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AN INVESTIGATION OF NEW MARKER ADHESIVE PROCESSES FOR BOTTS' DOTS

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Executive Summary

The problem: In past few years, research efforts have been made to automate the marker placement process in order to increase operator safety and minimize traffic hazards caused by the current manual process. Several automatic raised pavement marker machine (RPMM) prototypes have been developed and tested. The concept of automating the marker placement process was proven. However, The existing bulk adhesive melting method was found to be difficult and almost incompatible with the automation of marker placement. The handling of liquid adhesive is messy and often contaminates and malfunctions robotic components or the endeffector. Delivery of hot bitumen at approximate 204.4°C (400°F) also creates safety problems and causes unnecessary wear of mechanical parts. Hot bitumen dispensing system is prone to high maintenance and easy failure, the resulting start-stop process requires a long down time, therefore lowers productivity.

The project: In order to increase reliability and maneuverability of the automatic RPMM, a research has been conducted at University of California, Davis under the contract with Caltrans. This research investigates new marker adhesive processes aimed at eliminating the on-road bitumen melting and handling. With the proposed marker adhesive processes, marker are pre-attached with the adhesive layer on the bottom during manufacturing, laid onto road by the automated RPMM, and the adhesive layer will be then locally processed (with or without heating) to adhere to the pavement. The investigation performed were grouped into two categories, i.e. localized heating approach using bituminous adhesive and new adhesive material approach. New adhesive process methods and materials were investigated in close cooperation with Caltrans laboratories as well as adhesive and marker manufacturers including Stimsonite, Crafco, Davidson, Hellerbond and RISI.

In the localized heating approach, various heating methods were assessed for heating on-road bituminous adhesive pads. Three fast heating methods including resistance heating, inductive heating and explosive heating were tested. Two criteria in evaluating the alternative

heating method were bonding strength and heating cycle. The bonding strength of locally heated adhesive is expected to be equivalent to that of the bulk heated, and the heating cycle should meet the operating speed requirement of the automated RPMM (5 miles per hour).

In the new material approach, various tests were conducted on eight butyl based cold applied adhesive pads obtained from Stimsonite and Davidson. Their bonding strengths were compared with hot applied bituminous adhesive and the effects of various factors such as substrate, temperature, primer, force and time applied during installation and marker bottom condition on bonding strength. The test results and suggestions were fed back to the manufacturers for material improvement. Field investigation was conducted on the selected butyl pads in collaboration with Caltrans Traffic Operation Division in Los Angeles.

The results: The research showed that several alternatives appeared promising for automatic marker placement. The investigation revealed that the induction heating method is a most promising alternative to the bulk heated bituminous adhesive for the automated raised pavement marker machine. Fast heating with acceptable heating cycle and satisfactory bonding strength were achieved with the inductive heating method. Pyrotechnic heating method, although the bonding strength was found to be poor due excess ash layer formed at the interfaces, has demonstrated its potential of fast heating, low cost and simplicity. The firing technology developed has been proven to be effective and safe. Although the currently available cold applied butyl adhesives are not applicable for permanent marker placement due to its inadequate bonding strength, it was found to have favorable temperature and elastic recovery characteristics over hot applied bituminous adhesive.

Several testing technologies were developed during the investigation including shear strength, tensile strength, impact, elastic recovery as well as temperature and loading rate tests.

Recommendation: Further study on induction heating technology is strongly recommended. The main task of the extended work is to optimize the formula of adhesive mixture, electrical and geometric parameters of apparatus to further reduce heating cycle as well as to improve the overall performance of inductively heated bituminous adhesive. Development of an inductive heating prototype or test bed with road surface simulator is suggested prior to integrating this technology into the automated marker placement machine currently under the process of commercialization.

Further research and development on pyrotechnic heating to reduce the heating cycle and improve adhesion, including searching a proper fuel type material which produces minimum ash, optimizing the fuel-oxidizer ratio and the thickness of bitumen pad.

The cold applied adhesive is the most favorable alternative to the hot melt bitumen for the automatic raised pavement marker machine if an appropriate material can be developed. Searching and developing new cold applied adhesive with enhanced bonding strength and good temperature characteristics is recommended.

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Chapter 1
Introduction

1.1 BACKGROUND

In past few years, research efforts have been made to automate the marker placement process in order to increase operator safety and minimize traffic hazards caused by the current manual process. Several automatic raised pavement marker machine (RPMM) prototypes have been developed and tested. The concept of automating the marker placement process was proven. However, marker adhesive application was found to be troublesome. On these automatic prototypes, conventional mass heating systems (melters) were employed. Bulk bituminous materials were loaded in a large tank, heated and melted by propane flame or an electric heater, and then pumped to the adhesive dispensing device of the RPMM through a long hose. It takes about two hours to bring adhesive to the pouring temperature from cold start. This conventional marker adhesive handling method is messy. The hot bitumen often contaminates and malfunctions robotic components or the endeffector and thus lowers productivity. Delivery of hot bitumen at approximate 204°C (400°F) also creates safety problems and causes unnecessary wear of mechanical parts. Due to its physical/thermal properties, the fluidized marker adhesive held in the hose and dispensing unit solidifies every time the operation of RPMM is stopped. To re-fluidize the material in the system, additional heating systems need to be provided both in the dispensing area and along the 6 meter (20 foot) long hose between the melter and RPMM, which not only is inefficient and costly but also makes the whole marker operating system clumsy.

In order to develop a road-ready machine for automating the marker placement process, research into a new marker adhesive process aiming at eliminating the on-road bitumen melting and handling needs to be done. The elimination of the on-road adhesive melting and handling process will greatly simplify the automatic RPMM and will increase its reliability and maneuverability. With new adhesive processing technology, bulk marker adhesive handling will be completed during the manufacturing of the markers, therefore on-road high temperature material handling related safety problems will be eliminated.

1.2 OBJECTIVES

The ultimate goal of this project is to find an effective and speedy way to automate highway marker placement by developing a new marker process that can be used on an automatic RPMM.

The objectives are to:

- Search and develop a feasible localized heating method(s) for marker adhesive application on an automated RPMM.
- Evaluate and improve the available marker adhesive materials that can be cold applied; study the feasibility for permanent use of selected materials with acceptable marker retention quality.
- Establish additional marker adhesive testing and evaluation procedures.

1.3 RESEARCH SCOPE

The task of the project was to perform basic investigations and demonstrate a series of feasible concepts. The primary step was searching literature, assessing different materials and the current technologies for different adhesive processes and selecting a feasible method for marker adhesive application to test. A new marker adhesive process was proposed in the initial stage of this investigation. With the proposed new marker adhesive process, markers will be pre-attached with an adhesive layer of certain thickness on the bottom during manufacturing. These 2-ply markers will be laid automatically on the road surface by the RPMM at the required speed. The on-road adhesive layer underneath the marker will then be locally processed (with or without heating) and pressed into the pavement. The team also gathered suggestions and ideas from formal and informal brainstorming sessions. The proposed technologies and methods have been grouped into four categories as described below.

1. Eliminating on-road bulk melting and handling of bituminous adhesive -- localized heating approach.

The bituminous adhesive that is currently in use will still be employed to install raised pavement markers. It will be fabricated in the form of 10.1 cm by 10.1 cm (4"x4") pad which is pre-attached on the bottom of the marker during manufacturing. The two-ply markers will be placed by an automatic RPMM on the road surface, and the adhesive pad will then be melted. The install force can be applied during heating or cooling cycle. Various fast heating methods include resistance heating, inductive heating and explosive heating.

2. Eliminating heating process from Botts' Dot application -- new material approach.

The hot melt bituminous adhesive will be replaced by new adhesive materials which can be pre-attached to marker and cold applied onto the road surface.

3. Eliminating current Bott's Dots and replacing with other mechanical alternatives.

The basic idea was to use the same road pavement material for highway lane marking. One possible alternative is bituminous raised pavement marker and the other is built-in raised or depressed pavement lines. Eliminating current used markers will greatly reduce the cost of highway lane marking as well as eliminating windshield breaking problem caused by shatters of Bott's Dots. However, it may complicate road construction and maintenance. The research needs to be focused on two aspects: (1) the material strength and line durability and (2) the technique of providing color and reflectance.

4. Eliminating mechanical sensing and feedback, replacing with active electronic or high tech sensing, feedback and display. The proposed lane marking system consists two

subsystems: (1) on-road signal and (2) in-car sensing and broadcasting. The on-road signal includes visible on-road flat lane lines and on-line signal elements (optical, magnetic or electronic magnetic elements). The in-car sensing can be laser sensing, magnetometer or electromagnetic (radar). The driver can be alerted through hologram-virtue display on the windshield and alarm from a sensed roadway.

Due to the time limitation, the project was focused on scope I and II. The investigation on three localized fast heating technologies is presented in Chapter 2. Chapter 3 discusses the test procedures and presents the test results on various cold applied adhesives. The last chapter (Chapter 4) summarizes the important results of this investigation as well as the recommendations for the further study.

Research on new adhesive materials and concepts was carried out in close cooperation with Material Laboratories at Caltrans, as well as marker and adhesive manufacturers including Stimsonite, Crafco, Hellerbond, RISI. The research was focused on designing and conducting laboratory experiments to study the feasibility of alternative processes and to determine optimum parameters in meeting the requirements of the automated marker placement process (mainly operating speed of 5 miles per hour and marker firmness to the road surface). Field evaluation was conducted on selected cold applied adhesive with the assistance of Caltrans Traffic Operation Division in District 07 (in Los Angeles).

Chapter 2
Investigation of Localized Heating Technologies

2.1 INTRODUCTION

Bituminous adhesive has been widely used to adhere road markers for its low cost and good retention performance. However, the existing bulk melting system was found to be incompatible with the automation of marker placement. The process not only requires long warm-up and down time, but also contaminates robotic components as well as creates safety problem. The intention of investigating localized heating technologies was to eliminate the on-road adhesive melting while still applying currently used bituminous adhesive. The concept was to place the bituminous adhesive pre-attached markers on the road surface and then heat it on-site. The advantages of this process scheme are obvious. The above addressed problems diminishes with the elimination of bulk melting and hot liquid bituminous adhesive handling. It also makes the working condition superior to that of conventional melting process and benefits the environment.

In order to apply the adhesive on an automatic RPMM operating at 8 kilomters per hour (5 miles per hour), the on-site heating cycle must be within one second. The objective of this investigation was to search a feasible fast heating method that can be employed to heat the on-road adhesive pad with acceptable heating cycle and satisfactory bond strength.

A number of fast heating technologies were considered at initial stage of literature searching. After primary feasibility study, three alternatives including resistance heating, induction heating and pyrotechnic heating methods were investigated and are presented in this chapter. The resistance heating method encapsulates a conductive metal wire within a bituminous adhesive pad, applies electric current to the wire through two electrodes and generates heat to melt the pad. The induction heating method imbeds metal particles to the bitumen pad, applies an alternative magnetic field via a conductive coil to generate heat for melting the adhesive pad. The pyrotechnic method, on the hand, employs chemical energy generated by deflagration medium to fast heat the marker adhesive. In addition to the investigation of the above mentioned heating methods, the information of physical and thermal properties of bituminous adhesive is also included in this chapter.

2.2 PHYSICAL AND THERMAL PROPERTIES OF BITUMEN ADHESIVE

Physical and thermal properties of marker adhesives are of basic importance in the study of new heating methods. Some of the physical properties, such as melting point, flash point, viscosity, etc., can be found in Caltrans Standard Specifications[2]. However, the thermal properties of bituminous adhesive mixture were not readily available.

- Specific Gravity, Sg. The bituminous adhesive is a mixture of asphalt and solid filler. By Caltrans standard, it contains 25 - 35% of asphalt (Sg = 1) and 65 - 75% of calcium carbonate filler (Sg = 2.7) [12]. The specific gravity was calculated to be 1.7 ~ 1.89. Its density is 1700 - 1890 kg per cubic meter.

- Specific Heat, C.

The specific heat of bituminous adhesive was calculated using the following expression: [ ]

$$C_m = (1-x)\,C_a + x\,C_f$$

where x = per cent by weight of filler

C_m = specific heat of marker adhesive

C_a = specific heat of asphalt

C_f = specific heat of filler

The specific heat of asphalt at different temperature is given in Appendix A2. The specific heat of filler constituent follows the relation

$$C_f = 0.18 + 0.00006 * T\ (°\,C).$$

Since both C_a and C_f are functions of temperature, the specific heat of adhesive mixture is also a function of temperature. The resultant specific heat of bituminous adhesive containing 25% of asphalt is shown in Figure 2.2.1 and can be expressed as a linear function of temperature

$$Cm = 0.402 + 0.00081 * T\ (°C)$$

with unity correlation coefficient ($R^2 = 1$)

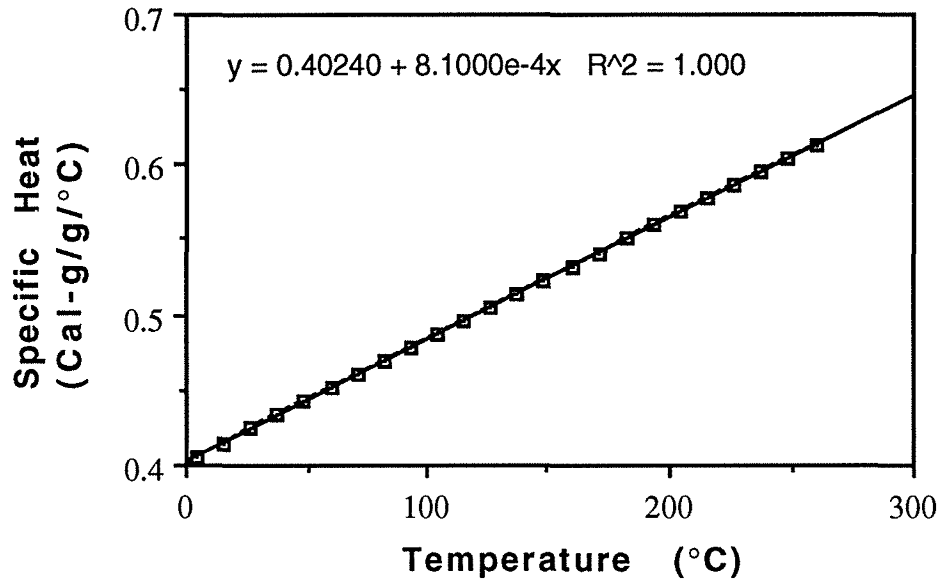


Figure 2.2.1 Specific heat of bituminous adhesive containing 25% of asphalt and 65% of calcium carbonate filler

• Thermal Conductivity, K

Similar to specific heat, the thermal conductivity of the adhesive mixture can be calculated using the expression:

$$K_m = (1-x)\, K_a + x\, K_f$$

where K_a is the thermal conductivity of asphalt

K_f is the thermal conductivity of calcium carbonate filler

K_m is the thermal conductivity of marker adhesive.

The value of K_a and K_f were obtained in the Chemical Engineers' Handbook [12] and converted to SI unit.

$$K_a = 0.744 \text{ w/m °K}$$

$$K_f = 2.25 \text{ w/m °K}$$

$$K_m = 1.72 \text{ w/m °K}$$

Note K_a and K_m change slightly with temperature.

• Thermal difudivity, D

$$D = K_m/(C_m \cdot \rho_m)$$

where ρ_m is density of the adhesive mixture.

• Energy requirement for localized heating

Assume the thickness of the adhesive pad is 3.2 mm (1/8"), then the mass of the pad for reflective marker M is 55.8 gram (0.123 lb) To heat this pad from 21.1°C (70 °F) to 204.4°C (400 °F), the energy required H can be calculated from the expression

$$H = (H_{400} - H_{70})\, M$$

Where H_{400} and H_{70} are the heat content of the adhesive mixture at 204.4°C (400 °F)and 21.1°C (70 °F) respectively (refer to appendix A3).

$$H_{400} = 111$$

$$H_{70} = 9.75$$

therefore, $H = 12.5$ Btu $= 13.1$ kW sec.

To provide the above amount of heat within one second, the minimum power input should be 14 kilowatts.

The physical and thermal properties of bituminous adhesive are listed in Appendix A1.

2.3 RESISTANCE HEATING METHOD

2.3.1 Introduction

Indirect resistance heating is extensively used in industry, where heat is produced in a heating element (resistor) and transferred to the workpiece by conduction, convention or radiation. Since bituminous adhesive is a very poor conductor both electrically and thermally, the idea of electric blanket was introduced to heat the bitumen pads. The basic concept was to implant the bitumen pad with uniformly distributed metal wire and utilize the heat generated in the wire by electric current to melt the pad.

2.3.2 Materials - bituminous adhesive pad preparation

• Adhesive pads.

The adhesive - resistance pad consists of two layers of bituminous adhesive and a patterned heating element made of metal wire. The bituminous adhesive lumps provided by CalTrans Chemical Lab was heated to approximate 43°C (110°F) using solar energy and then made into 3.2 mm (1/8") thick sheets with a hydraulic press. The sheet was cut with a thin metal sheet into 11.4 cm x 11.4 cm (4.5" x 4.5") square pads.

• Heating element

Metal wire was chosen to form the heating element for resistant heating. Two key factors in the heating element design were wire material selection and wire layout pattern. The parameters considered in wire selection were resistivity ρ, diameter d and melting point of the wire. The parameters considered in pattern design were number of the wire line segments n, space between the line segment s, the total wire length L, the margin of wire pattern to the edge of the marker and the connection of the line segments (i.e., in series or in parallel). The design criterion for the particular test conducted was to pull out the maximum power into the heating system (pads) within the capacity of the arc welder used in the experiment while assuring effective working life of the heating element, i.e., no premature wire breakage prior to the completion of the heating cycle.

Mild steel wire was first chosen for its relatively higher resistivity that generates heat more effectively compared to some other metal wire such as copper or aluminum and its lower cost compared to the alloy wires used in electrical heating. In addition, the flexibility of low carbon steel wire made the pattern easy to shape.

A number of combination of the parameters were tried during exploratory experiment. Larger margin was found to better secure the wire into the pads during heating but leave the edge unheated. On the other hand, the pad edge was found well melted with smaller margin but the wire was easily exposed to air which caused fire. To compromise, a 0.32 cm (1/8") margin was chosen for the layout. The length of the wire segment was set to

9.5 cm (3.75") accordingly. Small segment spacing was preferred for effective heat transfer in the adhesive pad. However, if the spacing was too small, wires may make contact due to deformation caused by thermal stress. This in turn, will create short circuit leading to broken wire. The number of wire segments affects the total resistance directly. Increasing this number, n, will increase the total resistance in series and decrease that in parallel. For the diameters chosen (3.2 mm / 1/8"), it was found that the number of segments over 16 would not utilize the power from the arc welder for both series and parallel pattern. Therefore, n was chosen to be 16, resulting a quarter inch spacing between the wire lines. The final patterns and parameters determined for the tests are shown in Fig. 2.3.1. However, in an attempt to input more energy to the pad, N = 18 was also used in the later test. For the same parameters, mainly p, d, l and n, the total resistance in parallel pattern is only $1/n^2$ of that in series pattern. For example, if the number of segment is 16, then the resistance in parallel is only 1/256 of that in series. As result, very little power was pulled into the heating system. In order to utilize higher power in the heating system, 0.4 mm (1/64") nickel alloy wire was used in the parallel pattern. Nickel alloy wire with smaller diameter (0.015 cm / 0.006") was also tried, but all 16 segments were burned out within 2 ~ 3 seconds.

The wire patterns were made by hand and soldered to two electrodes made of bronze strips. The large cross sectioned bronze strips greatly reduced the power consumption at the clamping points and prevented the clamps of the arc welder from heating up.

• Assembly of the heating pads.

The patterned wire was sandwiched in to two 11.4 cm x 11.4 cm x 0.32 cm (4.5" x 4.5" x 1/8") adhesive pads which were heated to about 37.8°C (100 °F). The heating pad "sandwich" was then attached to the bottom of the reflective marker.

The trapped air between the adhesive pads should be force to escape during sandwiching and the marker should be carefully aligned with the wire pattern.

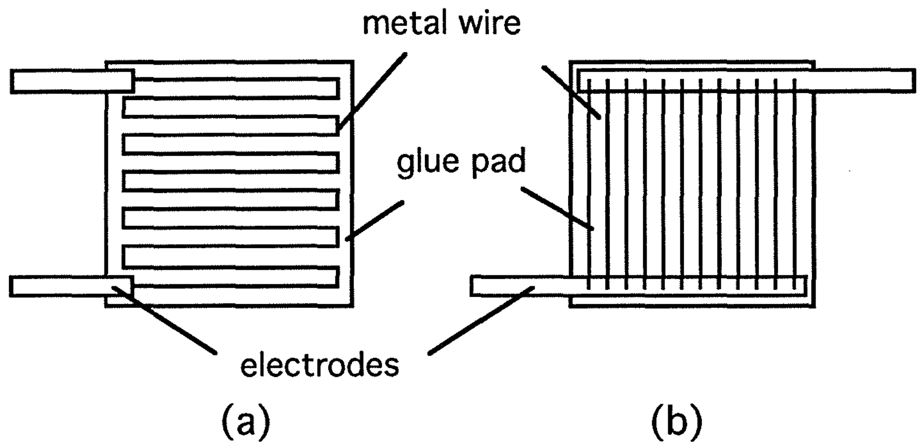


Figure 2.3.1 Patterns of the heating elements. (a) mild steel wire in series: d=0.79 mm (1/32"), R = 0.7 ohm, current setting I = 90 A; (b) alloy wire in parallel: d = 0.4 mm (1/64"), R = 0.06 ohm, current setting I = 150 A.

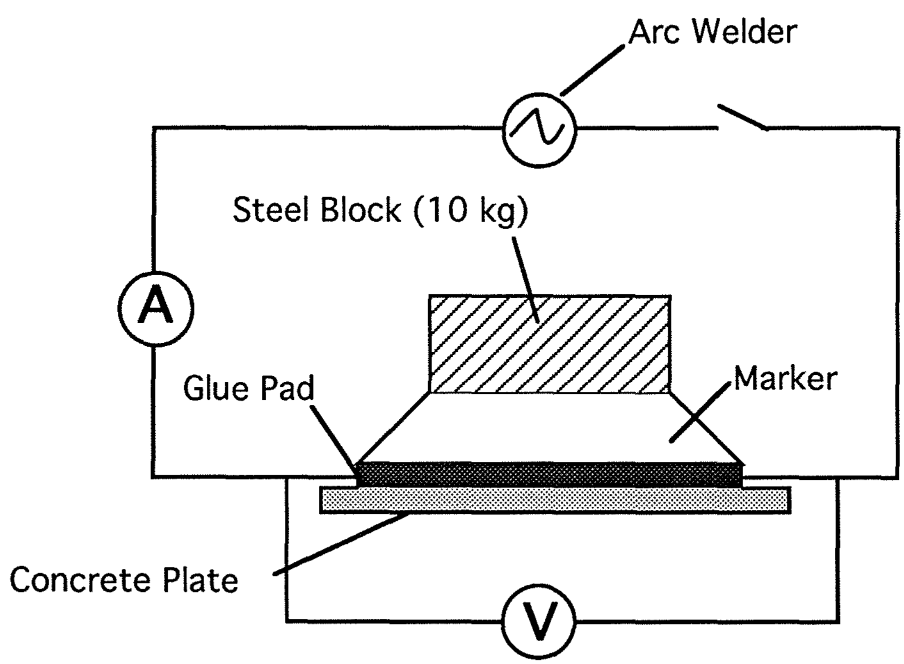


Figure 2.3.2 Setup of the resistance heating test.

2.3.3 Testing Method

The tests were conducted on a welding bench in an engineering teaching lab. The test setting is shown in Fig. 2.3.2. An arc welder Model AC-225-S with maximum output of 5 kW was used as a power supply. The marker assembly was laid on a concrete plate purchased from a local lumber store. A steel block of 10 kg was set atop of the marker to apply the installation force during heating process. A 60 cm x 30 cm (2' x 1') shield made of metal sheet was set in front of the testing unit to protect the operator from injury by hot melt bitumen. To avoid sparks, the clamps of the arc welder were connected to the bronze strips before the switch of the welder was turned on. The current of the arc welder can be varied form 40 amp. to 225 amp. The effective and applicable settings were 90 amp. and 150 amp. for series and parallel patterns respectively. The heating time, voltage and actual current were recorded during the tests.

2.3.4 Results and Discussions

1. Good melting and bonding was achieved with well prepared samples. The heating cycle was about 25 seconds.

2. Liquid bituminous adhesive jetting was frequently observed. Jetting usually occurred at weak boundary or where there was heat concentration such as a bad soldering spot. Sometime, hot melted bitumen started jetting a few seconds after heating started. This early jetting caused a great amount of adhesive material loss, resulting in a hollow heart in the pad.

3. Smoke was always observed, occasionally followed by fire. Fire occurred when the wire bared out into air due to mechanical force from the clamps or wire deformation resulting from thermal stress.

4. Wire was found broken at high current settings or burned out when exposed to air.

5. The voltage and current changes of a series patterned heating element during heating were recorded and are shown in Figure 2.3.3. The resistance of the element was

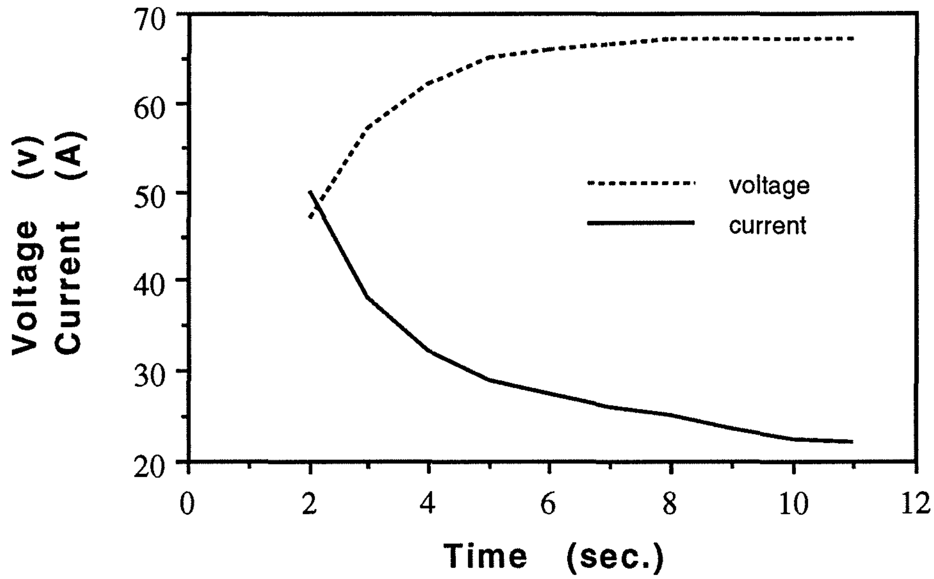


Figure 2.3.3 Voltage and current change during heating cycle.
Mild steel wire in series, n =18, R = 0.8 ohm,
current setting I = 90 A.

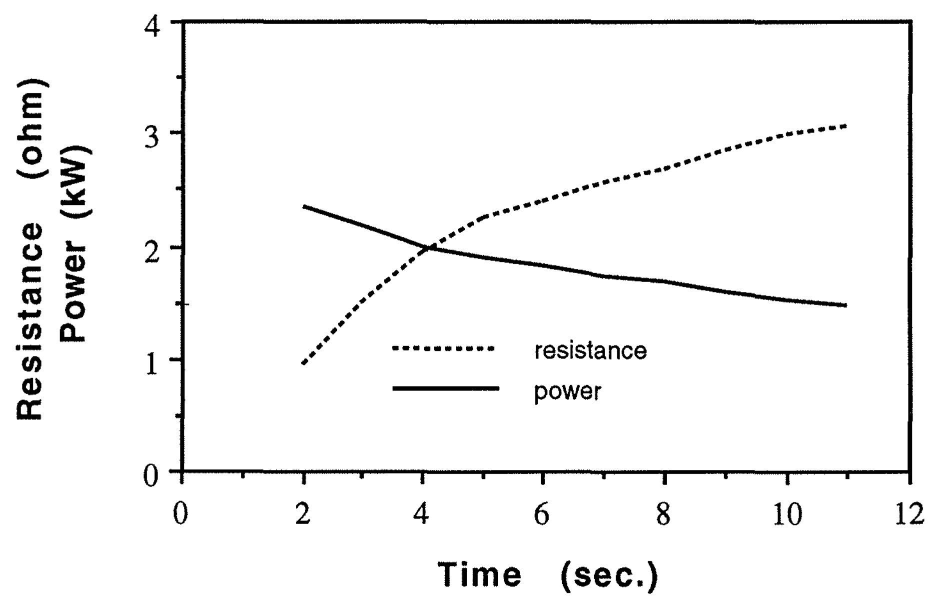


Figure 2.3.4 Resistance and power change during heating cycle.
Mild steel wire in series, n = 18, R = 0.8,
current setting I = 90 A.

0.8 Ω at room temperature and the current setting of the arc welder was 90 amp. The resistance and power input were calculated and are shown in Figure 2.3.4.

It can be seen from Figure 2.3.3 that the current of the wire decreases with time and this change is more sharply during the first three seconds. The current never reached the setting value and the arc welder was not able to keep it constant during the 11-second heating cycle. The current drops to half of the setting value in about two seconds. On the other hand, the resistance of the heating element increases with time and reaches nearly four times of its original value at room temperature. This is mainly due to temperature characteristic of the wire resistance. The resistivity of mild steel is a function of temperature as shown in Figure 2.3.5. Based on this characteristic, the temperature of the heating element during heating can be depicted in Figure 2.3.6 as a function of time. It can be found that at the end of the heating cycle, the wire temperature reached 449.6°C (841.3°F).

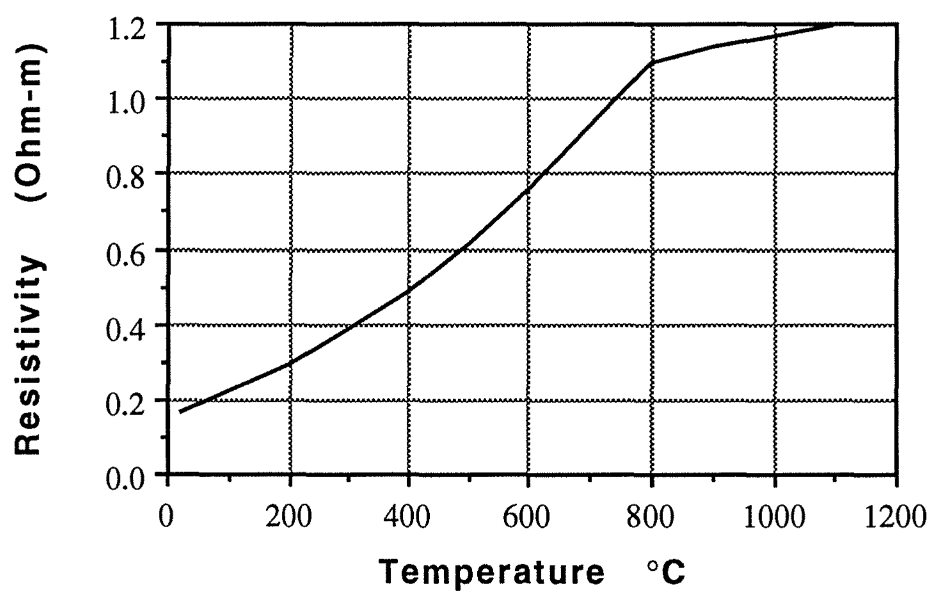


Figure 2.3.5 Resistivity of mild steel

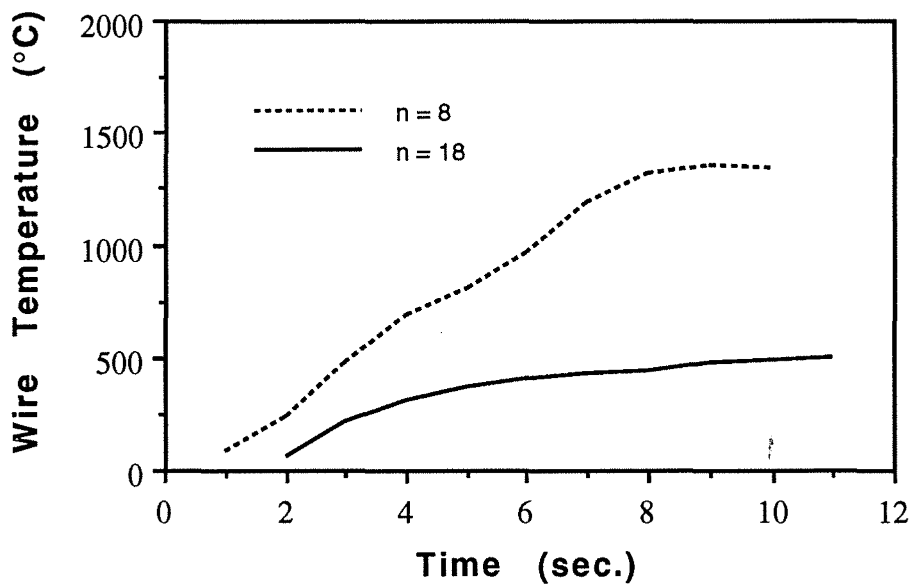


Figure 2.3.6 Wire temperature increasing during heating.

As a result of this resistance characteristic of the wire and the power limit of the arc welder, the power input into the heating system (pad) was far below the designed value (70 V x 90 A = 6.3 kW) and its level decreases with the time. The average power input during the heating cycle was 1.83 kW, which is only 7.5% of the power requirement to melt a 10.1 cm x 10.1 cm x 0.64 cm (4" x 4" x 1/4") pad (24 kW). This may partially explain why it took more than 20 seconds to get bituminous adhesive pad melted in this test.

It appeared that the previous test (n = 16 and I = 90 amp) might be beyond the power capacity of the arc welder. A half-sized pad, 5.1 cm x 10.1 cm x 0.64 cm (2" x 4" x 1/4") with n = 8 and current setting I = 40 amp was tested. The space between the wire segment was kept at 0.64 cm (1/4") so the heat transfer condition remained the same. The results are shown in Fig. 2.3.7 and Fig. 2.3.8. The current reached the setting value in this case, kept for one second and then decreased. Unlike the result from the previous test, the power input increased during the heating cycle. Fig. 2.3.9 and Fig. 2.3.10

compare the current and power changes in two cases. It can be noticed that the current for both cases stabilized at 22 amp., and the power stabilized at very close levels (1.3 ~ 1.4 kW). However, the unit power inputs (power input per segment) were quite different as shown in Fig. 2.3.11. The unit power input into the half-sized pad (n = 8) is higher than that into the full size pad (n = 18) most of the time except the first three seconds. In the later stage, the unit power for n = 8 is almost twice as that for n=16 and the total energy into the segments was 1312 joule and 927 joule, respectively. The higher unit power, in turn, resulted in more dramatically increase in wire temperature (refer to Figure 2.3.6). The wire temperature reached 1400°C in 11 seconds, and the wire burned out due to this extremely high temperature.

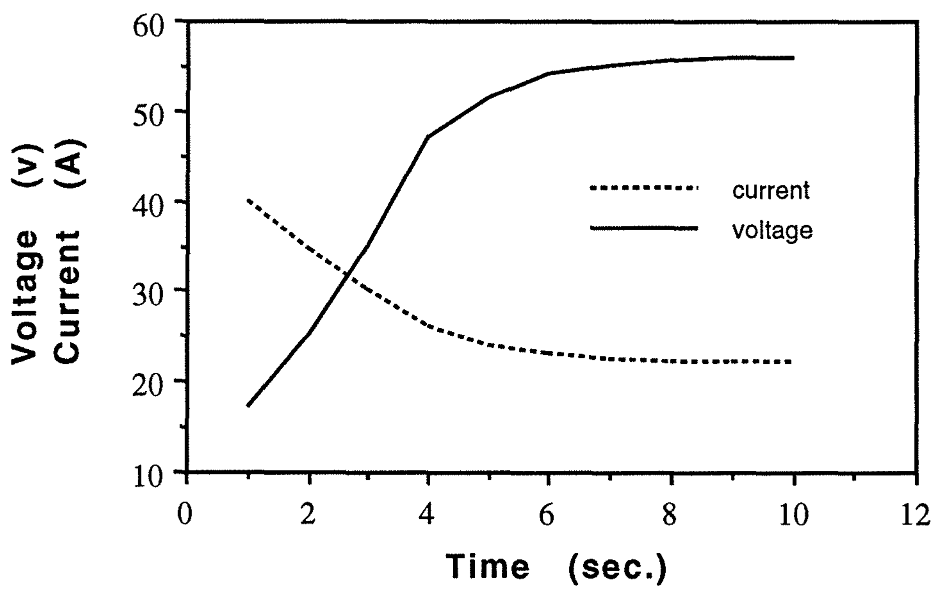


Figure 2.3.7 Current and voltage change during heating. Mild steel wire in series, n = 8, R = 0.36 ohm, current setting I = 40 A.

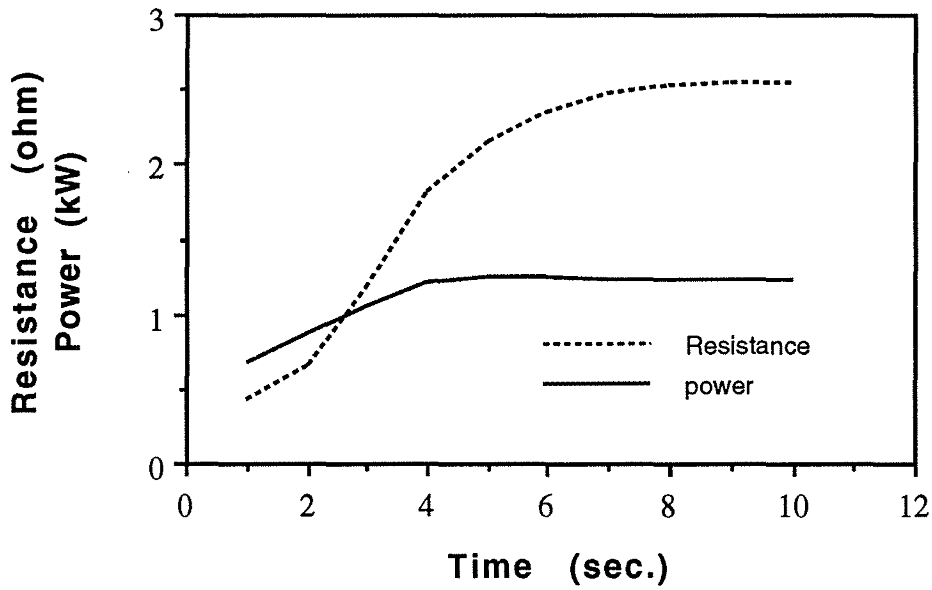


Figure 2.3.8 Resistance and power change during heating. Mild steel wire, n = 8, R = 0.36 ohm, current setting I = 40 A.

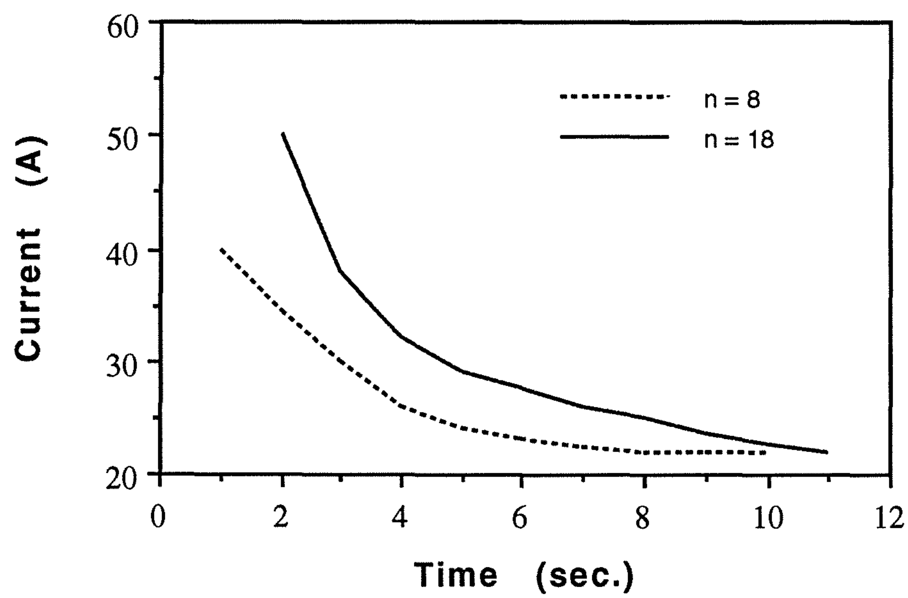


Figure 2.3.9 Comparison of current change for n = 8 and n = 18.

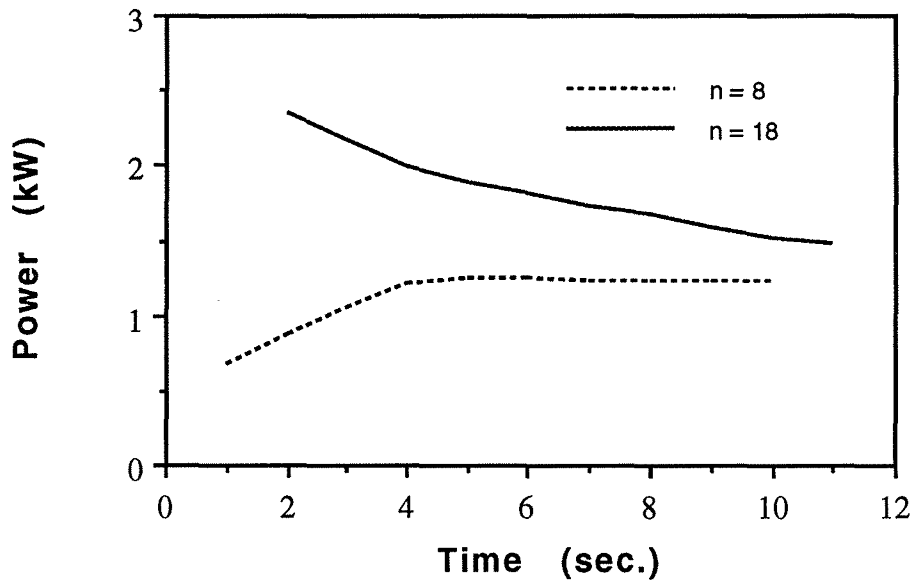


Figure 2.3.10 Power input into the heating elements for n = 18 and n = 8.

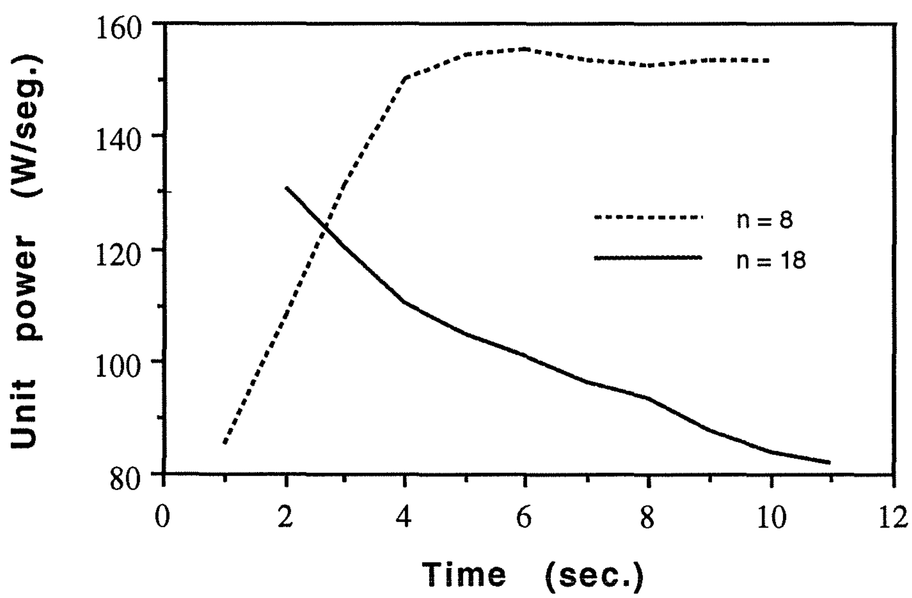


Figure 2.3.11 Power input into each segment (unit power).

6. Poor heat conductivity seems to be the main contribution of this slow heating process. The fact that increase of unit power input did not significantly speed up the process but led to fast rise in wire temperature indicates that the resistance heating rate may likely be limited by low conductivity of the bituminous adhesive. Beyond this limit, any increase of the power input will only contribute to temperature climbing and result in broken wire.

7. Bitumen aging was noticed at the area which had direct contact with wire whose temperature was much higher than the flash point of the bituminous adhesive.

2.3.5 Summary

Though the melting was accomplished much faster than bulk melting method, the heating rate of resistance heating was not satisfactory in meeting the speed requirement of the automatic RPMM. The nature of poor thermal conductivity of the bituminous adhesive seems to be the main obstacle of employing this concept to localized heating process of marker adhesive. Heat transfer can be improved to achieve fast and uniformly heating by increasing total surface area of wire through optimizing design and additional path such as fins or grids. However, excessive wire material may weak the bond strength to the road surface and worsen marker retention. Furthermore, this method requires high precision in laying resistance wire to reduce the edge effect and complicates adhesive pad preparation. In addition, bitumen aging due to over heating may also affect marker retention quality.

2.4 INDUCTION HEATING TECHNOLOGY

2.4.1 Introduction

Induction heating is a thermal process in which electrical energy in the form of a high intensity, high frequency magnetic field is applied to a metallic substance. The magnetic field induces eddy currents or hysteresis losses, which cause heat to be generated in the substance itself. This method has been in common use for melting and heat treating metals for many years. In past few decades, induction heating has also been introduced into the thermal processing of non-metallic materials, such as plastics, by mixing inductively heatable substances, such as metal or metal oxide particles. When appropriate particles are imbedded within or applied to a non-metallic medium and subjected to an alternating magnetic field of an appropriate frequency, heat is generated within the particles with corresponding thermally conductive heating of the non-metallic medium.

A significant development in heating processes based on inductive heating principles has been achieved for fast bonding and sealing plastics, elastomers, glass, paper and the like. The advantage of induction thermal processing include the fact that heat is generated only at the location where it is to be used, thereby providing ideal temperature distributions and permitting accurate and beneficial control of temperature. Additionally, since heat is not required to flow from an external source through the materials to the required location, quick heating rates are obtainable. The accurate temperature control and shortened exposure times prevent thermal damage, such as charring, warping, or distortion from occurring during the processing.

This investigation is to study the feasibility of applying the induction heating technology to fast heat bituminous marker adhesive. The research was carried out in collaboration with an induction bonding company, Hellerbond division.

2.4.2 Considerations of Test Design

The basic concept of induction heating applied here is to uniformly add magnetic iron powder into bituminous adhesive to make it inductively heatable, and then to apply radio frequency magnetic field through an inductor to the adhesive pad. Small particle size and uniform distribution of the heat-generating powder permit very short heat cycles with minimum heat transfer required.

There are five major components in an inductive heating system: 1) power supply; 2) water-cooled radio frequency generator; 3) induction coil; 4) bonding agent and 5) pneumatic cylinder to apply pressure on the work piece. It is generally necessary to operate the apparatus in parallel resonance with the power source as the current flow at such that a frequency is maximized. Resonant frequency is determined by the formula[6]

$$f_R = 1/(2\pi\sqrt{LC})$$

where L and C are inductance and capacitance of the apparatus, respectively. A high resonant frequency, for example, 4 megahertz, may be required in thermal processing non-metallic materials. This is significantly above the frequencies required for metallurgical applications that generally range from 3 kHz to 45 kHz. As mentioned in Section 2.1.2, to melt a 10.1 cm x 10.1 cm x 0.32 cm (4" x 4" x 1/8") bitumen pad in one second, a minimum of 14 kW is required. A 20 kW water cooled radio frequency (2 - 7 MHz) which is readily available in Hellerbond lab was used in our two batch tests. However, a 5 kW, 3 -7 MHz generator was used in a preliminary test. A spiral pancake type inductive coil was selected from the lab collection. The coil was made of 0.48 cm (3/16") copper pipe and was modified to the size and shape to fit both the square and round markers. The coil has 5 turns with its outside diameter of 11.8 cm (4 5/8"). The test setup is shown in Figure 2.4.1.

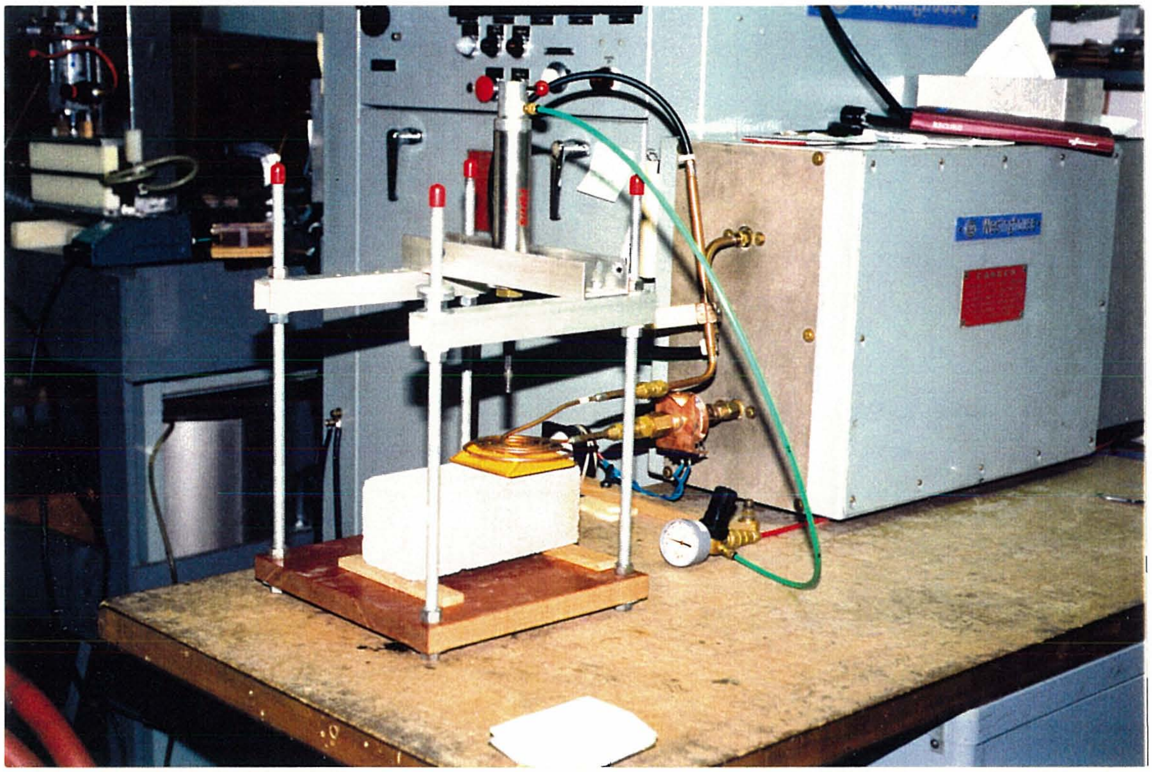


figure 2.4.1 Setup of induction heating test.

There are two classes of magnetic particles used for inductive heating. One is large sized conductive magnetic iron particles which, when a magnetic field is applied, generates heat mainly by eddy current. Another class of magnetic particles is non conductive ferromagnetic oxide, whose sizes including submicron sizes, generates heat as result of hysteresis. The research results have shown that the technology of integrated multiple particle heating agent developed at Hellerbond has a significant improvement in heating cycle. The integrated multiple particle heating agent consists essentially of significant portions of non-conductive particles and of conductive particles which are thoroughly intermixed into a distributed mass to interact in response to a magnetic field of a given radio frequency. When applied to resin, the rate of temperature rise increased by 11 times. However, this combination mixture is more complicated and more expensive to make than plain iron powder. Therefore, the plain iron powder with fairly cost was selected as the heating agent in this investigation.

2.4.3. First Batch Test

After a minimum heat cycle of 5 seconds was achieved using a 5 kW RF generator in a preliminary test, the first batch test was conducted.

<u>Test preparation</u>

The plain iron powder was mixed into the regular bituminous adhesive (35% of asphalt and 65% of calcium carbonate by weight) so that the contents were 40% wt of bituminous adhesive and 60% wt of magnetic iron powder. The mixing was done in the Plastic Division at Batttelle Memorial Institute using a roll mill. The roll mill consists of two identical steel rolls which were powered independently by two electric motors. The rolls were rotating in opposite direction with the ratio of revolution at 1:2. Both rolls were electrically heated to 66°C (150°F). The bitumen adhesive lumps were fed into the mill and then the powder was added gradually (see Figure 2.4.2). The adhesive sheet

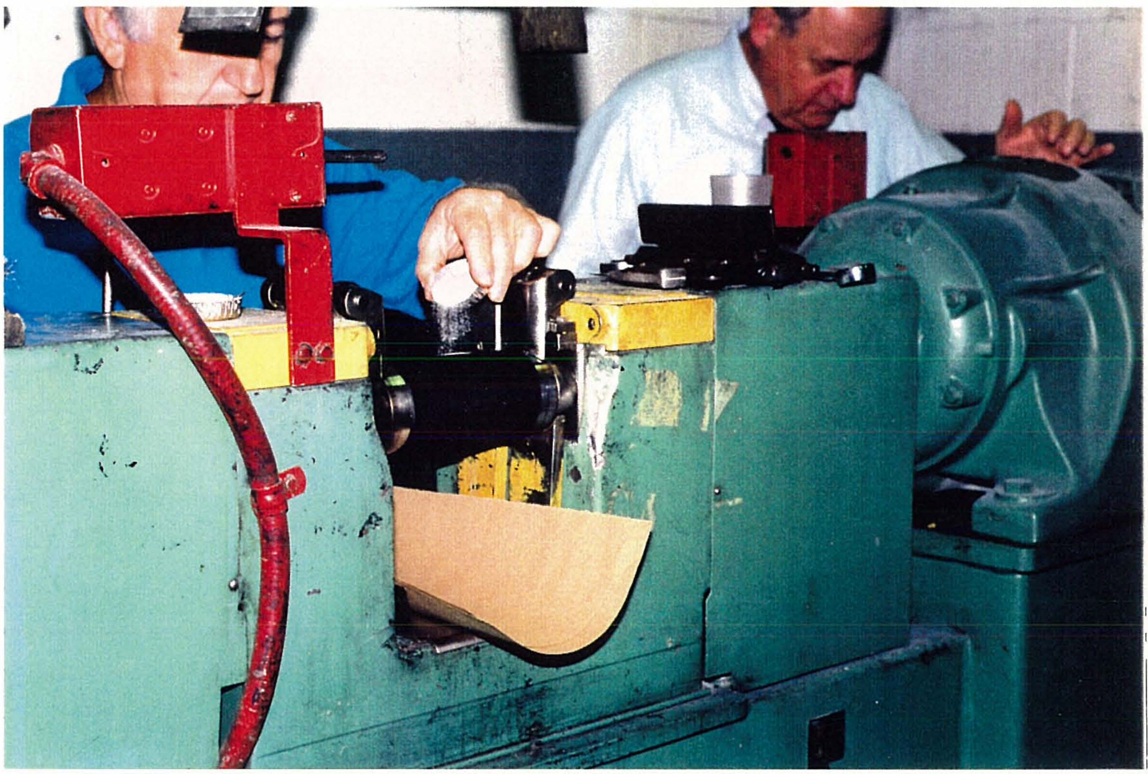


Figure 2.4.2 Bitumen - iron powder mixing using a roll mill.

was scrapped from the roll and fed into the mill again. The milling was repeated several times to assure the uniform distribution of the powder. The mixed lumps were then placed on a release paper and pressed out to 0.32 cm (1/8") in thickness on an electrically heated press with the plate temperature at 65.6°C (150°F). The mixed bitumen sheet was then made into washer type pads by hand. The dimensions of the pads for both round dots and reflective markers are shown in Figure 2.4.3. The markers were bonded onto concrete blocks that were locally purchased.

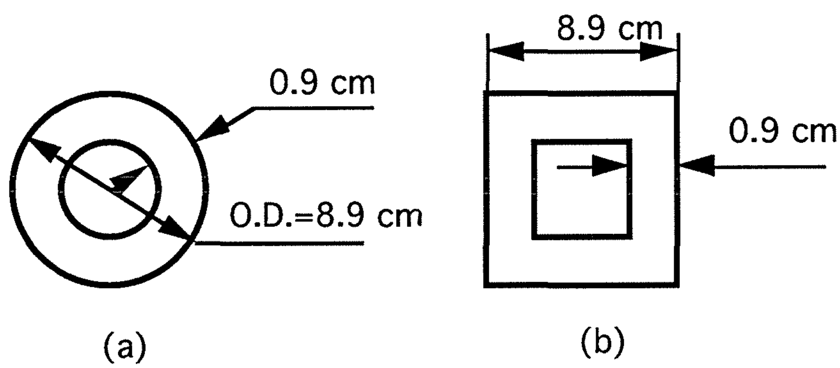


Figure 2.4.3 Dimensions of the BIPM pads used in the first batch
(a) - for round dots; (b) - for square markers

Test setup

The first batch tests were conducted in two settings. In setting 1, the workpieces (marker and adhesive pad) was sitting on the conductive coil and topped by a concrete block, as shown in Figure 2.4.4. A 67 N (15 lb) force was applied during the heating cycle. The heating cycle was set for 1 1/4 seconds. Setting 2 was a two-step installation as shown in Figure 2.4.5. The heat cycle completed before the workpiece was flipped over by hand and downward onto the concrete block. Since the moment of time required to grab the heated workpiece and position it on the block seemed to allow a little viscosity increase, a 1/4 second was added and the heat cycle was set for 1 1/2 seconds.

A 20 kW generator was used in both settings and current was set at 600 A.

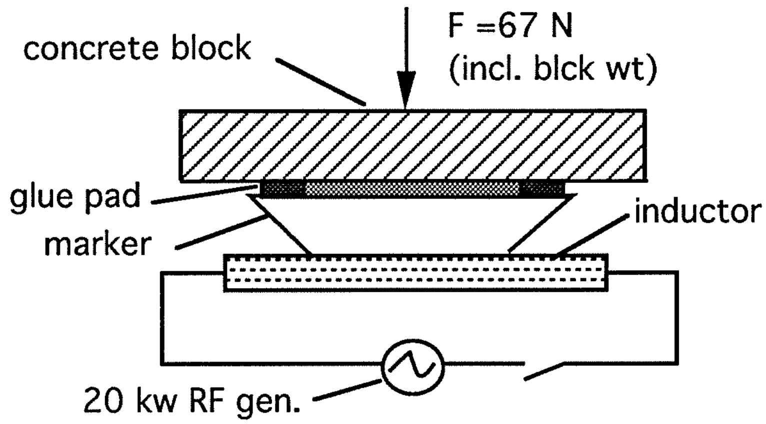


Figure 2.4.4 Schematic diagram of setting 1 in the first batch test

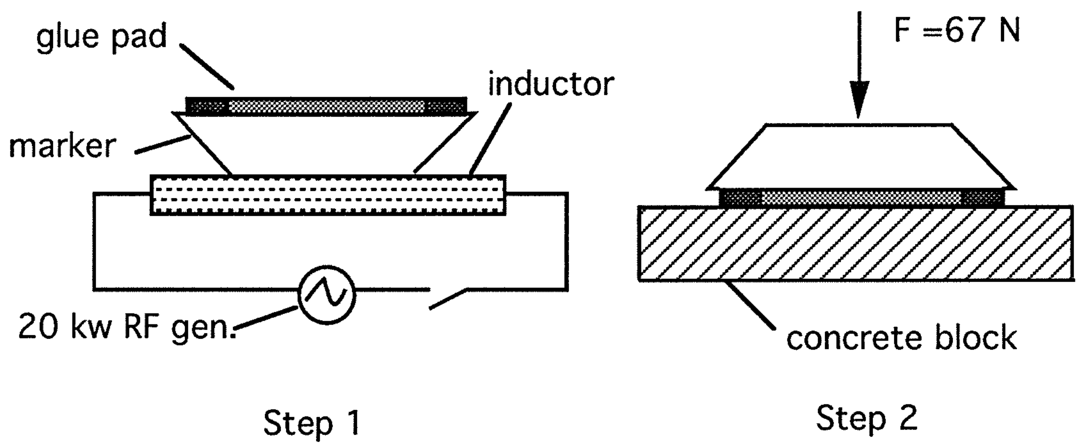


Figure 2.4.5 Schematic diagram of test setting 2 in the first batch test

<u>Results</u>

1) Bitumen - iron powder mixture (BIPM) was well heated and melted within 1 1/4 to 1 1/2 seconds.

2) No noticeable difference was found in heat rate between reflective and ceramic markers.

3) Ignition of the bitumen was observed, caused by sparking of the metal particles

during "open" heating process in the two step installation.

4) The bonded blocks using induction heating method were tested for the shear strength on the Instron testing machine. The shear strength of inductively heated bitumen adhesive, as shown in Figure 2.4.6, is much higher than that of the bulk heated.

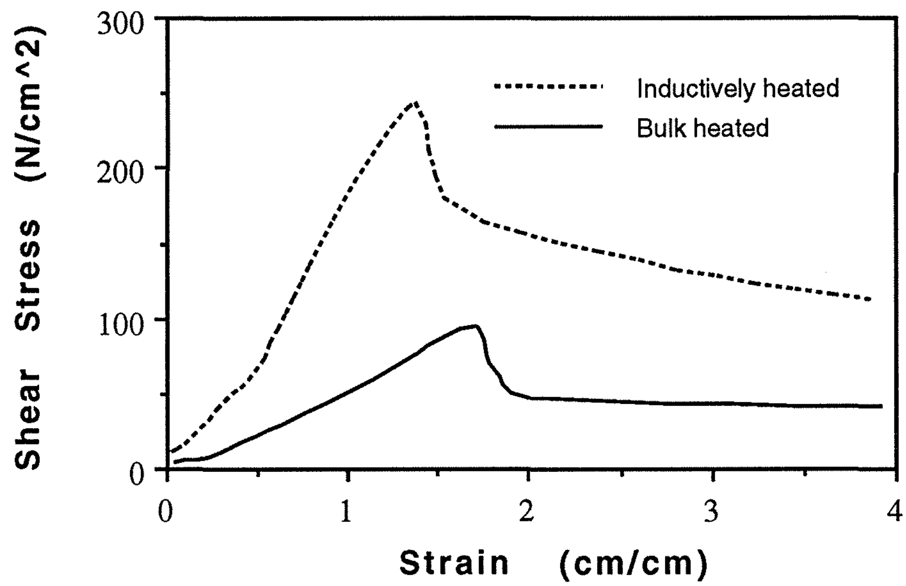


Figure 2.4.6 Comparison of shear stress of the inductively heated and the bulk heated.

5) However, the iron powder-bitumen mixture appears brittle at room temperature, which may effect marker retention quality. The asphalt content in the regular bituminous adhesive is about 35% by weight and 59% by volume. By adding 60% of iron powder into this adhesive, the asphalt content in the powder-bitumen mixture was 14% by weight and 44.7 % of volume. This significant reduction of asphalt content altered the brittleness characteristics of the marker adhesive.

2.4.4. Second batch test

In the second batch tests, attempts were made to reduce the brittleness of the mixture and determine the optimum size of the adhesive pad in order to maximize the bonding strength. The bituminous adhesive was modified such that the volume percentage of asphalt in inductive heat mixture was the same as in the bulk heated regular adhesive, which is about 59.3%. An adhesive containing 52% of asphalt and 48% of calcium carbonate filler was specially made by Crafco and then was mixed with magnetic iron powder using a roll mill. The final mixture was as the following:

Asphalt	20.8% by wt
Calcium carbonate filler	19.2% by wt
Magnetic iron powder	60% by wt

When using a pancake-type coil, the center of the adhesive pad fails to heat to the melting point due to the flux pattern. It is beneficial to have the pad hollowed at the center since the unmelted adhesive portion may effect the overall bonding strength. However, It is desirable to minimize the hollow area so that the total adhesive bond area can be maximized. The paper temperature indicators indicated that the adhesive in the center area of about 2.54 cm (1") diameter failed to heat to 193°C (380°F) during a 1 1/2-second heat cycle. Therefore, washer type pads with the dimensions shown in Figure 2.4.7 were used in the second batch test.

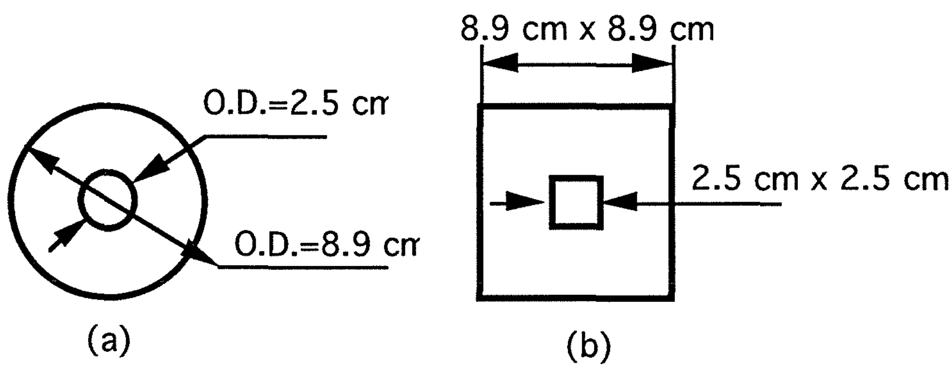


Figure 2.4.7 Diamensions of BIPM pads used in the second batch.
(a) - for round dots; (b) - for square markers

Test setting

Figure 2.4.8 is a schematic diagram of the setup in the second batch test. The same 20 kW water-cooled RF generator was used. The current and heat cycle settings are in Table 2.4.1. The markers were bonded on concrete blocks symmetrically for the subsequent shear test. The frequency was measured to be 0.4 MHz. A pneumatic force of 67 N (15 lb) was applied during heat cycle.

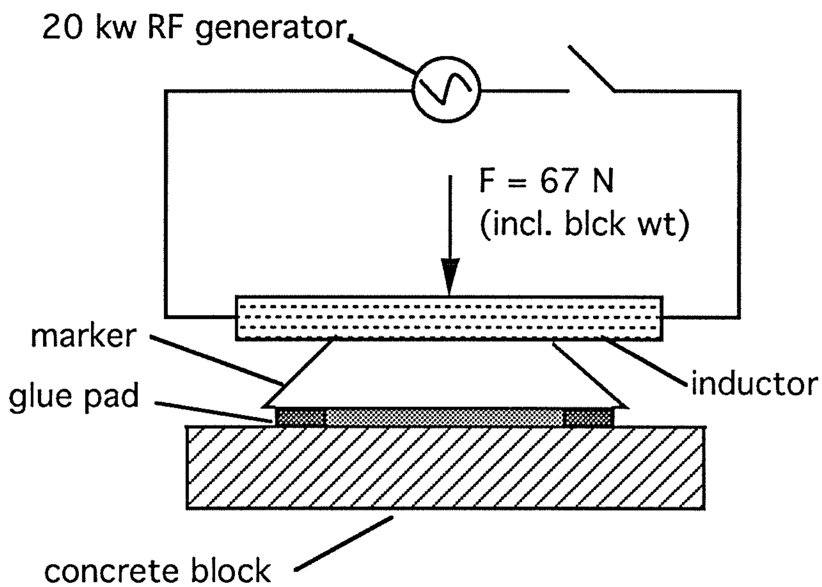


Figure 2.4.8 Schematic diagram of the test setup in the second batch.

Table 2.4.1 Current and heat cycle settings for the second batch test.

Adhesive	Marker	Current Setting (A)	Heat Cycle (sec.)
Bulk Heated	Reflective, smooth	N/A	N/A
BIPM	Reflective, smooth	300	2.8
BIPM	Reflective, smooth	400	1.2
BIPM	Reflective, rough	400	1.2
BIPM	Reflective, rough	400	1.5
BIPM	Ceramic round	400	1.2

Results and Discussion

Good bond was achieved in all cases. No sparks or ignition were observed. The shear strength of the adhesive using induction heating method at various current and heat cycle settings was tested on the Instron machine. The maximum shear stresses obtained are listed in Table 2.4.2.

Table 2.4.2 Maximum shear strength of BIPM obtained from the second batch test.

Adhesive	Max. Stress (N/cm^2)
Bulk-heated BA	71.4
BIPM, 300 A, 2.8 sec.	73.6
BIPM, 400 A, 1.5 sec.	67.3
BIPM, 400 A, 1.2 sec.	64.2

The shear strength of BIPM at current setting of 300 amp tops the rest, including that of the bulk heated as can be seen more clearly in Figure 2.4.9, which shows the shear stress - strain curves of bulk-heated bitumen and inductively-heated BIPM mixture at various settings. However, the heat cycle for 300 A is not acceptable. The shear strength of BIPM at 400 A was slightly lower than that of the bulk heated. This is more pronounced when the heat cycle was reduced from 1.5 seconds to 1.2 second. Figure 2.4.10 compares the shear strength of BIPM bonded on smooth and rough bottom of markers, showing that the texture of marker bottom has no significant effect on the bond strength.

The second batch of BIPM with improved formula did not appear brittle at room temperature but was slightly softer than conventional bituminous adhesive. It seems that the content of asphalt in the mixture can be decreased slightly to enhance the bond strength of inductively-heated BIPM while not to sacrifice the brittleness characteristics.

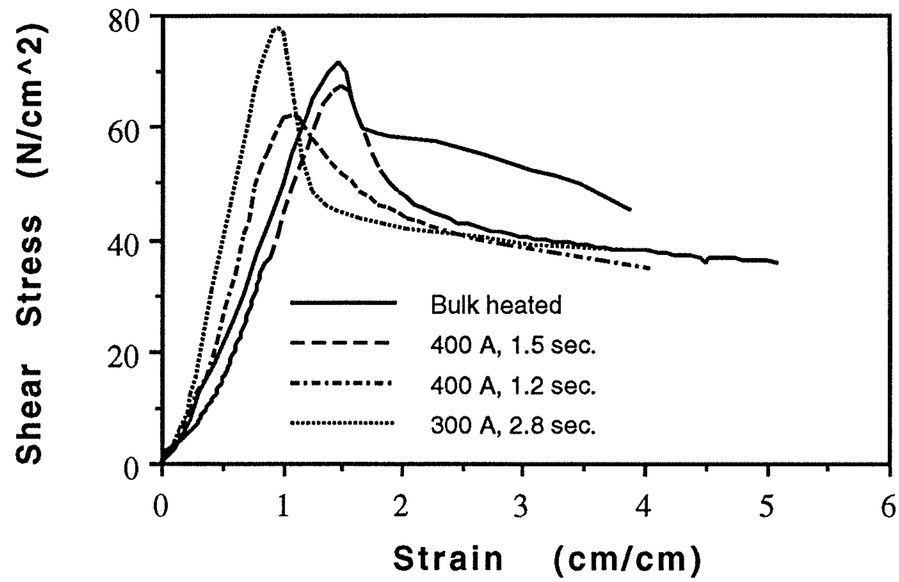


Figure 2.4.9 Shear stress-strain curves of the bulk heated BA and the inductively heated BIPM.

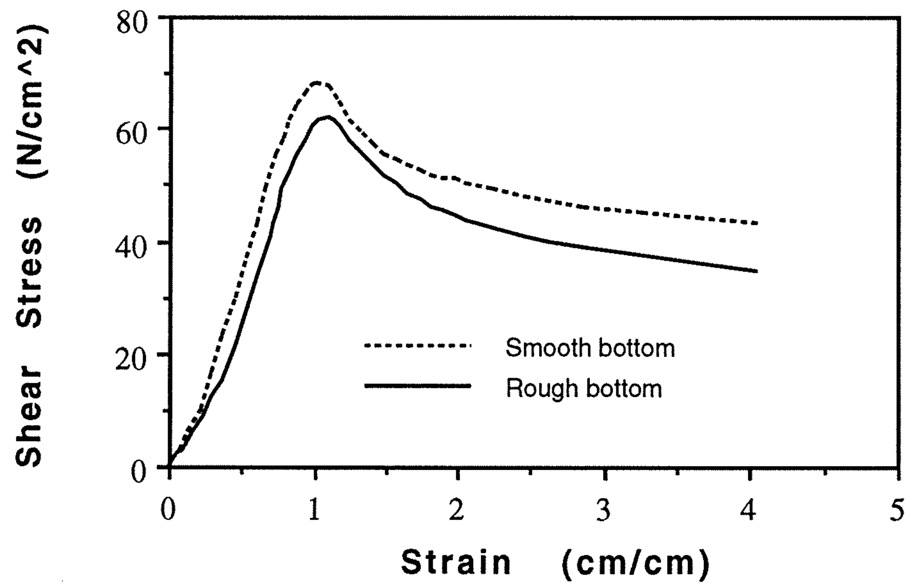


Figure 2.4.10 Shear stress curves of BIPM on smooth and rough marker bottoms (current at 400 A for 1.2 seconds)

The investigation of using induction heat technology to fast heat road markers has provided promising results. Though poor thermal conductivity of bituminous adhesive hinders fast heating, the induction heating method overcomes the obstacle by minimizing heat transfer requirement through uniformly distributed small particles that permits very short heat cycles. A heat cycle of 1.2 to 1.5 seconds was achieved in the two batch tests conducted. The resulting bond strength of inductively heated bitumen-iron powder mixture from the first batch was higher than that of bulk heated conventional bituminous adhesive. Though the shear strength of BIPM from the second batch was slightly lower than that of the bulk heated, it is believed that it can practically be improved by further optimizing the formula of the BIPM. The heat cycle also needs to be reduced to a more desirable level to match the required operating speed of the automated RPMM. The cost of BIPM pad was estimated to be $0.40 - 0.45 per marker for large volume operation, which is higher than that of conventional bituminous adhesive ($0.10 - 0.20 per marker). However this cost is considered to be practically acceptable.

2.5 EXPLOSIVE HEATING (PYROTECHNICS)

2.5.1 Introduction

Research of pyrotechnic heating was carried out in collaboration with an explosive technology company, Renold Instrument System Industries (RISI). Two key tasks in pyrotechnics heating research were safe firing technique and suitable deflagrating materials that generate energy in a very short time period to effectively melt bitumen but not too explosive. RISI has developed an explosive bridgewire system that can initiate an explosive in a few microseconds. In an exploding bridgewire system, a relatively large amount of energy is applied very rapidly into the bridgewire, which is made of gold. Due to the extremely small cross section of the wire, the current heats the wire through the melting, boiling and vaporization phases. For proper function of an exploding bridgewire, this energy must be applied at such a fast rate that the wire material phase change is restricted due to inertia. When this inertia is overcome, vaporization of the wire occurs as an explosion, giving off thermal energy and a shock wave. The resulting shock wave can be used to initiate a secondary explosive.

2.5.2 Test

The first attempt was to use thermite type materials as the deflagrating medium and explosive bridgewire for ignition. Figure 2.5.1 is a schematic diagram of the test setup. A 1 mm thick thermite material (cupric oxide plus aluminum) layer was sandwiched by bituminous adhesive pads of 0.32 cm (1/8") thick. The cross section of the sandwiched pad is illustrated in Figure 2.5.2. A separate firing module and control unit were used to fire the explosive bridgewire. The thermite material was ignited readily and the bitumen pad was melted. But deflagration velocity and gas generation were so rapid that the generated gas propelled the marker away from the bonding surface. In addition, the residual material consisted of many large copper globules.

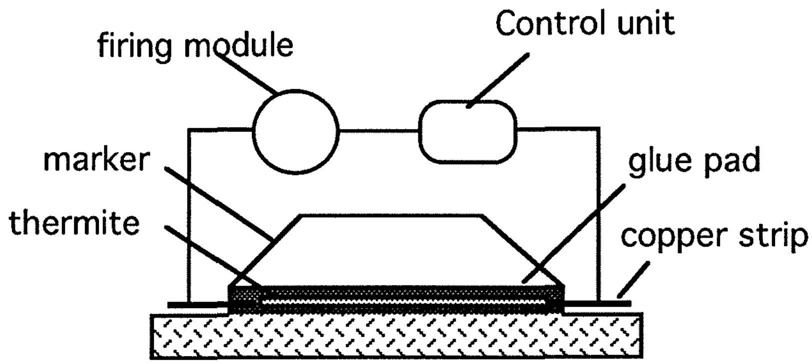


Figure 2.5.1 A schematic diagram of test setup using thermite and explosive bridgewire.

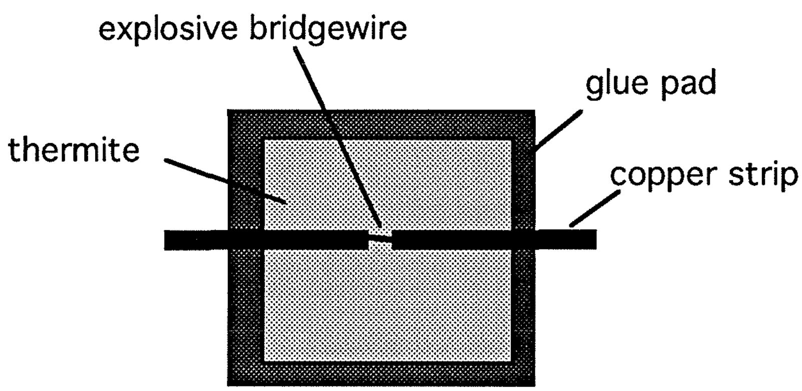


Figure 2.5.2 Cross section of adhesive pad sandwiched with thermite.

A literature search was performed to find a slower burning material with less ash. The literature search suggested the potassium nitrate as an oxidizer, which was already being used commercially in "hot patches" for vulcanizing rubber tire repairs. Various cellulose materials were suggested as inert. Discussion with consulting chemists from the Lawrence Livermore National Laboratory confirmed that potassium nitrate and possibly ammonium nitrate warranted further investigation. For some quick experiments, commercial "hot patches" were purchased and disassembled for the potassium nitrate and inert material (8% of potassium nitrate and 92% of inert). The patch was laid between the marker and the bitumen pad (see Figure 2.5.3). When ignited by match, the patch burned and the bitumen pad was melted. The major problem with the commercial "hot patches" was an excessive amount of ash remaining after the material was burned.

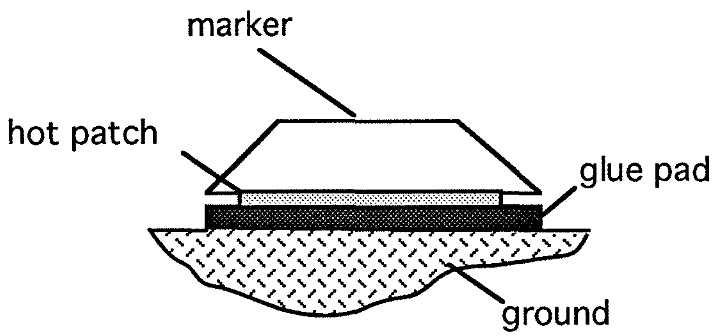


Figure 2.5.3 Heating bituminous adhesive pad with "hot patch".

A large number of experiments were then performed in an attempt to find an optimum mix of oxidizer and fuel. Both ammonium nitrate and potassium nitrate were evaluated with various carrier materials and various ratios of nitrates to carrier material. A potassium nitrate-shredded paper mixture was used for the test. To make the potassium nitrate-shredded paper biscuits, the potassium nitrate was dissolved in water. This solution was absorbed into the shredded paper which was then oven dried. A biscuit of this material was then placed on both side of a bitumen pad. The test setting is as shown in Figure 2.5.4. The sandwiched bitumen pad topped with a marker was laid on a concrete ground (see Figure 2.5.5.) The potassium nitrate-shredded paper layers were ignited through a pyrofuse powered by a power supply. Pyrofuse is a mixture of palladium and aluminum, which ignites upon the application of a small amount of current. In this test setting, a ribbon of this material is placed across each potassium nitrate biscuit with the ends exiting the sandwich. This provides a short length of ribbon material for the application of the electrical current. Functioning of the pyrofuse provides sufficient heat to ignite the potassium nitrate-shredded paper mixture.

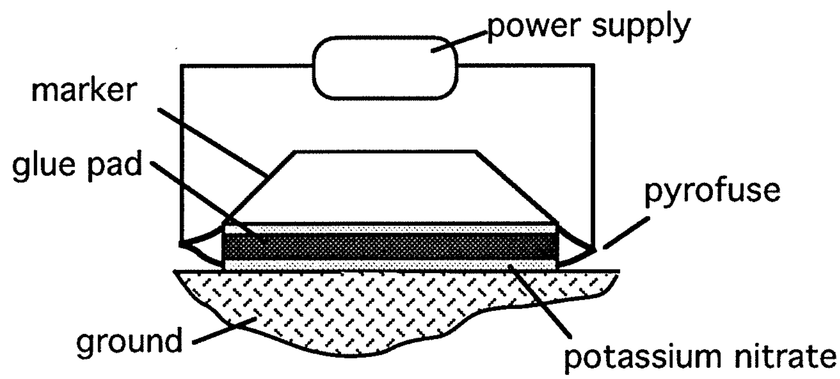


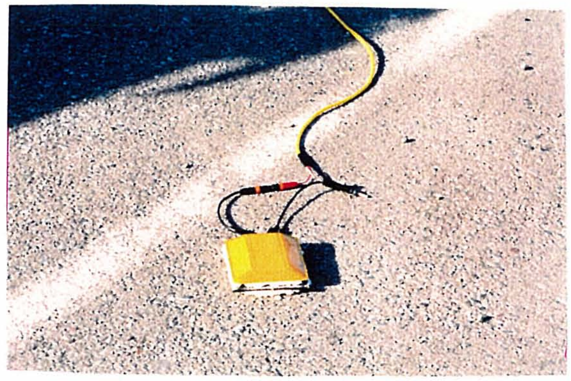
Figure 2.5.4 A schematic diagram of test setup using potassium nitrate - shredded paper.

2.5.3 Results and Discussion

The heating cycle was about 5 seconds and the firing system functioned very well. The bonding strength was found to be not satisfied due to ash layers formed at both bonding surfaces.

Further studies are needed to reduce the heating cycle and improve adhesion. Areas which require further study include the following:

- Finding a fuel type material which produces minimum ash.
- Optimizing the fuel-oxidizer ratio
- Optimizing the thickness of bitumen pad



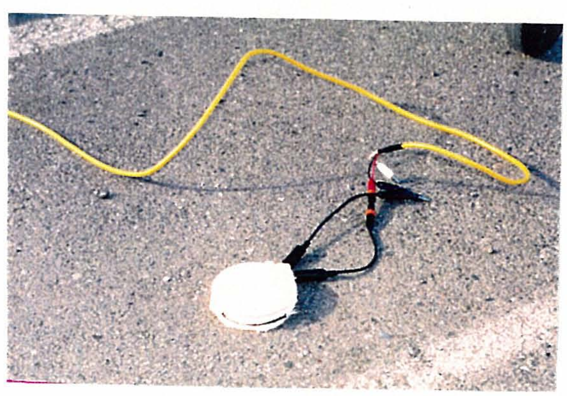


Figure 2.5.5 Pyrotechnic heating using potassium nitrate.
Top: Sample ready for firing; Middle: power is being cut off immediately after ignition; Bottom: test on a ceramic marker

Chapter 3
Investigation of Cold Applied Adhesives

3.1 INTRODUCTION

The goal of this investigation is to search and develop new marker adhesive materials which can be cold applied. The cold-applied adhesive has attracted researchers for several reasons. First, the problems associated with the existing bulk-heated bituminous adhesive can be resolved by completely eliminating the heating process. Secondly, It greatly simplifies the automated RPMM. Furthermore, compared to the localized heating methods, cold-applied adhesive requires little energy and provides better working condition.

The currently used cold-applied marker adhesives fall into two categories: two-part epoxy and butyl based pads. Epoxy adhesive was introduced to bond the markers to the pavement surface in 1965 and had been widely in use in 1970's through early 1980's. It has been gradually replaced by bituminous adhesive due to its disadvantages, including its slow curing, which requires long lane closure, high failures due to improper proportion and mixing, and its high stiffness causing road surface damage. Butyl based cold applied adhesive has been recently accepted by Caltrans for temporary applications such as two-week seal chips and six-month long term temporary markers.

The objectives of this investigation are:

- To search and evaluate available cold applied adhesive pads.
- To study the effects of various parameters on adhesive bond strength.
- To improve the adhesive materials to be feasible for permanent use with acceptable retention quality.
- To establish test procedures for marker adhesive evaluation.

The standard tests currently used by Caltrans are not adequate for new material investigation. An effort was made in this research to look insight into material visco-elastic property data that can be related to performance. The testing methods were selected in attempt to be performance related as well as to yield fundamental material property data. The laboratory tests conducted in this investigation include: slant shear strength, shear strength, tensile, shear impact, and elastic recovery. The performance of selected adhesive was later evaluated on highway in Southern California.

The parameters controlled during this study include: adhesive temperature, loading rate, with or without primer applied during installation, time and force applied during installation, marker bottom conditions, block surface conditions and butyl pad exposure time prior to installation.

3.2 TEST MATERIALS

Eight different cold applied adhesives were tested. They were obtained from Stimsonite and Davidson Plastic Co. and are all in roll form with release paper on one side. Most of these adhesives are butyl-based materials and currently used for temporary markers. The ID, product number, supplier and thickness of each tape are listed in Table 3.2.1.

Table 3.2.1 List of cold applied adhesives investigated

ID	Thickness mm (in)	Supplier
Hitack 1	2.4 (3/32)	Stimsonite
Hitack 2	2.4 (3/32)	Stimsonite
Hitack 3	2.4 (3/32)	Stimsonite
Hitack A	2.4 (3/32)	Stimsonite
Hitack B	1.6 (1/16)	Stimsonite
Hitack C	2.4 (3/32)	Stimsonite
Hitack D	3.2 (1/8)	Stimsonite
Davidson's 911	2.4 (3/32)	Davidson PCO

Hitack 1, Hitack C and Davidson's butyl pads are very sticky and soft. Hitack A is extremely tacky and basically bitumen in tape form. Hitack D is a single sided fibrous tape, where adhesive is laminated with a woven mat. Hitack B is much thinner and very elastic (like rubber band). Hitack 2 and 3 contain higher solids and less sticky but harder than the rest of the tapes.

Two kinds of primer were provided by Stimsonite and Davidson for their particular butyl pads.

Bituminous marker adhesive used in the tests as control was provided by Chemical Lab at Caltrans.

Markers used in the tests were Stimsonite reflectors Model 88 with two different bottom surfaces: textured (rough) and smooth bottoms. Davidson's temporary reflectors model RPM were used for its butyl pads and later on for Stimsonite's pads to analyze cross effects.

Three kinds of blocks were used as bonding substrate. The slant concrete blocks, a pair of 5.1 cm x 5.1 cm x 12.7 cm (2" x 2" x 5") for slant shear strength test and rectangular asphalt block, 7.6 cm x 7.6 cm x 14 cm (3.0" x 3.0" x 5.5") for shear strength test were made in Caltrans Concrete Lab and Asphalt Lab, respectively. The rectangular concrete blocks, 8.9 cm x 8.9 cm x 20.3 cm (3.5" x 3.5" x 8"), were locally purchased.

3.3 TEST METHODS

3.3.1 Slant Shear Strength Test

Slant shear strength test was designed based on the Caltrans standard test for marker adhesive (California Test 425, 1978) and the manufacturer requirements for installation of butyl pads. In this test, a pair of identical concrete blocks were bonded together with adhesive to be tested to produce a block of dimensions 5.1 cm x 5.1 cm x12.7 cm (2 inch x 2 inch x 5 inch). Strength of adhesive was tested by applying a compression load (Fig. 3.3.1)

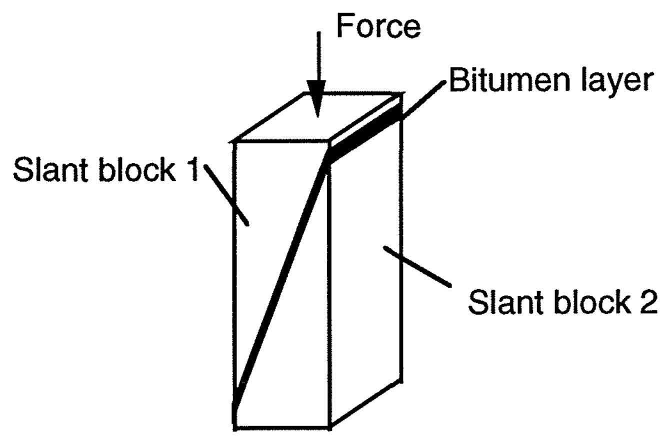


Figure 3.3.1 Slant shear strength test specimen

Sample preparation

• Slant blocks: the diagonal surfaces of all slant blocks were sand blasted to better simulate the road surface.

• Bituminous adhesive sample

Lumps of bituminous adhesive was heated to melt in a 20-cm (eight inch) pan with a 350w hot plate. An axial fixture was made to assure the required dimension of the paired blocks after being bonded together as well as to make two end surfaces parallel. The C-channel shaped fixture was made of three 5.08 cm x 0.95 cm (2" x 3/8") aluminum bars and its distance between two walls is 12.7 cm (5 inch). The block - fixture setting before pouring adhesive is as shown in Fig. 3.3.2.

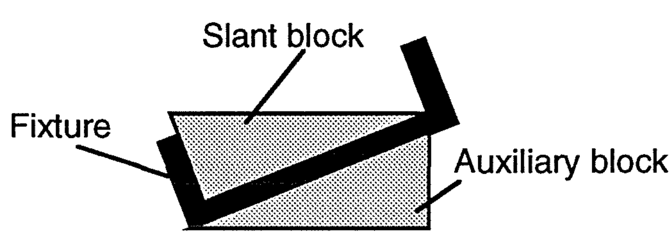


Figure 3.3.2 Slant block before puring adhesive

An additional slant block was used underneath the fixture to make the diagonal surface of the block to be bonded horizontal. Since hot melt bituminous adhesive is very flowy, the horizontal surface is desirable for preparing a sample with even thickness of an adhesive layer. A second slant block was placed on immediately after hot bitumen was poured on the first block. A force was then applied by hand. The thickness of bituminous adhesive layer was controlled to be 0.32 cm (1/8"). The blocks were slightly adjusted to make two end parallel as well as two sides aligned. Excess bitumen was cut off neatly when it simmered down before it hardened. The bonded slant block pairs were kept at the room temperature for 24 hours prior to the test.

In a cold weather, the concrete slant blocks were preheated before pouring the adhesive to achieve better bonding.

• Butyl pad samples

A 5.1 cm x 10.1 cm (2" x 4") pad was cut from a butyl pad roll and placed on the diagonal face of the first slant block, which was seated on the same fixture as used in preparing bituminous adhesive samples, with its end against one of the fixture wall. Then the release paper was peeled from the pad and the second slant block was placed on the peeled surface with its end against another wall of the fixture. The sides of two blocks as well as the edges of the pad were carefully aligned during the placement.

An installation force was applied on the slant shear block pair confined by the fixture. The force applied was determined according to the manufacture requirement for installing a particular kind of the butyl pads. This force was calculated using the following formula

$$F_s = F_m / 2 \cos 30°$$

where F_m is the force required to install a reflective marker with its bottom area 103.23 cm^2 (16 in^2) and

F_s is the installation force to be applied onto a slant block pair whose bonding area is 51.6 cm^2 (8 in^2).

The actual forces applied on the butyl pads tested for slant shear strength are listed in Table 3.3.2 and time for which the force applied was 6 seconds in all cases.

Table 3.3.2 Installation force applied for various butyl pads

Butyl Pad	Force required for marker installation N (lb)	Force applied in slant shear test N (lb)
Hitack 1	2,225 (500)	1,137 ~ 1,333 (250 ~ 300)
Hitack 2	6,674 (1500)	3,783 ~ 4,008 (850 ~ 900)
Hitack 3	6,674 (1500)	3,783 ~ 4,008 (850 ~ 900)

<u>Testing</u>

Slant shear strength was tested using an Instron testing machine Model 4204. The testing machine is fully computer controlled, consisting of a main Instron testing machine, a console, an HP personal computer and a printer/plotter. The load cell used for the tests was 10,573 N (10,000 lb) and electronically calibrated.

A detailed testing procedure can be found in Appendix B, "Methods for Testing Adhesives for Pavement Markers" Part II and Appendix C, "Instron 4204 Operating Instructions." The specimen was placed on the base plate upright with its diagonal bonding line facing the operator for safety purpose (see Figure 3.3.3 on page 47). An effort was made to assure a perfect contact between the specimen and the fixture on the crosshead.

The slant shear strength tests conducted included basic slant shear strength test and slant shear strength both at selected temperatures and under various loading rates.

1. Basic slant shear strength test: Hitack 1, Hitack 2 and Hitack 3 were tested at room temperature (21.1 ~ 24.4°C / 70 ~ 76°F) with bituminous adhesive as a control. The loading rate was set at 2.0 cm (0.8 inches) per minute.

2. Slant shear test at selected temperatures: This test was designed to test the temperature susceptibility of both bituminous and butyl adhesives. The selected temperatures were 4.4°C (40°F), 21.1°C (70°F), 37.8°C (100°F), 48.9°C (120°F) and 60°C (140°F) to cover all possible ground temperatures in California. The slant blocks prepared for 4.4°C (40°F) test were kept for 24 hour in a refrigerator at controlled temperature of 4.4°C (40°F). The slant blocks for 37.8°C (100°F) and 48.9°C (120 °F) were heated in an thermostatically controlled oven and kept there for 6 hours in order to obtain uniform temperature distribution within the block and the adhesive layer. Due to the limitation of the heating facility, the 60°C (140°F) temperature level was not included in the test conducted. The lowest temperature level was later changed to 10°C (50°F) to avoid shattering of the bitumen samples and overloading of the load cell.

The temperature of adhesive layer of each specimen was checked with a thermal couple prior to the test. The loading rate used for this set of tests was 2.0 cm (0.8 inch) per minute.

3. Slant shear strength test with various loading rates: Since both cold applied adhesive (butyl pads) and bituminous adhesive appear visco-elastic behavior in which the stress and strain relationship is time dependent, this test was designed to study the effect of loading rate on adhesive strength. Both adhesive were divided into four groups and tested at the loading rates 2.0, 3.8, 7.6 and 12.7 cm/min. (0.8, 1.5, 3.0 and 5.0 in/min.). The maximum loading rate of 12.7 cm/min. (5.0 in/min.). was subjected to the limit of the Instron testing machine. All specimen were tested at room temperature.

3.3.2 Shear Strength Test

The shear strength test was designed to investigate bonding strength of marker adhesive when applied to bond the markers onto the substrate blocks. In the shear strength test, a pair of identical reflective markers were bonded to a block symmetrically with the adhesive to be evaluated. The shear strength of adhesive was tested by applying a compressive load on both markers. The sample configuration was intended to resemble the marker-adhesive-pavement system on highway. Double markers were bonded to assure the load balance during testing.

Materials

Eight different types of cold applied adhesives provided by Stimsonite (Hitach 1, Hitach 2, Hitach 3, Tape A, B, C and D) and Davidson Co. (tape 911) were evaluated in the shear strength test. Three additional tapes were also tested to investigate the effect of thickness and fabric configuration on bonding strength. They were double layer Hitack B (DB), Hitack D sandwiched with 15 x 15 carbon fiber and Tape D sandwiched with 45 x 45 carbon fiber.

Two types of blocks were used during this investigation, resembling the most common roadway surfaces. The majority of the blocks were concrete measuring 8.9 cm x 8.9 cm x 20.3 cm (3.5" x 3.5 " x 8"), which were purchased locally. The other type of the blocks (asphalt) measuring 7.6 cm x 7.6 cm x 14 cm (3.0" x 3.0" x 5.5") were obtained from Caltrans Asphalt Lab in Sacramento. Bituminous adhesive was tested as control.

Two different types of primer were provided by the adhesive companies for their particular butyl pads.

Sample preparation

• Cleaning the blocks. Both the concrete and asphalt blocks were cleaned before the markers were adhered. Cleaning included removing as much dirt as possible with a wire brush and then using compressed air to eliminate the remaining debris.

• Applying primer. After the blocks were thoroughly cleaned, primer, if desired, was applied on the appropriate block. The primer was either brushed or sprayed onto the block surface, depending on the manufacturers' instructions. A minimum of 60 seconds was required for solvent to evaporate before placing the marker.

• Bonding with butyl pads. The butyl pads were cut from the pad roll to the dimension matching the bottom of the marker and adhered onto the marker bottom. The release paper was then peeled from the pad and the marker/adhesive was adhered to the block at the desired position with a pre-load of approximately 108 N. To insure correct marker-pad-block alignment, a guide was used for the installation (Figure 3.3.4).

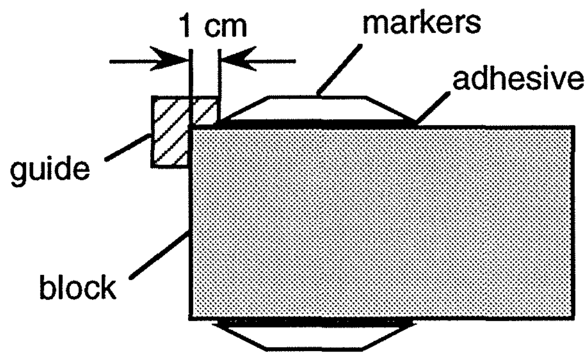


Figure 3.3.4 Marker alignment using a guide

After two maker-pad combinations were adhered onto the block symmetrically, the specimen was placed in a hydraulic press and loaded according to the manufacturer's requirement unless a different installation force was desired (as in the evaluation on effect of installation force and time). A force of 6,674 N (1500 lb) was applied for 6 seconds on Hitack 2, Hitack 3 and Hitack B. Only 2,225 N (500 lb) were applied on the rest of butyl pads.

• Bonding with bituminous adhesive. The bituminous adhesive was heated to approximately 204.4°C (400°F) and then poured onto the marker. The testing fixture (refer to Figure 3.3.6) was used to properly align two markers. Without delay, a desired block (concrete of asphalt) was placed on top of the bitumen. The block was pressed by hand for 30 seconds to produce an adhesive thickness of 0.32 cm (1/8"). The excessive adhesive was trimmed while it was still warm. The same procedure was done to the other side of the block. All bitumen samples were kept at room temperature for 24 hours prior to the test.

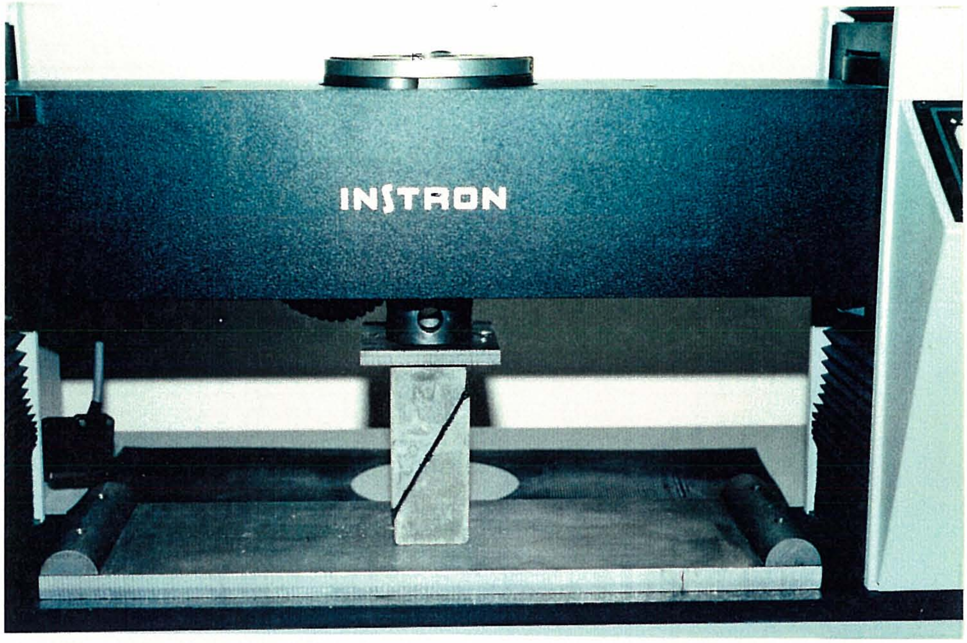


Figure 3.3.3 Slant shear test using an Instron testing machine

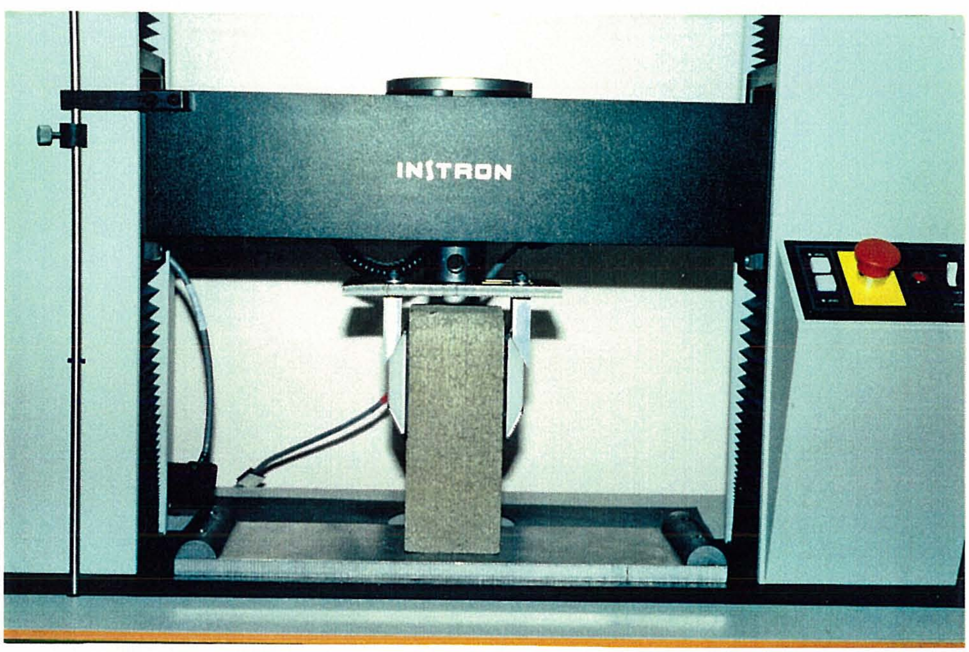


Figure 3.3.6 Shear strength test on the Instron machine.

The shear strength tests were conducted using the same Instrron testing machine described in Section 3.3.1. The specimen was placed upright on the base plate. A fixture with web-shaped arms was made to transfer the downward force from the crosshead to the reflective markers on both sides of the block to produce a shear load (see Figure 3.3.5). Figure 3.3.6 shows a concrete specimen under testing on the Instron testing machine.

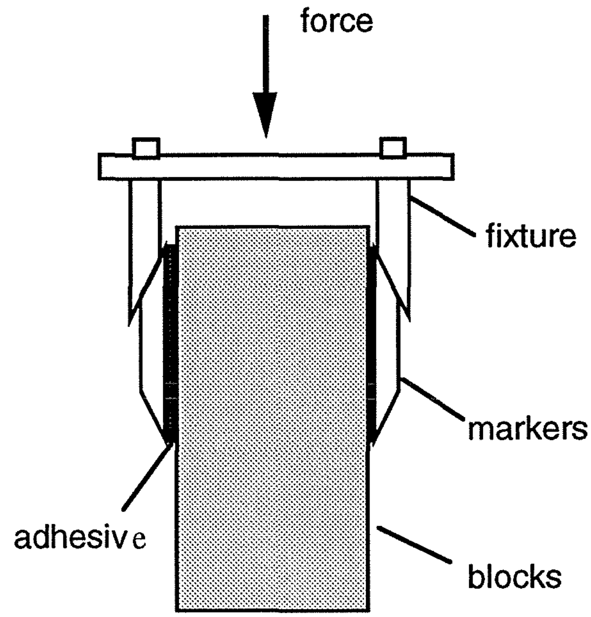


Figure 3.3.5 Shear test fixture and test setup

The tests conducted in this investigation included the following:

1. Basic shear strength study of various butyl pads.

2. Investigating the effect of primer on bonding strength. The selected pads that had higher strength were tested with or without primer applied on concrete and asphalt block surfaces.

3. Examining the effect of the time and force applied during installation. This test was only conducted on Hitach 2 pads. The force and time required during installation by the manufacturer was 6,674 N (1500 lb) for 6 seconds. The parameters selected in the test were 6,674 N (1500 lb) and 11,123 N (2500 lb) both for 3, 6 and 9 seconds.

4. Evaluating substrate effect. The bonding strength on different substrate (concrete and asphalt) was compared only on Hitach 2.

5. Study the effect of marker bottom on bonding strength. The textured and smooth bottomed Stimsonite Model 88 markers were bonded to the concrete blocks and the shear strength was compared. Later, newly approved Davidson's long-term temporary reflective marker Davidson RPM that has "Gripper/Grabber" plastic Bottom was also tested with Hitach 2 pads.

6. Testing the effect of exposure time of pads on bonding strength. The butyl pads usually have a shelf life of 6 months. It is also required to install the pad immediately after the release paper is peeled. The concern of this test is to see how quickly the pad loses its adhesion when exposed to the environment after the release paper has been removed. The exposure time of the pads for this investigation varied from 15 minutes to 24 hours.

3.3.3 Tensile Test

The tensile test was to examine the bond strength of adhesive under the tensile load. The test was designed based on the Caltrans standard test for epoxy adhesive (California Test 420, 1978). The test method is currently used in Caltrans Transportation laboratory for testing the strength of various marker products.

In this test, a marker was bonded to an aluminum pipe cap with the adhesive to be evaluated (Figure 3.3.7). The pipe caps measuring 5.1 cm (2 inches) in diameter were obtained from Caltrans Transportation laboratory. The bottom of the pipe caps were all sand blasted to increase its roughness and then cleaned with compressed air prior to use. The butyl pad was cut from the roll and pressed on the pipe cap. The release paper was then peeled and the cap/pad was seated at the center of the marker bottom. An appropriated force was

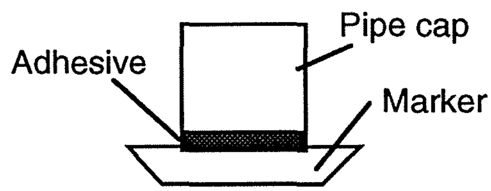


Figure 3.3.7 Tensile specimen.

applied using a hydraulic press according to the manufacturers' requirement for installation. The excess material around the cap was trimmed. When the bituminous adhesive was tested, the hot melt bitumen was poured on the marker bottom and the cap was immediately pressed on the marker bottom at its center by hand (for detailed procedure, see Appendix B). The adhesive layer was then trimmed to the size of the cap base (5.1 cm / 2 inches in diameter)

A fixture was designed to apply tensile load on the adhesive layer using the Instron testing machine (see Figure 3.3.8). The test setup is shown in Figure 3.3.9.

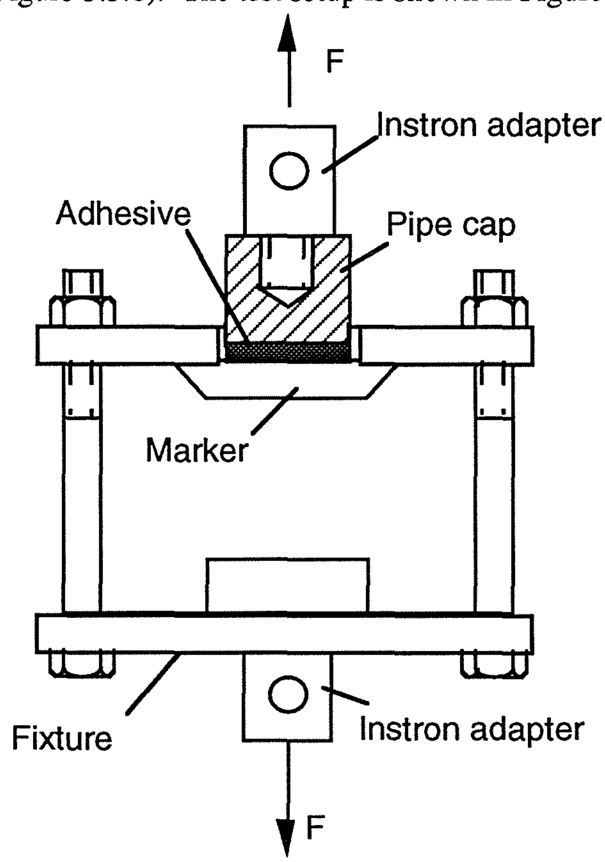


Figure 3.3.8 Tensil test fixture

Only Hitack 1 and Hitack 2 were evaluated in the tensile test, with bituminous adhesive as control. All samples were tested at room temperature. The loading rate was set at 2.0 cm/min. (0.8 in/min.).

3.3.4. Elastic Recovery Test

The setup of the elastic recovery of the adhesive was as the same as the shear strength test. Hitack 2, Hitack 3 and bituminous adhesive were evaluated. The displacement limit was set to 0.64 cm (0.25 inches). Three positions of the marker during the test were marked and measured. They were the initial position before the load applied, the position after the load was removed and the end position one minute after the load was released. The elastic recovery was calculated using the formula

$$R = (d_1 / d) * 100\%$$

where R is the elastic recovery in %, d is the total displacement of the marker during the test cycle and d_1 is the amount of the displacement recovered one minute after the load was removed.

3.3.5 Impact Test

The properties of bituminous adhesive is very temperature dependent. At low temperature it appears to be brittle. The low temperature stiffness/brittleness is one of the concerns on marker adhesive performance. The impact test was designed to study the effect of low temperature stiffness/brittleness of marker adhesive on its performance. Since marker adhesive undergoes the impact from vehicles at 96 km/hr (60 mph) on the highway, impact method was employed in this test.

The test was conducted using a pendulum impact machine that provides an impact shear load on the adhesive sample. A fixture was made and bolted on the base of the machine to hold a 0.64 cm x 0.64 cm x 1.91 cm (1/4" x 1/4" x 3/4") adhesive sample (see Figure 3.3.10). An impact head housing an accelerometer was attached to the pendulum at its center of gyration. Figure 3.3.11 is a schematic diagram showing the setup of the

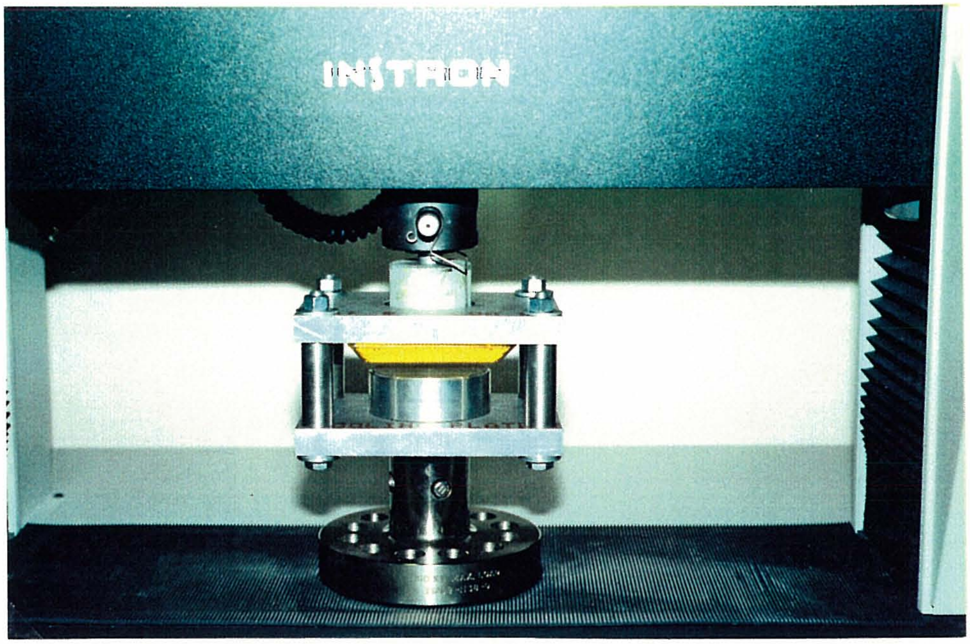


Figure 3.3.9 Tensile test on the Instron machine.

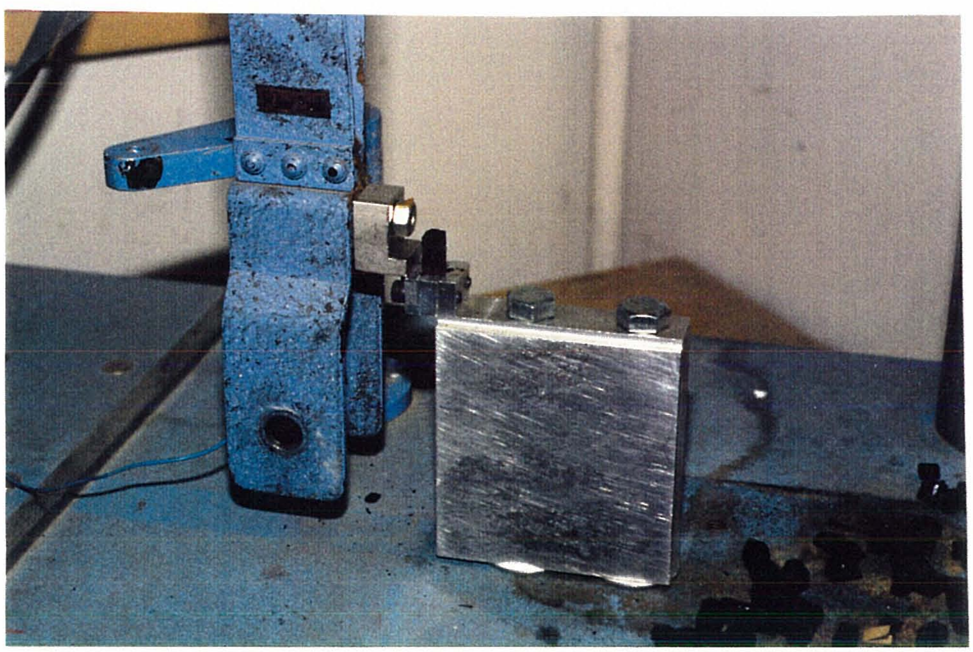


Figure 3.3.10 Fixture for shear impact test.

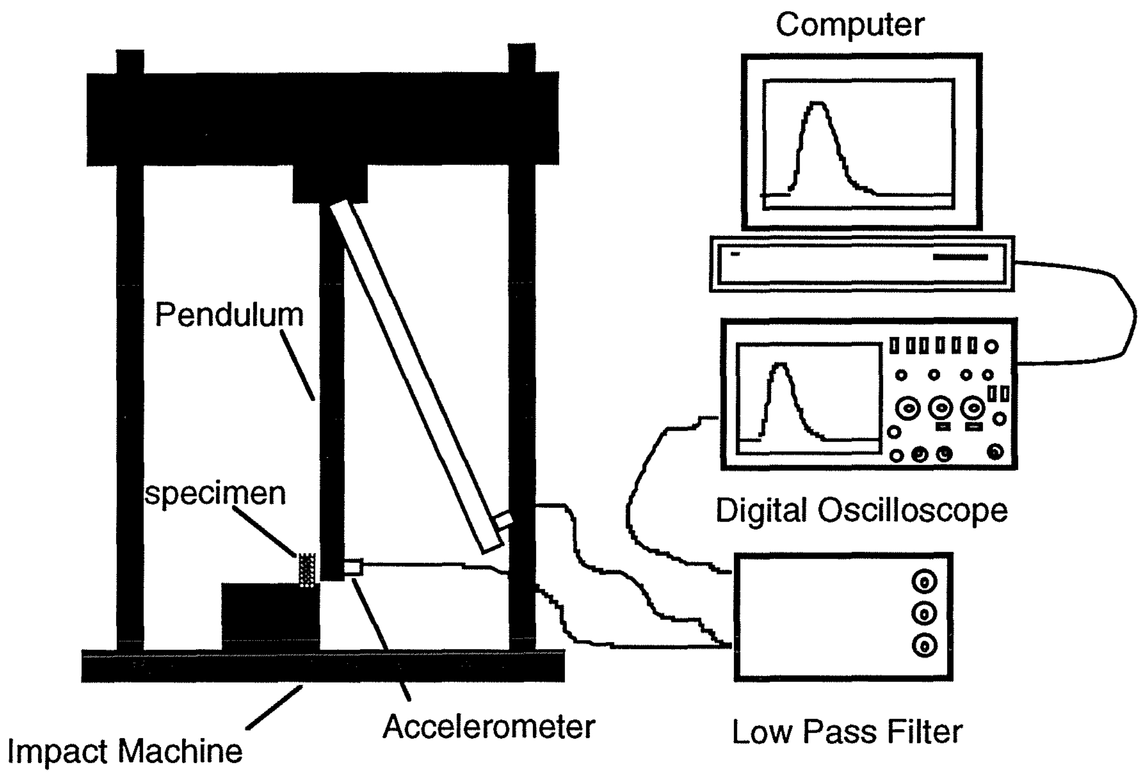


Figure 3.3.11 Schematic diagram of impact test setup.

instrumentation for measuring the impact response of each sample. The signal from the accelerometer was recorded and displayed using a Tektronix 2230 digital-storage oscilloscope at a sampling rate of 51,200 readings per second. A low pass filter was built to filter out high frequency noise (higher than 1000 Hz) from the system. The data were transferred to an IBM PC computer for subsequent analysis.

Bituminous adhesive and Hitack 2 were used in the impact test. Samples were divided into two groups. One group of samples was tested at the room temperature (24.4 °C / 76°F) while the other was stored in the refrigerator for 24 hours to bring the sample temperature down to 4.4 C (40°F). The initial position of the pendulum was set from 20° to 90° with an interval of 10° for Hitack 2. For bituminous adhesive sample, the dropping angle of the pendulum was set from 15° to the angle at which the sample broke.

The bitumen samples at 4.4°C (40°F) were also tested at a dropping angle of 18° to carefully determine its breaking point.

A computer program was developed to calculate and display the angular acceleration, angular velocity, angular displacement and the energy absorbed by the adhesive sample during the impact. The equations and formulae used in the program were listed in Table 3.3.3. The programs for retrieving and processing the impact data are included in Appendix D.

Table 3.3.3 Equations and formula in the shear impact programs.

$$\omega(t_0) = \sqrt{2g(1-\cos\theta)/q}$$

$$\omega(t) = \omega(t_0) + \int_{t_0}^{t} \alpha(t)dt$$

$$\phi(t) = \int_{t_0}^{t} \omega(t)dt$$

$$I_o = mK_o^2 = m\bar{r}q$$

$$F(t) = ma(t)$$

$$F(t)q = I_o\alpha(t)$$

$$E(t) = I_o \int_{\phi(t_0)}^{\phi(t)} \alpha(t)d\phi(t)$$

$$\alpha(t) = a(t)/q$$

$$a_i = (A_i - A_1)Bg/Cal$$

Where,

- I_o - Moment of inertia of the pendulum about pivot O
- m - Mass of the pendulum, m = 1.51 kg
- K_o - The radius of gyration of the pendulum about O
- $\bar{r}$ - The distance of Cg to pivot O, $\bar{r}$ = 0.18 M
- q - distance from center of percussion to pivot O, q = 0.4 M
- $\omega(t_0)$ - Initial angular velocity of the pendulum
- θ - drop angle, degree
- $\phi(t)$ - angular displacement, rad.
- F(t) - Impact force at center of percussion
- a(t) - Linear acceleration at Q
- $\alpha(t)$ - Angular acceleration of pendulum
- A_1, A_i - Accelerometer response in bytes
- g - Gravitational acceleration, g = 9.8 m/sec/sec
- B - Conversion fact.
- Cal - Accelerometer calibration factor, Cal = 10.13

3.3.6 Field Test

After the laboratory investigation, two types of butyl pads, i.e., Hitack 3 and Hitack B, were selected to be placed in actual traffic environment to examine their road performance (Hitack 2 was not available by the time of the field test). The location for this test was on northbound of I-710, the Harbor Freeway on-ramp from the Pacific Coast Highway (State Highway 1). The ADDD in this area is approximately 130,000 [State of California Memorandum from DOT on Jan. 25, 1993]. There is a heavy truck concentration and a lot of weaving due to the proximity of on-ramps. The abnormal amount of commercial trucks is the primary reason for marker breakage and losses. The markers with selected cold applied adhesives were placed on July 18, 1993. The traffic control was provided by the special crews from Caltrans District 07 (in Los Angeles).

White Stimsonite reflective markers with rough bottom were used for the field evaluation. A total of 40 samples were prepared prior to the placement. Pads were cut to the dimension of the marker bottom and then adhered onto the markers by hand. Twenty-five markers were adhered with Hitack 3 and the rest with Hitack B. Samples were placed between slow and middle lanes starting near north post a7022 and ended near south post a7011. The ambient temperature was approximately 29°C (85°F). After examining the concrete road surface, it was considered relatively debris-free and no road surface preparation was conducted. Markers were placed on the pavement with no attention to spacing since the existing markers were already adhered to the road surface. They were, however, placed no closer than three feet to either existing or other testing markers (see Appendix E). Primer was brushed onto the road followed by marker placement after approximately one minute. To study the effect of primer on adhesive field performance, some of the markers were installed without primer applied.

Once a marker was on the ground, a three-ton truck (approximately 6,674 N / 1,500 lb per tire) rolled on top of each sample with the driver side front tire for 6 - 10 seconds as the manufacturer instructions indicate. The marker installation is summarized in Table

3.3.4.

Table 3.3.4 Marker installation.

Batch #	No. of Samples	Adhesive	Primer
1	15	Hitack 3	Yes
2	10	Hitack 3	No
3	8	Hitack B	Yes
4	7	Hitack B	No

3.4 RESULTS AND DISCUSSIONS

3.4.1 Results From Low Loading Tests

1. The results from shear strength tests of eight cold-applied butyl pads are shown in Fig. 3.4.1. It is obvious that the shear strength varies from product to product, with the lowest maximum load of 294 N (66 lb) (Hitack 1) and the highest of 5,341 N (1200 lb) (Hitack B). The products with low shear strength, (namely, Hitack 1, A, C, D and Davidson's) are basically for temporary marker installation, while Hitack 2, Hitack 3 and Hitack B are the improved products for permanent marker application. Hitack 2 and Hitack 3 were essential the same products but received in separate patches, and Hitack 3 was shelved longer than Hitack 2. The average maximum shear strength of Hitack B was higher than that of Hitack 2 (25 N/cm^2 versus 19.5 N/cm^2). The relative lower slope of the curve of Hitack B indicates its lower apparent shear modulus. It can be noticed that the maximum strength occurred at a large displacement (about 1 cm), while at small displacement, for instance, 0.5 cm, the shear strength of Hitack B is much lower than both Hitack 2 and Hitack 3. In an observation made on the sample blocks stored on the shelf in the lab one month after the test, Hitack B pads were found separated from the block surfaces and the remaining part could be easily peeled off. While Hitack 2 and Hitack 3 pads remained attached without noticeable change. This fast-aging problem of Hitack B would certainly affect its field performance. The results from the tests on Hitack D with 15 x 15 and 45 x 45 carbon fabric showed little improvement over Hitack D. Testing on Double layer B indicated that the shear modulus decreased as the thickness of Hitack B doubled. Therefore, Hitack 2 and Hitack 3 were considered the best products among the cold applied adhesive materials under this investigation.

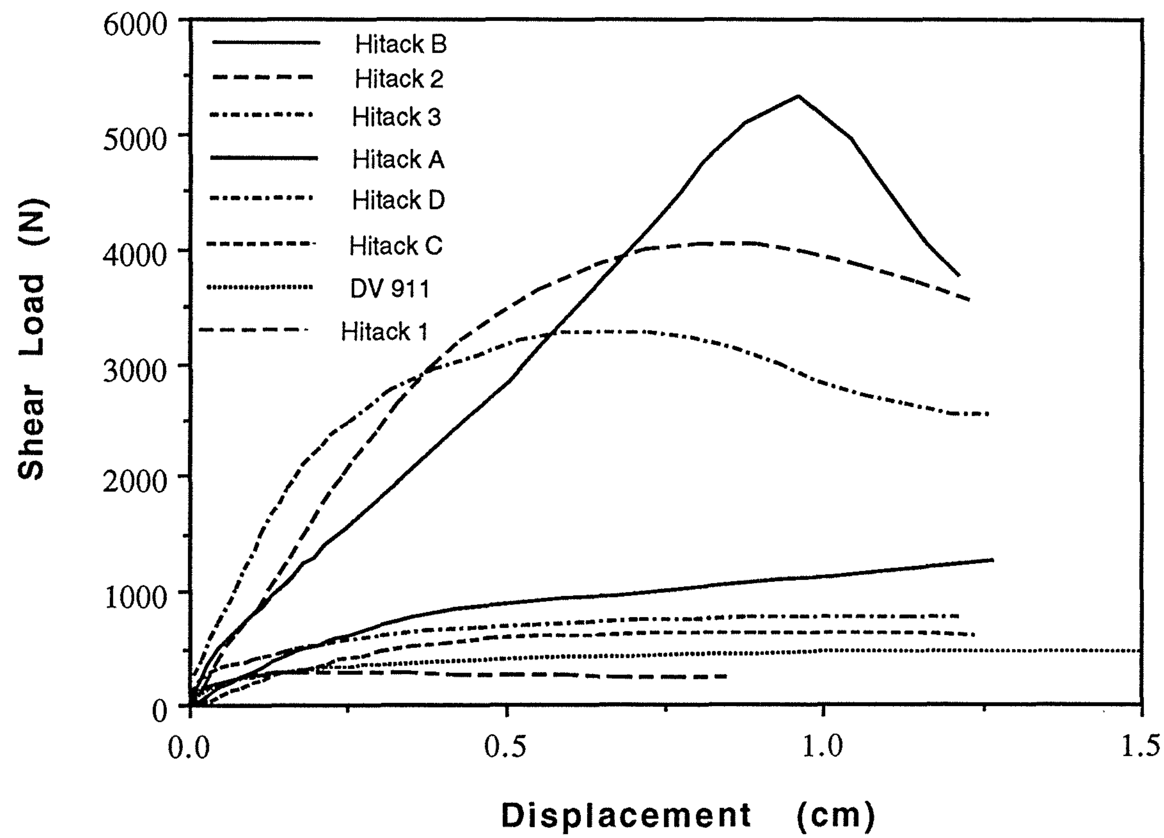


Figure 3.4.1 Shear strength of various butyl pads.

2. Shear and tensile strength of bituminous adhesive and Hitack 2 pads.

Figures 3.4.2 and 3.4.3 are typical load - displacement curves showing results from shear and slant shear strength tests, respectively, comparing Hitack 2 and Bituminous adhesive. It is seen that at room temperature under slow-loading condition, the strength of cold applied Hitack 2 pad is much lower than bitumen. The average maximum stress and the apparent shear modulus are listed in Table 3.4.1.

Table 3.4.1 Average maximum shear stress and apparent shear modulus of selected adhesives.

Substrate	Adhesive	Max. Load N	Max. Stress N/cm^2	Shear Modulus N/cm^2
Concrete	Bitumen	14,850	79.4	50.2
	H2 no primer	3,924	21.0	10.5
	H2 w/ primer	2,390	12.7	9.2
	HB no primer	4,675	25.0	5.2
	HB w/ primer	1,695	11.0	3.6
Asphalt	Bitumen	12,591	81.3	53.5
	H2 no primer	3,018	19.5	10.3
	H2 w / primer	2,634	17.0	9.9

The maximum stress of bitumen is about four times of Hitack 2 pads and its apparent shear modulus is about five times of Hitack 2 pads. In most cases, shear failure of bituminous adhesive was found to be a material failure, while the failure of Hitack 2 usually occurred at the interface (see Figure 3.4.4). This phenomenon indicates that the shear strength obtained in the test represents the interfacial bonding strength rather than the material strength. In another word, the overall shear strength of Hitack 2 can possibly be improved by preventing the adhesive from early interfacial failure.

The same is valid in tensile tests. the bitumen exhibits much higher bonding strength than Hitack 2 does as can be seen in Figure 3.4.6. Again, the failure of Bitumen was

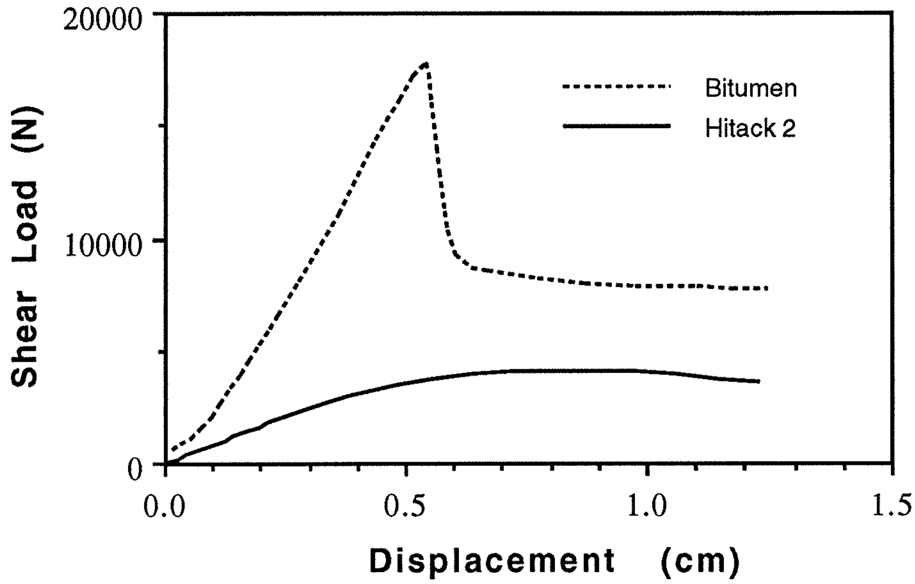


Figure 3.4.2 Shear strength of bitumen and Hitack 2 at room temperature.

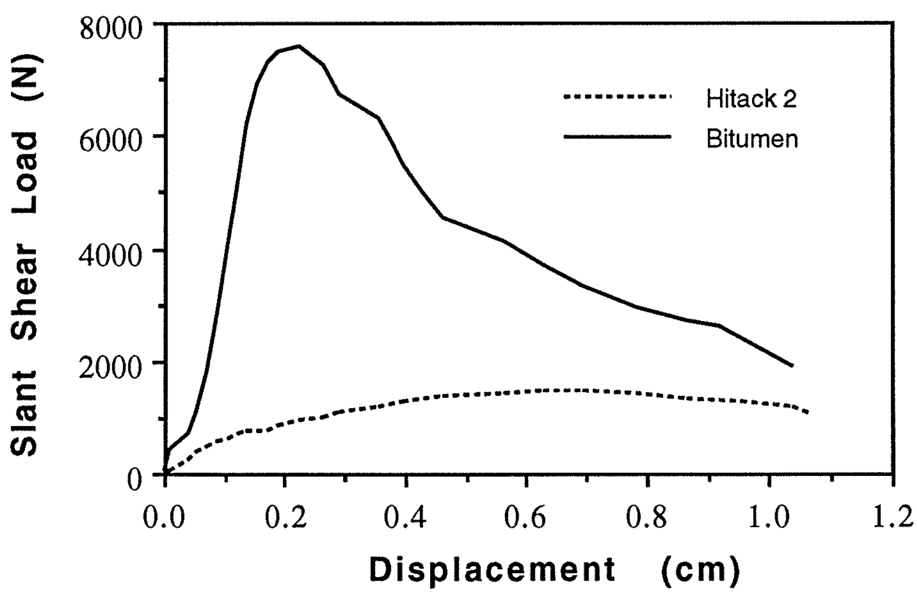


Figure 3.4.3 Slant shear strength of bitumen and Hitack 2 at room temperature.

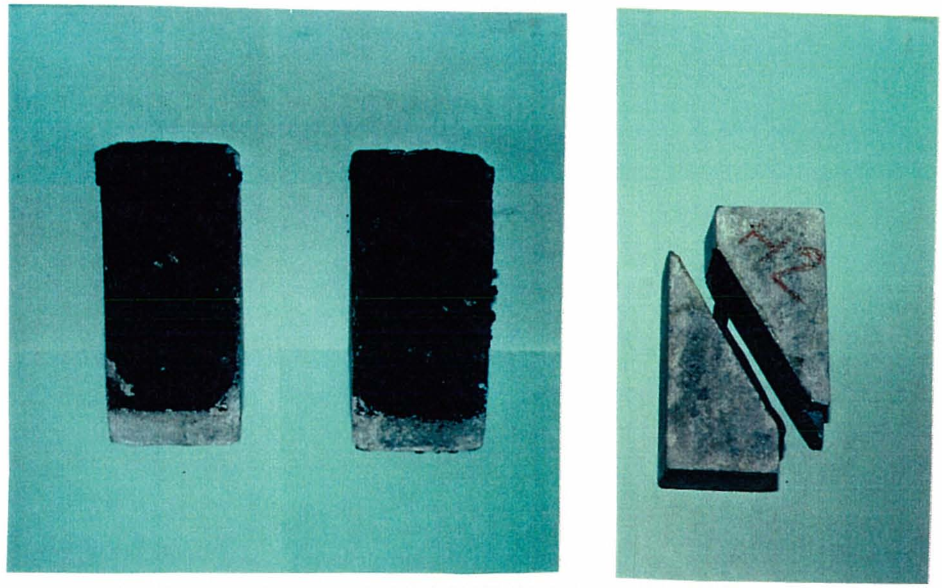


Figure 3.4.4 Slant shear failure
Left: bitumen fails within the material
Right: Hitack 2 fails at bonding interface

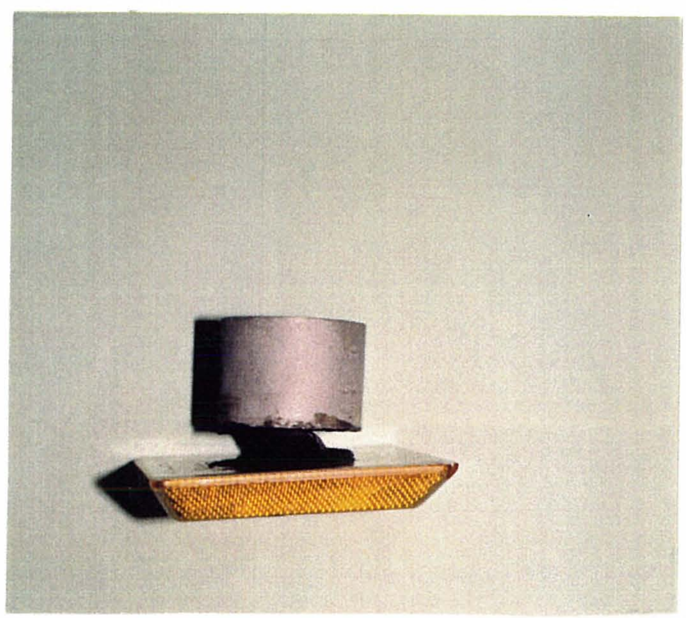


Figure 3.4.5 Failure of Hitack 2 under tensile load.

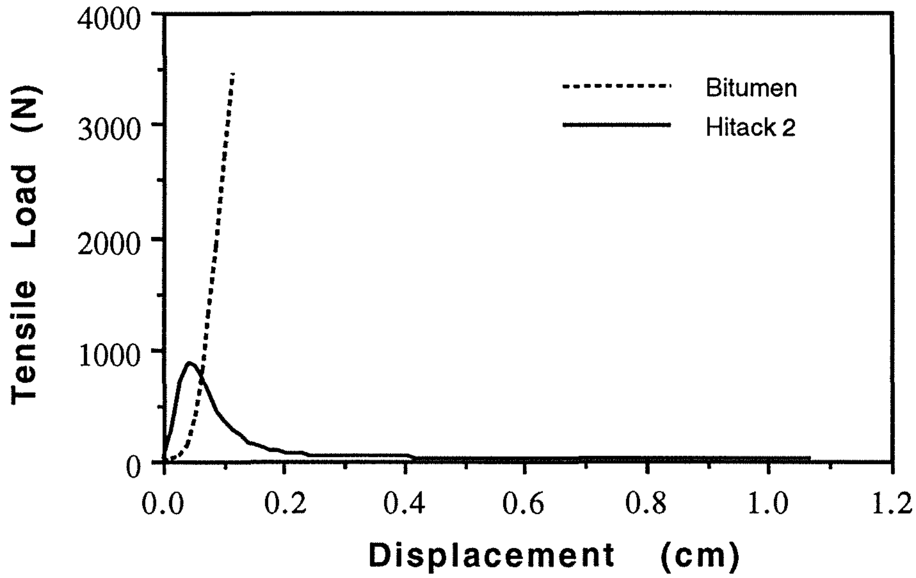


Figure 3.4.6 Comparison of tensile strength of bitumen and Hitack 2.

failure in which the adhesive layer fractured under tensile load, while the failure of Hitack 2 always occurred at the interface of either the marker or the pipe cap (see Figure 3.4.5). The marker and pipe cap were never found to be separately completely within the displacement of 12.7 mm (0.5"). This kind of failure was "repairable," and the marker could be bonded back when a compression force was applied.

3. Effect of temperature on bonding strength.

The results from the temperature test indicate that the bonding strength of bituminous adhesive decreases sharply as the temperature increases. Figure 3.4.7 shows that the slant shear strength of bitumen at 21.1°C, 37.8°C and 48.9°C (70 °F, 100 °F and 120°F). The maximum load decreased from 4,449 N (1000 lb) to 666 N (150 lb) as the temperature increases from 21.1°C to 37.8°C (70 °F to 100 °F). At 48.9°C (120°F), its maximum strength is only 8% of that at 21.1°C (70°F). The shear strength of Hitack 2 also declined with increasing temperature but in a much milder way as shown in Figure 3.4.8. Figures 3.4.9 and 3.4.10 compare the strength of these two kinds of adhesives at 37.8°F (100°F) and 48.9°C (120°F), respectively. The average maximum strength change were summarized in Figure 3.4.11. It clearly shows that although at room temperature the bonding strength of bitumen is much higher than that of Hitack 2, it declines to nearly the same level as Hitack 2 at 37.8°C (100°F). While at 48.9°C (120°F), the adhesive of Hitack 2 is slightly better than bituminous adhesive. At low temperature (4.4°C), the bituminous adhesive shattered due to its brittleness.

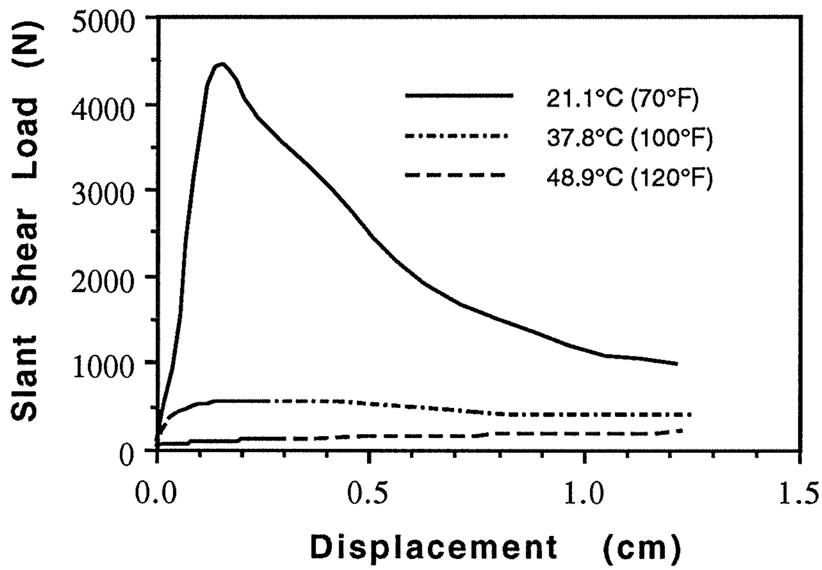


Figure 3.4.7 Slant shear strength of bitumen at different temperature.

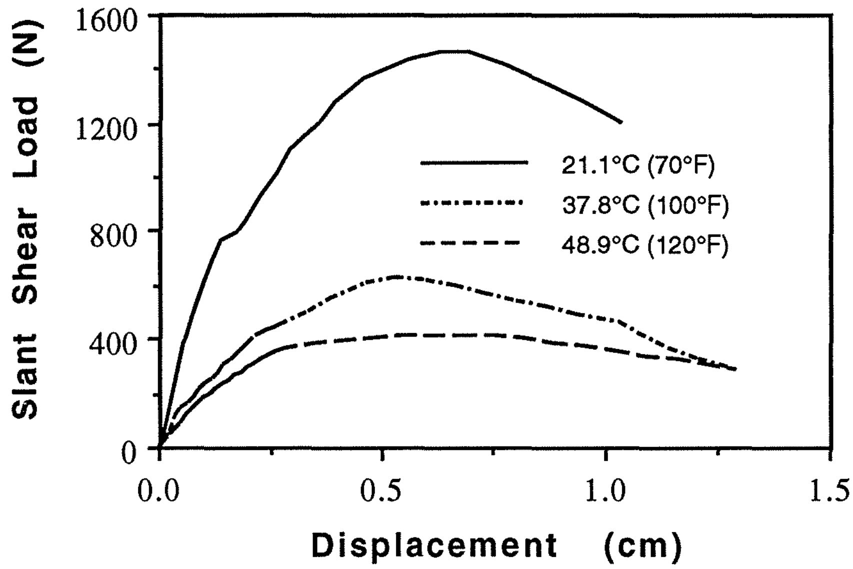


Figure 3.4.8 Slant shear strength of Hitack 2 at different temperature.

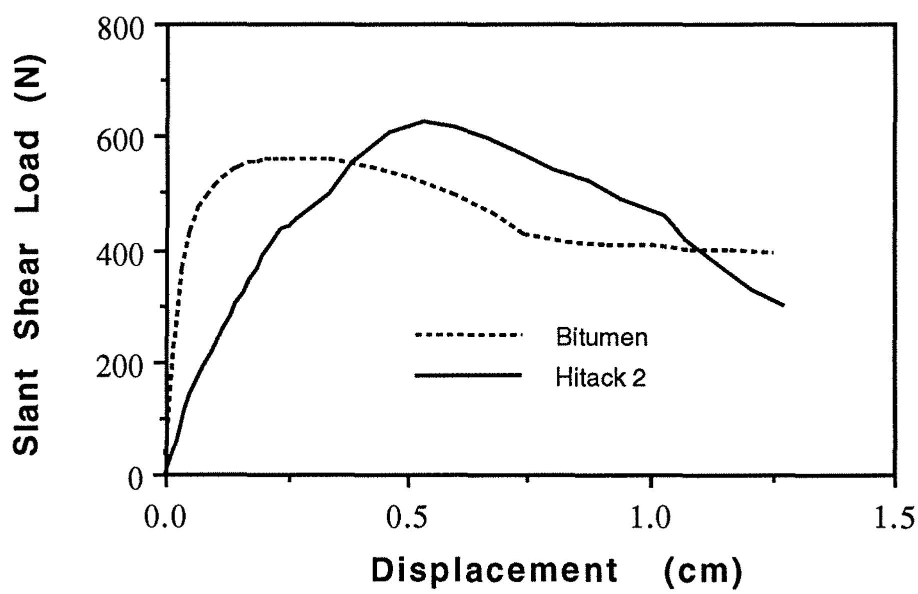


Figure 3.4.9 Slant shear strength of bitumen and Hitack 2 at 37.8°C.

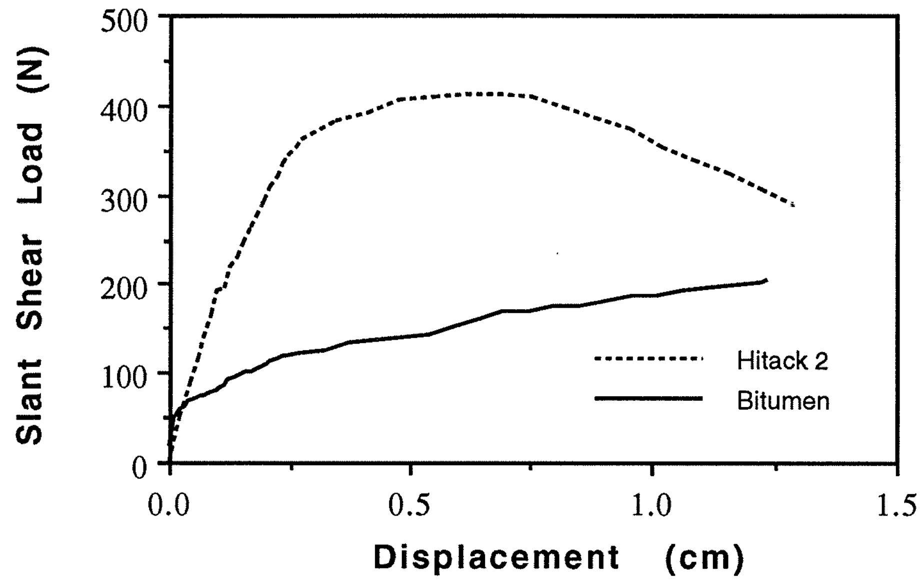


Figure 3.4.10 Slant shear strength of bitumen and Hitack 2 at 48.9°C.

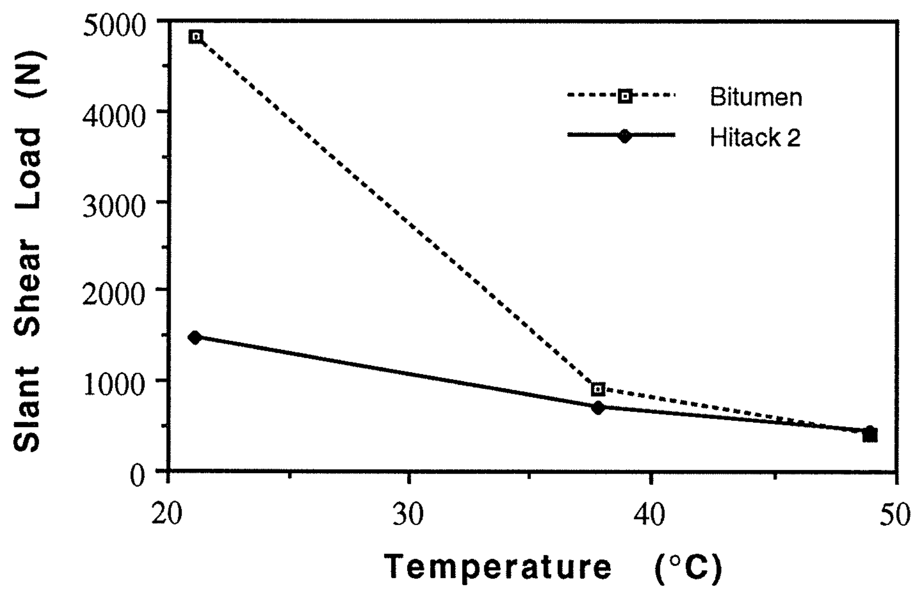


Figure 3.4.11 Average maximum slant shear load of two adhesives.

4. Effect of substrate on bonding strength.

The results from the shear tests on two commonly used substrates, concrete and asphalt, indicate that the substrate exhibits little effect on bonding strength for both bitumen and Hitack. Fig. 3.4.12 and 3.4.13 show the stress-strain relations on these two substrates for bitumen and Hitack 2 respectively. The average maximum stress and apparent modulus on two substrates are very close for both materials.

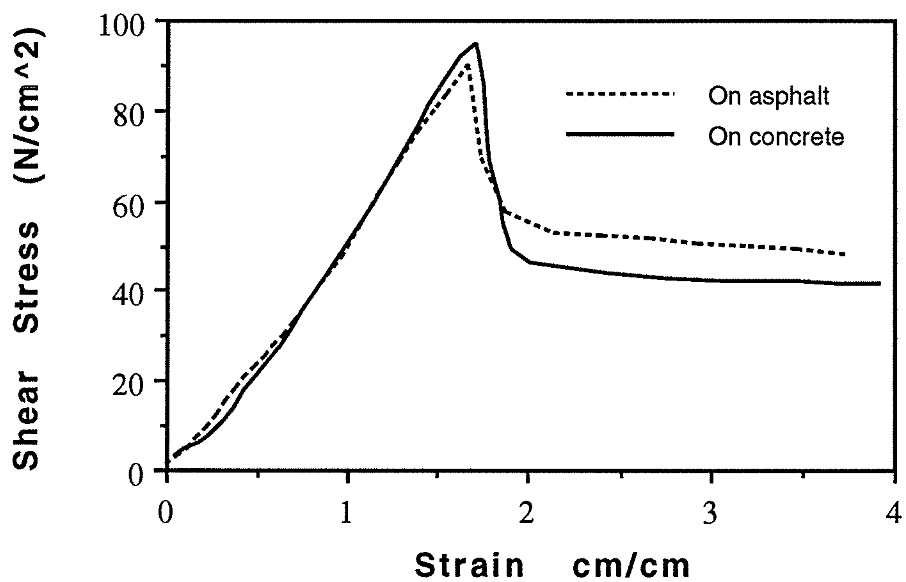


Figure 3.4.12 Stress-strain curves of bitumen on asphalt and concrete surfaces.

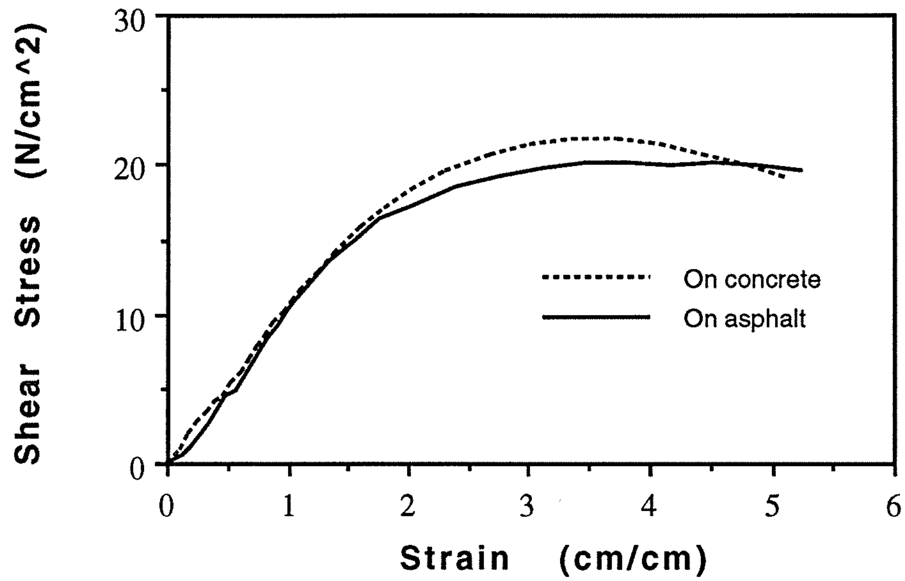


Figure 3.4.13 The stress-strain curves of Hitack 2 on different substrates.

5. Effect of primer on bonding strength.

When butyl pads are applied on concrete (old and new) and old asphalt road surfaces, primer is required prior to installation as road surface conditioner and for fast strength development. However, the results from the primer test showed that the primer has a negative effect on the shear strength. This was true for all the butyl pads tested, including Hitack 1, Hitack 2, Hitack B, Hitack D and Davidson's pad. Figures 3.4.14 and 3.4.15 compare the shear strength of Hitack 2 with and without primer applied on asphalt and concrete blocks.

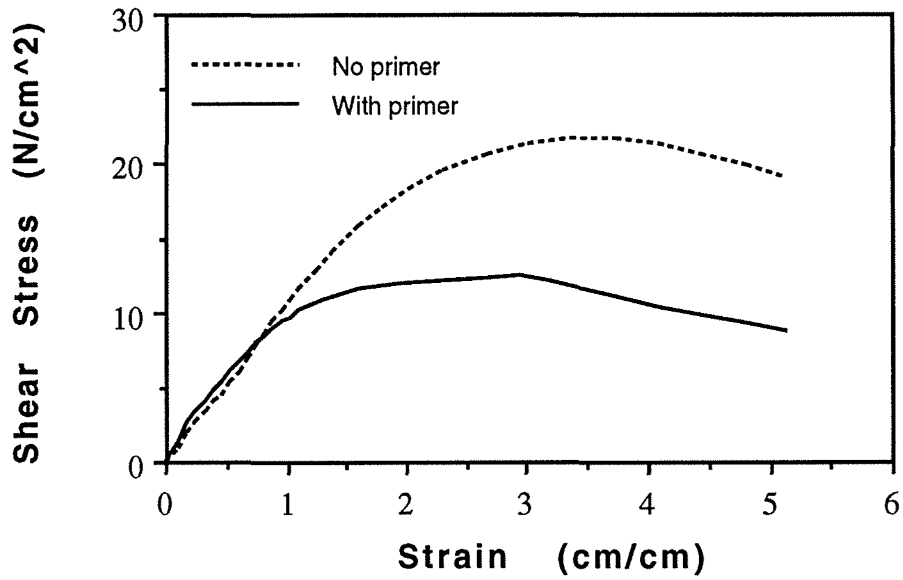


Figure 3.4.14 Effect of primer on shear stress of Hitack 2 on concrete surface.

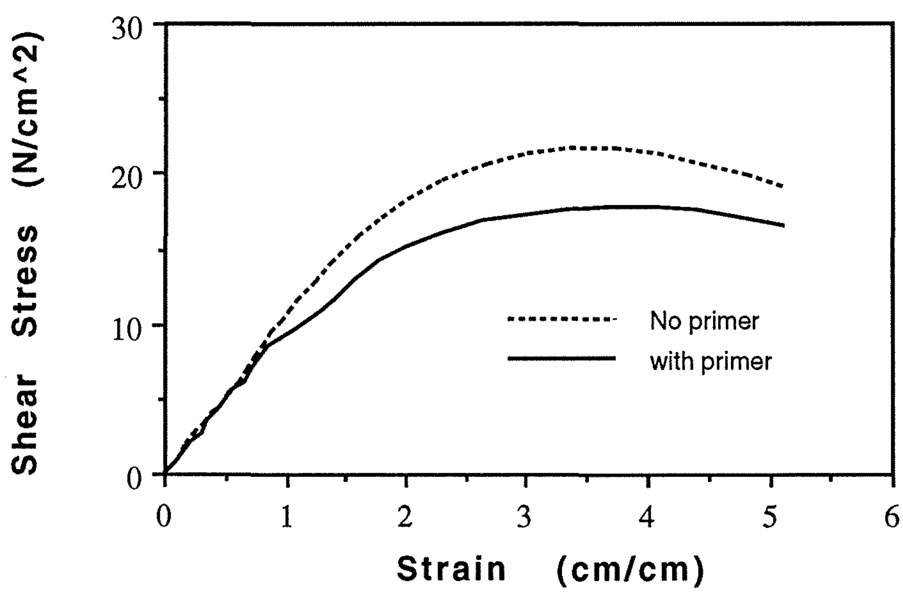


Figure 3.4.15 Effect of primer on shear stress of Hitack 2 on asphalt surface.

In all cases, the shear strength decreased when primer was used. This reduction was more pronounced on the concrete surface. The average maximum stress was only 12.77 N/cm^2 (18.52 psi) which was much lower than that without primer (21.0 N/cm^2). It was found during the test that the shear failure always occurred at the interface of marker bottom and butyl pad when primer was not applied. With primer applied, the failure always occurred at the bonding surfaces between the pad and the substrate (concrete or asphalt) on which primer was applied. This phenomenon was more obvious on concrete surface (see photo on Fig. 3.4.16). One may conclude that this shear strength reduction is due to the interaction between the primer and the butyl pad. Primer also tended to reduce the tensile strength of cold applied adhesive as can be seen in Figure 3.4.17 which shows that the tensile strength reduced significantly when primer was applied.

Figure 3.4.16 Shear failure of Hitack 2 on concrete.
Left: Without primer; right: with primer

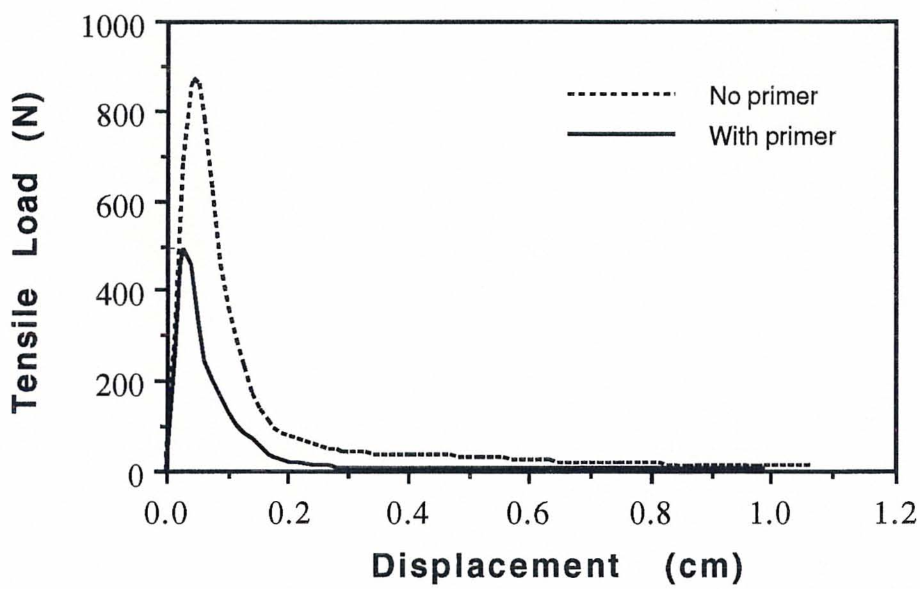


Figure 3.4.17 Comparison of tensile load of Hitack 2 with or without primer.

6. Effect of installation condition on bonding strength.

The effect of installation condition on shear strength of butyl pads were investigated by varying the force and time applied during installation. Two levels of forces (6,674 N and 11,123 N) and three levels of time (3, 6 and 9 seconds) were selected. The average maximum loads are listed in Table 3.4.2 as well as plotted in Figure 3.4.18.

Table 3.4.2 Average maximum load of Hitack 2 under various installation conditions.

Time (sec.)	Max. Load at 11,123 N (2500 lb)	Max. Load at 6,674 N (1500 lb)
3	3,662	3,591
6	3,902	4,004
9	3,621	4,111

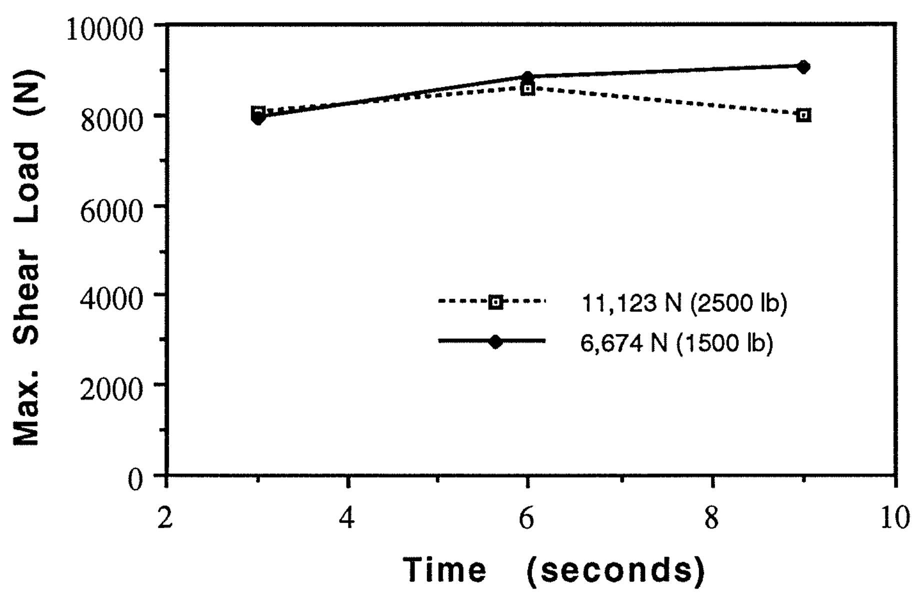


Figure 3.4.18 Effect of installation on shear strength of Hitack 2.

A statistical analysis was conducted with ANOVA using Statview on a Macintosh computer. The result indicated that there is no significant difference between these force and time levels. It seems that the installation condition has little influence on the apparent shear module as can be seen from the sample curves shown in Figures 3.4.19 and 3.4.20. This result may indicate that the installation force and time are not very critical within the tested region. However, by carefully examining the data in Table 3.4.2, one may notice that the shear strength in the cases of 3 seconds for both force level and 9 seconds for 11,123 N (2500 lb) is in the lower region. This may imply that 3 seconds are not adequate for strength build-up and 9 seconds at 11,123 N (2500 lb) force level is too long to remain the full strength development. The result indicates that the manufacturer's requirement for installation (6,674 N / 1500 lb for 6 seconds) is an optimum one and the force applied during installation may be extended to 11,123 N (2500 lb) for 6 seconds without losing its full strength.

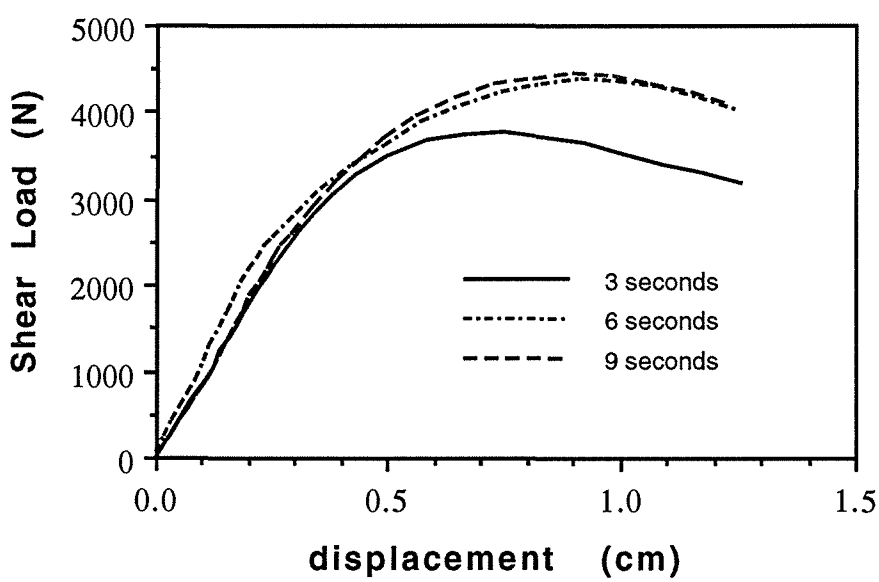


Figure 3.4.19 Shear strength of Hitack 2 installed under 6,674 N (1500 lb) for 3, 6 and 9 seconds

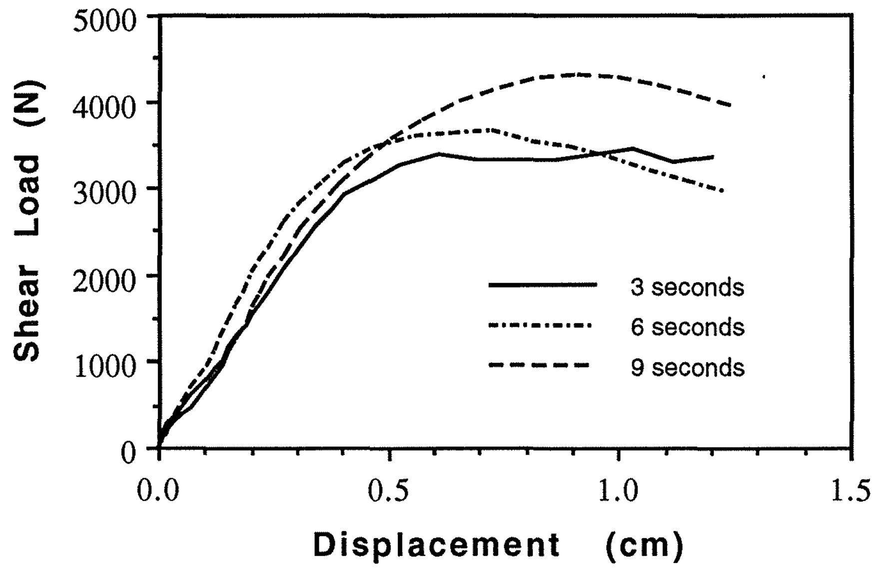


Figure 3.4.20 Shear strength of Hitack 2 installed under 11,123 N (2500 lb) for 3, 6 and 9 seconds.

7. The effect of exposure time of pads on shear strength.

The shear strength of the Hitack 3 pads that were exposed in a dust-free environment were tested. The average maximum loads of the pads for various exposure time are plotted in Figure 3.4.21 as well as listed in Table 3.4.3. The results indicate that there is no trends of enunciation of strength with increasing exposure time as was concerned. The slight difference in strength may reflect the variation of concrete blocks or sample preparation. It was concluded that the exposure of butyl pads within 24 hours has little effect on the bonding strength. However, this may not be valid in the case of a rather dusty environment.

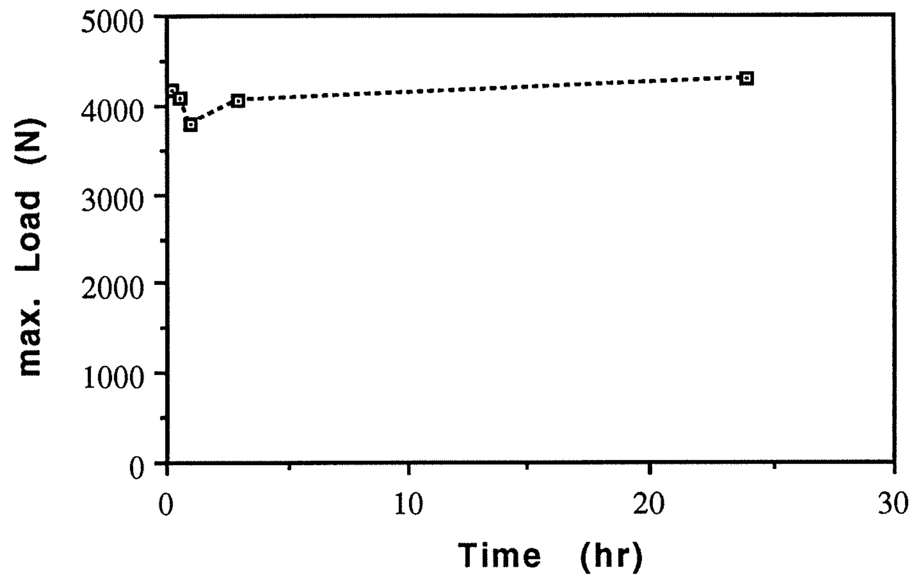


Figure 3.4.21 Average maximum shear load of Hitack 2 pads with various exposure time.

Table 3.4.3 The maximum shear load of Hitack 2 exposed for various time.

Time Exposed (hr)	Maximum Load N (lb)
0.25	4,173 (938)
0.5	4,071 (915)
1.0	3,976 (853)
3.0	4,062 (913)
24	4,293 (965)

8. The effect of marker bottom texture on shear strength.

The test was conducted using Model 88 with smooth and rough bottom surfaces. The shear strengths of Hitack 3 and Hitack B on smooth and rough marker bottoms are compared in Figures 3.4.22 and 3.4.23 and the average maximum load and stress are listed in Table 3.4.4. The rough marker bottom tended to increase the bond strength of both Hitack 3 and Hitack B by approximately 10 %.

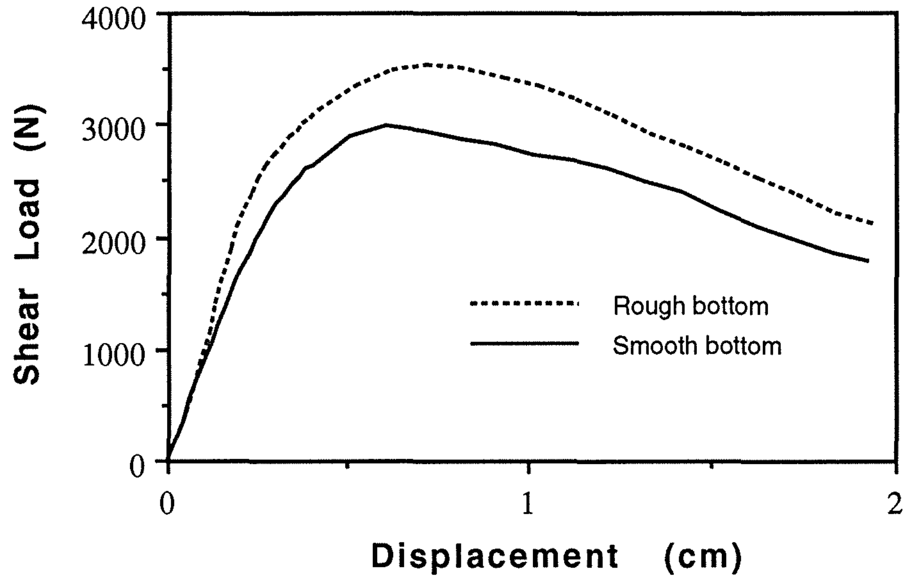


figure 3.4.22 Effect of marker bottom on shear strength of Hitack 3.

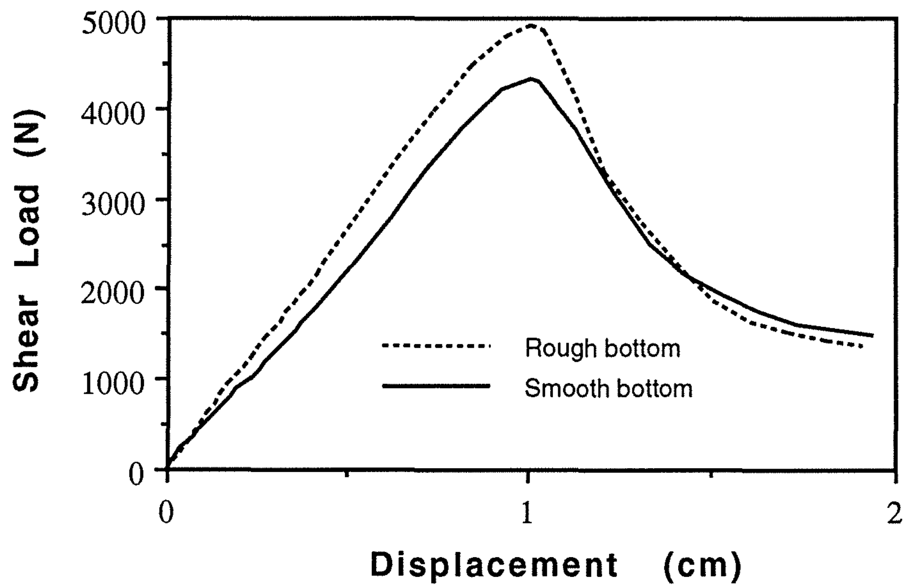


Figure 3.4.23 Effect of marker bottom on shear strength of Hitack B.

Table 3.4.4 Comparison of shear strength on smooth and rough bottom markers.

Adhesive	Max. Load (N)		Max. Stress (N/cm^2)	
	Smooth	Rough	Smooth	Rough
Hitack 3	3,172	3,457	16.6	18.5
Hitack B	4,146	4,564	22.1	24.4

10. The effect of loading rate on slant shear strength.

Figure 3.4.24 shows the maximum slant shear load of Hitack 3 and bituminous adhesive under various loading rates. The slant shear strength of both adhesives increases as the loading rate increases. It appears that, within the loading rates tested, the loading rate has more effect on bituminous adhesive than on the butyl pads.

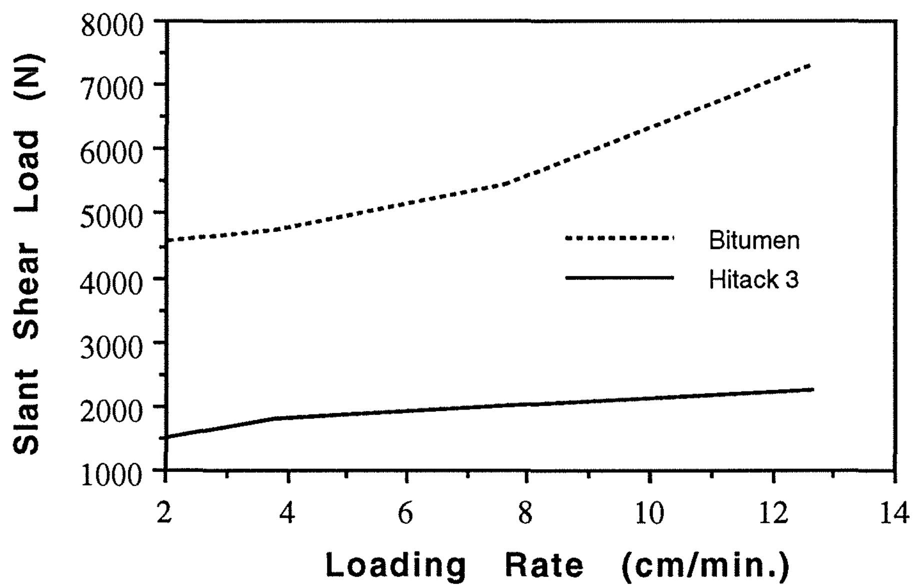


Figure 3.4.24 Average maximum shear strength increases with loading rate.

11. The elastic recovery.

The results of elastic recovery test is summarized in Table 3.4.5. It shows that at 21° C, Hitack B pad has the highest elastic recovery (66.7%), while the bituminous adhesive does not show any recoil when measured after one minute.

Table 3.4.5 Elastic recovery of three adhesives.

	Bitumen	Hitack 3	Hitack B
Initial Displ. (cm)	0.3175	0.556	0.953
Final displ. (cm)	0.3175	0.278	0.314
Elastic Recovery (%)	0	50	66.7

3.4.2 Results From Impact Test

1. The typical output curves showing the impact responses in terms of angular acceleration, velocity and displacement are illustrated in Figures 3.4.25 to 3.4.31. The energy absorbed and maximum angular acceleration, maximum angular velocity and maximum angular displacement are summarized in Table 3.4.6. Though there are significant differences in hardness of two adhesive materials at different temperature, Table 3.4.6 shows that at same dropping angle, the energy absorbed by the adhesive samples was almost the same. This indicates that the energy absorbed by the adhesive during the impact was solely a function of the drop angle of the pendulum. This is demonstrated much clearer in Figure 3.4.32 which shows that the data points of absorbed energy in different case fall onto the same curve. As an example, Figure 3.4.33 shows two acceleration curves of Hitack 2 pad at same drop angle but different temperature which are nearly identical.

Figure 3.4.34 compares the acceleration responses of bitumen samples at dropping angle of 20° at different temperature. Since bitumen adhesive at 40°F is much stiffer than that at 76°F, its impact response was much higher. However, its duration of the impact was shorter. As result, the areas under the two acceleration curves, which are the energies absorbed, are almost the same. Since there were no swing over and little bouncing back of the pendulum during the impact, the adhesive samples essentially absorbed all the impact energy input from the pendulum.

2. At room temperature, bitumen samples broke completely when hit by the pendulum at the dropping angle of 40°. While at low temperature of 4.4°C (40°F), the

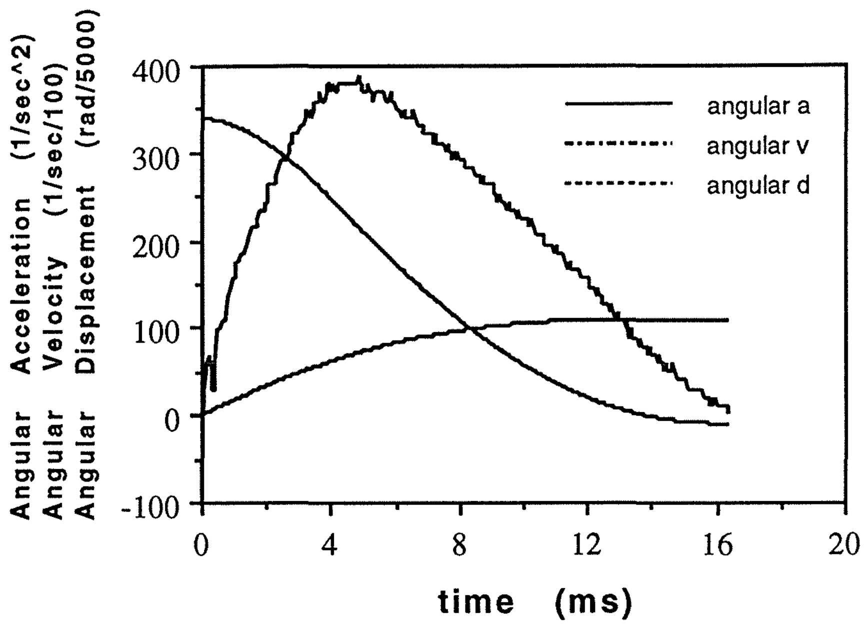


Figure 3.4.25 Impact responses of H2 pad. Dropping angle: 40°, temperature: 24.4°C

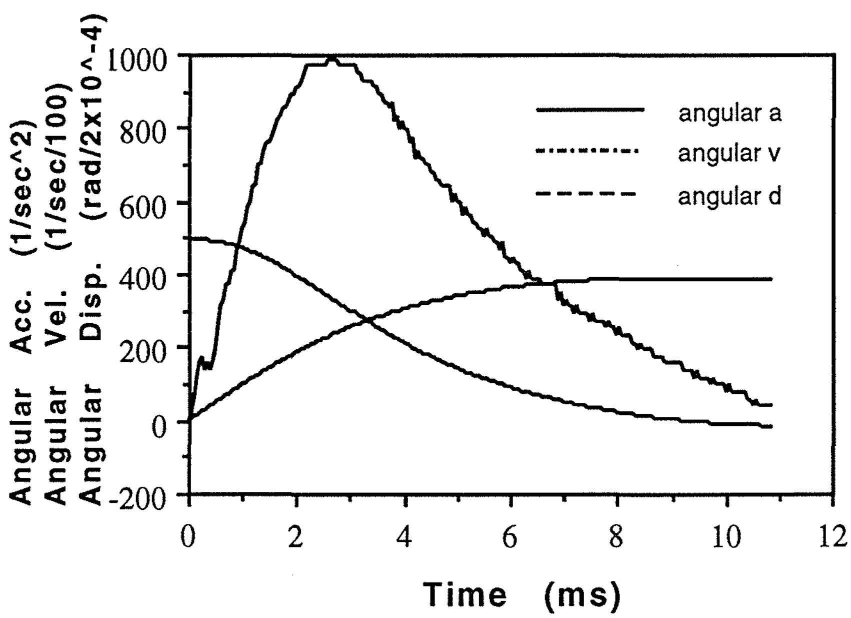


Figure 3.4.26 Impact responses of H2 pad. Dropping angle: 60°, temperature: 24.4°C

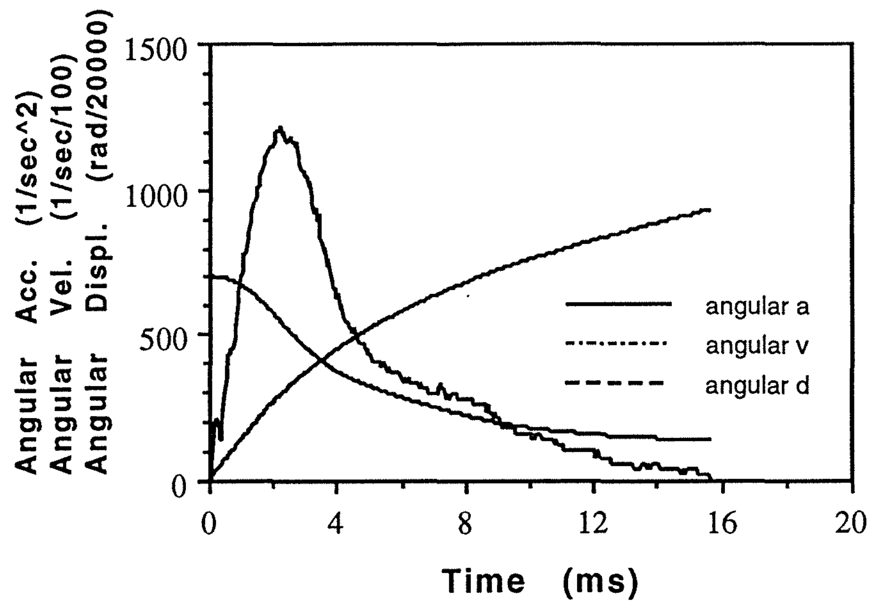


**Figure 3.4.27 Impact responses of H2 pad.
Dropping angle: 90°, Tamperature: 24.4°C.**

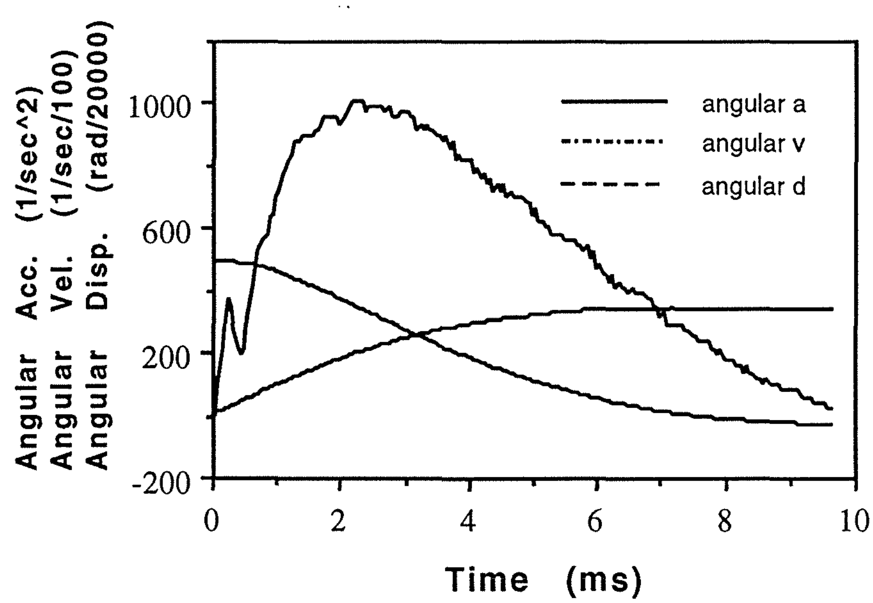


**Figure 3.4.28 Impact responses of H2 pad.
Dropping angle: 60°, temperature:4.4°C.**

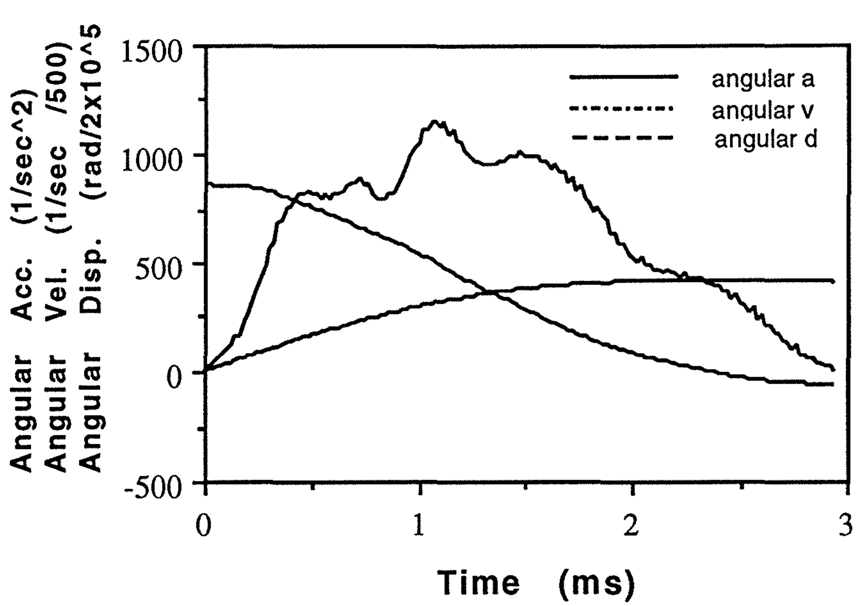


Figure 3.4.31 Impact responses of bituminous adhesive. Dropping angle: 20°, temperature: 4.4°C

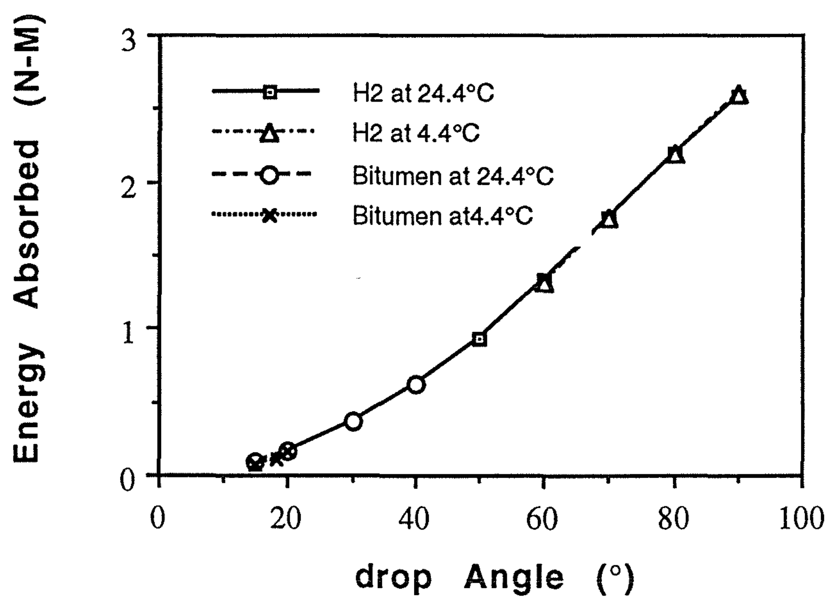


Figure 3.4.32 Energy absorbed by different adhesives under various impact condition

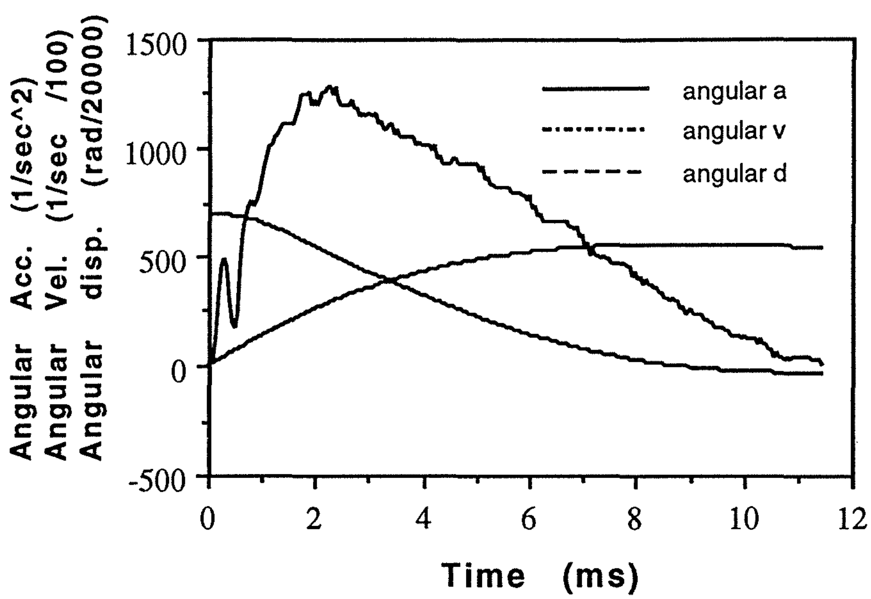


Figure 3.4.29 Impact responses of H2 pad. Dropping angle: 90°, temperature: 4.4°C

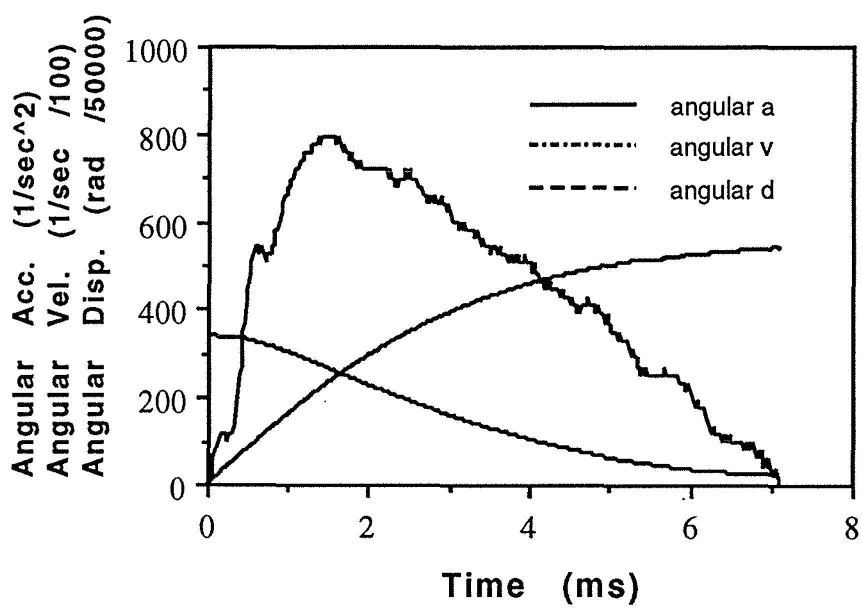


Figure 3.4.30 Impact responses of bituminous adhesive. Dropping angle: 40°, temperature: 4.4°C

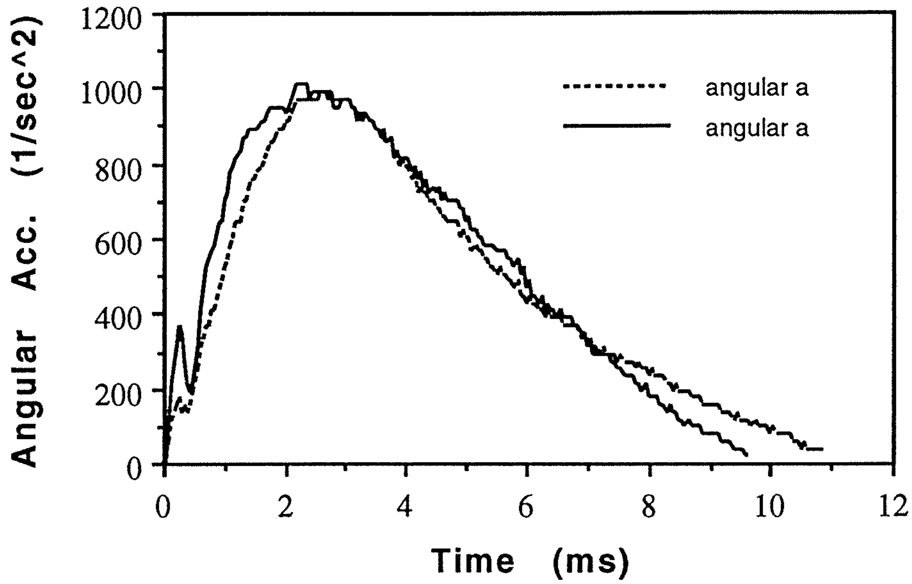


Figure 3.4.33 Acceleration response of H2 pad at same drop angle.

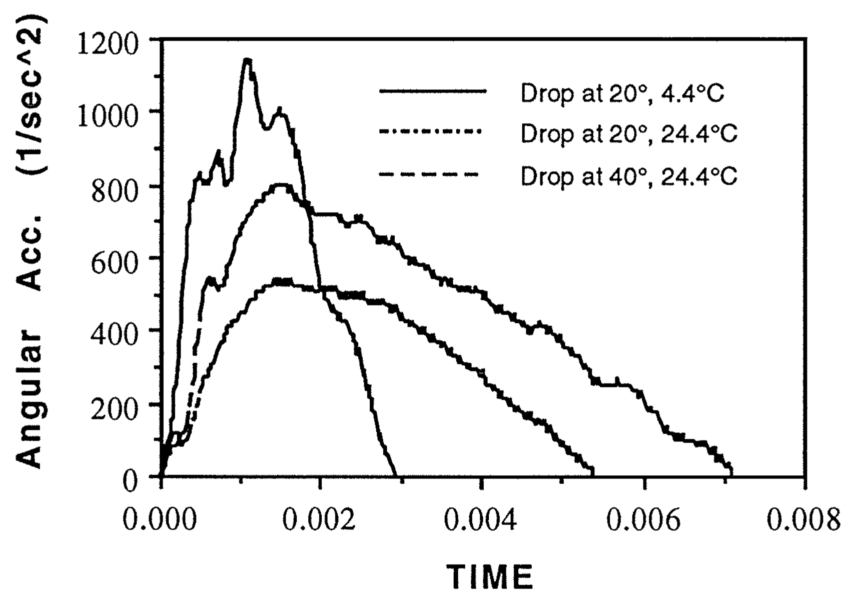


Figure 3.4.34 Comparison of acceleration responses of bitumen samples.

Table 3.4.6 Summary of shear impact respones of two adhisves

Adhesive	Temperature (°C)	Drop Angle (°)	Energy Absorbed (N-M)	Max. Ang. Acc. (Rad/sec^2)	Ini. Ang. Vel (Rad/sec)	Max. Ang. Disp. (0.01 Rad)
HiTack 2	24.4	20	0.160	184.00	1.720	1.227
HiTack 2	24.4	30	0.357	280.84	2.563	1.778
HiTack 2	24.4	40	0.622	387.36	3.388	2.166
HiTack 2	24.4	50	0.934	426.10	4.186	3.046
HiTack 2	24.4	60	1.336	987.78	4.952	1.933
HiTack 2	24.4	70	1.754	1,065.25	5.681	2.649
HiTack 2	24.4	80	2.202	1,239.57	6.366	2.786
HiTack 2	24.4	90	2.577	1,320.20	7.003	4.637
HiTack 2	4.4	60	1.326	1,007.15	4.952	1.714
HiTack 2	4.4	70	1.751	1,510.72	5.681	1.587
HiTack 2	4.4	80	2.196	1,549.46	6.366	2.825
HiTack 2	4.4	90	2.600	1,723.77	7.003	2.757
Bitumen	24.4	15	0.091	484.21	1.293	0.252
Bitumen	24.4	20	0.160	542.31	1.720	0.398
Bitumen	24.4	30	0.357	697.26	2.563	0.650
Bitumen	24.4	40	0.622	794.10	3.388	1.077
Bitumen	4.4	15	0.080	871.57	1.293	0.186
Bitumen	4.4	18	0.115	1,142.73	1.549	0.258
Bitumen	4.4	20	0.160	1,588.19	1.720	0.304

samples shattered when the dropping angle was set at 20° (see Figure 3.4.34). From the response data, it can be found that the bitumen samples with a cross section of 0.64 cm x 0.64 cm (1/4" x 1/4") broke to half at the energy level of 0.622 N-M when tested at 24.4° C (76°F) and they shattered at the energy level of 0.160 N-M when tested at 4.4°C (40°F). The energy level of breakage of bitumen sample at 4.4°C (40°F) is only about one quarter of that at 24.4°C (76°F).

3. For the Hitack 2 adhesive, when tested at room temperature at the dropping angle of 40°, the sample did not break but only deformed leaving about 0.08 cm (1/32") deep rut at the hitting line. At low temperature, when the pendulum was dropped at 20°, the deformation was barely noticeable (see Figure 3.4.35). Though the deformation increased with dropping angle, the sample did not break in any cases even at the highest energy level of 2.6 N-M (90° dropping angle). The deformation of all the samples were not permanent and can be shaped back. At same dropping angle, Hitack 2 samples at low temperature appeared less deformed than they were at room temperature. This may indicate that this kind of cold applied adhesive has better performance at low temperature due to its higher resistance to deformation.

<u>Summary</u>

The results from the shear impact test show that under dynamic (impact) loading condition, bituminous adhesive fails in the form of fracture or shattering at certain impact energy levels. However, these kind of failure did not occur on butyl adhesive. It was also found from the test that the temperature has significant effect on the performance of the adhesives especially bitumen. At low temperature, bitumen samples failed at lower impact energy level than they did at room temperature due to their low temperature stiffness /brittleness. This may imply that the bituminous adhesive is likely to fracture or shatter during cold weather. On the other hand, the strength of Hitack 2 enhances as the temperature decreases due to its low temperature hardness.

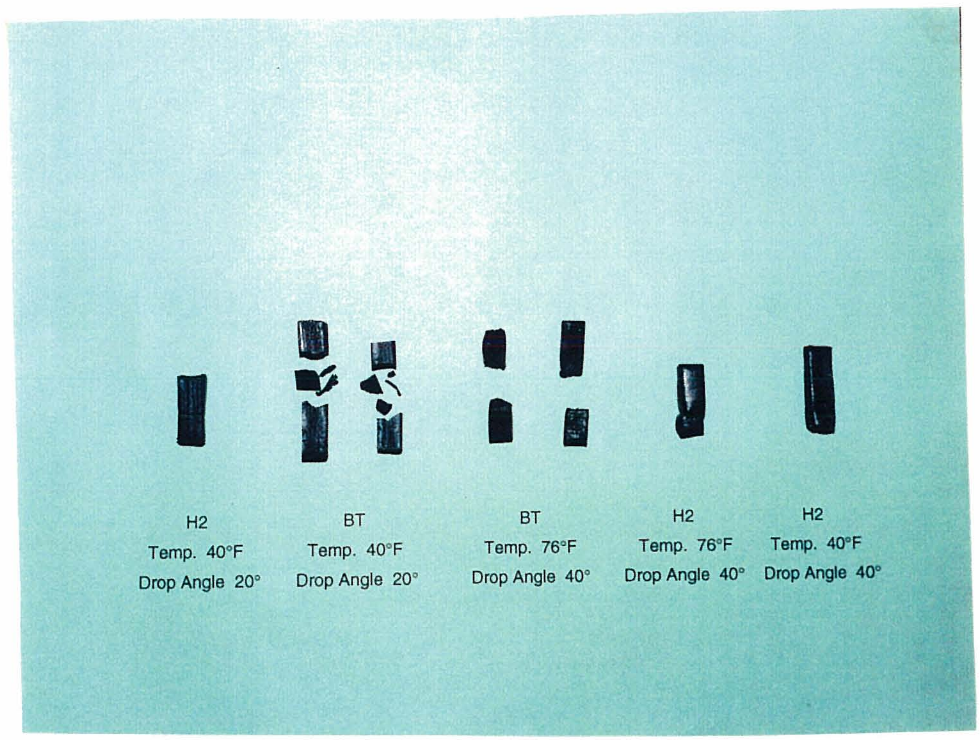


Figure 3.4.35 Specimens after shear impact.

3.4.3 Result from field evaluation

The markers with cold-applied adhesives placed on northbound of I-710 were examined monthly after the installation on July 18, 1993, with an exception of November. An additional observation was made two weeks after the placement. The final field evaluation with traffic control (lane closure) was not conducted in January, 1994 as scheduled due to the earthquake in Los Angles area. The final results summarized in Table 3.4.6, were based on the observation from slowly moving vehicle or road-side.

Table 3.4.6 Field results 6 month after installation

Adhesive	Total # of markers	Missing markers	Broken markers	marker Rotation	Ave. Creep
H3, primer	15	0	2	4 at 10 -15°	2.5 -3.8 cm
H3, no primer	10	2	1	1 at 10 -15°	1.3 - 2.5 cm
HB, primer	8	6	2	1 at 30°	2.5 - 3.8 cm
HB, no primer	7	3	3	none	2.5 cm
Bitumen, 66GB	100	>10	?	?	?

All markers retained with no noticeable creep and rotation after two-month exposure to the traffic. At third monthly observation, four markers were found missing and markers started to creep and rotate. At one observation, one pad was noticed to allow the mark to move and re attach itself a few inches from the initial point of installation. Little remaining adhesive material was found at the spots where the markers were missing and no intact missing marker was found in the area. It is not clear how markers were missing. Since there is high marker breakage (with bituminous adhesive or epoxy) in this portion of the highway due to high volume of heavy truck, it is likely that markers were cracked, broken and then removed by vehicle portion by portion till they are all gone. The adhesive pad was then subjected to tire impact directly and gone with the tire.

With limited amount markers tested, two out of twenty-five markers (accounting for 8%) adhered with Hitack 3 within six months. The marker breakage was 12%. It seems that the main problems of Hitack 3 were creep and rotation. All marker creep was found in the direction of traffic and marker rotation appeared to be in both direction depending on traffic merge. Although two markers without primer applied were missing while none was missing when primer was used, markers appeared to have higher creep and rotation with primer than they did without primer. However, no statistically conclusion on effect on primer on field performance of adhesive can be drawn due to very limited sample population.

The performance of Hitack B was very poor as predicted. Nine out of fifteen markers were missing which account for 60% and marker breakage was 33.3%. It is interesting that the creep of Hitack B without primer was a two-way creep. This is possible due to its lower shear modulus and high elastic recovery characteristics.

Six other types of long-term temporary markers were evaluated at the same location and installation period as our samples by Caltrans. Since final review was not conducted due to the heavy load of road construction on district crews after the earthquake, no detailed results were available on those markers at the time this report is due. However, the video tape taken from a moving vehicle shows that a number of other types of markers, including Stimsonite 66GB that were adhered with bitumen adhesive, were missing due to a very harsh roadway environment.

Chapter 4
Summary

4.0 INTRODUCTION

This report investigates new adhesive processes for the automatic RPMM as alternatives to the existing on-road bituminous adhesive bulk melting method. The investigation has been directed to two areas, i.e., localized fast heating technologies and cold applied materials, which are summarized in the following sections.

4.1 FAST HEATING TECHNOLOGIES

Three localized fast heating technologies, namely, resistance heating, induction heating and pyrotechnic heating, were studied in this work.

The investigation revealed that induction heating method is a promising alternative for bulk heated bituminous adhesive for the automated RPMM. The formulated adhesive mixture was melted within 1.5 seconds and good bonding was achieved with the strength equivalent to that of the bulk heated bitumen. It is with little doubt that the heat cycle can be further reduced as well as the adhesion improved. Further investigation on induction heating in strongly recommended. Suggestions for the further study was made to optimize the formula of adhesive mixture, electrical and geometric parameters of the apparatus to further reduce the heat cycle as well as to improve the adhesion of the inductively heated bituminous adhesive. Evaluation of the physical and thermal properties of the optimized bitumen-iron powder mixture and its overall performance should be included in the extended work. A study on the economic feasibility of this method is necessary before the final recommendation of applying this method is made. It is also suggested that prior to integrating this technology into the automatic RPMM, an induction heating prototype or test bed with a road surface simulator needs to be developed.

Pyrotechnic heating method, though the bonding strength was found to be poor due to ash layers formed at both bonding interfaces, appears attractive for its low cost and simplicity. In addition, the firing technology developed for deflagrating the fuel has been proven to be effective and safe. Searching a proper fuel type material which produces minimum ash will be the main task for the further study. It is predicted that should ash problem be solved, pyrotechnic will be the most effective heating method for marker adhesive to be applied on the automated RPMM.

The resistance heating method was concluded to be unsuitable approach due to poor thermal conductivity of bituminous adhesive and the complexity of adhesive pad preparation.

4.2 COLD APPLIED ADHESIVE

In this investigation, the feasibility of cold applied adhesives as an alternative of currently used bituminous adhesive was studied. The study was directed into three categories: basic characteristics of the butyl based adhesives, the factors effect their bonding strength and field performance of selected adhesives.

The basic strength tests, including slant shear, shear and tensile strength, indicate that the strength of butyl-based adhesives vary from product to product significantly. The difference was over 10 times for the extreme cases. Although Hitack B topped the rest with its shear strength, its low shear modulus and its rapid deterioration of adhesion at the interface greatly affect its performance. Hitack 2 and Hitack 3 were considered the best among the materials under this investigation.

The installation conditions (force and time applied), the substrates (concrete or asphalt surfaces)and adhesive exposure time prior to installation were all found to have little effect on shear strength. Slightly effect of marker bottom texture resulted. The strength with rough marker bottom was nearly 10% higher than that with smooth marker bottom.

Although primer is generally required when butyl pads are applied on concrete or not-newly constructed asphalt pavement as surface conditioner, the results from the laboratory tests revealed the negative effect of primer on shear strength. Primer intended to reduce the strength for all the adhesives tested. It also altered the failure occurrence from the marker-adhesive interface to substrate-adhesive interface where primer being applied. This reduction was more pronounced on the concrete surface. Primer was also found to intend to increase marker creep and rotation in the field test.

The shear and tensile strength of cold applied adhesive was found far too low in comparison with that of bitumen adhesive. The average maximum shear strength of Hitack 2 is only one quarter and the apparent shear modulus is merely 1/5 of that of bitumen adhesive. This insufficient bonding strength greatly affects its roadway performance as revealed in the field evaluation. All the markers adhered with Hitack 3 had an average 2.5 cm creep and 20 % of the markers were found to rotate at 10 - 15° six months after installation.

However, the results from temperature and impact tests indicate that the butyl-based adhesive has favorite temperature characteristics over bituminous adhesive. Bitumen adhesive was found to be more susceptible to temperature than the butyl pads. Its strength decreased sharply as temperature increases. Although its shear strength is much higher than butyl pads at room temperature, bitumen lost nearly 90% of it when temperature increase from 21.1°C to 37.8°C and its strength was nearly the same level of Hitack 2. The shear impact test revealed that bitumen appeared to have lower impact strength than Hitack 2. Under dynamic loading condition, bitumen adhesive failed in the form of fracture of shatter, which did not occur to butyl pads. At low temperature, it failed at lower impact energy level due to its low temperature stiffness or brittleness. While the strength of Hitack 2, on the other hand, enhanced as the temperature decreased due to its low temperature hardness.

The cold applied adhesives under this investigation may provide less populated areas with sufficient lane division but are not well suited for permanent marker application in heavy traffic areas. However, the cold applied adhesive is the most favorable alternative to the hot melt bitumen if an appropriate material can be developed. Efforts need to be made to further improve both the material strength and bonding interface strength of this butyl-based adhesive or to search for other materials in order to implant the concept of cold applied marker adhesive into the automation of raised pavement marker placement.

4.3 TESTING TECHNOLOGIES DEVELOPED

In addition to the standard tests currently used by Caltrans, an effort was made in this research to look insight into material visco-elastic property data which can be related to performance. The testing methods were developed in attempt to be performance related as well as to yield fundamental material property data. These methods include the shear strength, tensile strength, impact and creep tests as well as the temperature and loading rate tests.

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APPENDIX A1

Physical and Thermal Properties of bituminous marker adhesive

(containing 35% of asphalt and 65% of calcium carbonate filler)

Specific Gravity:	$S_g = 1.7 - 1.89$	
Density	1700 - 1890 kg/m^3	
specific Heat	$C = 0.253 + 0.0001965T$	Cal-g/g /°C
	$C_{204°C} = 0.331$ Cal-g/g /°C	
	$C_{21°C} = 0.267$ Cal-g/g /°C	
Heat content	$H = -5.0996 + 1.2507\ T$ kJ	
	$H_{204\ °C} = 252.7$ kJ	
	$H_{21\ °C} = 22.7$ kJ	
Heat conductivity	$K_{ave.} = 1.72$ w /m. °k	
Flash point:	287.8 °C (550°F) min.	
Softening Point	93.3 °C (200°F) min.	
Viscosity at 204 °C (400°F):	3000 - 6000 cps	
Penetration at 25 °C (77°F):	10 - 20 dmm	

APPENDIX A2

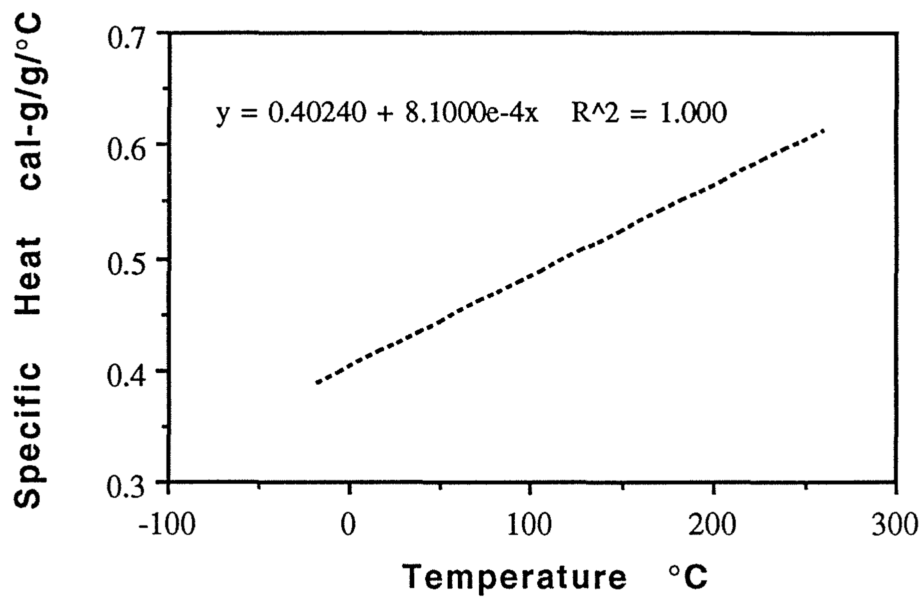
Specific heat of bitumen adhesive containing 35% asphalt and 65% of filler

Temperarure °C	C_a, Cal-g/g/°C	C_f, Cal-g/g/°C	C_m, Cal-g/g/°C
-17.8	0.388	0.180	0.253
-6.7	0.397	0.181	0.257
4.4	0.406	0.182	0.261
15.6	0.415	0.184	0.265
26.7	0.424	0.185	0.269
37.8	0.433	0.186	0.272
48.9	0.442	0.187	0.276
60.0	0.451	0.188	0.280
71.1	0.46	0.190	0.284
82.2	0.469	0.191	0.288
93.3	0.478	0.192	0.292
104.4	0.487	0.193	0.296
115.6	0.496	0.194	0.300
126.7	0.505	0.196	0.304
137.8	0.514	0.197	0.308
148.9	0.523	0.198	0.312
160.0	0.532	0.199	0.316
171.1	0.541	0.200	0.320
182.2	0.55	0.202	0.324
193.3	0.559	0.203	0.327
204.4	0.568	0.204	0.331
215.6	0.577	0.205	0.335
226.7	0.586	0.206	0.339
237.8	0.595	0.208	0.343
248.9	0.604	0.209	0.347
260.0	0.613	0.210	0.351

C_a - Specific heat of asphalt

C_f - Specific heat of filler

C_m - Specific heat of bitumen adhesive

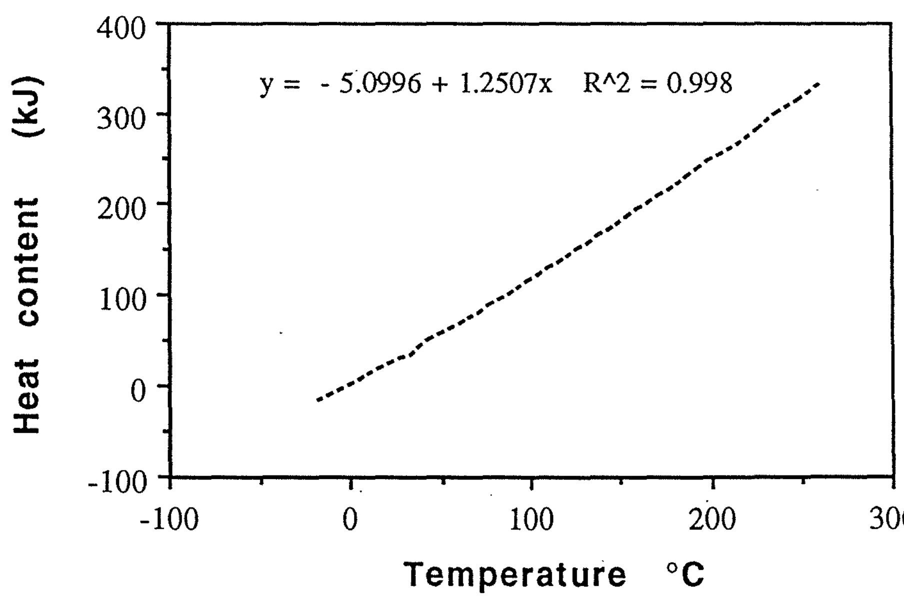


Specific Heat cal-g/g/°C
0.7
0.6
0.5
0.4
0.3
y = 0.40240 + 8.1000e-4x R^2 = 1.000
-100
0
100
200
300
Temperature °C

APPENDIX A3

Heat content of bitumen adhesive containing 65% calcium carbonate filler

Temperature °C	Heat Content kJ
-17.8	-18.0
-12.2	-12.2
-6.7	-7.0
-1.1	0.0
4.4	4.6
10.0	11.0
15.6	17.4
21.1	22.7
26.7	29.1
32.2	33.1
37.8	42.4
43.3	48.8
48.9	55.2
54.4	62.2
60.0	66.8
65.6	73.8
71.1	80.2
76.7	87.2
82.2	93.5
87.8	99.9
93.3	106.9
98.9	115.0
104.4	122.0
110.0	128.4
115.6	135.4
121.1	141.8
126.7	148.7
132.2	155.7
137.8	163.8
143.3	170.8
148.9	177.2
154.4	184.2
160.0	192.9
165.6	199.3
171.1	208.0
176.7	215.0
182.2	221.9
187.8	230.1
193.3	237.0
198.9	245.8
204.4	252.7
215.6	266.1
226.7	283.5
237.8	298.6
248.9	314.9
260.0	331.8



METHODS FOR TESTING ADHESIVES FOR RAISED PAVEMENT MARKERS

A. SCOPE

The procedures used for testing adhesives for raised pavement markers are described in this test method.

This test method is divided into the following parts:

Part I. Slant Shear Tests
Part II. Shear Tests
Part III. Shear Tests
Part IV. Elastic Recovery Test
Part V. Impact Test

PART I. SLANT SHEAR TESTS

A. MATERIALS

Portland concrete blocks. Each diagonal concrete mortar block has a square base with 5.1 cm (2 in) sides and having one diagonal face 5.1 cm x 10.2 cm (2" x 4") starting about 1.9 cm (3/4 in) above the base. The diagonal faces of two such blocks are bonded together, producing a block of dimensions 5.1cm by 5.1 cm by 12.7 cm (2" x 2" x 5"). The blocks are made according to California Test 425, 1978 part IX, Section B consisting of 64.04% of Ottawa sand, ASTM C109, 25.75% of Portland cement Type II and 10.21% of water by weight.

Cure blocks 28 days in a fog room to obtain full strength.

B. APPARATUS

1. Teflon pot and hot plate (for heating bitumen adhesive)
2. Sand blaster
3. Air hose/compressor
4. Clean rags
5. Utility knife
6. Spacers (for controlling thickness of hot applied adhesives)
7. Slant shear fixture
8. Hydraulic press
9. Instron testing machine
10. Computer and printer

C. SAMPLE PREPARATION

1. Lightly sandblast the diagonal faces of the blocks and remove loose particles with compressed air.
2. Cold applied adhesive without primer:
   a. Cut a piece of cold applied adhesive pad measuring 5.1 cm by 10.2 cm (2" x 4").
   b. Place the pad of the diagonal face of the first block, press the pad by hand and seat the block in the fixture with its base against one of the fixture walls.
   c. Peal the release paper, place the second block on the pad with its base against another wall of the fixture and align the two blocks.
   d. Apply installation force with a hydraulic press according to manufacturer's requirements. Calculate the force applied using the following formula:

   $$F_s = F_m / 2\cos 30°$$

   Where
   F_m is required force for a reflective marker by manufacturer,
   F_s is the installation force for slant blocks.
   e. Cut off excess material.

3. Cold applied adhesive with primer:
   a. Coat bonding surfaces with primer. Wait for at least 60 seconds to allow primer to dry.
   b. Follow same procedures in Section C.2 in Part I.

4. Bituminous adhesives:
   a. Heat adhesive to melting temperature (193 - 204 °C). Stir frequently if there is no agitator. Avoid over heating.
   b. Preheat the blocks if necessary in cold weather.
   c. Place one slant block in the fixture (see fig.) so that bonding surface rests horizontally and pour hot melt adhesive on.
   d. Put 1/8" spacers in place. Pour hot adhesive onto the bonding surface. place second block bonding side down on the adhesive. Press and align the blocks by hand before the adhesive cools down.
   e. Trim off excess adhesive. Keep the samples in room temperature for 24 hours prior to test.

5. Samples for temperature test: Selected temperatures are: 10, 21.1, 37.8, 48.9 and 60°C.
   a. 10°C test - Place samples in a temperature controlled refrigerator for 24 hours.
   b. 21.1°C test - Keep samples at room temperature.
   c. 37.8°C, 48.9°C and 60°C tests - Heat the samples in a thermostatically controlled oven for 6 hours.
   d. Test the samples immediately and check the sample temperature with a thermal couple prior to test.

D. TEST PROCEDURE

1. Record the room temperature.
2. Place a specimen on the base plate upright of the Instron testing machine with its diagonal bonding line face the operator.
3. Operate the Instron machine according to "Instron 4204 Operating Instruction" (Appendix).
4. Choose "Compression" test program on the computer, and set the program parameters according to program guidelines.
5. Choose 2.0 cm/min. as the loading rate for all tests except loading rate tests.
6. Choose 2.0, 4.8, 7.6 and 12.7 cm/min. for the loading test. Conduct the loading test at room temperature.
7. Save all data to disc, print the test reports and graphs.

PART II. TENSILE TESTS

A. MATERIALS

1. Pavement markers.
2. Five cm (2") diameter aluminum pipe caps.

B. APPARATUS

1. Teflon pot and hot plate (for heating bitumen adhesive)
2. Sand blaster
3. Air hose/compressor
4. Clean rags
5. Utility knife
6. Spacers (for controlling thickness of hot applied adhesives)
7. Tensile test fixture
8. Hydraulic press
9. Instron testing machine
10. Computer and printer

C. SETUP PROCEDURE

1. All pipe caps are sandblasted, air hosed to remove loose sand particles.

2. Cold applied adhesive without primer:
   a. Cut a 5 cm by 5 cm (2" x 2") cold applied adhesive pad, and then place the pad, centered, on the bottom of a pavement marker.
   b. Peel the release paper, firmly press the base of the pipe cap onto the pad. Apply additional pressure according to the manufacturer's requirements with a hydraulic press.
   c. Cut off excess cold applied adhesive.

3. Cold applied adhesive with primer:

a. Coat base of pipe caps with primer. Wait for at least 60 seconds for primer to dry.
b. Follow same procedures as for C.2 in Part III.

4. Hot applied adhesive:
  a. Heat adhesive to melting temperature (193 - 204 °C). Stir frequently if there is no agitator. Avoid over heating.
  b. Preheat the pipe caps if necessary in cold weather.
  c. Pour melted adhesive onto the center of the bottom of a pavement marker. Place the base of a pipe cap onto the center of the adhesive. Apply even pressure on the pipe cap until the adhesive begins to solidify. The final adhesive thickness is 1/8".
  d. Trim off excess hot applied adhesive. Keep at room temperature for 24 hours.

D. TEST PROCEDURES

1. Record the room temperature.
2. Assemble testing fixture on the Instron machine.
3. Operate the Instron machine according to "Instron 4204 Operating Instruction" (Appendix -).
4. Choose "Tensile" test program on the computer, and set the program parameters according to program guidelines.
5. Choose 2.0 cm/min. as the loading rate for all tests.
6. Save all data to disc, print the test reports and graphs.

PART III. SHEAR TESTS

A. MATERIALS

1. Road Markers
2. Concrete Blocks (3.5"x3.5"x9")
3. Asphalt Blocks (3"x3"x5.5")

B. APPARATUS

1. Teflon pot and hot plate (for heating bitumen adhesive)
2. Sand blaster
3. Air hose/compressor
4. Utility knife
5. Pad installation guide
6. Shear test fixture
7. Hydraulic press
8. Instron testing machine
9. Computer and printer

C. SETUP PROCEDURE

1. Clean Blocks. Use a wire brush. Blow loose dirt off with an air compressor.

2. Apply primer to appropriate samples, using manufacturer's instructions for application procedures.

3. Cold applied adhesives:
  a. Cut adhesive pads to the outer dimensions of the markers. Adhere markers to the pads by hand. Limit the pad exposure to the air according to 15 seconds.
  b. Peel the release paper and adhere marker/pad to the block using the installation guide to ensure proper alignment of the marker/pad unit. Install two markers symmetrically on one block.
  c. Apply installation force using a hydraulic press according to manufacturers' requirements.

4. Hot applied adhesives:
  a. Heat adhesive to melting temperature (193 - 204 °C). Stir frequently if there is no agitator. Avoid over heating.
  b. Use the test fixture for alignment. Pour the hot adhesive onto the marker. Immediately place the block onto the exposed adhesive and align correctly in the test fixture. Apply approximately 25 lbs. for 30 sec., creating a thickness of 1/8". Trim edges.
  c. Repeat for the other side of the block.

D. TEST PROCEDURE

1. Record the room temperature.
2. Place a specimen on the base plate upright of the Instron testing machine with two markers face the sides. Place the shear test fixture on the specimen.
3. Operate the Instron machine according to "Instron 4204 Operating Instruction" (Appendix).
4. Choose "Compression" test program on the computer, and set the program parameters according to program guidelines. Set loading rate at 2.0 cm/min.
5. Save all data to disc, print the test reports and graphs.

PART IV. ELASTIC RECOVERY TEST

1. Follow the same procedures as in Part III (Shear Test)
2. Record the initial deformation (d) of the specimen immediately upon the completion of the shear test on Instron. Wait for a certain time period, measure the deformation (d1).
3. Calculate the elastic recovery using the following formula:

$$R = \left(\frac{d - d1}{d}\right) x \%$$

PART V. IMPACT TEST

A. APPARATUS

1. Teflon pot and hot plate (for heating bitumen adhesive)
2. Utility knife
3. Impact test fixture
4. Impact testing machine
5. Digital oscilloscope
6. Light weight accelerometer
7. Lowpass filter
8. IBM pc computer

B. SETUP PROCEDURE

1. Heat bituminous adhesive as described in Section 4a, Part I.
2. Made both hot and cold applied adhesives into 0.62 cm x 0.62 cm x 2 cm specimens.
3. Divide the specimens into two groups. Keep one group at room temperature and the other in a refrigerator to 4.4°C.

C. TEST PROCEDURES

1. Place the specimen into the compartment of the fixture, tight the screw.
2. Set up the instrumentation as illustrated in Fig. 3.3.11 .
2. Operate the oscilloscope follow the operation instruction.
3. Set the pendulum at the designed position and release.
4. Record the deformation or failure of the specimen.
5. Save data to disc and analyze data using programs included in Appendix D on an IBM pc computer.

APPENDIX C

INSERTION 4204 OPERATING INSTRUCTIONS

The Instron testing machine is fully computer-controlled testing instruments that are capable of conducting a wide variety of mechanical properties measurements. The following procedures are for conducting shear and tensile tests of marker adhesives in which the load and crosshead displacement are measured.

Machine warm-up

The Instron machine should be allowed to warm up for approximately 30 minutes in order to ensure accurate readings.

Computer Set-up

To set-up the computer system for data acquisition and control, begin by turning on the monitor, computer and printer. At the prompt, enter the user name and the password. At this point, you should be at the main menu.

The test programs for testing marker adhesive were created prior to tests. The test programs specify test type, load and displacement limits, loading rate, sampling rate, parameter input method as well as report and plot formats.

Select "Test a Sample" by scrolling, then pressing <ENTER>. The following entries must then be made:

1. Operator name: Your name
2. Sample ID: Ex. H2-NP (for HiTack 2 with no primer applied)
3. Test type: [T]ension or [C]ompression
4. Test method: 99 if [T] was selected or 50 if [C] was selected

Calibration and specimen Installation

The testing machine must be calibrated prior to installing a specimen. This calibration is entirely electronic, and can be accomplished by following these steps:

1. Set the unit button on the back of the control console to "ENGLISH"
2. On the Instron control console, press "IEEE" to turn off computer control (red light off), press "Load Cal", then press [ENTER] when the console displays "10,000".

3. When the Load Cal light goes off, you may install a specimen with an appropriate fixture.

4. Move the crosshead using the jog keys to make a good contact between fixture and specimen testing surface.

5. Set the initial position of the crosshead by pressing the '"Gage Length" button on the machine console (with the IEEE light off). This will cause the gage length button to light, and all displacement measurements will be made with reference to this position.

6. Set the mechanical limit switches by moving the stops on the long bar on the left front of the machine. In general, the lower stop should be set to prevent any further downward travel of the crosshead from a maximum displacement designed from this initial position.

7. Press the "IEEE" button on the console to enable computer control of the testing machine.

Running a test

1. Press [T] (for test) to start a testing routine.

2. Follow the instruction on the screen (enter specimen dimensions and environment parameters if necessary)

3. Press enter when ready to start the test. During the test, data will be plotted on the screen. The test ends when the limit switch hits the stop or the displacement of the crosshead reaches pre-set limit on computer. Press <ESC> to terminate the test at any point if necessary.

4. Move the crosshead back to the starting position by pushing return button on the console (with IEEE light off) and remove the specimen

5. Press <ESC> to quit after the test has ended.

6. Follow the instructions on the screen to create the necessary test reports and data files.

Analysis of Test Data

1. To review the data as needed using the Re analysis option or the raw data routines. The former essentially recreates the same display as seen during the actual test. The raw data p[options enable the user to scale a plot properly for nest appearance and to create an ASCII data file that can be read by a variety of spreadsheet and plotting programs for further analysis.

2. To create a plot of the test data, select "Plot Raw Data" from the main menu. Enter the Sample ID, then work through the options list to set - up the plot. Display the plot on the screen to adjust if necessary. Chose "Graphic Printer" as the display device to get a hard copy.

3. To create an ASCII data file on a floppy disc, select the "Utilities" option from the main menu, then:

- Select "Display Raw Data".
- Select "Dump to [A]SCII File.
- Make through selections on the screen
- The file name will be [Sample ID].MAD

APPENDIX D1

Impact Program 1

```
2  ********************************************************************  *
4  * THIS PROGRAM IS TO RETREIVE, DISPLAY AND STORE THE IMPACT           *
6  * RESPONSE DATA FROM A TEKTRONIX 2230 OSCILLOSCOPE                    *
7  *                                              SONJA SUN 9/14/93      *
8  * ********************************************************************  *

10  CLS:LOCATE 10,10:PRINT "PREPARE SCOPE AND PRESS ANY KEY WHEN
    READY"
20  KEY 1,"LC"+CHR$(27):KEY 2,"LC"+CHR$(26):KEY 3,"   ":KEY 4,"   ":KEY
    5,"NEW":KEY 6,"STO":KEY 7,"   ":KEY 8,"   ":KEY 9,"RC"+CHR$(27):KEY
    10,"RC"+CHR$(26)
30  A$=INPUT$(1):DIM D%(8,64)
40  OPEN "COM1:2400,N,8,2" AS 1
50  PRINT#1,"CH1? VOL"+CHR$(13);
60  FOR I=1 TO 500:IF LOC(1)>0 THEN 90  ELSE NEXT I
70  BEEP:PRINT:PRINT "SCOPE NOT RESPONDING--CHECK CONNECTIONS AND
    PRESS ANY KEY TO TRY AGAIN"
80  A$=INPUT$(1):GOTO 50
90  INPUT#1,S$:IF LEFT$(S$,3)="CH1" THEN 170
100 FOR I=1 TO 100:NEXT I
110 CLOSE:GOTO 40
170 PLAY "T600O4L8O3GL16GL8O4C"
171 CLS:LOCATE 10,1:INPUT "ENTER DATA FILE NAME ",FINAM$
180 OPEN FINAM$ AS 2:IF LOF(2)=0 THEN CLS:PRINT:GOTO 195
190 CLOSE 2:PRINT:PRINT """;FINAM$;:INPUT """ ALREADY EXISTS--CHOOSE
    ANOTHER FILE NAME ",FINAM$:GOTO 180
195 CLOSE 2:KILL FINAM$:OPEN FINAM$ FOR OUTPUT AS 2
200 LOCATE 10,1:PRINT "ENTER REFERENCE MEMORY YOU WISH TO TRANSFER
    (1,2,or 3)         "
210 PRINT "(PRESS 'ESC' TO EXIT)":R$=INPUT$(1):IF R$=CHR$(27) THEN 1010
215 R1$=INPUT$(1):IF R1$<>CHR$(13) THEN BEEP:CLS:GOTO 200
220 IF R$="1" OR R$="2" OR R$="3" THEN 230 ELSE BEEP:GOTO 200
```

```
230 PRINT#1,"DAT SOU:REF"+R$+CHR$(13);:INPUT#1,A$:IF LEN (A$)><6 THEN 230
235 PRINT:INPUT "DROP HEIGHT (cm)";DH
250 CLS:LOCATE 10,10:PRINT "PRESS ANY KEY TO TRANSFER DATA"
260 A$=INPUT$(1)
270 PRINT#1,"WFM? YMU"+CHR$(13);:INPUT#1,VERT$
271 VRT=VAL(MID$(VERT$,14,7))
280 PRINT#1,"WFM? XIN"+CHR$(13);:INPUT#1,HORIZ$
281 HRZ=VAL(MID$(HORIZ$,14,7))
290 PRINT#1,"WFM? NR.P"+CHR$(13);:INPUT#1,PT$
320 XOFS=100:YOFS=20:GOSUB 1050
350 PRINT#1,"CURVE?"+CHR$(13);:A$=INPUT$(9,1)
360 FOR I=1 TO 8:D$(I)=INPUT$(128,1):NEXT
370 PSET (XOFS,YOFS+ASC(MID$(D$(1),1,1))/2)
380 FOR V=1 TO 8
390 FOR I=2 TO 128 STEP 2
400 D%(V,I/2)=ASC(MID$(D$(V),I,1))
410 LINE -(XOFS+64*(V-1)+I/2,YOFS+128-(D%(V,I/2)/2)/.8)
420 NEXT I
430 NEXT V
440 LOCATE 23,1:PRINT "LEFT CURSOR";:LOCATE 23,64:PRINT "RIGHT
    CURSOR";:LOCATE 1,1
450  LOCATE 24,1:PRINT "---- ------";:LOCATE 24,64:PRINT "----- ------";:LOCATE 1,1
460 CVAL=D%(1,1)
470 FOR V=1 TO 8
480 FOR I=1 TO 60 STEP 4
490 IF ABS(D%(V,I+4)-CVAL)>5 THEN 520 ELSE
500 NEXT I
510 NEXT V
520 IF I<5 THEN I=64+I:V=V-1
530 LCSR=(V-1)*64+I-4
540 LINE (XOFS+LCSR,YOFS+68)-(XOFS+LCSR+5,YOFS+78)
550 LINE -(XOFS+LCSR-5,YOFS+78)
560 LINE -(XOFS+LCSR,YOFS+68)
570 CVAL=D%(8,64)
580 FOR U=8 TO 1 STEP -1
590 FOR J=64 TO 4 STEP -4
```

```
600  IF ABS(D%(U,J-3)-CVAL)>3 THEN 630
610  NEXT J
620  NEXT U
630  IF J>60 THEN J=J-64:U=U+1
640  RCSR=(U-1)*64+J+4
650  LINE (XOFS+RCSR,YOFS+68)-(XOFS+RCSR+5,YOFS+78)
660  LINE -(XOFS+RCSR-5,YOFS+78)
670  LINE -(XOFS+RCSR,YOFS+68)
680  CVAL=D%(8,64)

690  LOCATE 21,1:PRINT "USE FUNCTION KEYS TO MOVE CURSORS,GET A NEW
     WAVEFORM, OR STORE THIS WAVEFORM";
700  LOCATE 3,43:PRINT (RCSR-LCSR)*2;:A$=INPUT$(3)
710  IF A$="STO" THEN 830
720  IF A$="LC"+CHR$(27) THEN 770
730  IF A$="LC"+CHR$(26) THEN 780
740  IF A$="RC"+CHR$(27) THEN 790
750  IF A$="RC"+CHR$(26) THEN 800
760  IF A$="NEW" THEN 810
762  FOR I=1 TO 100:NEXT
764  A$=INKEY$
766  IF A$="" THEN 700 ELSE 764
770  CSR=LCSR:CSRMOV=-1:LCSR=LCSR-1:GOSUB 1180:GOTO 700
780  CSR=LCSR:CSRMOV=1:LCSR=LCSR+1:GOSUB 1180:GOTO 700
790  CSR=RCSR:CSRMOV=-1:RCSR=RCSR-1:GOSUB 1180:GOTO 700
800  CSR=RCSR:CSRMOV=1:RCSR=RCSR+1:GOSUB 1180:GOTO 700
810  SCREEN 0:GOTO 200
830  LCSR=LCSR*2:RCSR=RCSR*2:NPTS=RCSR-LCSR
840  PRINT#2,DH;VRT*1000;HRZ*1000000!;NPTS;
850  V=LCSR\128+1:I=LCSR MOD 128:IF I=0 THEN I=128:V=V-1
860  FOR J=1 TO NPTS
870  IF I>128 THEN I=1:V=V+1
880  PRINT#2,ASC(MID$(D$(V),I,1));
890  I=I+1
900  NEXT J
970  CLOSE 2
```

```
980  SCREEN 0:LOCATE 10,1:PRINT "DO YOU WANT TO OPEN A NEW FILE?
     (Y OR N)"
990  A$=INPUT$(1):IF A$="Y" THEN 170
1000 IF A$<>"N" THEN BEEP:GOTO 980
1010 CLOSE:END
1020 PRINT "PRESS THE SPACE BAR TO CONTINUE OR PRESS 'ESC' TO EXIT"
1030 A$=INPUT$(1):IF A$=CHR$(32) THEN 200
1040 IF A$=CHR$(27) THEN 1010 ELSE 1030
1050 SCREEN 2:CLS
1060 LINE (XOFS,YOFS)-(XOFS+512,YOFS+128),,B
1070 FOR I=1 TO 49
1080 X=XOFS+512*I/50
1090 IF I MOD 5=0 THEN LINE (X,YOFS+128)-(X,YOFS) ELSE LINE (X,YOFS+66)-
       (X,YOFS+62)
1100 NEXT I
1110 FOR I=1 TO 39
1120 Y=YOFS+128*I/40
1130 IF I MOD 5=0 THEN LINE (XOFS+512,Y)-(XOFS,Y) ELSE LINE (XOFS+253,Y)-
       (XOFS+259,Y)
1140 NEXT I
1150 LOCATE 11,2:PRINT VRT*25;"V/DIV"
1151 LOCATE 20,40:PRINT HRZ*100;"SEC/DIV"
1160 LOCATE 1,43:PRINT FINAM$
1170 RETURN
1180 LINE (XOFS+CSR,YOFS+68)-(XOFS+CSR+5,YOFS+78),0
1190 LINE -(XOFS+CSR-5,YOFS+78),0
1200 LINE -(XOFS+CSR,YOFS+68),0
1210 CSR=CSR+CSRMOV
1220 LINE (XOFS+CSR,YOFS+68)-(XOFS+CSR+5,YOFS+78)
1230 LINE -(XOFS+CSR-5,YOFS+78)
1240 LINE -(XOFS+CSR,YOFS+68)
1250 RETURN
```

APPENDIX D2

Impact Program 2

```
5    * ******************************************************************* *
10   *  THIS PROGRAM IS FOR READING IMPACT TESTING DATA OF A              *
20   *  GIVEN ADHESIVE SAMPLE FROM AN IMPACT OUTPUT FILE AND              *
25   *  CALCULATINGIMPACT PAREMETERS WHICH WILL BE SAVED IN               *
30   *  DISKETT FOR SPREAD SHEET APPLICATION.      SONJA SUN  9/15/93     *
40   * ******************************************************************* *

50   DIM AA(1000), W(1000), FI(1000)
60   INPUT "ENTER INPUT FILEMANE"; FILE$
70   OPEN FILE$ FOR INPUT AS #3
80   SCREEN 2: SCREEN 0, 0, 0
90   INPUT #3, a, B, C, N
100  FOR I = 1 TO N
110  INPUT #3, AA(I)
120  NEXT
130  PRINT a, B, C, N
140  FOR I = 1 TO N: PRINT AA(I); : NEXT
150  DA = a * 3.1416 / 180: DT = C / 1000000#: S = N
160  PRINT DA
170  GOSUB 970
180  CAL = 10.13
190  R = .18
200  Q = .4
210  RQ = R * Q
220  G = 9.810001
230
240  A1 = AA(1)
250  FOR I = 1 TO S
260  AA(I) = (AA(I) - A1) * B / CAL
270  NEXT
280  FOR I = 1 TO S: PRINT AA(I); : NEXT: PRINT " "
290
300  MASS = 1.51
```

```
310  MM = MASS * RQ
320 REM ** W(1)= INITIAL ANGULAR VELOCITY IN 1/S ***
330 W(1) = SQR(2 * 9.810001 * (1 - COS(DA)) / Q)
555 W1 = W(1)
560 GOSUB 810
570 GOSUB 910
80  GOSUB 740
590 STOP

600 GOSUB 2000
605 PRINT "EIN"; EIN: PRINT "EAB"; EAB
610 LOCATE 20, 20
690 PRINT "AMAX,W1,W2,FIMAX,a"; AMAX, W1, W2, FIMAX, a
720 END

730 '  SUBROUTINE FOR CALCULATING ABSORBED ENERGY
740 EAB = 0
750 FOR I = 1 TO IEND
760 EAB = EAB + (FI(I) - FI(I - 1)) * (AA(I) + AA(I - 1)) / 2
770 IF W(I - 1) > 0 AND W(I) < 0 THEN EIN = EAB
780 NEXT: EIN = EIN * G * MM / Q: EAB = EAB * G * MM / Q
790 RETURN
800 'SUBROUTINE FOR CALCULATING AMAX, TMAX, FIMAX
810 AMAX = 0
820 FIMAX = 0
830 FOR I = 1 TO S
840 W(I + 1) = W(I) - .5 * (AA(I) + AA(I + 1)) * DT * G / Q
850 FI(I + 1) = FI(I) + .5 * (W(I) + W(I + 1)) * DT
860 IF AA(I) > AMAX THEN AMAX = AA(I)
870 IF FI(I) > FIMAX THEN FIMAX = FI(I)
875 PRINT FI(I)
880 NEXT: AMAX = AMAX * G / Q: TMAX = AMAX * MM * G / Q:
890 RETURN

900 '  SUBROUTINE FOR CALCULATING W2, FIPER
910 W2 = W(I): FIPER = FI(I): IEND = I: IMPTIME = I * DT: GOTO 950
```

```
950  IMPTIME = IMPTIME * 1000
960  RETURN

970  ' SUBROUTINE FOR REMOVING UNWANTED POINT IN ACC CURVE
975  FLAG = 0
980  FOR I = 1 TO S
990  IF FLAG = 1 GOTO 1050
1000 IF AA(I) - AA(1) < 2 GOTO 1100
1010 IFIRST = I - 2
1020 FLAG = 1
1050 IF AA(I) <= AA(IFIRST) GOTO 1102
1100 NEXT
1102 ILAST = I
1110 S = ILAST - IFIRST + 1
1120 FOR I = 1 TO S
1130 AA(I) = AA(I + IFIRST - 1)
1140 NEXT
1150 RETURN

2000 ' SUBROUTINE FOR PLOTING ACC-,VEL-, AND DEF-CURVES
2010 SCREEN 1, 0: CLS
2012 X0 = 50: XEN = 250
2020 LINE (X0, 150)-(X0, 50)
2030 LINE (XEN, 150)-(X0, 150)
2040 COLOR 9, 1
2050 FOR I = 1 TO S
2060 X1 = (2 * I * 100 / S) + 50
2070 Y1 = -AA(I) + 150:
2080 LINE -(X1, Y1), 2
2085 NEXT
2090 LINE (50, -15 * W(1) + 150)-(50, -15 * W(1) + 150)
2100 FOR I = 1 TO S
2110 LINE -((2 * I * 100 / S + 50), (-15 * W(I) + 150)), 3: NEXT
2120 LINE (50, 150)-(50, 150)
2130 FOR I = 1 TO S
2140 LINE -((2 * I * 100 / S + 50), (-2000 * FI(I) + 150)), 1
```

```
2150 NEXT
2160 RETURN
```

APPENDIX E

I-710

Marker installation on ~~H-710~~

marker	Interval (ft)	marker	Interval (ft)
1		23	5
2	4	24	6
3	4	25	3
4	4	26	16
5	4	27	5
6	4	28	3
7	4	29	3
8	6	**30**	3
9	6	31	3
10	12	32	5
11	3	33	4
12	3	34	4
13	4	35	4
14	3	36	16
15	3	37	3
16	2	38	3
17	2	**39**	3
18	16	40	3
19	3	41	3
20	3	42	5
21	3	43	3
22	7	44	3

Note: Markers 5,16,30, and 39 were already down