	4	16	16	4	16
(failure mode)										
Tension Bond	avg	31	21	37	3	24	25	45	35	46
Concrete Base	max	35	23	41	4	24	33	52	35	49
(psi)	min	27	18	33	1	24	16	37	35	43
(failure mode)										
Freeze/Thaw Bond	avg	8	10	12	0	11	13	10	16	16
Asphalt Base	max	10	10	14	0	12	13	11	17	16
(psi)	min	6	9	10	0	10	12	8	14	16
(failure mode)										
Freeze/Thaw Bond	avg	43	29	45	5	24	43	41	64	30
Concrete Base	max	50	30	45	5	25	53	41	68	33
(psi)	min	35	27	45	4	22	32	40	60	27
(failure mode)										

Appendix C: Project Data Table — Processed Data (continued)

Extreme Temperature Tests

Test or Property		ECM PSG			IRD		
		0° C	25° C	50° C	0° C	25° C	50° C
Flexural Bond	avg	318	187	3	236	366	13
Asphalt Base	max	345	199	8	251	399	16
(psi)	min	264	169	0	208	332	8
(failure mode)							
Flexural Bond	avg	860	561	134	494	441	67
Concrete Base	max	1069	598	150	521	545	70
(psi)	min	649	521	116	472	333	62
(failure mode)							
Shear Bond	avg	156	119	37	38	78	9
Asphalt Base	max	156	128	42	42	98	10
(psi)	min	156	110	32	34	58	8
(failure mode)							
Shear Bond	avg	225	110	48	193	136	43
Concrete Base	max	254	220	48	202	160	45
(psi)	min	195	0	48	184	111	41
(failure mode)							

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