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16. Abstract

This report summarizes the research results obtained from laboratory and field tests of spall repair materials. Repair materials tested included cement-based ready-mix materials, polymer-based materials, and concrete containing accelerating admixtures. Tests were conducted to measure time of setting, compressive and flexural strengths, fracture toughness, and bond shear strength between repair material and base concrete. These tests can be used to characterize spall repair materials. Researchers found that properties of the repair materials depend on the age and environmental factors. Spall repairs with these materials on concrete pavement were evaluated in the Houston area. Performance of repair patches depends on the strength, especially bond strength, developed at the time when the repaired road is open to traffic.

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INVESTIGATION OF SPALL REPAIR FOR CONCRETE PAVEMENT

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Research Report 2919-3
Research Study Number 7-2919
Study Title: Spall Repair, Base and Subgrade Stabilization, and
Non Destructive Test (NDT) Services for the Houston District, Phase II

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IMPLEMENTATION STATEMENT

This report presents several test methods for selecting materials for concrete pavement repair. With these test methods, spall repair materials can be well characterized. The tests used and developed include those for measuring time of setting, compressive strength, flexural strength, fracture toughness, and bond shear strength between repair material and base concrete. Change in these properties with age and environmental factors (temperature and relative humidity) is also reported. The methods presented can be used for different types of repair materials including cement-based ready-mix materials, polymer-based materials, and use of accelerating admixtures in repair concrete.

Researchers evaluated the use of these repair materials in spall repairs made in the Houston area. Development of damage in these repair patches was observed and is recorded in this report. Combining field observation of spall repair performance and laboratory test results, researchers found that bond strength between the repair material and base concrete is a very important factor for a durable spall repair. Bond shear strength can be obtained by testing a cylindrical slanting bond specimen in the laboratory or conducting a torsion test in the field.

Mechanical properties of repair materials develop quickly at early ages. Therefore, the proper time to open the spall repaired pavement to traffic depends on strength levels (i.e., bond strength level) developed at the time of opening. Researchers suggest using the concept of maturity to measure the age of cement-based repair materials.

This study was conducted for the Houston District, but many of the test data in the report are also useful to other districts. However, when planning to select repair materials, different tests may be required for the areas with environmental conditions different from the Houston area.

DISCLAIMER

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

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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SUMMARY

This report summarizes the investigation on spall repair for concrete pavement in the Houston area. The research focused on the behavior and performance of spall repair materials. The three types of repair materials studied included cement-based ready-mix materials, polymer-based materials, and concrete materials using accelerating admixtures. Since spalling is not just a long-term age-dependent phenomena, but caused by the initial cracking and delamination which are formed very early, properties of these repair materials at early ages were measured by a series of laboratory tests. These properties included time of setting, compressive strength, flexural strength, fracture toughness, and the bond strength between the repair material and base concrete. These tests distinguished between the repair materials very well and showed that they can be used in selecting repair materials.

For cement-based, rapid-setting repair materials, the evaluation of field spall repairs in the Houston area showed that repair material remained in the patch for a long time after small cracks on the patch surface occurred. Although these cracks may eventually cause failure of the repair patch, they did not adversely affect the performance of the spall repair. This indicates that bonding of the repair material to the base concrete is a very important factor for a durable patch. Evaluation of laboratory tests and field repairs showed that some polymer-based repair materials could provide good performance as spall repair patches because of their low modulus and sufficient bonding to base concrete.

This investigation used two methods to measure the bond shear strength, one for laboratory use - the cylindrical slanting bond specimen test, and the other for field use - the torsion test. Both methods provided satisfactory results. The bond shear strength increased with the age of the repair material. Different cement-based repair materials exhibited different rates of increase in bond shear strength. As tests showed, a repair material had higher ultimate strengths (including bond strength) than another repair material, but they might have similar strengths at an age of eight hours. The field evaluation of repairs showed that the two repair materials performed similarly. It indicated that the strength (including bond strength) of repair materials at the time when the repaired road was opened to traffic is a decisive factor for durable repair.

The effects of temperature, relative humidity, and curing methods on the strength (including bond strength) of repair materials were also investigated. The effects of saw cuts on the repair patch was also observed. All the data from tests and field surveys are reported.

CHAPTER 1: INTRODUCTION

This study investigated spall repairs on concrete pavement with an emphasis on the performance of repair materials. The investigation consisted of three phases: laboratory tests, field tests, and evaluation of spall repairs on actual concrete pavements in the Houston area. Laboratory tests were conducted in the concrete materials laboratory of the Texas Transportation Institute, College Station, Texas. Field tests were conducted on the Texas A&M University Riverside Campus, Bryan, Texas. Systematic monitoring of road spall repairs was conducted at two locations: the main lanes of Beltway 8 in north Houston, and the frontage road of Beltway 8 in west Houston. All the pavement sections at these places where spalls were repaired and evaluated came within the jurisdiction of the Houston District of the Texas Department of Transportation.

The Houston area is, generally speaking, a high traffic area. Spall repair of pavements in such an area poses a special problem: the need to install a durable patch with the least possible disruption of traffic. This need requires that repair materials set rapidly and obtain sufficient strength at early ages. The spall repair materials investigated in this study fall under three categories: rapid-setting cement-based materials, polymer-based materials, and concrete containing accelerating admixtures. All these materials are currently available. A basic objective for making spall repairs is for the repair material to remain in place for a certain period of time. Therefore, the field repairs were evaluated in terms of the mechanism of spalling.

Spalling is considered to be a distress in Portland cement concrete pavements where a visible surface distress is caused by pieces of concrete being dislodged from the surface of the pavement. Spalling generally occurs only at transverse cracks or joints in a concrete pavement. It is a form of distress which is common to both continuously reinforced concrete pavements (CRCP) and jointed concrete pavements (JCP). Spalling results in a rough ride, and also gives the traveling public a negative perception of the integrity of the pavement. From a technical standpoint, loss of concrete due to spalling may lower the load transfer efficiency across the transverse random cracks (in CRCP) or joints (in JCP). A reduction in load transfer efficiency will increase the stress level due to traffic loading in the pavement and will eventually lead to more severe forms of distresss such as punchouts in CRCP and joint faulting in JCP.

It has been suggested in previous research that the formation of spalls occurs due to temperature induced stresses, as well as stresses caused by freeze-thaw of the concrete pavement. When temperature in the pavement increases, the concrete expands. Unless there is room for this expansion, stresses will develop in the pavement depending on the level of restraint present for the expansion. In the absence of any restraint, no stresses will develop; however, if there is full restraint which prevents the pavement from expanding, the maximum level of stress will develop. It has been argued that when debris is deposited in joints and transverse cracks in concrete pavements, the debris acts as a restraint to the expansion of the pavement. For a concrete slab to develop spalls in this manner, either extremely high stresses (at least of the order of 20 MPa) have to develop for sudden failure, or repeated action of stresses lower than the compressive strength must occur, resulting in fatigue failure.

Field observation recently conducted by the Texas Transportation Institute (TTI) has found that spalling is not just a long-term, age-dependent phenomenon. It is believed that de-bonding cracks at the aggregate-cement paste interface occur very early in the life of the pavement and then develop into a continuous flaw (a delamination). Subsequently, with time, these delaminations develop into spalls due to fatigue damage caused by repetitive load applications. Delaminations may be the result of differential shrinkage stresses ocurring in the concrete pavement slabs at very early ages and weakening over time due to water penetration from rain fall.

Once a delamination occurs in concrete, its development into a spall can happen because of a number of mechanisms. It is believed that traffic stresses, shrinkage stresses, and thermal stresses contribute to this spalling. Once we understand the mechanisms of delamination and spalling, it is important to find out ways to minimize spalling through the use of improved materials, design methods, construction techniques, and quality control methods. It is also important to find ways to obtain durable repair patches for spalls, including repair material selection criteria, which was the purpose of this study.

Despite of a variety of marketing claims, few valid tests have been established for most of the materials now available for rapid patching of concrete spalls. Conventionally, these materials have been required to be "at least as durable as the surrounding material." This requirement is based on common sense. Since the patched area is relatively much smaller than the total surface of the pavement, it is therefore economical to use a "better" material for the repair. The bond strength of the patch to the base concrete is very important to the performance of the spall repair. Based on the knowledge on the mechanism of concrete pavement spalling, this study adopted and also developed test methods to evaluate repair materials. These tests include tests for time of setting (for cement-based materials only), tests for compressive and flexural strengths, tests for fracture toughness (ability of a material to withstand cracking), tests for bond shear strength in the laboratory, and tests for bond torsional shear strength in field (for cement-based materials only). Strength of the bond to the base concrete is an important property for a repair material because high bond strength protects against delamination - the major cause of spalling. Researchers observed on improvement of all these properties with the age of the repair material. A repair material should attain a minimum strength (both in terms of tensile and bond to the base concrete) before the repaired road section is open to traffic. Selected repair materials were tested in the laboratory and field, and their performance of these materials in road repairs was evaluated.

This report consists of five chapters. Laboratory test methods and test results for selected repair materials are included in Chapter 2. Field tests are summarized in Chapter 5, while evaluation of highway pavement spall repairs on the two locations is included in Chapters 3 and 4, respectively. The discussion of field tests follows the chapters on the evaluation of highway pavement spall repairs since the field tests were conducted after the pavement repairs were placed.

CHAPTER 2: LABORATORY TESTS OF REPAIR MATERIALS

2.1. SELECTED REPAIR MATERIALS TESTED IN THE LABORATORY

Repair materials selected for testing fall under the following three categories:

(1) Portland cement concrete with accelerating admixtures,

(2) Portland cement-based ready-mix compositions, and

(3) Polymer-based concrete repair materials.

Accelerating admixtures tested were:

(1) Supercrete, and

(2) Gill33.

Cement-based repair compositions tested were:

(1) Rapid Set (ready-mix concrete), and

(2) Quikrete (ready-mix concrete).

Polymer-based repair materials tested were:

(1) Penatron (a two-part polymer),

(2) Sylcrete concrete mender and flexible cement (two-part polymers, products of Percol),

(3) Resurf (a polymer binder added to the concrete mix),

(4) Flamecoat products (flame-sprayed recycled rubber and other products).

2.2. PROPERTIES EVALUATED

Spall repair patches require a combination of fast setting, high strength and durability in order to minimize traffic control for repair and extended life of the pavement. To meet these requirements, different repair materials were tested to determine the following properties:

(1) Time of setting,

(2) Compressive and flexural strengths,

(2) Bond strength, and

(3) Fracture toughness.

Time of setting

A repair material should be able to set rapidly. Setting is defined as the onset of the rigidity evolved from the fresh state. On the other hand, material setting characteristics should allow a minimum amount of time for placing the material in place. Fast setting of a repair material enables construction personnel to open the road to traffic early enough to reduce the inconvenience caused by closing the road for the repair. Besides properties of the material, setting time may also depend on the temperature conditions. Setting time should be considered in selection of a repair material for the repair operations at different climatic conditions.

When a hydraulic cement is mixed with water a paste is formed. During the hardening of this paste considerable plasticity is maintained for a period of time referred to as the dormant period. After this period of time, the paste starts stiffening and less and less plasticity can be observed. Finally, little plasticity is manifested and the paste becomes more and more brittle with time, although at final set (as determined by ASTM C 403) the concrete is still without any measurable strength. This stiffening process results in the setting of the concrete and is the result of a series of reactions between the cement and the water. The stiffening is not a drying process; it takes place even if the fresh cement paste is kept under water. The gain of strength, that is, the hardening process, takes place subsequent to the setting. One can say that the setting period is the first stage of changes taking place in the cement-water mixture during which the reactions are accelerating, whereas the hardening is the second stage during which the reactions are decelerating. The so-called initial setting is basically the beginning of the stiffening, and the final setting is marked by the gradual disappearance of plasticity. There is no strict dividing line between setting and hardening. For practical purposes, it is convenient to incorporate test methods for the approximate determination of the time when stiffening starts, and when plasticity is gone. The time of setting of a paste or concrete is usually determined by measuring repeatedly the changes in its resistance to penetration by specified needle sizes. The test procedure included in ASTM C 403 was followed as part of the test program to determine initial and final setting times.

Compressive and flexural strengths

Compressive and flexural strengths are basic quality indices of cement-based materials and other related materials. Although failure of the spall patch is subject to a variety of different loading and stress conditions, the compressive strength of the repair material is still one of the most important and useful properties. Concrete exhibits tensile and shear strength; compressive strength is frequently used as a measure of these properties. The tensile strength of concrete is roughly 10 to 12 % of the compressive strength, and the flexural strength of plain concrete, as measured by the modulus of rupture, is about 12 to 20 % of the compressive strength.

Bond strength

The weakest plane in a repair typically is the interface between repair material and the base concrete. Hence, bond strength of a repair material is one of the most important properties, as it plays a major role in service of repair. A repair material is expected to penetrate into the porous structure of the base concrete or pavement, and develop a strong bond. On the other hand, it is also expected to develop the compressive strength required to withstand the loads due to traffic and remain in place. Bond strength should develop quickly to minimize the amount of time lanes are closed for repair operations.

Researchers at the National Institute of Standards and Technology (NIST) have evaluated two test methods (slanting shear and uniaxial tension) for measuring the bond strength of Portland cement-based repair materials to concrete (Knab and Spring, 1989). They concluded that both the slant shear test method and the pipe nipple grips uniaxial tension test method are promising methods for screening and selecting repair materials of Portland cement concrete and latex-modified concrete for overlaying or patching Portland cement concrete. Their results from studies of three repair materials showed that the relative precision, as measured by the coefficient of variation, of the slant shear test method was as good as, and in some cases possibly better, than the two uniaxial tension test methods. In addition, the slant shear test method provides a great amount of convenience in specimen preparation, and has been standardized (ASTM C 882) for bond strength of epoxy-resin systems used with concrete. The ASTM C 882 slant shear bond strength test can be easily modified by replacing one half of the slant shear specimen with a repair material. The test procedure will be described later.

Fracture toughness

In the conventional strength theory, stress or strain is used to define the failure criterion. For concrete, the ultimate tensile stress is usually specified as the strength criterion. In fracture mechanics, the energy required to form a new crack surface is considered the failure criterion. Fracture toughness is the parameter presenting the required energy. Many experimental results have indicated that this criterion is more precise than the strength theory based on the ultimate tensile stress for concrete. It has been observed that the ultimate tensile stress in a larger concrete structure is lower than that in a smaller concrete structure. Using fracture mechanics, this phenomenon, referred to as size effect, can be easily explained.

To characterize the nonlinear behavior of concrete in fracture, at least two fracture parameters are required (Barrr and Swarts, 1995). The Size Effect Law (Bažant and Kazemi, 1990) is a nonlinear fracture model and involves two material fracture parameters: fracture toughness K_{If} and process zone length c_f. With these fracture parameters, the strength of a specimen or structure of any size and any shape can be determined. This model was used to evaluate concrete materials in Study No. 1244 conducted at the Texas Transportation Institute (TTI) and the Center for Transportation Research (CTR), the University of Texas at Austin (Tang et al., 1995). As for the repair material, a sufficient strength at the early ages is required since the repaired road should be open to traffic in a very limited period of time for economical purposes.

Study 1244 indicated that concrete is so brittle that linear elastic fracture mechanics can apply to concrete at early ages (Zollinger et al., 1993; Tang et al., 1995). Therefore, at the early ages, c_f can be neglected and fracture toughness K_{If} determines the strength of concrete. This conclusion has allowed engineers to simplify tests to characterize the fracture properties of cement-based repair materials at the early ages, thereby facilitating a high degree of testing convenience. The fracture toughness K_{If} of a cement-based repair material can be obtained by testing a single-side notched beam specimen.

2.3. TEST PROGRAMS

The material properties described in Section 2.2 were evaluated for the selected repair materials listed in Section 2.1. The effects of climatic factors, temperature and humidity on the compressive strength and fracture toughness were observed. All the test methods and procedures used are provided in this section. Results of the tests are summarized in the following sections: 2.5. Tests of Cement-Based Repair Materials and Results, and 2.6. Tests of Polymer-Based Repair Materials and Results.

Test for the time of setting

ASTM C 403 gives the test procedure for determining the time of setting for concrete mixtures by penetration resistance. The penetration resistance apparatus is a spring reaction type graduated from 45 to 580 N (10 to 130 lb.) in increments of 9 N (2 lb.) or less. In the test, a vertical force is applied to the rod of the apparatus until the rod penetrates the mortar to a depth of 25 ± 1.5 mm (1 ± 1/16 in.). The time required to penetrate to the 25 mm (1 in.) depth must be within 10 ± 2 seconds. The force required to produce the 25 mm (1 in.) penetration and the time of testing is measured in terms of elapsed time after initial mixing of the concrete. The penetration resistance is calculated by dividing the recorded force by the bearing area of the needle. The tests data are plotted as the penetration resistance versus the time. From regression analysis, the times when the penetration resistance equals 3.5 MPa (500 psi) and 27.6 MPa (4000 psi) are the times of initial and final setting, respectively.

Tests for compressive and flexural strengths

ASTM C 39 was followed for the compressive strength of cement-based repair materials. A cylindrical specimen of a polymer-based repair material cannot be broken under compression even when the compressive stress is very high. Beam specimens of polymer-based repair materials were tested for the flexural strength (modulus of rupture).

Test for bond strength

ASTM C 882 for an epoxy-resin system used with concrete was followed as the basis for bond strength. (ASTM C 1042 gives a similar test procedure for latex systems used with concrete.) However, in our test program, the sample was tested at ages earlier than the standards suggest. The purpose of the modification was to determine the bond strength developing at early ages of the repair materials. For this test, a concrete cylinder of 76 mm (3 in.) in diameter and 152 mm (6 in.) in length was prepared and then cut at a 30 degree vertical angle. The bottom portion of the cylinder was retained (Fig. 2.1). After this portion was put in a 76-mm diameter model, the top portion of the mold was filled in with the repair material to form a test specimen. The cross-sectional area of the specimen was 4.561×10^{-3} m^2 (7.07 $in.^2$) and the elliptical bond plane area is 9.123×10^{-3} m^2 (14.14 $in.^2$). The failure "bond" stress per the standard was calculated by dividing the failure load, P, which is collinear with the cylindrical axis of the specimen, by the elliptical bond plane area, that is, 9.123×10^{-3} m^2 (14.14 $in.^2$). Actually, the nominal shear bond stress is $(\cos 30° \times P)/9.123 \times 10^{-3}$ m^2, which can be easily obtained by an analysis using Mohr's circle. It is lower than the ASTM calculated stress. However, the ASTM stress will be used as the "shear bond stress" in this report.

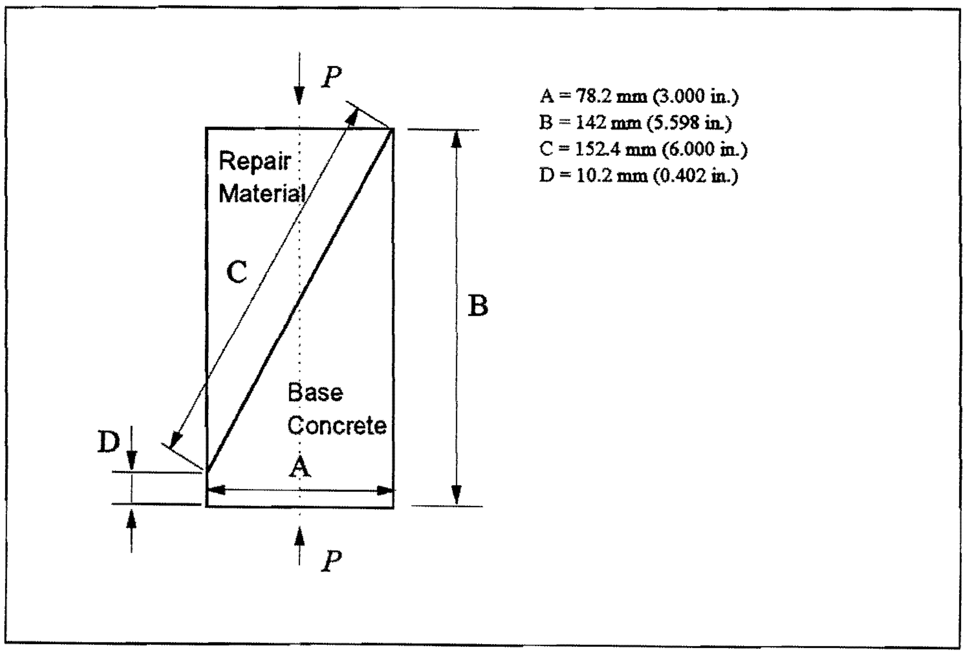

Fig. 2.1. Slanting Shear Bond Test Specimen.

Because of the characteristics of the repair material, the base concrete, and the bond of the repair material to the base concrete, researchers considered the failure pattern (amount and location of the failure surface) during analysis. The different characteristics of repair materials result in different failure patterns. The failure pattern is important because it indicates where the composite bond specimen (repair material and base concrete) fails. Failure in the base concrete, for example, can be desirable and indicates that the base concrete is controlling the strength rather than the repair material or its bond to the base concrete.

Test for fracture toughness

Mature concrete is not as brittle as concrete at the early ages, therefore, besides fracture toughness, another parameter is required to determine the ultimate load of a concrete specimen or structure. RILEM has recommended testing a three-point bend beam (or center point beam) for the fracture parameters. The American Concrete Institute (ACI), the American Society of Testing and Material (ASTM) and the Society of Experimental Mechanics (SEM) are preparing fracture test standards, where a three-point bend beam will be chosen as the test specimen. In our program, the three-point bend beam applies but the test procedure is even simpler, because only one parameter - fracture toughness K_{If} is required to be determined for concrete at early ages, as discussed in the previous section. The size of the beam used in our test program was the 76 × 76 × 305 mm (3 × 3 × 12 in.) with a support span of 191 mm (7.5 in.) (Fig. 1.2). Fracture toughness, or critical stress intensity factor, K_{Ic} , can be calculated with the following formulas (Tada et al., 1985):

$$K_{Ic} = \sigma_N \sqrt{\pi a}\, F(\alpha) \tag{1}$$

where

$$\sigma_N = 1.5\frac{sP}{bd^2} \tag{2}$$

is called the critical nominal stress,

$$F(\alpha) = \frac{1.0 - 2.5\alpha + 4.49\alpha^2 - 3.98\alpha^2 + 1.33\alpha^4}{(1-\alpha)} \tag{3}$$

is the geometry factor, $\alpha = a/d$; P is the ultimate load, d is the specimen depth, b is the specimen thickness, s is the support span, and a is the notch length.

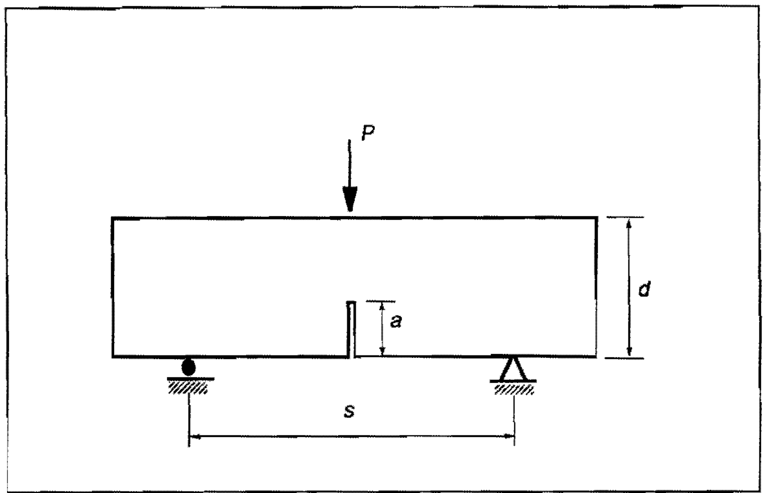

Fig. 2.2. Three-Point Bend Beam for Fracture Test.

Testing under different temperature and humidity conditions

Climatic factors have significant effects on time of setting, bond strength and fracture toughness. Considering the differences in weather conditions between summer and winter in the Houston area, these material properties should be determined at different temperatures and humidities. In the test program previously described, three different combinations of temperature and relative humidity were used to simulate the weather conditions of different seasons of the year. TTI laboratories have thirteen temperature and relative humidity controlled rooms, or environmental chambers. Two of these controlled rooms were selected to cure and test the samples to find the strength development of the selected repair materials at various temperatures and relative humidities. The first chamber was maintained at 10°C (50°F) and the other chamber was maintained at 60°C (140°F). Relative humidity in the 10°C chamber was maintained at 50%, but the actual relative humidity in pores of the sample has been estimated to be close to 100%. Relative humidity in the 60°C chamber was maintained at 25%, and the actual pore relative humidity in the sample was estimated to be in the range of 85-90%. In the laboratory, the room temperature was 25°C (77°F), and the pore relative humidity was estimated as 100%. Relative humidity field data measured for concrete and ambient conditions in the field have been used for estimation of relative humidity in the samples in the environmental chambers. All the samples were prepared at room temperature

(25°C). Some were then moved to the environmental chambers just after the completion of preparation. All the samples were kept in sealed polyethylene bags to avoid rapid evaporation of moisture. Samples were tested to determine the time of setting, bond strength and fracture toughness at the different temperatures and pore relative humidities previously described.

A typical winter day temperature with workable conditions was considered to be 10°C and an extreme summer day temperature in the pavement was taken as 60°C. These two temperatures were selected for testing the bond strength between four cement based repair materials and base concrete.

2.4. MIX DESIGN FOR BASE CONCRETE AND REPAIR MATERIALS

Concrete mixtures were prepared for the base concrete used in the test specimen (Fig. 2.1) for determining the bond strength. The same mixture was also used with an accelerating admixture as a repair concrete. Table 2.1 shows the mixture quantities needed to produce 0.170 m^3 (6 $ft.^3$) of concrete. The cement factor of the mix was 4.5 sacks a cubic yard of concrete. The water/cement ratio was 0.53. For repair materials, an accelerating admixture, Supercrete or Gill33, was added in accordance to the instructions given by the admixture supplier.

Table 2.1. Concrete Mix Design.

Component	Specification	Quantity
Cement	Type I	42.7 kg (94 lb. or a sack)
Coarse aggregate	River gravel (maximum size: 16 mm or 5/8 in.)	227 kg (501 lb.)
Fine aggregate	Concrete sand	109 kg (240 lb.)
Water	Tap water	22.7 kg (50 lb.)

2.5. TESTS OF CEMENT-BASED REPAIR MATERIALS AND RESULTS

Rapid Set ready mix, Quick ready mix, Supercrete added mix, and Gill 33 added mix were tested for the time of setting, bond strength and fracture toughness. The test results are summarized as follows.

Time of setting of cement-based repair materials

Rapid Set, Quikrete, and Supercrete and Gill33 added concrete were all tested for the time of setting by following ASTM C 403. The time of setting of the specimen cured at 25°C (77°F) for each material is shown in Table 2.2.

Table 2.2. Time of setting of cement-based repair materials measured by ASTM C 403.

Repair material	Time of setting
Rapid Set ready mix grout	45 minutes
Quikrete ready mix	> 4 hours
Cement paste with Gill33	2 hours 30 minutes
Cement paste with Supercrete	3 hours

The time of setting time was also determined at 10°C (50°F), and 60°C (140°F). Fig. 2.3 shows the decrease in setting time with increasing curing temperature for each material. It is clear from the figure that:

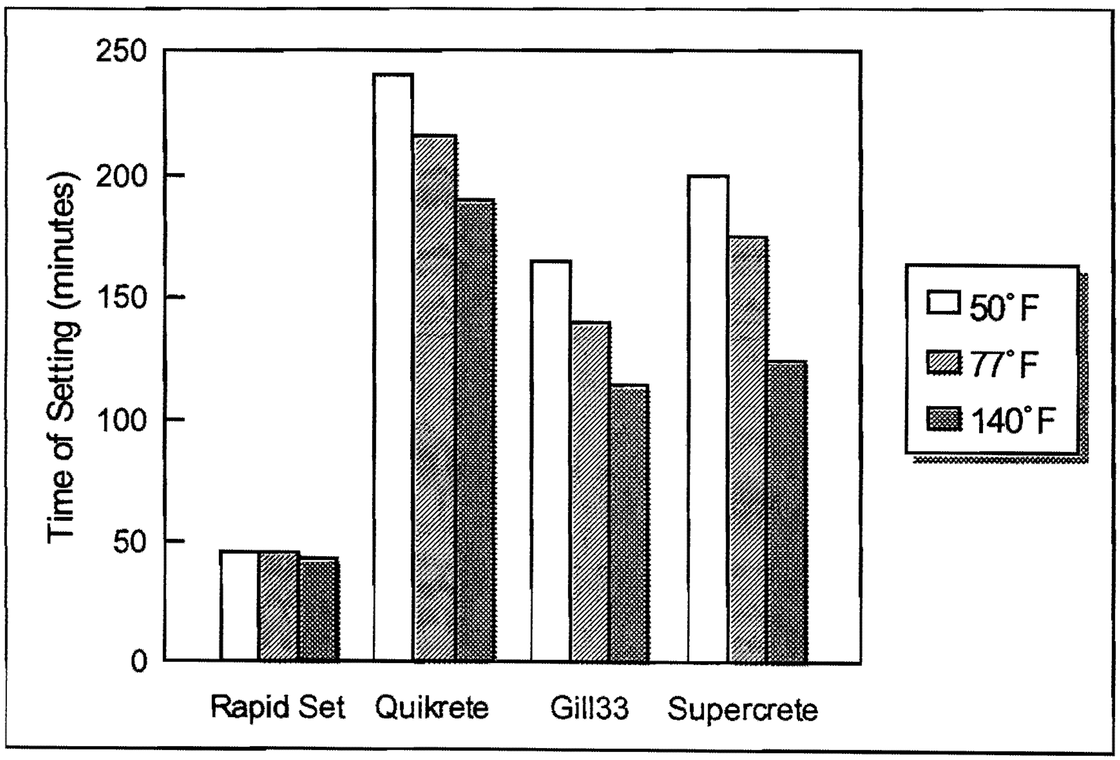

Fig. 2.3. The Time of Setting of the Cement-Based Repair Materials.

(1) Concretes with Supercrete and Gill 33 admixtures do not make very fast setting repair materials in comparison with Rapid Set. Concretes with Gill 33 set more quickly than concretes with Supercrete. Curing temperature has an obvious effect on the time of setting of the materials to which either of the admixtures is added. These admixtures cause setting of the concrete to be slow at low temperature and faster at high temperatures.

(2) Concretes with Quikrete set very slowly. The time of setting is also affected by the change in temperature.

(3) Concretes with Rapid Set set very fast. There is no obvious temperature effect of the time of setting for Rapid Set ready-mix concrete.

Compressive strength of cement-based repair materials

Twelve samples, 76 mm (3 in.) in diameter and 152 mm (6 in.) in length were prepared using each cement based repair material at room temperature (10°C or 50°F) that were made into three batches and cured at three different temperatures, 10°C (50°F), 25°C (77°F) and 60° C (140°F), for testing. These samples were tested for compressive strength at four and 24 hours after molding. Test results are shown in Figs. 2.4 and 2.5. It can be observed from the figures that concrete containing Supercrete and Gill 33 developed good strength at an age of one day, but the strengths were low four hours after molding. Rapid Set gained high strength in four hours and there was little change in compressive strength 24 hours after molding. Concrete with Quikrete did not set at four hours and its strength at 24 hours age was very low in comparison with concretes with Supercrete and Gill 33.

For Rapid Set, curing temperature did not show an effect on the development of compressive strength, whereas the effect of curing temperature on the development of the compressive strength of the accelerating admixture added concrete was very apparent. The compressive strength of the accelerating admixture added concrete develops much more slowly at 10°C (50°F) than at 25°C (77°F) and 60°C (140°F).

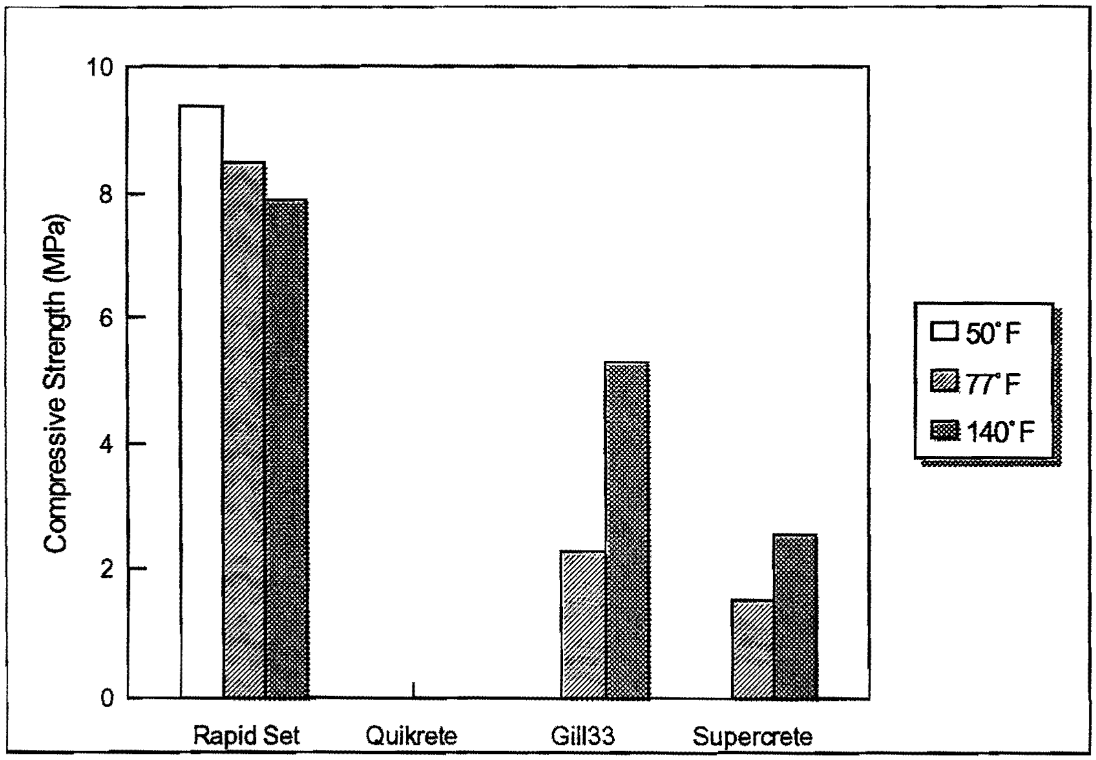

Fig. 2.4. Compressive Strength of Cement-Based Repair Materials at the Age of Four Hours.

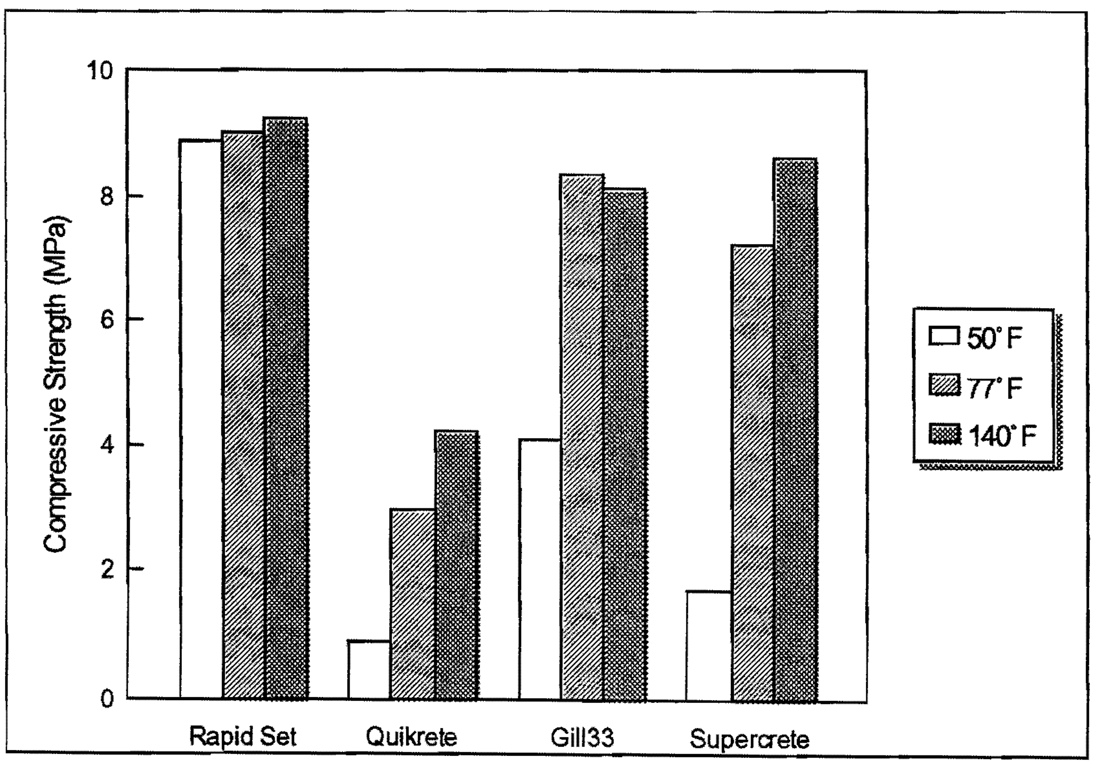

Fig. 2.5. Compressive Strengths of Cement-Based Repair Materials at the Age of 24 Hours.

Fracture toughness of cement-based repair materials

Beams of 76 × 76 × 305 mm (3 × 3 × 12 in.) were molded and cured at the three temperature conditions (previously described), and tested at four hours and 24 hours after molding. Test results are plotted in Figs. 2.6 and 2.7. As can be seen in the figures, the following conclusions were drawn:

(1) Concretes containing Gill 33 and Supercrete admixtures developed high fracture toughness at one day after molding, but the samples were soft at four hours after molding. Fracture toughness of these two materials were higher than that of Rapid Set at one day. Rapid Set gained high fracture toughness in four hours and there was little change in fracture toughness after one day. Quikrete was not set at four hours and its fracture toughness was low at an age of 24 hours.

(2) Fracture toughness of either Gill 33 or Supercrete concretes was influenced by the temperature and humidity curing condition. Samples cured at 10°C (50°F) and 100% relative humidity failed at much lower loads than samples cured at 77°F and 140°F. The difference in fracture toughness values of Rapid Set samples cured at different temperatures was insignificant. Quikrete was also influenced by the temperature and humidity conditions.

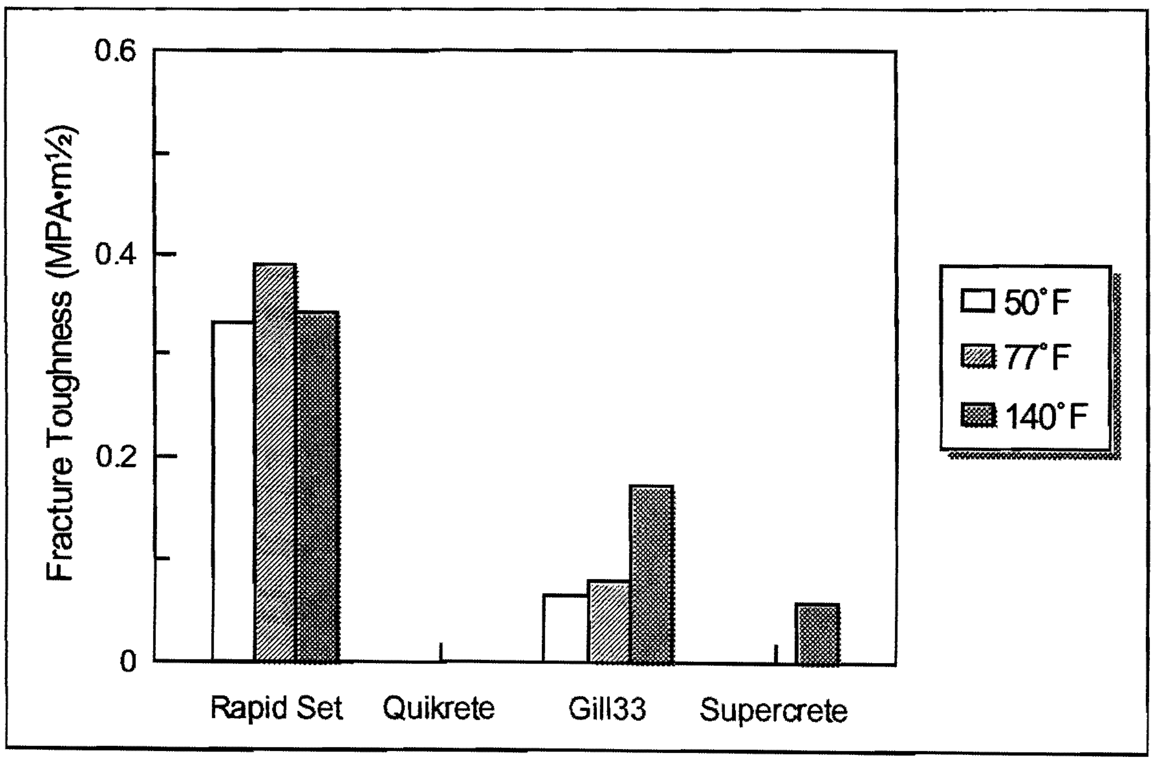

Fig. 2.6. Fracture Toughness of Cement-Based Repair Materials Four Hours After Molding.

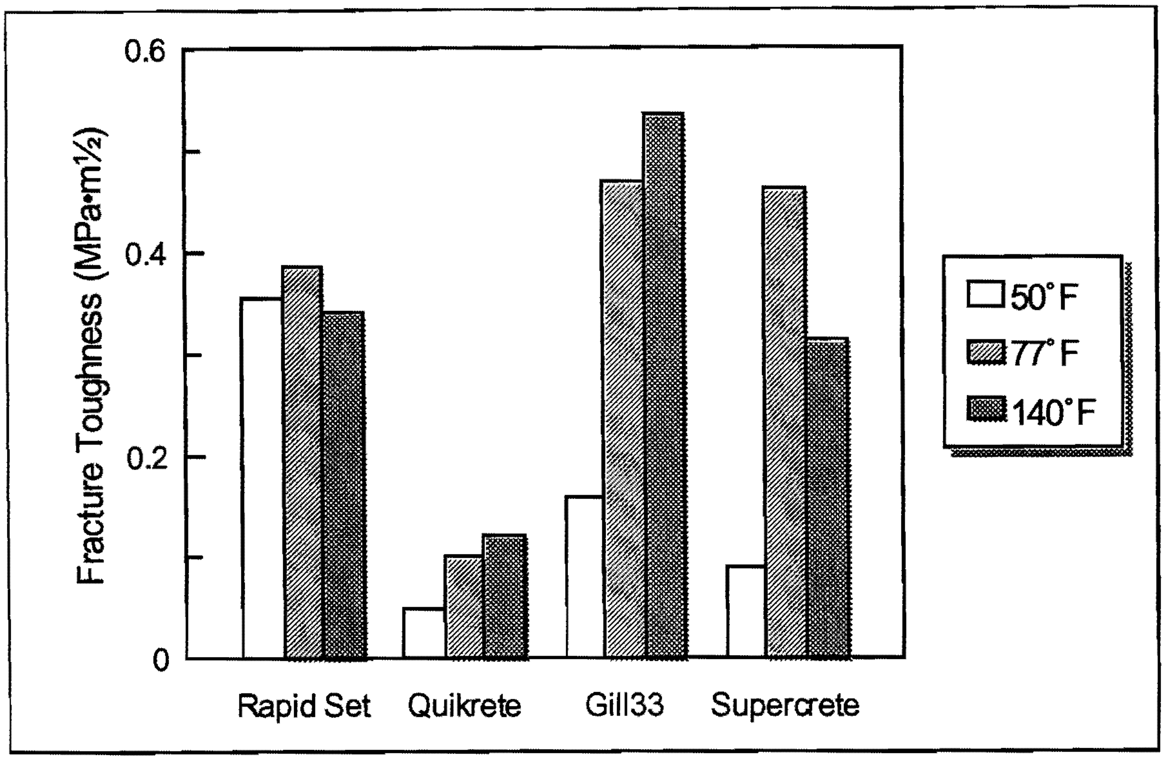

Fig. 2.7. Fracture Toughness of Cement-Based Repair Materials 24 Hours After Molding.

Bond strengths of the cement-based repair materials

The test procedure using the slanting shear bond test specimen (Fig. 2.1) for determining bond strength was explained in Section 2.3. The slanting shear specimen may fail in different modes: shear failure at the bond, compressive failure of the repair material, or compressive failure of the base concrete. However, in our tests, we observed no compressive failure of the base concrete. All the tests were conducted four or 24 hours after specimen casting, but one Supercrete specimen was tested four days after casting. All the test data are shown in Tables 2.3 to 2.5, where compressive strength was calculated by dividing the measured peak load by the area of the cross-sectional area of the specimen, while the shear bond strength was calculated by dividing the measured peak load by the elliptical bond plane area. Bond shear strength values shown in shaded cells in the tables are false bond strengths because the specimen failed in compression failure instead of bond failure, which means that the repair material was weaker than the bond. By contrast, compressive strength values shown in shaded cells are false compressive strengths because the specimen failed along the bond, which means that the material was stronger than the bond.

Table 2.3. Bond Strengths of the Cement-Based Repair Materials Cured at 25°C (77°F).

Material	Specimen	Peak Load (kN)	Bond Shear Strength (MPa)	Compressive Strength (MPa)	Failure mode	Specimen Age (hrs.)
Rapid Set	1	36.3	3.98	7.96	compressive	4
Rapid Set	2	43.8	4.8	9.6	compressive	4
Rapid Set	3	39.4	4.32	8.64	compressive	24
Rapid Set	4	43.1	4.73	9.45	compressive	24
Quikrete	1	6.94	0.76	1.52	bond shear	24
Quikrete	2	9.79	1.07	2.15	bond shear	24
Supercrete	1	32.1	3.52	7.03	bond shear	24
Supercrete	2	41.3	4.53	9.06	bond shear	24
Supercrete	3	38.9	4.26	8.53	bond shear	24
Supercrete	4	42.7	4.68	9.36	bond shear	4 days
Gill33	1	9.79	1.07	2.15	bond shear	4
Gill33	2	8.9	0.98	1.95	bond shear	4
Gill33	3	38.7	4.24	8.48	compressive	24
Gill33	4	34.4	3.77	7.54	compressive	24
Gill33	5	43.1	4.74	9.46	compressive	24

Table 2.4. Bond Strengths of the Cement-Based Repair Materials Cured at 60°C (140°F).

Material	Specimen	Peak Load (kN)	Bond Shear Strength (MPa)	Compressive Strength (MPa)	Failure mode	Specimen Age (hrs.)
Rapid Set	5	34.3	3.77	7.53	compressive	4
Rapid Set	6	36.9	4.05	8.1	compressive	4
Rapid Set	7	36.3	3.98	7.95	comp./shear	24
Rapid Set	8	40.5	4.45	8.89	compressive	24
Quikrete	3	18.1	1.98	3.96	bond shear	24
Quikrete	4	18.6	2.03	4.07	bond shear	24
Gill33	6	19.9	2.18	4.35	bond shear	4
Gill33	7	20.1	2.21	4.42	bond shear	4
Supercrete	5	3.75	0.41	0.82	bond shear	4
Supercrete	6	3.34	0.37	0.73	bond shear	4

Table 2.5. Bond Strengths of the Cement-Based Repair Materials Cured at 10°C (50°F).

Material	Specimen	Peak Load (kN)	Bond Shear Strength (MPa)	Compressive Strength (MPa)	Failure mode	Specimen Age (hrs.)
Rapid Set	9	39.7	4.35	8.71	comp./shear	4
Rapid Set	10	41.9	4.6	9.19	compressive	4
Rapid Set	11	37.8	4.14	8.29	comp./shear	24
Rapid Set	12	41.4	4.54	9.07	compressive	24
Quikrete	5	2.72	0.3	0.6	bond shear	24
Quikrete	6	30	0.33	0.66	bond shear	24
Gill33	8	8.63	0.95	1.9	comp./shear	4
Gill33	9	8.15	0.89	1.79	comp./shear	4
Supercrete	7				(not set)	4
Supercrete	8				(not set)	4

Comparing the data in Tables 2.3 to 2.5, one finds that:

(1) Rapid Set gained both compressive strength and bond strength faster than other tested cement-based repair materials. In the earliest four hours after specimen casting, the bond shear strength basically developed faster than the compressive strength of the material itself. Curing temperature seemed to have no effect on the strength development in Rapid Set.

(2) In the range of the three curing temperatures, the rate of strength growth in Quikrete is very curing-temperature dependent. A decrease in curing temperature slowed down the strength growth. When Quikrete was cured at 10°C, either the compressive strength or the bond strength developed very slowly. Another characteristic of Quikrete was that the bond strength developed more slowly than the compressive strength.

(3) The accelerating admixture (Gill33 or Supercrete) added repair material has an apparent curing-temperature effect. High curing temperatures induced faster setting and faster development of compressive strength. However, higher curing temperatures might not necessarily be a favorable factor for the development of the bond strength. The bond strength was greater when the material was cured at 60°C and lower than when it was cured at 25°C.

Researchers speculated that the high temperature affected the rate of hydration resulting in weaker bonding.

2.6. SPECIMENS OF POLYMER-BASED REPAIR MATERIALS

Methods of applying polymer-based materials are different from concrete mixing and placing. Different polymer-based materials require different procedures. Material suppliers for Resurf, Sylcrete and Flamecoat, as well as those for Rapid Set and Supercrete were invited to the TTI laboratory of to demonstrate the application of the repair materials to spalled pavement segments, which were cut from the BW 8 westbound frontage road near the intersection with I 45. Specimens of Penatron, Resurf and Sylcrete were prepared and tested for their properties. Following is the record for specimen preparation in the laboratory.

Penatron

Penatron is a polymer composition of two monomers blended at a prescribed ratio. When used for repair, mineral aggregates are placed in the spalled area first. The monomers of Penatron are blended and then placed in the gaps between the aggregates, which are not disturbed. Penatron was used to make samples for bond strength tests and flexural strength tests and was observed to be set before it passed through the voids between the aggregates. A picture of an unfinished beam with Penatron is shown in Fig. 2.8. Mixing and pouring instructions in the producer's manual indicate that the polymer composition should be poured into the aggregates within 50 seconds after mixing. This timing was very critical. The high viscosity of Penatron composition and its rapid clotting characteristics reduced its ability to penetrate through the aggregate, especially when aggregate of smaller size (with the maximum size of 9.5 mm or 3/8 in.) was used. This indicates that care should be taken in repairing with Penatron in this regard.

Resurf

Resurf is a polymer composition with a resin and a catalyst to make the resin clot, or set. Resurf is closer to ordinary cement-based repair materials in terms of mixing and placing operations. This polymer composition is prepared by mixing a catalyst and a resin in the

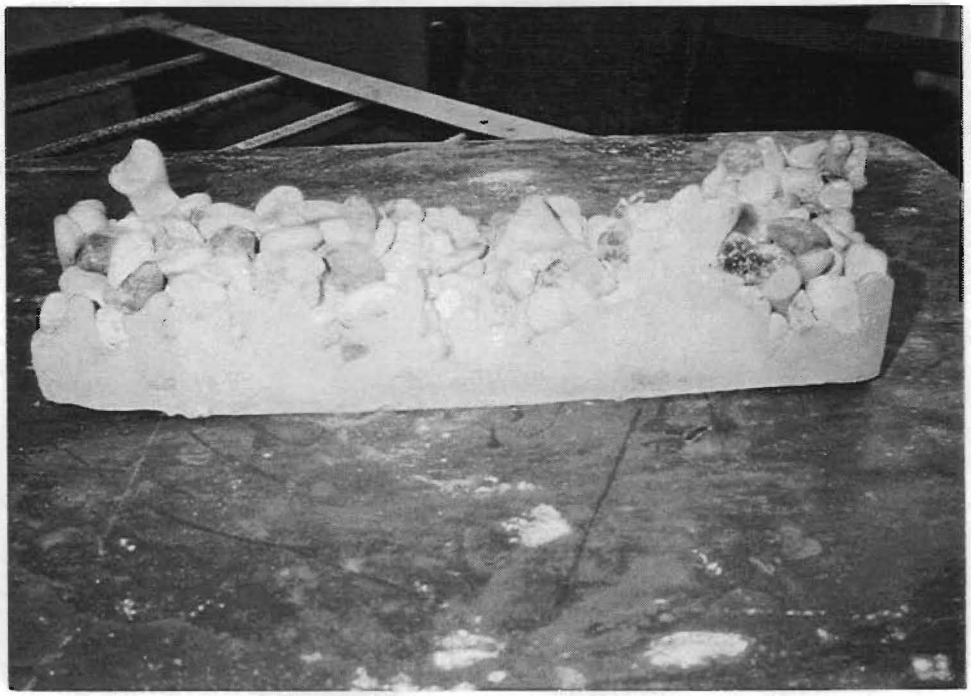

Fig 2.8. Incomplete Beam Made of Penatron with its Bottom Up.

prescribed ratio and pouring into the mixer into which an aggregate has been poured. Resurf has been observed to be a very slow setting polymer composition. Resurf samples remained soft at the age of four hours but gained high strength in 24 hours. In bond strength tests using Resurf concrete, the failure plane occurred in the base material which was a regular concrete of 30 days old. A picture of a tested cylinder made of Resurf concrete and base concrete has been shown in Fig. 2.9. It can be seen in the figure that the bond between Resurf concrete and the base concrete was unaffected and the sample failed vertically through the base material. This material showed high strength but was very brittle.

Sylcrete

Sylcrete is also a two-part polymer composition which is mixed in a gun at a one to one ratio. After mixing, Sylcrete is filled in the gaps of the placed aggregates. Sylcrete has two different types of compositions: 1) Sylcrete flexible cement, and 2) Sylcrete mender.

Fig. 2.9. A Tested Slanting Shear Specimen of Resurf Blended with Sand as Repair Material.

Sylcrete flexible cement is more viscous than the mender and is very flexible after setting. Mender is less viscous and brittle after setting.

The first attempt to make samples for testing failed as this polymer composition could not penetrate through the aggregates (with the maximum size of 9.5 mm or 3/8 in.) in the mold of three inches in depth. Again high viscosity and very fast setting characteristics led to this result. To overcome this problem, a larger size aggregate should be used and the specimen should be prepared layer by layer. Specimens were successfully prepared in two layers by using aggregate with the maximum size of 16 mm or 5/8 in. The first lift consisted of polymer material that was pumped into the mold around prior placed aggregate which filled the mold approximately halfway. Subsequently, the aggregate was filled to the top of the mold and the polymer composition was pumped in again for the second lift of the specimen.. Although this procedure resulted in properly prepared specimens, there were signs of bleeding of the polymer composition from the specimens. This bleeding was due to the improper blending of the two components of the composition. One of the two monomers was pumped into the aggregates and remained unset as there were insufficient amounts of its counterpart for the chemical reaction. Adequate procedures need to be established to ensure proper mixing of these monomers under field use.

Pictures of a finished and tested slanting shear cylinder made of Sylcrete mender and river gravel on top of a base concrete piece are shown in Figs. 2.10 and 2.11. Both the Sylcrete products were tested for shear strength and fracture toughness.

Fig. 2.10. A Finished Slanting Shear Specimen of Sylcrete Mender Blended with Aggregates.

2.7. TESTS OF POLYMER-BASED REPAIR MATERIALS AND RESULTS

Tests similar to those conducted for the cement-based repair materials in the lab program were applied to the selected polymer-based repair materials, but specimens were all cured in the laboratory at 25°C (77°F). No tests were performed for the time of setting of the polymer-based materials. However, time of setting was judged by examination.

Time of setting

Specimens of these polymer-based materials were observed until they felt solid to the touch. Resurf developed good strength in one day, but was not properly set four hours after molding. Penatron is a very fast setting material. Sylcrete mender and flex appeared to set as early as one hour after placement, but no strength tests were conducted until four hours after placement.

Fig. 2.11. A tested slanting shear specimen of Sylcrete mender blended with aggregates.

Flexural strength

Resurf and Sylcrete products were tested for flexural strength, or modulus of rupture. Beams of the same size as those of the cement-based repair materials were tested. Flexural strengths were calculated from the maximum load and are shown in Table 2.6. It had been observed on I-45 in the Rosenburg area that Sylcrete mender repairs were spalled not long after placement, although the mender was designed for concrete repair. The mender was less viscous than the flexible cement so that the mender flowed into concrete cracks more easily. However, since the flexible cement had low modulus, it would result in less stress than the mender under the same deformation. Besides beams made of the mender and the flexible cement, respectively, a composite beam was cast with its top half made of Sylcrete flexible cement and it bottom half made of Sylcrete mender. The composite beam was intended to have a low rigidity by using Sylcrete flexible cement to form its top half . In the test described above, the load was applied on the flexible cement side such that the mender failed in tension. Data from the composite beam is included in Table 2.6 too.

For the Sylcrete flexible cement beam, the maximum load of 5900 N was recorded when the deflection of the midpoint of the beam reached 13 mm (about half an inch). It indicated, with very low elastic modulus, that the Sylcrete flexible cement beam was very flexible. Because the modulus of flexible cement concrete was lower than that of mender concrete, the bottom half of the composite beam developed more stretch and higher stresses than the beam made of mender alone for the same load, which caused the composite beam to fail at a lower load. In conclusion, to use the mender for the bottom part of repair might not be appropriate. However, flexural strength of the polymer-based materials is higher than that of cement-based materials.

Table 2.6. Flexural Strength of Polymer-Based Repair Materials.

Material	Load at failure (kN)	Flexural strength (MPa)	Age of specimen (hrs.)
Resurf	34.2	22.1	24
Sylcrete mender	16.2	10.5	4
Sylcrete flex	N/A	N/A	4
Sylcrete composite	10.9	(not calculated)	4

Fracture toughness

In fracture tests, some beams broke at the notch in the fracture beam specimens (Table 2.7), but a notched beam of Sylcrete flexible concrete was did not fail under a load of 20,200 N and a midpoint beam deflection of 13 mm (about half an inch). Fracture toughness of these polymer-based materials is higher than that of cement-based materials.

Table 2.7. Fracture Toughness of Polymer-Based Repair Materials.

Material	Notch length (mm)	Load at failure (kN)	Fracture toughness ($MPa \cdot m^{1/2}$)	Age of specimen (hrs.)
Resurf	19	12.85	1.87	24
Sylcrete mender	19	8.36	1.22	4
Sylcrete flex	19	(N/A)	(N/A)	(N/A)

Bond strength

Slanting bond shear test specimens (Fig. 2.1) were made with concrete as the base material using the mix design shown in Section 2.4. Resurf blended with sand and Sylcrete mender filled in preplaced aggregates were used as the repair materials for the slanting bond shear test specimens. These specimens all broke in the base concrete (Fig. 2.7) or in both the base concrete and the repair material (Fig. 2.9). The Resurf mortar showed a splitting failure pattern whereas the Sylcrete mender-based material showed a crushing failure mode. The bond of the polymer-based repair material was well bonded to the base concrete. Test data are shown in Table 2.8.

Table 2.8. Bond Test Results of Polymer-Based Repair Materials.

Material	Load at failure (kN)	Compressive strength (MPa)	Maximum shear stress at bond (MPa)	Age of specimen (hrs.)
Resurf (Specimen 1)	43.5	9.54	4.77	24
Resurf (Specimen 2)	54.1	11.9	5.93	24
Sylcrete mender	58.8	12.9	6.44	4

2.8. CONCLUSIONS

The following conclusions were drawn from the laboratory tests:

(1) The laboratory tests conducted for the properties of the cement-based and polymer-based materials, including the time of setting, compressive strength, flexural strength, fracture toughness and shear strength of the bond between the repair material and base concrete, distinguished the properties of these repair materials very well and showed that they can be used in selecting repair materials.

(2) Of the cement-based materials, Rapid Set sets quickly and gains compressive strength and bond shear strength fast when it is cured in a temperature range from 10°C (50°F) to (60°C) 140°F. It can be used for spall patching in all seasons.

(3) Accelerating admixtures Gill33 and Supercrete accelerate setting, and increase concrete strength and bond strength, but development of their full strength needs at least one day. Curing temperature has apparent effects on the development of strengths in the accelerating admixture added concrete. Caution should be exercised in using the accelerating admixtures at extreme temperatures (in very cold or very hot weather), because the extreme temperatures may result in lower bond strength.

(4) Polymer-based repair materials provide high strengths (compressive, flexural and bond). If the polymer sets very fast, it is suggested that larger aggregates be used and repair be conducted in layers.

(5) Resurf (a polymer) blended with sand does not set fast, but it provides high strengths in one day.

(6) Sylcrete mender has a higher modulus of elasticity than Sylcrete flexible cement. Although the material producer suggested Sylcrete mender as a spall repair material, the laboratory tests have indicated that Sylcrete flexible cement is a better choice for a repair material.

CHAPTER 3: EVALUATION OF SPALL REPAIRS IN BW 8 NORTH

3.1. REPAIRS WITH CEMENT-BASED MATERIALS IN BW 8 NORTH

Two inner lanes of the eastbound road of BW 8 in North Houston were repaired with the cement-based repair material Pyramid in May 1993. Pyramid is a ready-mix concrete that is similar to Rapid Set. A 954-m (2770 ft.) long pavement section (AB in Fig. 3.1) located between Intercontinental Airport of Houston (IAH) and I-45 was selected for rehabilitation and monitoring. Included in this section, in the westbound, inside lanes, were spalled cracks repaired with Flamecoat products (CD) and Sylcrete products (EF), which will be described later in this chapter.

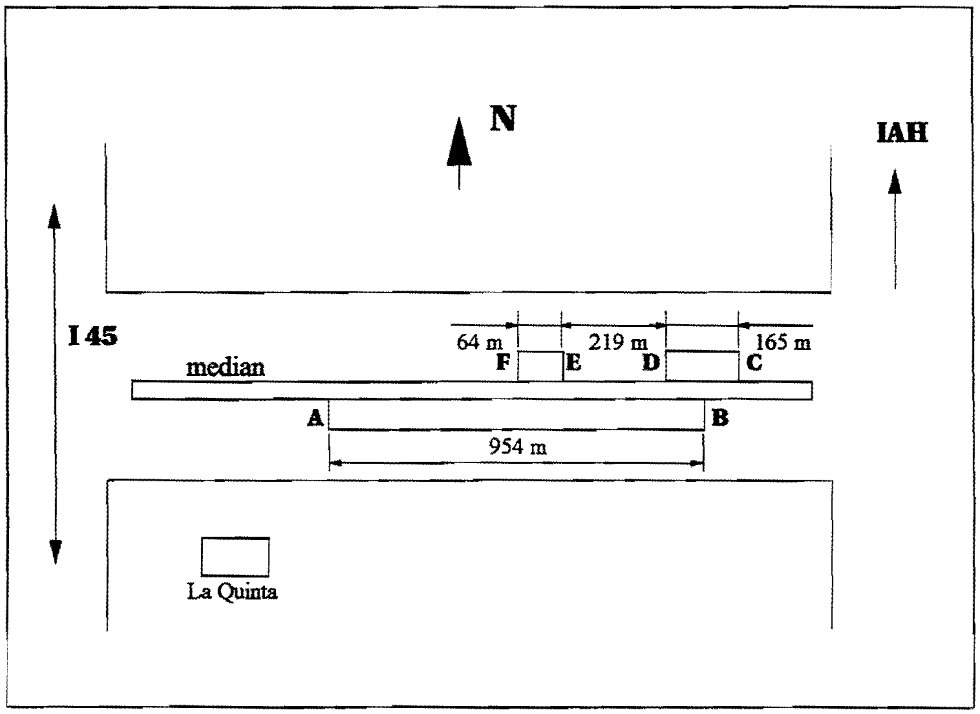

Fig. 3.1. Layout of the Pavement Sections Monitored in BW 8 North.

By designating the west end of the 954-m long section, point A in Fig. 3.1, as the reference point, each repair section was then located with respect to its longitudinal distance from point A. Information about all the repairs made between points A and B is recorded in Table A.1 (shown in Appendix: Test Data). The patch series number is associated with a specific patch location. These patch series numbers were marked on the concrete median for future reference. The number of patches at each location is shown in the table. "Block repair" indicates that the repair extended across the entire lane (3.66 m or 12 ft.). Patches made with Pyramid were placed on May 5 or 13, 1993, in the two inner lanes (marked accordingly in Table A.1). Patches of Rapid Set are also recorded in Table A.1, although they were placed in the outer lane in 1992. The exact date of these repairs is unknown. Those rows in the table providing information about Rapid Set patches are shaded. Pyramid patches with series numbers 5-9, 11, 13, 14, and 38-40 were placed on May 13, while all others were placed on May 5.

The repaired spalled areas were prepared by removing loose aggregates from the spall area with a jack hammer. After jack hammering, compressed air was used to blow the loose aggregates and dust out of the spall area. The repair material was immediately placed in the "cleaned" spalls after mixing. Neither water nor any curing compound was used for curing. On some of the repairs, a saw cut was made by a conventional "water" saw. The purpose of the saw cut was to induce cracking in order to reduce spall potential of the repair. Saw cut locations were recorded and are shown in Table A.1. Saw cuts were placed on the Pyramid patches sometime between July 21 and July 28, 1993.

3.2. REPAIRS WITH POLYMER-BASED MATERIALS IN BW 8 NORTH

Polymer-based repaired materials were also used to patch spalls in the westbound road of BW 8 at the North Houston site. Flamecoat products were used for a section in CD in Fig. 3.1 on July 21, 1993; whereas Sylcrete products were used for another section in EF in Fig. 3.1, a week later on July 28, 1993.

All the repairs using Plastic Flamecoat products were made in the innermost lane. Three different Flamecoat product types were used. The repair information is recorded in Table A.2. Product PF113-H101 was a low viscosity material while product PR111-H101 was a high viscosity material. Product PH100 was made from recycled tires. The Flamecoat material was applied by using the flame spray method (Fig. 3.2). The polymer product was melted by a flame and thus flowed into pavement cracks and spalls. On three occasions (at patch series numbers 4, 5 and 8) patching was done by using Rapid Set Concrete after the

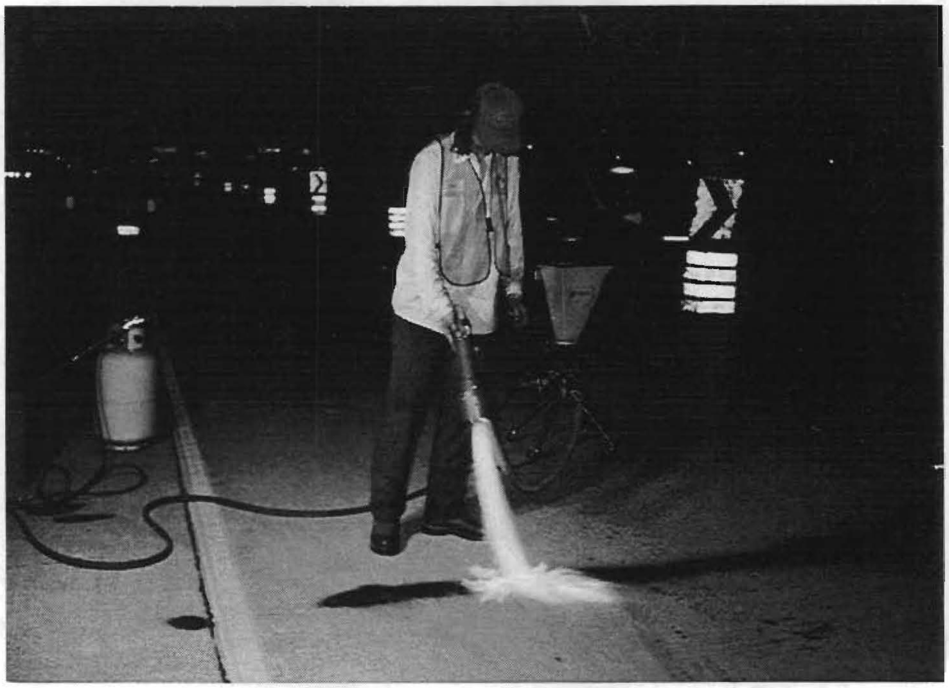

Fig. 3.2. Flame Spray Process in the Repair Section on BW 8 North.

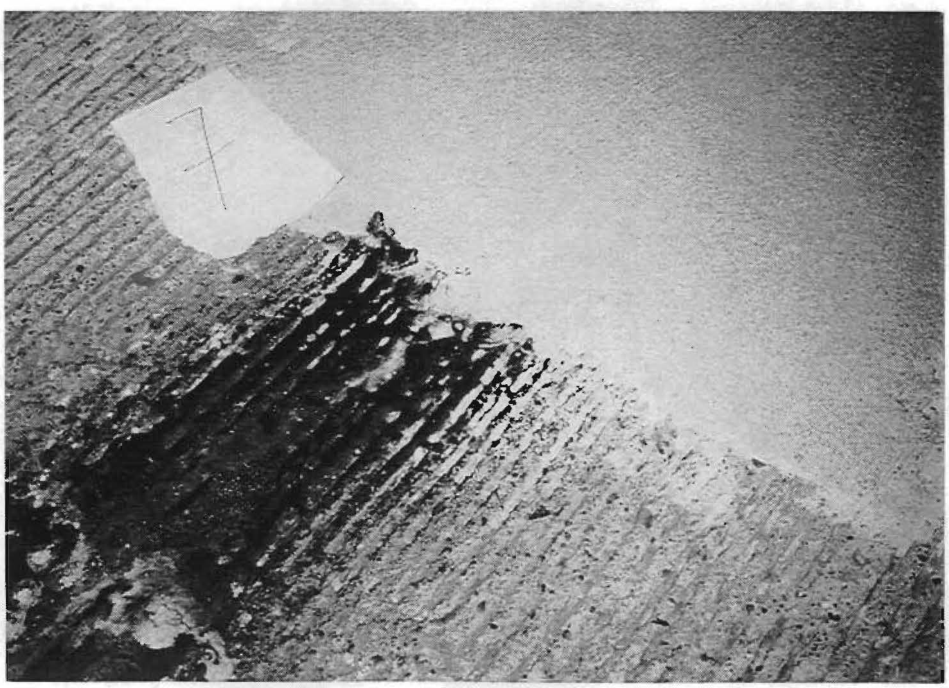

Fig. 3.3. Patch 7 in the Flamecoat Repaired Section.

application of Flamecoat products. Fig. 3.3 shows patch 7 Rapid Set Concrete covering part of Flamecoat repair.

Before the Flamecoat product was sprayed, the spall area was cleaned and debris was blown off with compressed air. The Flamecoat product had sufficient (4-cm wide at least) overlap on each side of the crack in every patch. The repair surface looked smooth at placement, however, results of a survey conducted in October 1993 (three months after repairing) found that the Flamecoat patch was easily removed (as noted later in this chapter.)

The test section for the Sylcrete products (in EF in Fig. 3.1) starts 219 m from Point D, the end of the test section for Flamecoat products. The products used were Sylcrete concrete mender and Sylcrete flexible cement. The flexible cement has a lower modulus and mender has a lower viscosity. Both mender or flexible cement are two-part polymers. These products were tested in the laboratory, as reported in Chapter 2 of this report. According to the material supplier these products are made by Percot in California.

Before the repair material was applied, the spalls had been sandblasted and chipped. Loose concrete and dirt were removed with compressed air. The cracks were mechanically cleaned by using a wire-brush power tool and, in some instances, a hand operated pneumatic hammer (Fig. 3.4). Once the repair area was cleaned and dried, the mender was poured into the crack. After waiting a few seconds, the flexible cement was then poured over the repair area (Fig. 3.5). At places where spalling was extensive, crushed limestone was placed immediately after placement of the mender. After the flexible cement was applied, sand was sprinkled over it for better skid resistance on the surface. Nine repairs were made with the Sylcrete products and are listed in Table 3.1. Repair 1 resulted in a rough surface due to improper tooling.

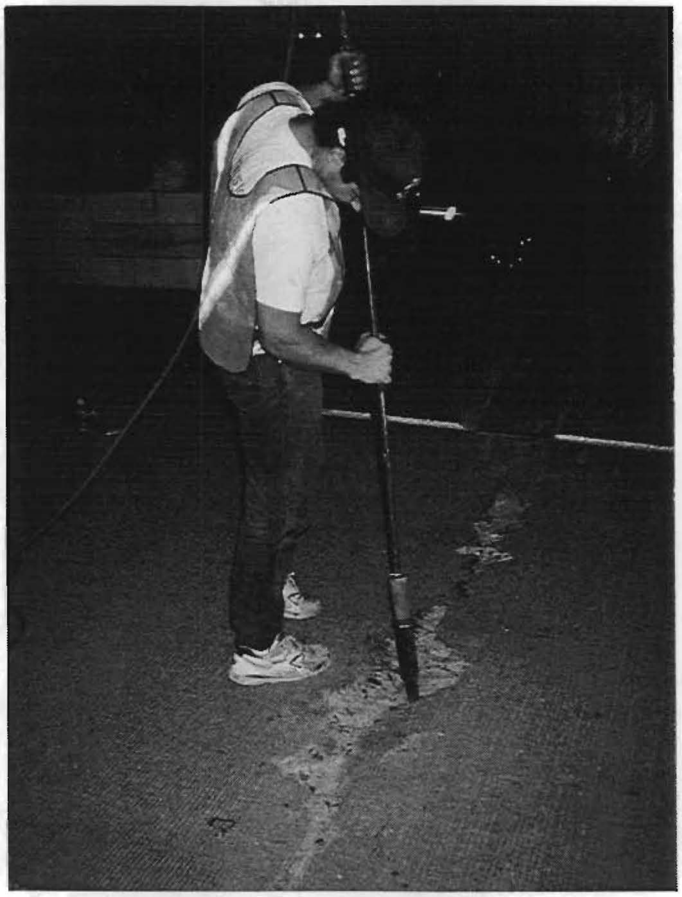

Fig. 3.4. Cleaning Operation Using a Wire-Brush Power Tool.

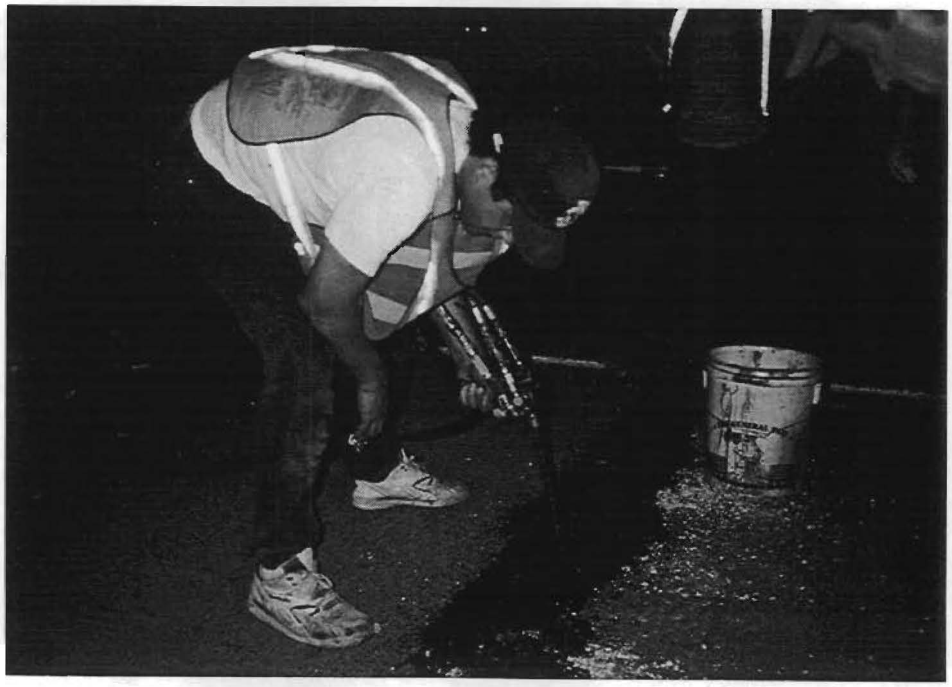

Fig. 3.5. Pouring of the Flexible Cement Over the Mender.

Table 3.1. Spall Repairs with Sylcrete Products.

Patch series number	Distance (m)	Distance (ft.)	Repair material	Lane
1	0	0	mender+flexible cement	Inner
2	10.1	33	mender+flexible cement	Inner
3	13.3	43.5	mender+flexible cement	Inner
4	15.2	50	mender+flexible cement	Inner
5	15.5	51	mender+flexible cement	Inner
6	45.4	149	mender+flexible cement	Inner
7	51.8	170	mender+flexible cement	Middle
8	60.4	198	mender+flexible cement	Middle
9	63.7	209	mender+flexible cement	Middle

3.3. SURVEY OF REPAIRS WITH CEMENT-BASED MATERIALS

The pavement section repaired with Pyramid in BW 8 North was revisited in October 20, 1993, June 16, 1994, and January 20, 1995, to observe the performance of the repairs. The distresses observed included: (1) cracking around the edge of the patch, which may indicate debonding of the repair material from the base concrete along the circumference of the patch (Fig. 3.6); (2) spalling of the repair material; (3) transverse cracking across the patch, which may be a reflection from the crack in the base concrete (Figs 3.7 and 3.8); and (4) map cracking (Fig. 3.6). On the surface of most of the sawcut patches, transverse cracks did not occur, as observed in the survey (Fig. 3.7) done January 20, 1995. A slanting sawcut, as shown in Fig. 3.8, apparently did not control cracking. These transverse cracks in the patch were usually connected with the cracks in the pavement (Figs. 3.7 and 3.8). When the saw cuts were placed along the orientation of the original crack, a zigzag crack still occurred in the surface near the sawcut and basically parallel to the sawcut.

Fig. 3.6. Debonding and Map Cracking Observed on October 20, 1993.

Fig. 3.7. Transverse Cracking and Minor Spalling (January 20, 1995).

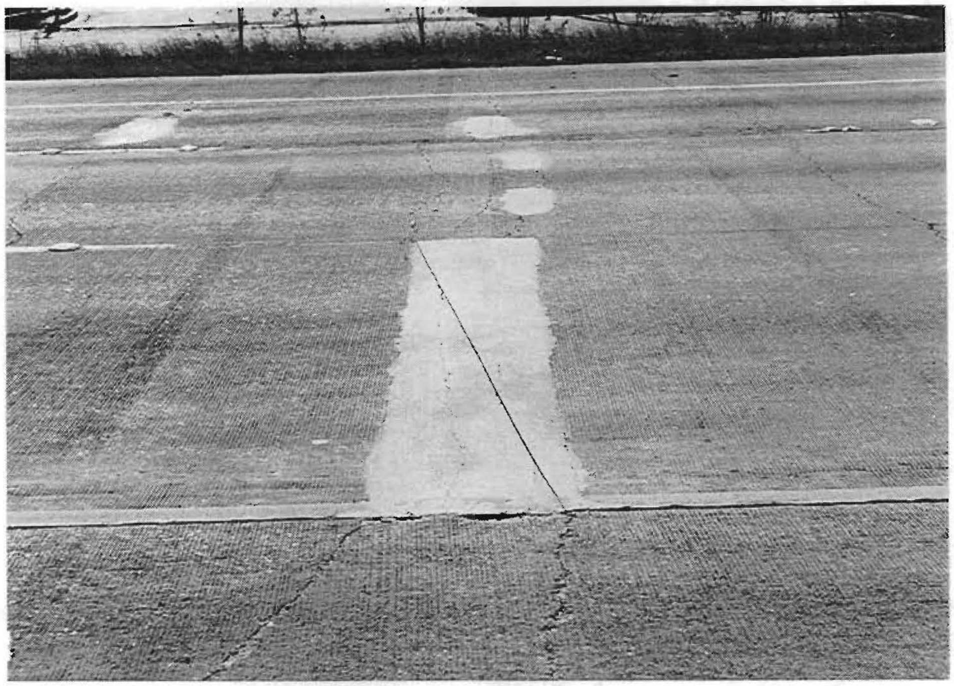

Fig. 3.8. Transverse Cracking and Minor Spalling in a Block Repair (January 20, 1995).

Table A.3 records these observed distresses marked with numbers the 1-4 for the different distresses. In most of the patches, there were apparent map cracking. Map cracking is not recorded in Table A.3 except for those patches where map cracking was severe. Since the outer lane was open to traffic during the inspection, crack width measurements on the Rapid Set patches could not be obtained. In the survey conducted on June 16, 1994, patches 47-84 were not inspected because sudden heavy rainfall interrupted the survey. From Table A.3, it can be seen that distresses in the repairs have gradually developed. However, until January 1995, most of the repairs were still in place and providing adequate performance. Continued performance monitoring of the patches is recommended.

Data for the Pyramid patches where transverse cracks and spalls were observed on October 20, 1993, and January 20, 1995, are summarized in Fig. 3.9 and 3.10, respectively. These figures show the rate of the development of the distresses in the spall repair. The

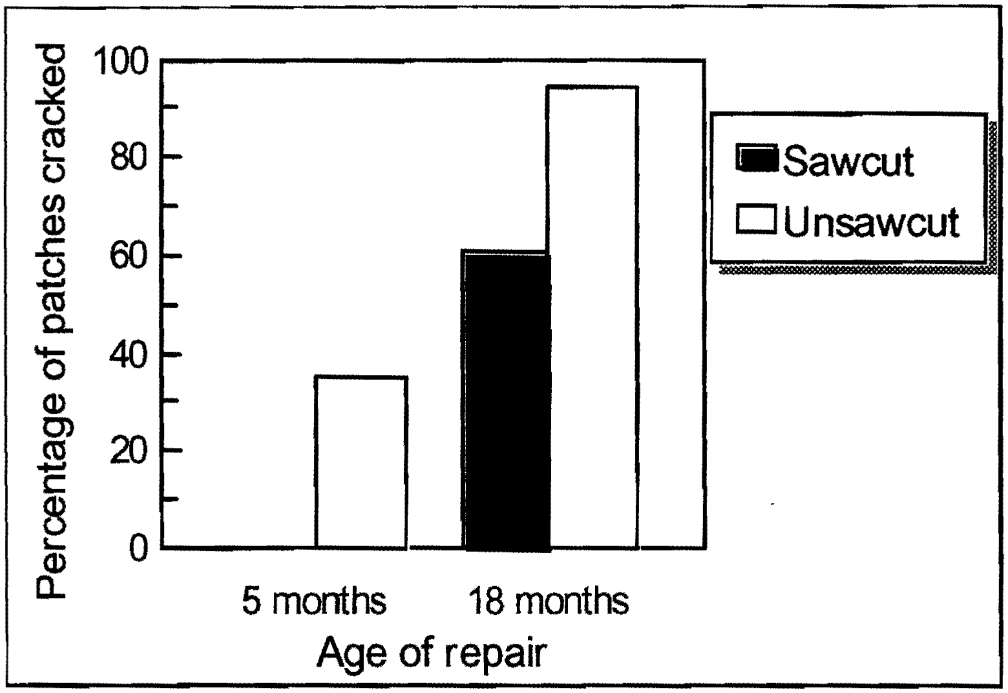

Fig. 3.9. Percentage of the Pyramid Patches Where Cracks Were Observed.

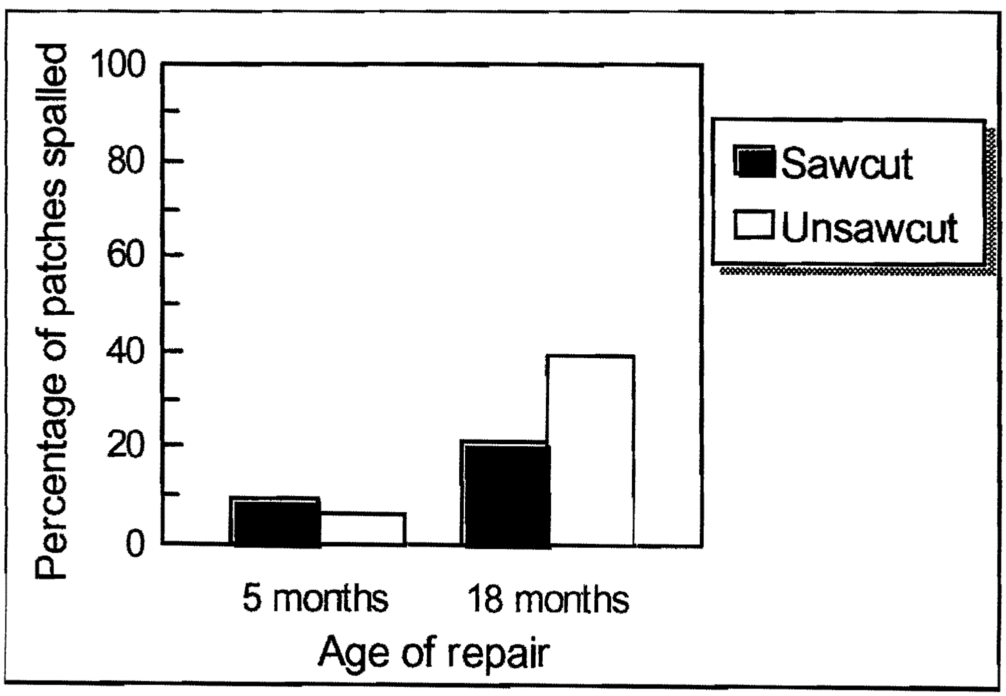

Fig. 3.10. Percentage of the Pyramid Patches Where Spalls Were Observed.

increase in the percentage of spalling in the Rapid Set patches, sawcut and unsawcut, is summarized in Fig. 3.11. The ages of repair shown in the figure are estimated, since the date of the Rapid Set repair in 1993 is not known. It seems that, after two and half years, the percentage of sawcut and unsawcut patches where spalls occurred is similar.

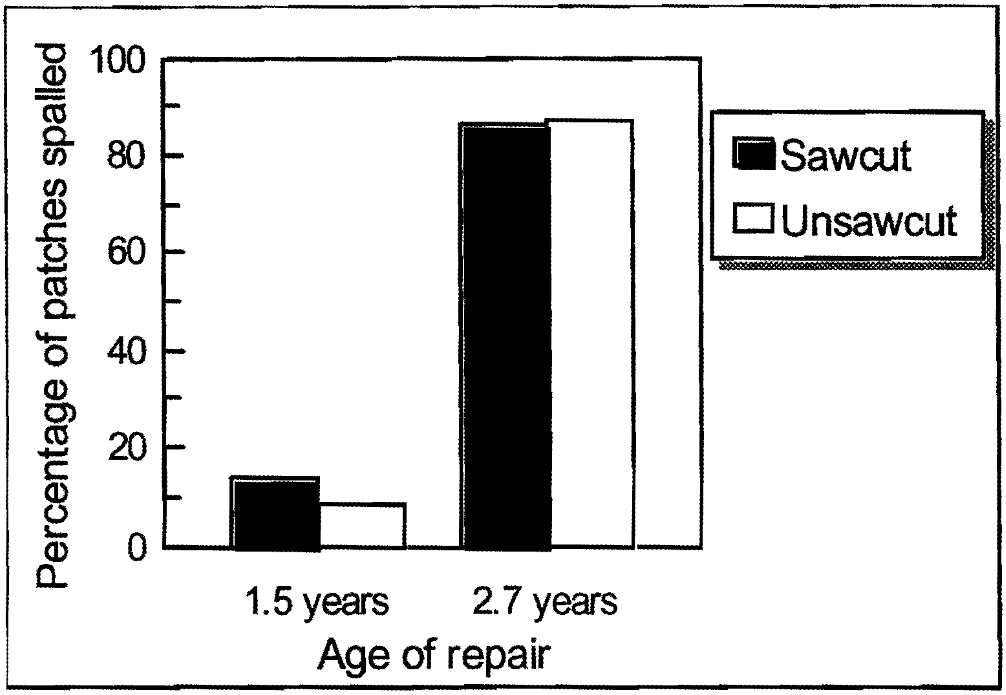

Fig. 3.11. Percentage of the Rapid Set Patches Where Spalls Were Observed.

Although patches 47-87 were not inspected on June 16, 1994, patches 1-46 were carefully observed. Besides visible distresses, debonding of the pavement concrete around each of patches 1-46 was detected by sounding with a hammer. The hollowed area indicates the area of delamination in the pavement (Table 3.5). Because delamination is a major cause of spalling, these hollowed areas are locations of prospective spalls.

Table 3.2. Hollowed Areas Around Patches Repaired with Pyramid.

Patch series No.	Distance from the lane edge (cm)	Width (cm)	Length (cm)
1	89	15	30
13	274	45	43
21	244	13	15
22	185	15	28
24	102	15	66
31	64	20	38
34	241	13	15
44	46	15	15
46	284	15	15

3.4. SURVEY OF REPAIRS WITH POLYMER-BASED MATERIALS

The pavement sections repaired with Flamecoat products and Sylcrete products in BW 8 North were also surveyed on October 20, 1993, June 16, 1994, and January 20, 1995. On October 20, 1993, three months after placement of Flamecoat products, distresses had occurred in most of these patches. The most general distress was stripping of the repair material. These peeled pieces of repair materials were easily torn off by hand. Figs. 3.12-3.14 show damages in repairs made with three different Flamecoat products, PF113-H101, PH100, and PR111-H101. On June 16 1994, many patches were missing. The material had turned very stiff and contained numerous microcracks. The material PH100 showed good adhesion at the boundaries of the repairs. The stripping was predominant in all the sections repaired by the material PR111-H101, except at repair locations 27 and 29. According to the inspection on January 20, 1995, the material PF113-H101 (for repairs 1-10) and the material PR111-H101 (for repairs 21-31) were completely peeled off, while the material PH100 (for repairs 11-20) was severely cracked and spalled except for repairs 13-15, where there was minor cracking, spalling and debonding.

Up until the last survey on January 20, 1995, all the repairs with Sylcrete mender and flexible cement had no apparent damage except at repair location number 1, where a rough

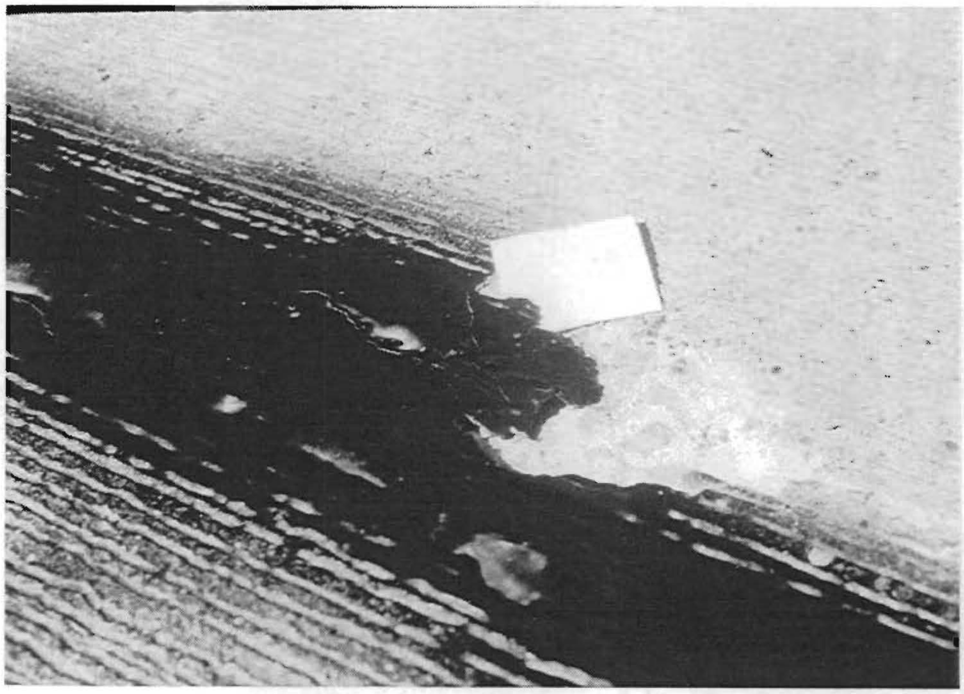

Fig. 3.12. Repair No.6 with Flamecoat PF113-H101 Observed on October 20, 1993.

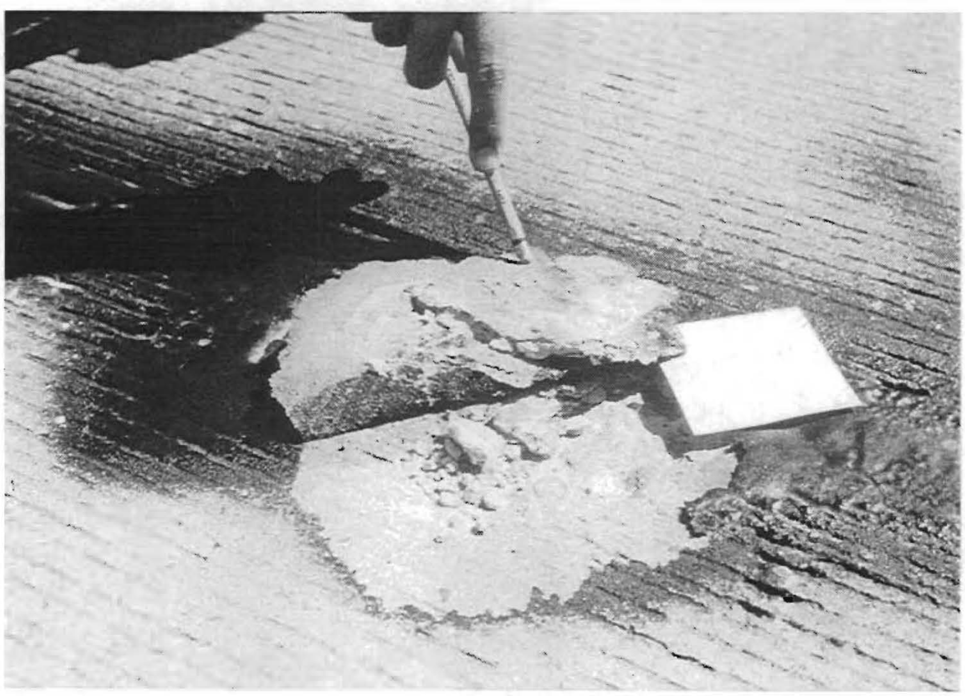

Fig. 3.13. Repair No.16 with Flamecoat PH101 Observed on October 20, 1993.

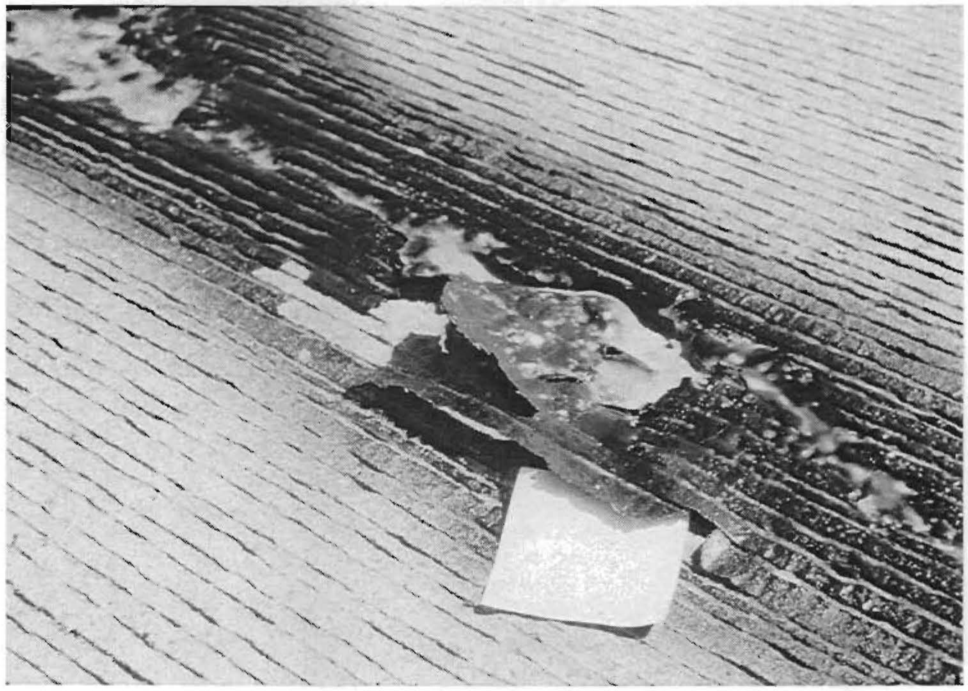

Fig. 3.14. Repair No.28 with Flamecoat PR111-H101 Observed on October 20, 1993.

surface finish was caused by improper finishing. Fig. 3.15 shows a Sylcrete product repair with no visible damage. It is worthwhile to note here that the spall repairs using Sylcrete mender on I-59 in the Rosenburg area had completely failed shortly after the repair was complete. Sylcrete flexible cement appears to be a better pavement material because of its lower modulus, although the material manufacturer recommends the mender for concrete repair. Pavement around these Sylcrete product repairs was sounded by hammering. Some hollowed areas were found and are noted in Table 3.3.

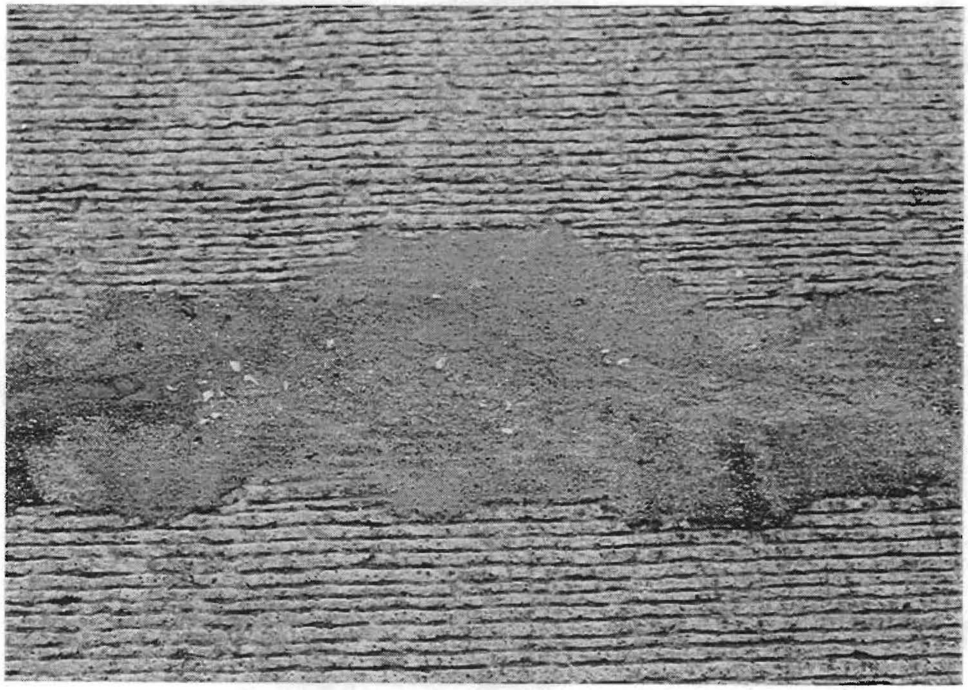

Fig. 3.15. Sylcrete Repair with No Distress Observed on January 20, 1995.

Table 3.3. Hollowed Areas Around Patches Repaired with Sylcrete.

Patch series No.	Distance from the lane edge (cm)	Width (cm)	Length (cm)
6	198	15	15
7	43	15	15
8	137	15	15
9	122	15	60

3.5. CONCLUSIONS

Some preliminary conclusions were obtained from the field monitoring of the pavement repairs. They are summarized as follows.

(1) Spall repairs with Pyramid, a cement-based repair material, on BW 8 North in Houston, have been monitored for more than one and a half years since placement. All the repairs have remained in place. However, spalls in these patches have been redeveloping.

Besides some minor spalls and other distresses, most of the patches have cracked transversely. In contrast, spall repairs with Rapid Set in the test section on BW 8 of West Houston were more effective (See Chapter 4.). It is possibly because water was sprayed over these repairs on BW 8 of West Houston but neither water nor any curing compound was used for the test section on BW 8 of North Houston. Curing is an important factor for durable repairs.

(2) Spall repairs with Rapid Set, another cement-based repair material, have been observed also. These repairs are about one year older than the monitored Pyramid repairs. Some Rapid Set repairs have spalled. After two and a half years of service, spalls have occurred in more than eighty-five percent of the patches, whether saw cut or not. Accompanying with most of the new spalls is transverse cracking of the repair.

(3) Visible distresses observed in the cement-based material repaired patches include debonding of the patch from the base concrete pavement, transverse cracking, spalling, and map cracking. Pavement around some patches was sounded, indicating delamination. It is important to note debonded areas that may eventually cause the repair to fail.

(4) Plastic Flamecoat products are not suitable for use as spall repair materials. Spall repairs with Flamecoat products started to show damage at very early ages.

(5) Polymer-based materials, Sylcrete mender and flexible cement (products of Percot), can be used for pavement repair. After more than one and a half years, no damage was seen on the repairs with these materials. However, delaminated areas in the pavement around these patches have been detected. How these delaminated areas will affect the performance of the polymer patch is uncertain. Continued monitoring is recommended.

CHAPTER 4: EVALUATION OF SPALL REPAIRS IN BW 8 WEST

4.1. REPAIRS WITH CEMENT-BASED MATERIALS ON BW 8 WEST

Spalls in a pavement section on the southbound frontage road of BW 8 in West Houston, from Station 364+00 to Station 356+00, approximately 236 m (775 ft.) long, were repaired on October 27, 1993. Two cement-based repair materials, Rapid Set Concrete Mix and Quikrete Fast-Setting Concrete, were used. Both of the materials were mixed with Supercrete (a fluid admixture). After placing the mixture in the spalling areas, Supercrete GPS sealer was sprayed on the repair patches.

Fig. 4.1 shows the layout of the repair section with the station numbers. Part A was repaired with Rapid Set, and Part B was repaired with Quikrete. Part A was 168 m (550 ft.) long while Part B was 65 m (212 ft.) long. Repairs were only performed in the outer and middle lanes of the three-lane frontage road. Loose aggregates in the spall areas were taken

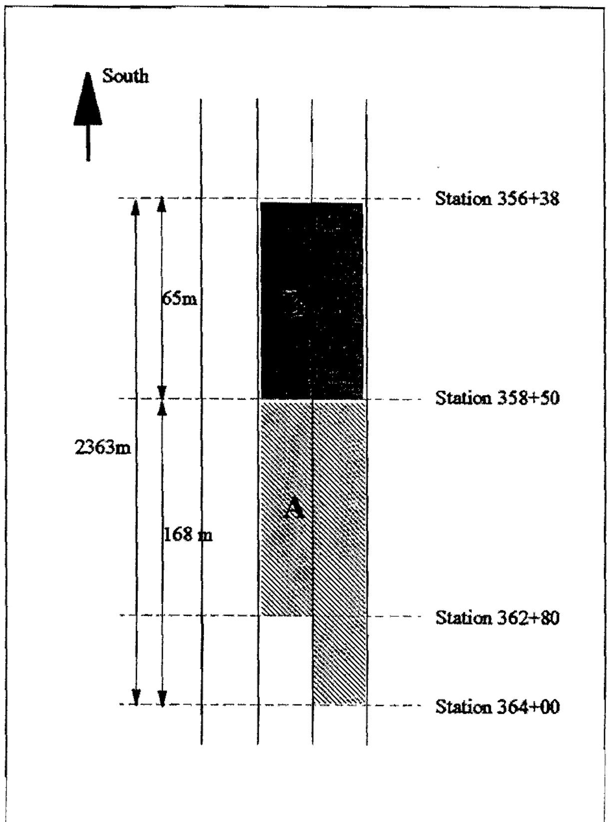

Fig. 4.1. Layout of the Repair Section on the Southbound Frontage Road of BW 8 West.

with a jack hammer. Fig. 4.2 is a view of the repair section after the spalls are "cleaned." The repair material was immediately delivered to and poured to the spalls after mixing (Fig. 4.3). Then water was sprayed over all the repairs for curing. In some of the repairs, a cut was made about half an hour after material placing to induce a controlled crack. Different from the conventional method of saw cutting used in the repair section reported in Chapter 3, the saw cut in this section was made much earlier with the early-aged method of saw cutting, so that the saw blade did not need water cooling. The depth of the cut was 19 to 25 mm (3/4 to 1 in.). In order to observe the effect of saw cut, about half of the spall repair patches were cut while the remainder were not cut. Figs. 4.5 and 4.6 illustrate the same spalled area before the repair material was filled and after the repair was completed. The saw cut was oriented in the direction of the direction of the original transverse crack in the existing pavement (Fig. 4.7).

Fig. 4.2. A View of the Repair Section After the Spalls Were Cleaned.

Fig. 4.3. Placing of Repair Mixture.

Fig. 4.4. Saw Cutting.

Fig. 4.5. Spalling Spots Before Filling of Repair Mixture.

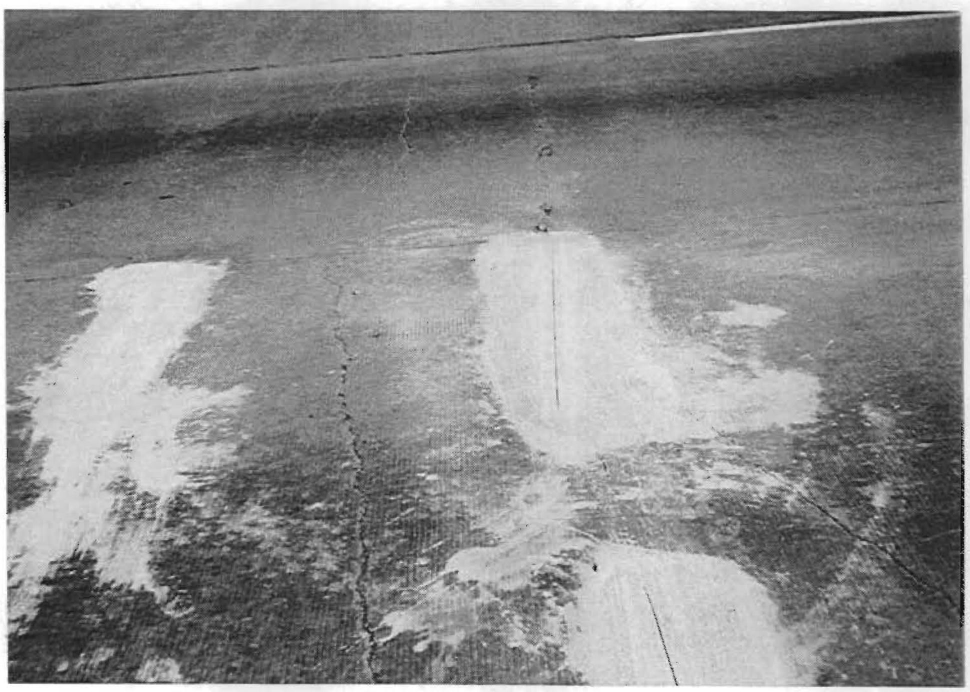

Fig. 4.6. Spalling Spots After Repairing and Saw Cutting.

Fig. 4.7. An Extended Spall Repair with a Saw Cut.

Information about each repair, including the repair material used is recorded in Table A.4 (shown in Appendix: Test Data) with the repair located by the distance from Station 364+00, or the north end of the section.

4.2. SURVEY OF REPAIRS ON BW 8 WEST

Repairs reported in this section were inspected on June 9, 1994, and again on January 4, 1995. The length of this section was shorter than the repair section with Pyramid on BW 8 North. In addition, the traffic was not as heavy as in BW 8 North. Therefore, traffic control provided sufficient inspection time for closer observation. Distresses observed in this test section were grouped into three types: (1) apparent spalling (Fig. 4.8); (2) transverse cracks nearby the saw cut (Fig. 4.9); (3) transverse cracks through the uncut patch (Fig. 4.10); and

(4) cracking around the edge of the patch. Tables A.5 and A.6 (in Appendix: Test Data) show the inspection records for Rapid Set and Quikrete repairs, respectively. "No" in the columns for distress types indicates that no distress was noted, except for some minor map cracks (Fig. 4.11). From Table A.5, it is seen that, in the patches repaired with Rapid Set, no spalling had occurred fourteen months after repairing and very few cracks had occurred along the patch edge. It can also be seen that the early saw cut controlled transverse cracking in the first seven months according to the survey done on June 9, 1994, but transverse cracks in saw cut patches were observed in the survey done on January 4, 1995, indicating that transverse cracks developed seven months after repair. However, it was noted during the survey that transverse cracks had been formed near the saw cut. These transverse cracks were basically parallel to the saw cuts. All the distresses observed were minor. Unlike the Rapid Set repairs, Quikrete repairs cracked earlier. The distresses observed in January 1995 had been initiated and developed in June 1994. A transverse crack occurred in almost every patch regardless of whether there was a saw cut or not. The transverse crack in the saw cut patch was always very close to the saw cut and in a similar orientation. The material between the saw cut and

Fig. 4.8. Repair No. 28: Minor Spalling Along The Saw Cut (January 4, 1995).

Fig. 4.9. Repair No. 5: A Transverse Crack Near the Saw Cut (January 4, 1995).

Fig. 4.10. Repair No. 37: A Transverse Crack on the Uncut Patch (January 4, 1995).

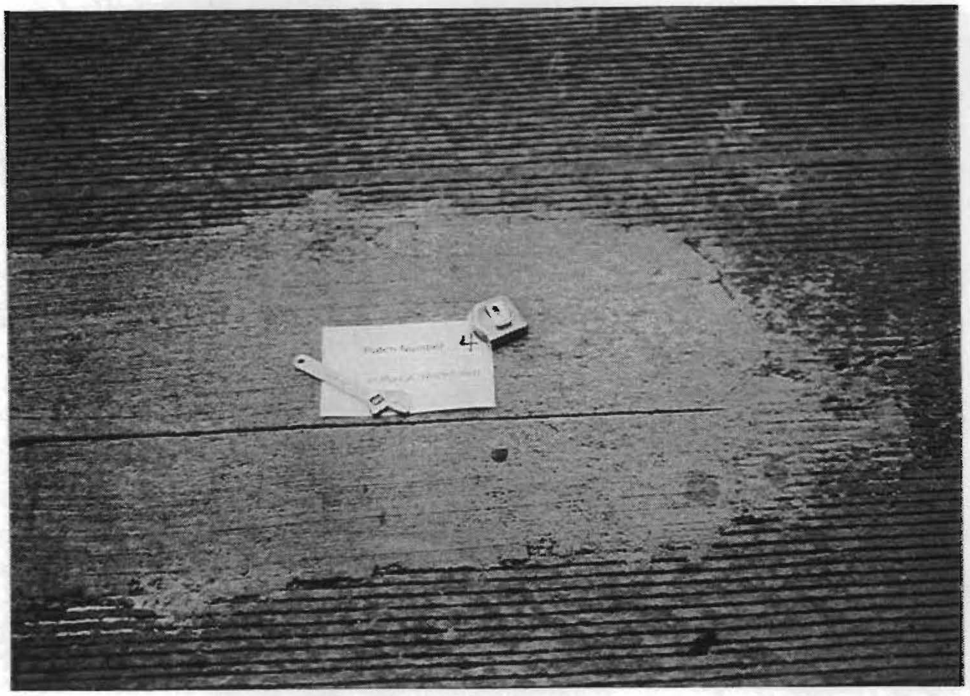

Fig. 4.11. Repair No. 4: No Random Crack on a Saw Cut Patch (January 4, 1995).

and the crack parallel to the saw cut would easily spall. Spalls were found in every saw cut patch of Quikrete. The laboratory tests reported in Chapter 2 have shown that Quikrete has a much lower strength than Rapid Set. Data in Tables A.4 and A.5 for transverse cracks concerning the development of transverse cracks observed in the test section are summarized in Figs. 4.12 and 4.13. Fig. 4.12 presents the development of transverse cracks in the uncut patches, while Fig. 4.13 presents the development of transverse cracks in the saw cut patches. Comparing these two charts, one finds that the saw cut did not control transverse cracking.

4.3. CONCLUSIONS

Some preliminary conclusions for the pavement spall repair on BW 8 West are as follows:

(1) Two cement-based repair materials, Rapid Set Concrete Mix and Quikrete Fast-Setting Concrete, were used to repair spalls of concrete pavement in a test section on the southbound frontage road of BW 8 in West Houston. All the patches were still in place

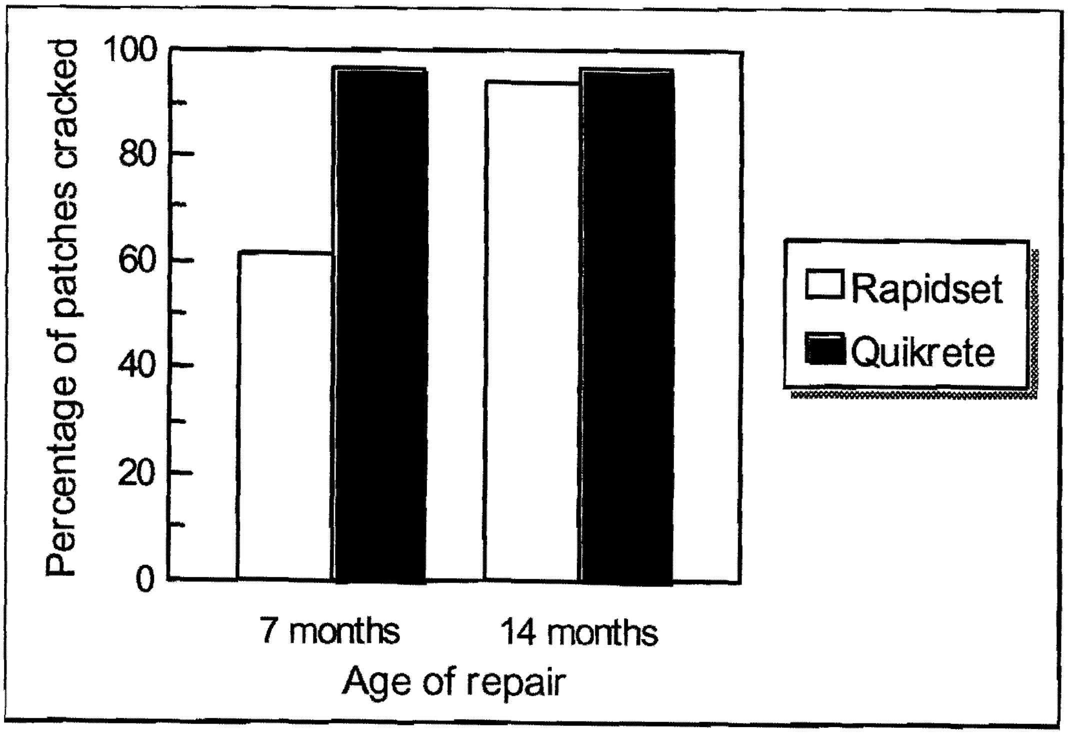

Fig. 4.12. Percentage of Uncut Patches Where Transverse Cracks Occurred.

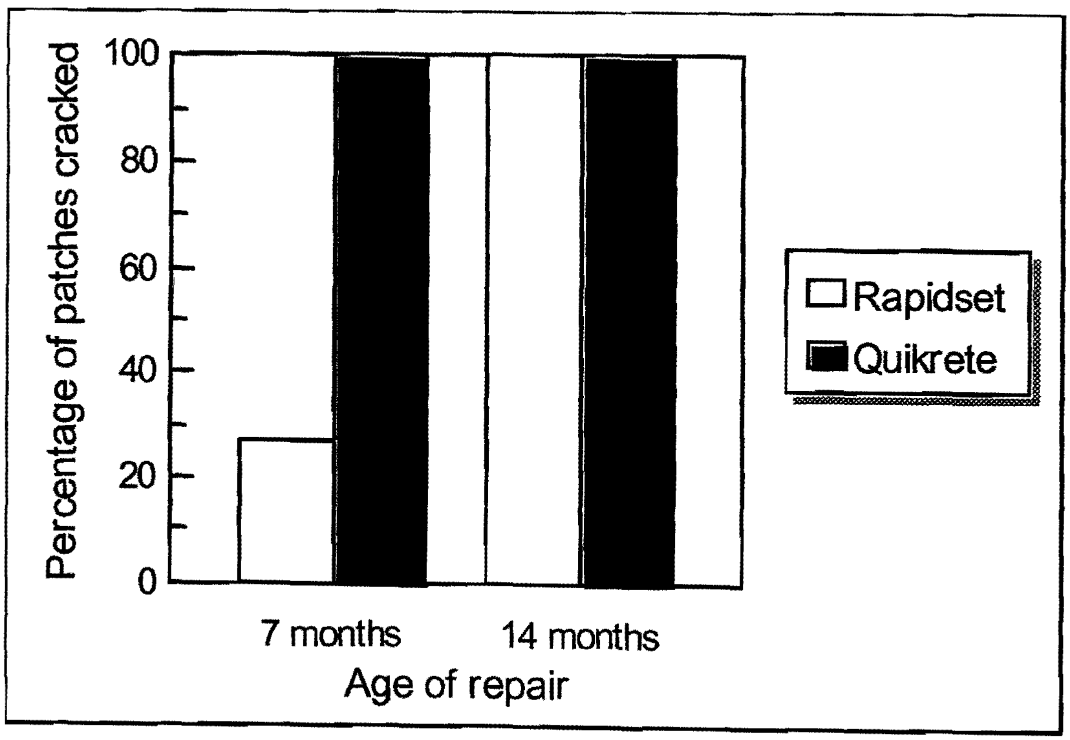

Fig. 4.13. Percentage of Saw Cut Patches Where Cracks Occurred Parallel to the Saw Cut.

fourteen months after placement, although cracking and minor spalling had started. This is possibly because all the repairs in this test section were cured by sprayed water. In contrast, neither water nor any curing compound was used for spall repairs in the pavement section on BW 8 in North Houston (See Chapter 3.), where repairs were seriously damaged. Curing is a very important measure for making durable repairs.

(2) In the Rapid Set patches that were saw cut by the early-aged method of saw cutting, transverse cracking did not occur in the first several months. After fourteen months, transverse cracking occurred in almost every Rapid Set patch, regardless of whether the patch was saw cut or not. However, no spalling of the patches was observed.

(3) Quikrete manifested lower strength than Rapid Set. Transverse cracking was observed in every Quikrete patch seven months after the repair job. In the saw cut patches, a transverse crack paralleled the saw cut. Spalling was not observed seven months after the repair. However, spalling was observed fourteen months after the repair in every Quikrete patch that was saw cut while spalling was not observed in any uncut Quikrete patch at that time.

(4) For low-strength repair material, such as Quikrete, saw cutting is not suggested. The effect of saw cut on crack control needs to be further investigation by continued monitoring; distresses in saw cut and uncut patches of Rapid Set should be closely inspected and compared.

(5) Although Rapid Set showed greater strength than Quikrete, Rapid Set did not exhibit better performance until fourteen months after placement. This indicates that the strength of the repair material might not necessarily be important, but the bond strength of the repair material to base concrete is a more important factor for repair performance. (See Chapter 5 about the bond strength of these repair materials to base concrete.)

CHAPTER 5: FIELD TESTS OF REPAIR MATERIALS

5.1. FIELD TESTS ON THE TEXAS A&M UNIVERSITY RIVERSIDE CAMPUS

Spall repair materials were evaluated in the field in Chapters 3 and 4, in terms of distress development. However, it should be pointed out that performance of these repairs largely depends on their debonding behavior at the early ages, because debonding initiates spalling. In order to investigate early age bond strength of repair materials to existing concrete pavement and the factors influencing the strength, a series of field tests were conducted on the Texas A&M University Riverside Campus in Bryan, Texas, during August 1995.

In this field test program, two cement-based repair materials, Rapid Set Concrete Mix and Quikrete Ready-Mix Concrete were evaluated, were evaluated. These two repair materials had been tested in the laboratory in terms of setting times, compressive and flexural strengths, bond strength (i.e., shear strength), and fracture toughness at different levels of temperature and humidity (Chapter 2). The test program described herein consisted of specially prepared bonded overlays on individual test slabs. The slab surface, preparation and temperature and curing conditions were controlled in order to determine the effects of these factors on early-aged bond behavior. All the overlays were 0.61-m (2 ft.) wide, 3.66-m (12 ft.) long and 25 mm (or 1 in.) thick and were placed on clean, dry surfaces. The test program was conducted over a short period of time with some placed in the morning and some placed in the afternoon to examine the effects of placement at different ambient temperatures. Two curing methods were used. One method was no curing protection; that is, the overlay was exposed to the ambient conditions with no curing compound during the hardening process. The other curing method involved spraying type II liquid membrane-forming curing compound on the overlay after placement. The curing compound forms a liquid membrane over the concrete surface, which reduces the loss of water during the early hardening period. The type II curing compound is white pigmented, which also reduces the temperature rise in concrete exposed to radiation from the sun. Fig. 5.1 illustrates the layout of the individual concrete pavement test slabs on the Texas A&M University Riverside Campus. The shaded

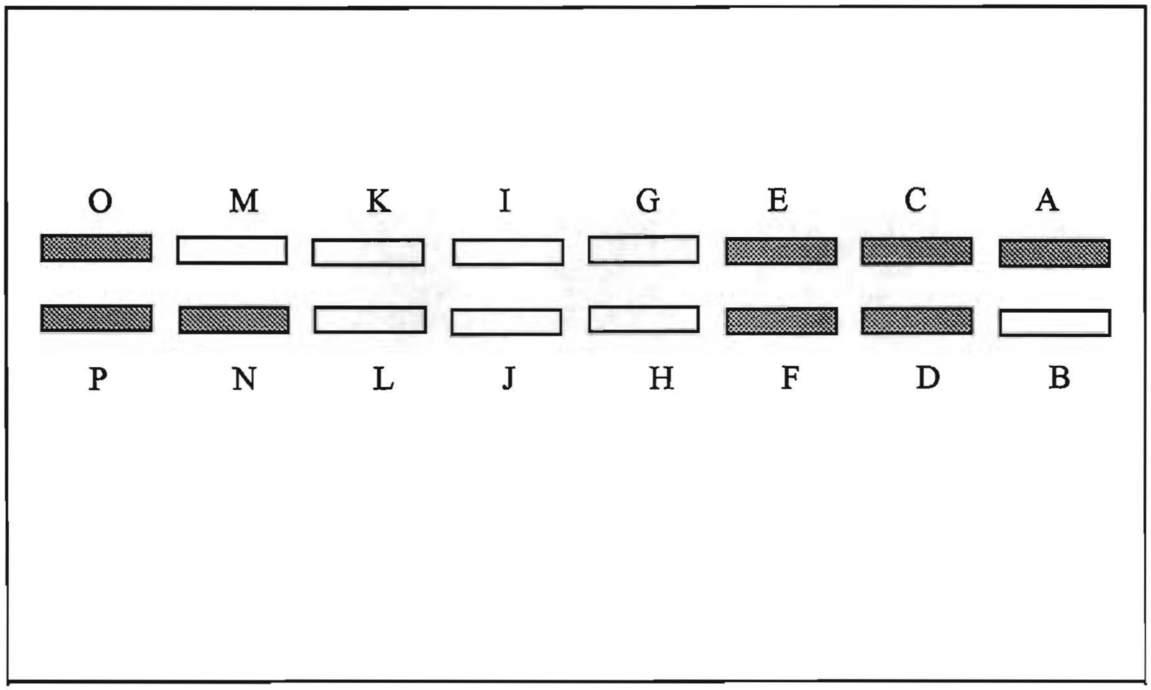

Fig. 5.1. Layout of the concrete pavement slabs on the Texas A&M University campus.

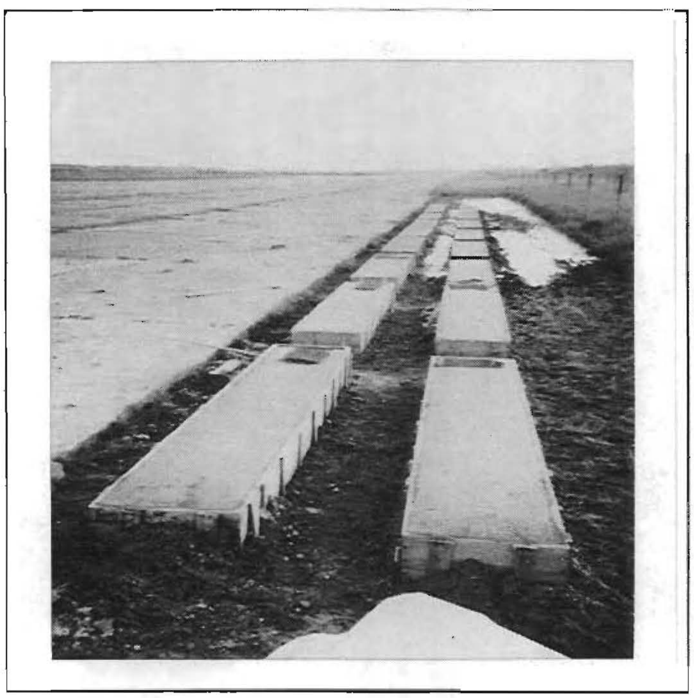

Fig. 5.2. A view of the concrete pavement slabs.

Fig. 5.3. Appearance of the pavement surface before placement of overlay.

rectangles represent the slabs that were used in this field test program. Fig. 5.2 shows a view of these slabs and Fig. 5.3 shows the appearance of the pavement surface ready to be overlaid.

The test conditions are listed in Table 5.1. In the table, "strength" means shear strength of the bond of the repair material to the concrete pavement surface, which was measured by a torsional device described below. Temperature in the repair material was measured by thermocouples. "Moisture" indicates pore relative humidity, which was determined based on readings by a dew point reader. The dew point temperatures were calculated to relative humidity.

5.2. TORSION DEVICE FOR MEASURING BOND SHEAR STRENGTH

A torsional test device (torque wrench) was used to measure shear strength of the bonding of the repair material to the concrete pavement surface. This equipment was originally developed at the Center for Transportation Research (CTR), the University of

Table 5.1. Test Conditions.

Test No.	Pavement slab No.	Repair material	Design factors		Measurement		
			Placement	Curing	Strength	Temperature	Moisture
1	E	Quikrete	Afternoon	Type II	Yes	Yes	Yes
2	P	Quikrete	Morning	Type II	Yes	Yes	Yes
3	O	Quikrete	Afternoon	Natural	Yes	Yes	Yes
4	A	Quikrete	Morning	Natural	Yes	Yes	No
5	F	Rapid Set	Afternoon	Type II	Yes	Yes	No
6	D	Rapid Set	Morning	Type II	Yes	Yes	No
7	N	Rapid Set	Afternoon	Natural	Yes	Yes	Yes
8	C	Rapid Set	Morning	Natural	Yes	Yes	No

Texas at Austin, for measurement of overlay bond strength (Whitney et al., 1990), but was modified considerably to allow for early-aged measurements.

Fig. 5.4 illustrates the complete assembly of the torsional equipment. The PVC sleeve isolates a cylindrical portion of the overlay so that, when the torque wrench is slowly rotated, the torque is delivered to the interface between the overlay and the existing concrete pavement slab surface. The maximum torsional shear stress over the interface can be calculated based on mechanics of materials:

$$\tau_{max} = \frac{M}{J}\frac{d}{2}$$

where M is the torque, d is the diameter of the cylindrical overlay segment, and J is the polar moment of inertia, which can be calculated with the following equation:

$$J = \frac{\pi d^4}{32}$$

The torque can be read from an indicator on the torsional test device. The diameter of the cylinder d is 102 mm (4 in.). When the overlay interface fails, the reading M reaches its maximum value. Therefore, the torsional shear strength can be calculated from the maximum value of M.

Torsional shear strength was measured at the center and edge of the concrete overlay. For each overlay, six test locations were established at the center, and six at the edge of the slab. Fig. 5.5 shows a typical overlay, with locations of shear tests illustrated. Shear strength at both the center and edge of the concrete overlay was measured six times within 48 hours

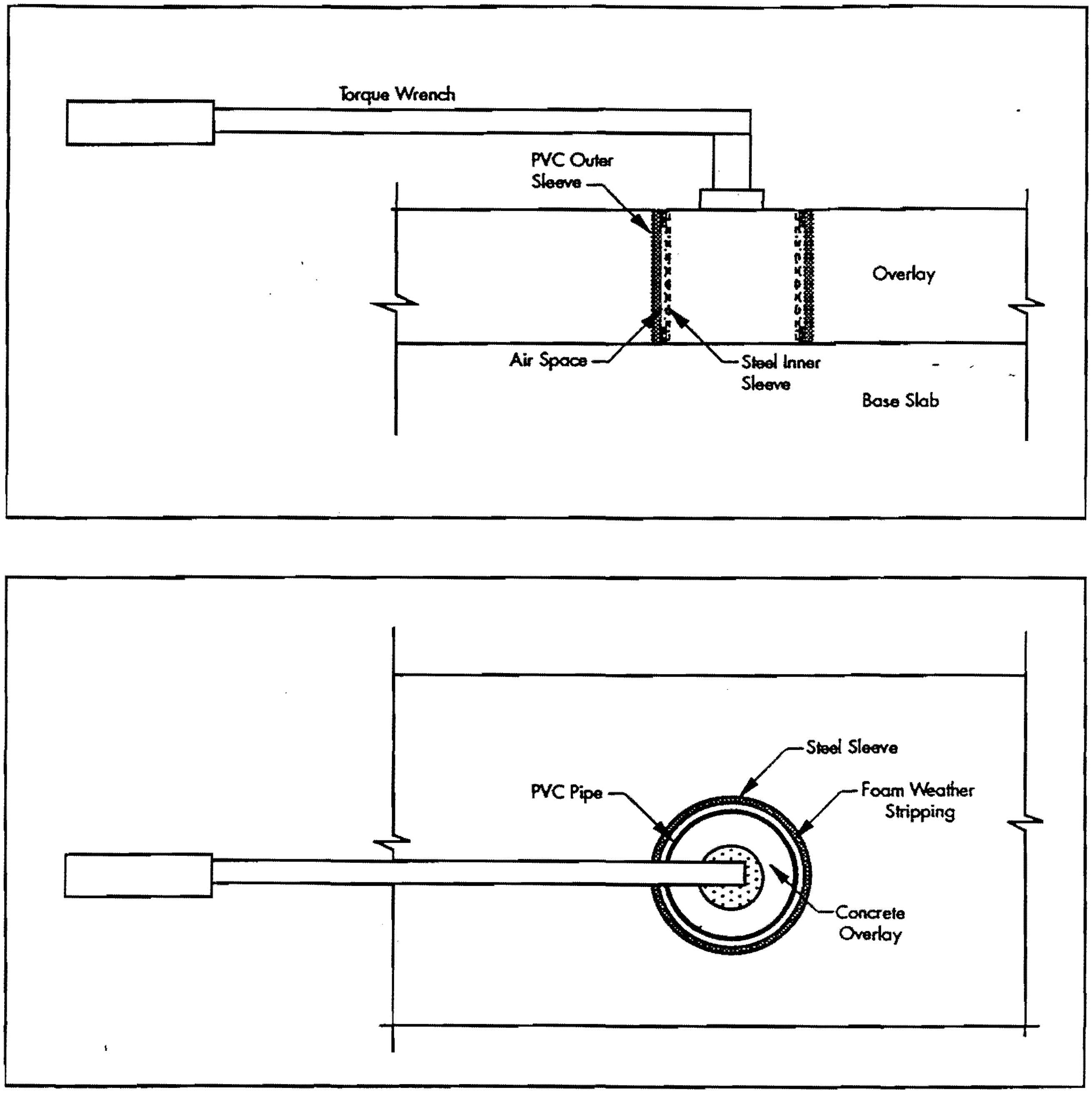

Fig. 5.4. Torsion Test Equipment Showing Complete Assembly (from Whitney et al., 1990).

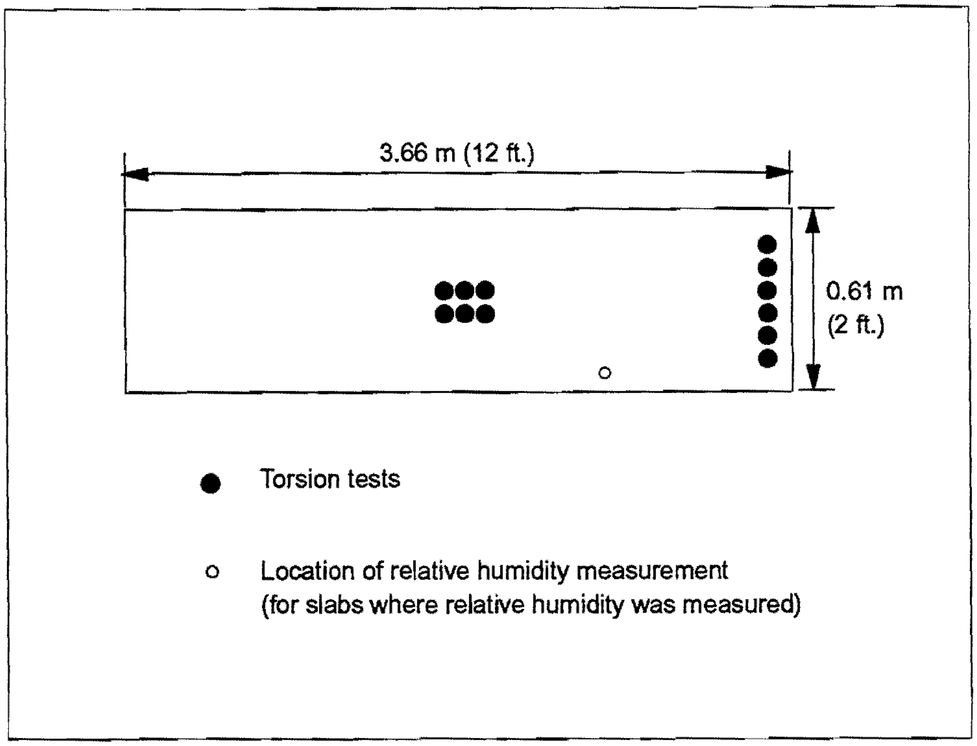

Fig. 5.5. Locations of Measurements in the Overlay.

48 hours after the overlay was placed. The six tests were planned at one, three, eight, 12, 24 and 48 hours, respectively, but some tests were not conducted at the exact planned time due to unexpected delays in the field. Actual test times are reported in the following section.

Whitney, et al. (1990) reported that results of the tests using the torsional test device they developed had a high coefficient of variation (greater than 50 %). Also, the capacity of the torque wrench (271 m-N or 200 ft.-lb.) may limit the use of this equipment (Lundy, et al., 1991). In this test program, it was noted that the capacity of the torque wrench was sufficient for measuring the torsional shear strength within 48 hours after placement and that careful operation of the test equipment results in data with very little variation.

5.3. TEST RESULTS

Development of shear strength for each overlay is shown in Fig. 5.6 to 5.13, which are plotted based on the field tests. More data from the tests, including all the measurements

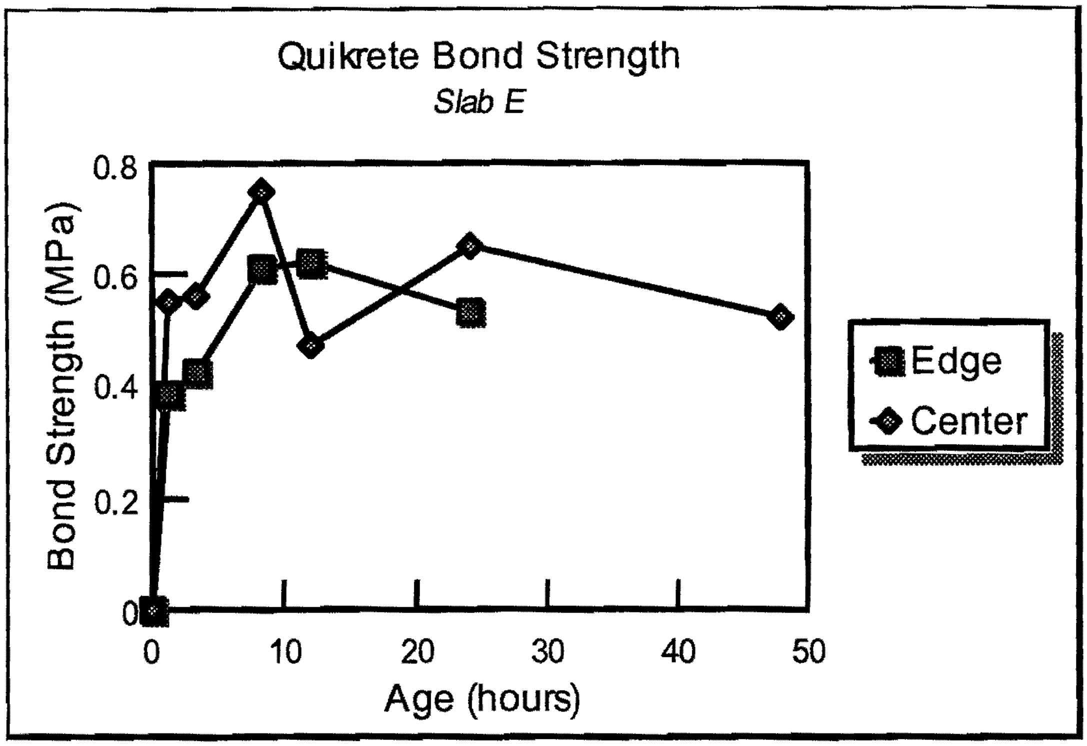

Fig. 5.6. Development of Shear Strength of Bonding in Test 1 (Quikrete on Slab E), Placed in the Afternoon and Cured with Type II Curing Compound.

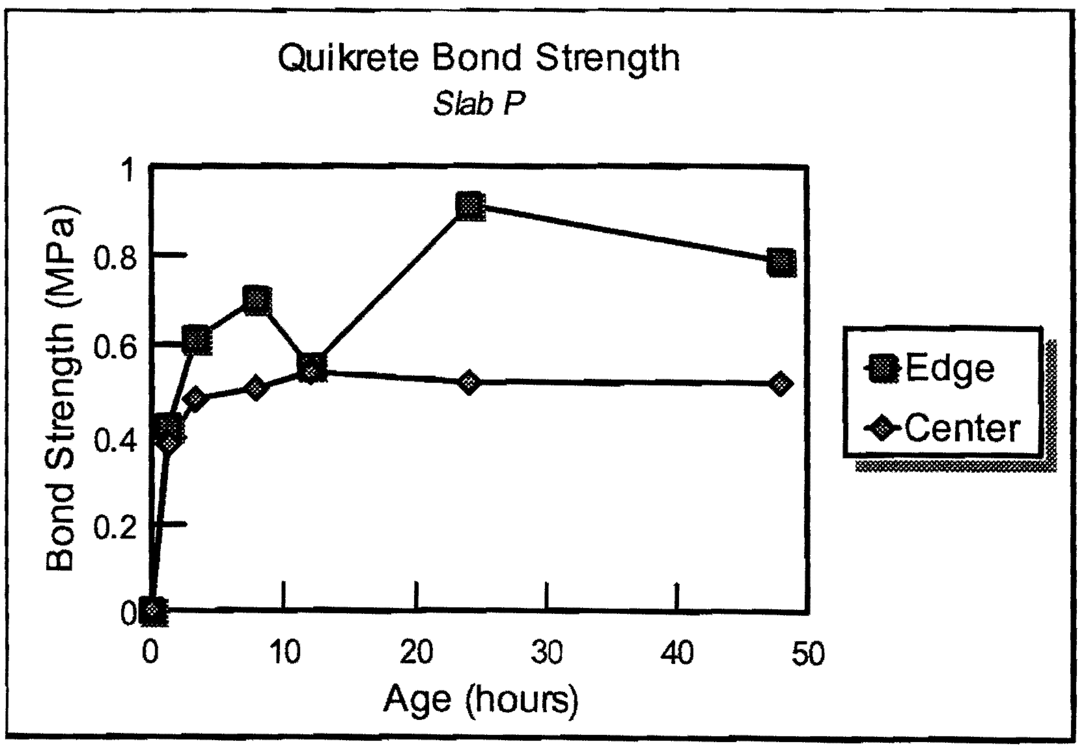

Fig. 5.7. Development of Shear Strength of Bonding in Test 2 (Quikrete on Slab P), Placed in the Morning and Cured with Type II Curing Compound.

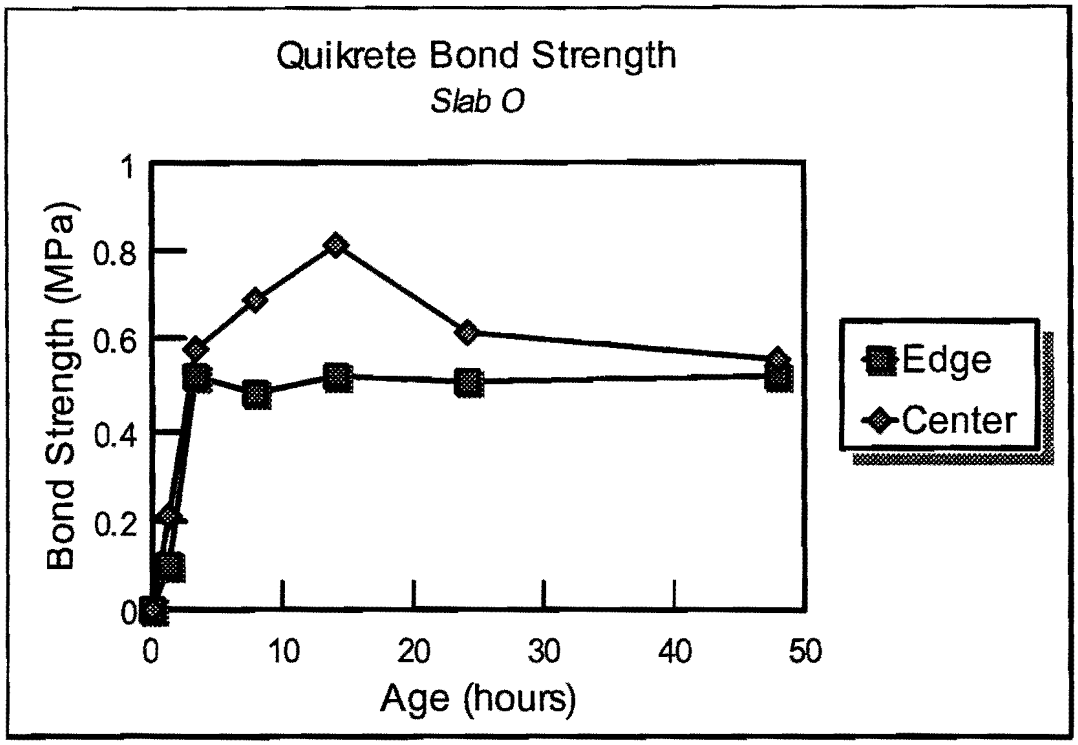

Fig. 5.8. Development of Shear Strength of Bonding in Test 3 (Quikrete on Slab O), Placed in the Afternoon and Cured Naturally.

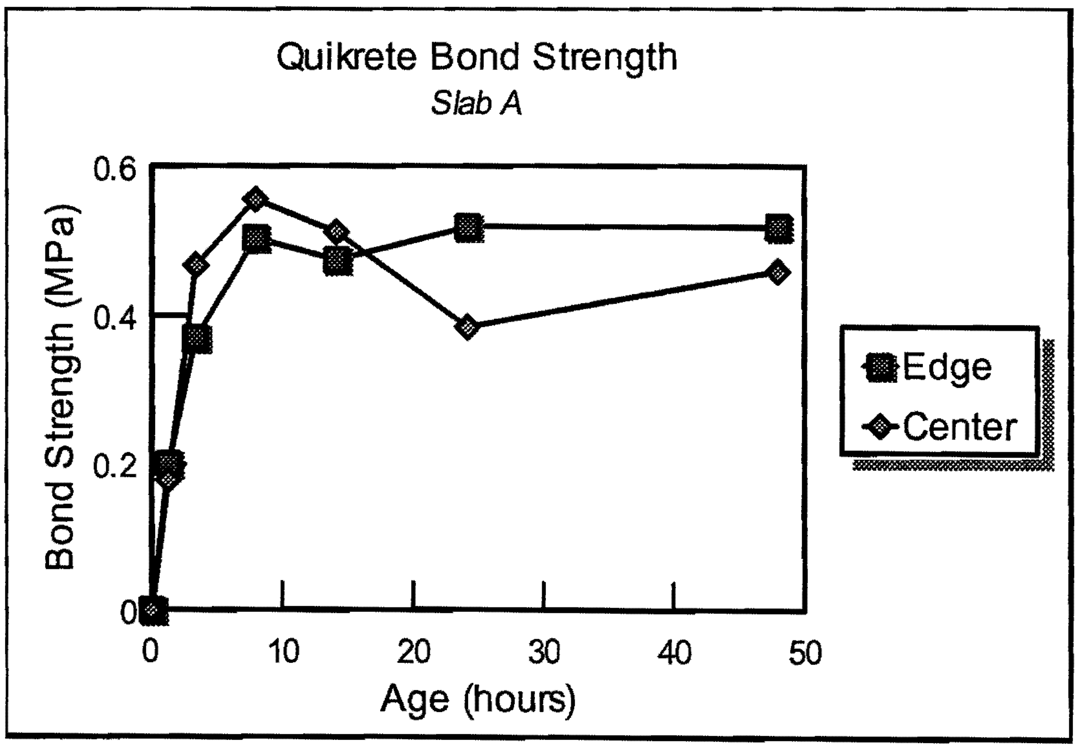

Fig. 5.9. Development of Shear Strength of Bonding in Test 4 (Quikrete on Slab A), Placed in the Morning and Cured Naturally.

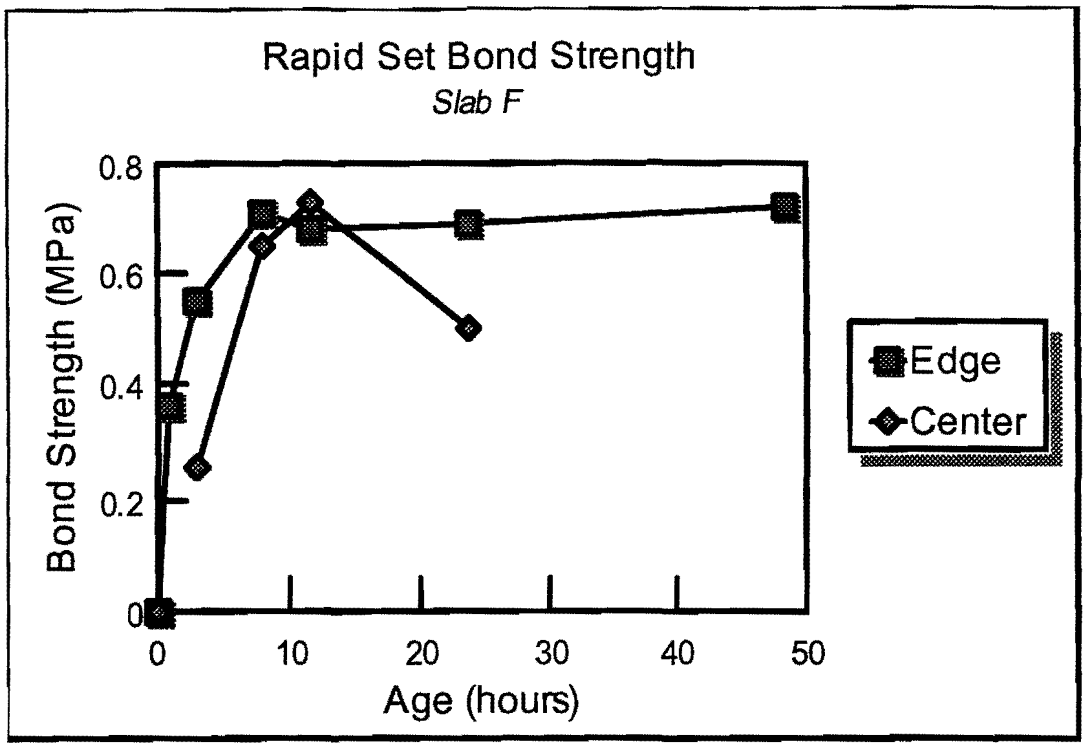

Fig. 5.10. Development of Shear Strength of Bonding in Test 5 (Rapid Set on Slab F), Placed in the Afternoon and Cured with Type II Curing Compound.

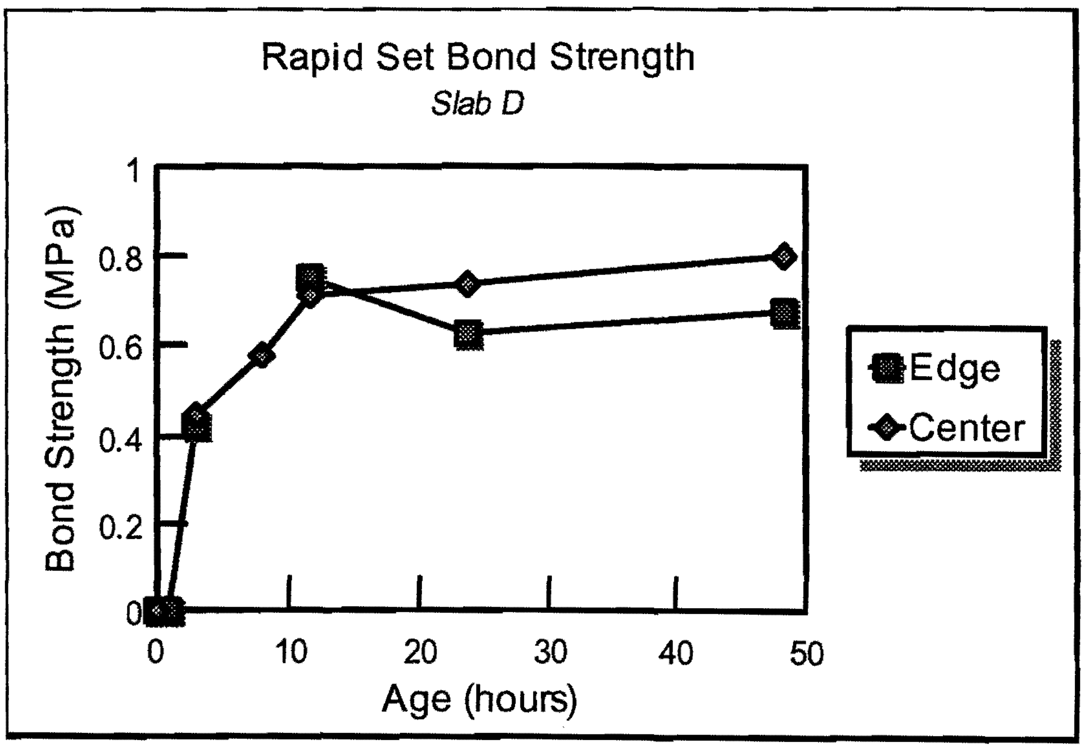

Fig. 5.11. Development of Shear Strength of Bonding in Test 6 (Rapid Set on Slab D), Placed in the Morning and Cured with Type II Curing Compound.

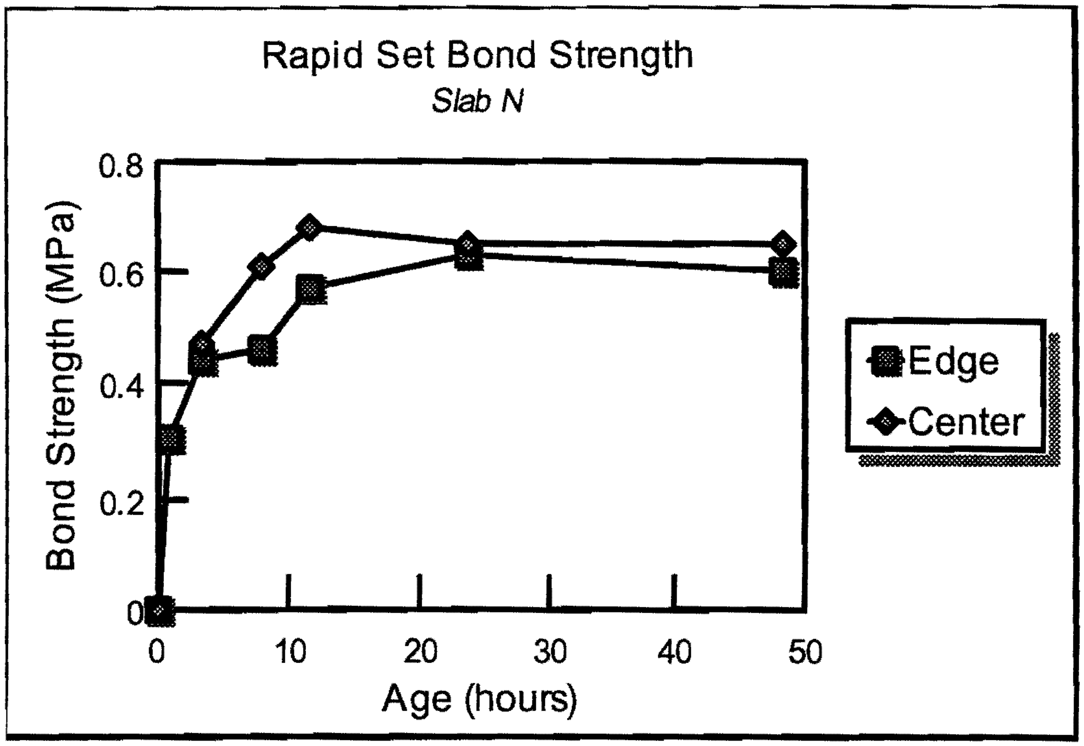

Fig. 5.12. Development of shear strength of bonding in Test 7 (Rapid Set on Slab N), placed in the afternoon and cured naturally.

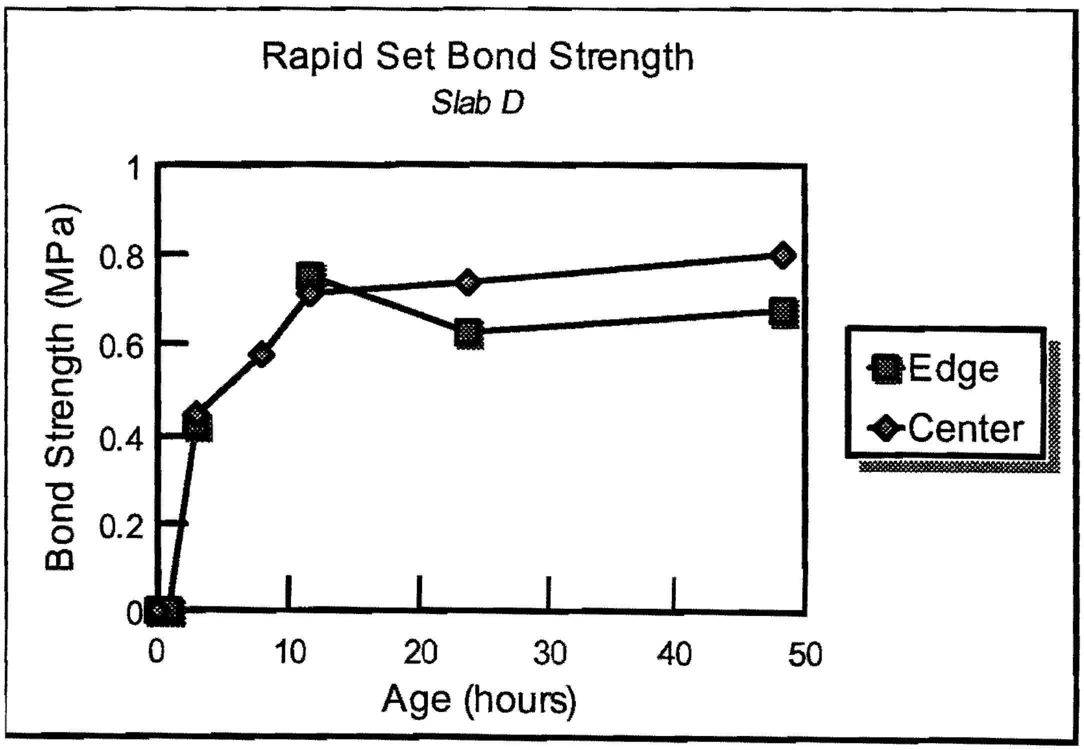

Fig. 5.13. Development of shear strength of bonding in Test 8 (Rapid Set on Slab C), placed in the morning and cured naturally.

of shear strength, ambient temperature, and temperature of the repair material for each repair test are recorded in Tables A.7 to A.14 (shown in Appendix: Test Data).

From these figures, it can be seen that the difference between the torsional shear strengths of the bond at the edge and center of the overlay is random, with little indication regarding the effect of the test location. The difference between them is much less than 50%, as previously reported (Lundy, et al., 1991). The existing variation of the strength should be attributed to the properties of the cement-based material, for which scatter of test data is normal. It is worthwhile to note that the strength measured at different locations is a material property; that is, a property of the repair material and the base concrete under the field conditions and is structure independent (independent of the pavement system). Although the overlay may curl and warp, which may cause some damage at the bonded interface, this effect was not evident in the test data. This may have been due, in part, to the PVC cylinder isolating the repair material from the body of the overlay.

Bond shear strength of Rapid Set increased quickly within 12 hours after placement. After 12 hours, the strength continued to increase, but at a slower rate. Bond shear strength of Quikrete increased quickly in the first eight hours, but afterwards that there was no apparent trend of continuous strength increase. Although, ultimately, Rapid Set had a higher bond shear strength than Quikrete, there was no apparent difference in the bond strength between them in the first eight hours. This suggests that Rapid Set spall repairs may provide better performance where the repaired road section is opened to traffic 12 or more hours after placement. However, Rapid Set and Quikrete repairs may perform equally if the repaired road is opened to traffic in eight hours or less. It may be clearer to use the concept of maturity to express the increase of the bond shear strength. Maturity may be defined as:

$$M = \sum (T - T_0)\Delta t$$

where M is maturity at time t, T is average temperature of the concrete during time interval Δt, and T_0 is the datum temperature, which is usually taken -10°C. The growth of the bond shear strength with maturity for Quikrete and Rapid Set is shown in Figs. 5.14 and 5.15, respectively.

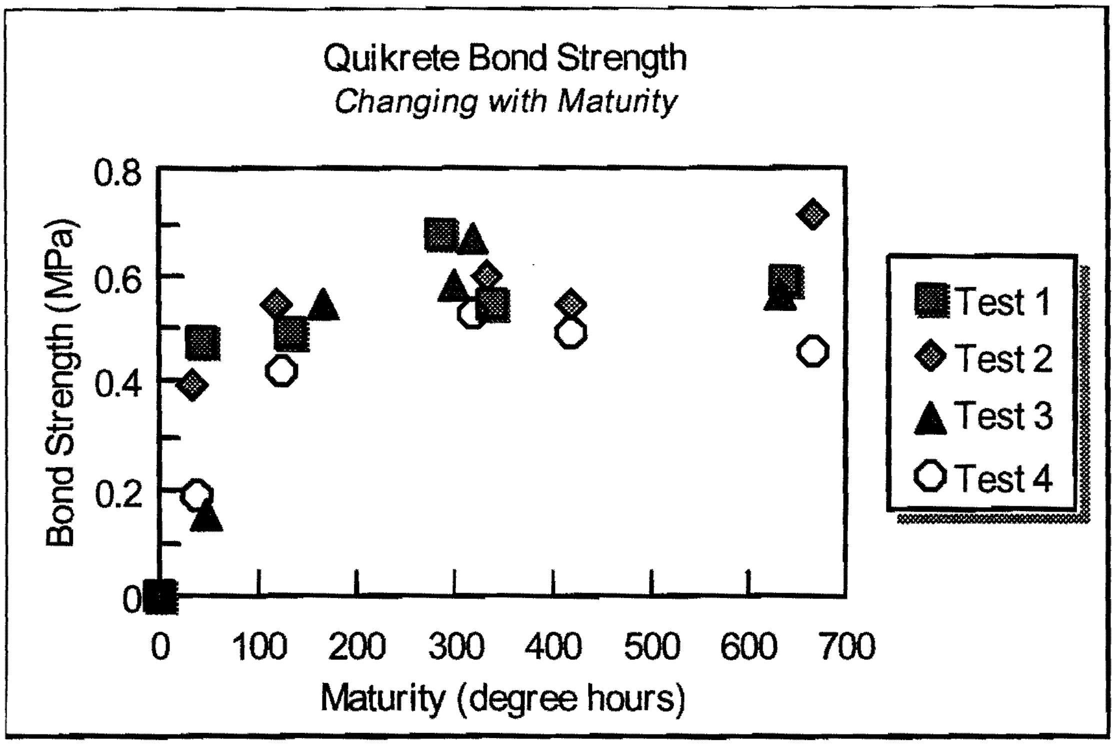

Fig. 5.14. Quikrete Bond Shear Strength Versus Maturity.

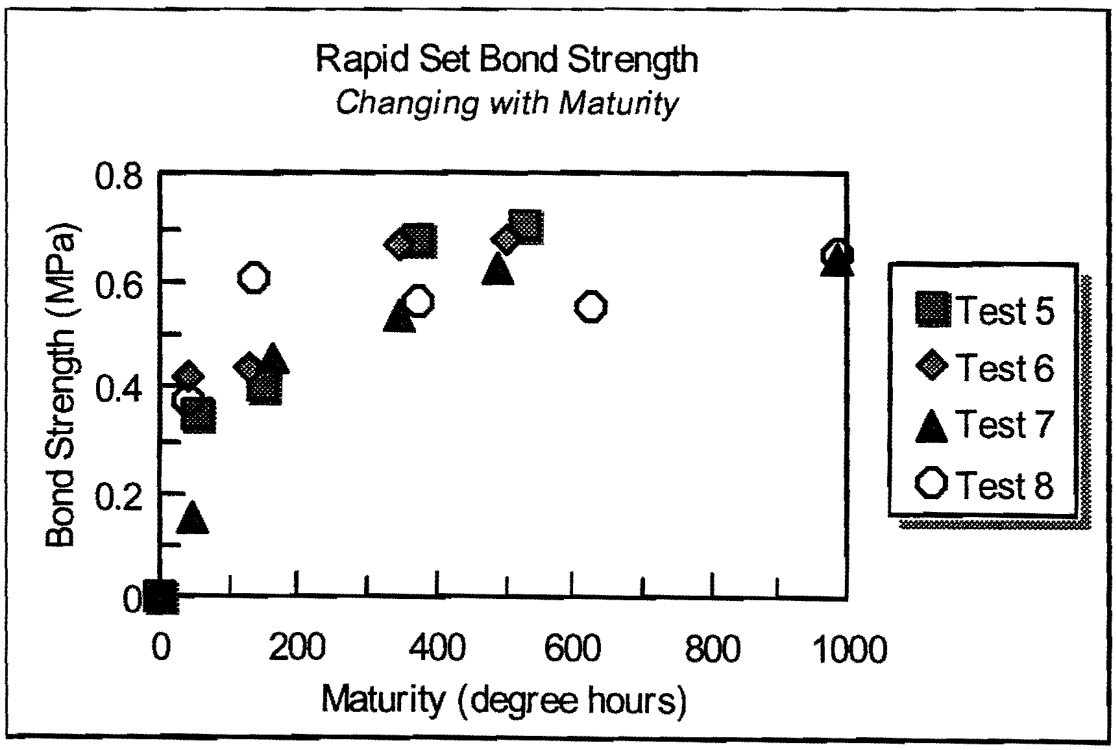

Fig. 5.15. Rapid Set Bond Shear Strength Versus Maturity.

The figures show that the bond strength for Rapid Set reached its full value when the maturity of the material increased to about 500 degree•hours while the bond strength for Quikrete reached its full value when the maturity increased to about 300 degree•hours. Bond shear strength and maturity of Quikrete at right hours are listed in table 5.2. In Table 5.3, values for Rapid Set at 12 hours are noted. The values may be used to monitor when full bond strength has been achieved.

Table 5.2. Quikrete Bond Shear Strength Versus Maturity Eight Hours after Placement.

Test	1	2	3	4
Slab	E	P	O	A
Repair Material	Quikrete			
Placement time	afternoon	morning	afternoon	morning
Curing	Type II	Type II	Natural	Natural
Maturity (degree•hours)	296	318	296	331
Average bond shear strength (MPa)	0.684	0.603	0.585	0.531

Table 5.3. Rapid Set Bond Shear Strength Versus Maturity 12 Hours after Placement.

Test	5	6	7	8
Slab	F	D	N	C
Repair Material	Rapid Set			
Placement time	afternoon	morning	afternoon	morning
Curing	Type II	Type II	Natural	Natural
Maturity (degree•hours)	531	501	487	530 (estimated)
Average bond shear strength (MPa)	0.730	0.675	0.630	0.650

The maturity function quantifies the effect of temperature and time on strength gain. For a certain maturity value, such as 300 or 500 degree•hours, different periods of curing time would be needed under summer versus winter construction conditions. In this program, all the tests were conducted in August 1995. Although repair materials were placed in either the afternoon or the morning, the small difference in ambient temperature between afternoon and morning did not make a significant difference in maturity in a period of eight or 12 hours. In other seasons, placement time, in the afternoon or the morning, may play an important role. Usually, concrete placed in the afternoon would gain maturity and, hence, strength faster than concrete placed in the morning.

Curing seems to be an important factor for Quikrete bond strength gain in the first hour after placement. Use of Type II curing compound improved strength gain in the first hour after placement (Fig. 5.10). Although the test data do not exhibit an apparent effect of the curing compound from four hours to 24 hours after placement, average bond shear strength 48 hours after placement for overlays cured with Type II curing compound (Tests 1 and 2) was higher than that for overlays naturally cured (Tests 3 and 4), by a factor of about 30%, when the maturity exceeded 600 degree•hours (Fig. 5.14).

5.4. CONCLUSIONS

(1) Tests of spall repairs with two cement-based repair materials, Rapid Set Concrete Mix and Quikrete Ready-Mix Concrete, were conducted. Clean, dry concrete pavement surfaces were used to simulate the spall surfaces to be repaired. A 25-mm (1 in.) thick overlay was placed on the pavement slab and shear strength of the bond between the repair material and pavement was measured.

(2) Rapid Set provided approximately its full shear strength when its maturity reached 500 degree•hours, while Quikrete provided its full strength when its maturity reached 300 degree•hours. These maturity values may be used as criteria for spall repairs open to traffic.

(3) Rapid Set provided higher ultimate bond strength than Quikrete, which was also shown in the laboratory tests (Chapter 2), but it took a longer time for Rapid Set to achieve its full bond strength than Quikrete. The bond strengths for Rapid Set and Quikrete were about the same when their maturities were less than 300 degree•hours. When the repaired road needs to be open to traffic at or before 300 degree•hours, these two repair materials may perform equally.

(4) Curing compound Type II was found effective for increasing bond strength for Quikrete. Time of placement is also an important factor for early age bond strength.

(5) The torque wrench originally developed at CTR was modified to allow for early-aged measurements of bond shear strength. It is recommended for a standard test procedure for measuring bond shear strength.

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APPENDIX: TEST DATA

Table A.1. Spall Repairs with Pyramid and Rapid Set in the Eastbound Road of BW 8 North.

Patch series No.	Distance (m)	Distance (ft.)	Repair Material	Sawcut	Lane	Number of patches
1	4.3	14	Pyramid	Yes	Inner	4
2	6.4	21	Pyramid	Yes	Inner	4
3	25.3	83	Pyramid	Yes	Inner	4
4	32.6-36.6	107-120	Pyramid	Yes	Inner	2
	32.6-36.6	107-120	Pyramid	Yes	Middle	3
5	43.9-44.8	144-147	Pyramid	Yes	Inner	block repair
6	49.7	163	Pyramid	Yes	Inner	block repair
7	53	174	Pyramid	Yes	Inner	block repair
8	63.4	208	Pyramid	Yes	Inner	block repair
9	68.6	225	Pyramid	Yes	Inner	2
10	74.7	245	Pyramid	Yes	Inner	2
11	78.9	259	Pyramid	Yes	Inner	block repair
12	89.6	294	Pyramid	Yes	Inner	4
13	102.4-105.1	336-345	Pyramid	Yes	Inner	block repair
14	109.1	358	Pyramid	Yes	Inner	2
15	115.2	378	Pyramid	Yes	Inner	4
16	138.7	455	Pyramid	Yes	Inner	2
17	153	502	Pyramid	Yes	Inner	2
18	160.6	527	Pyramid	Yes	Inner	2
19	162.8	534	Pyramid	Yes	Inner	4
	162.8	534	Pyramid	Yes	Middle	3
20	168.2	552	Pyramid	Yes	Inner	2
21	170.4	559	Pyramid	Yes	Inner	2
22	175.3	575	Pyramid	Yes	Inner	5
23	180.1	591	Pyramid	Yes	Inner	2
24	187.8	616	Pyramid	Yes	Inner	5
25	189	620	Pyramid	Yes	Inner	2
	189	620	Pyramid	Yes	Middle	3
26	193.2	634	Pyramid	Yes	Inner	2

	193.2	634	Pyramid	Yes	Middle	2
27	197.5	648	Pyramid	Yes	Inner	2
28	207.3	680	Pyramid	Yes	Inner	4
	207.3	680	Pyramid	Yes	Middle	3
29	218.2	716	Pyramid	Yes	Inner	2
30	223.4	733	Pyramid	Yes	Inner	3
	223.4	733	Pyramid	Yes	Middle	3
31	227.7	747	Pyramid	Yes	Inner	4
	227.7	747	Pyramid	Yes	Middle	block repair
32	232	761	Pyramid	Yes	Inner	4
33	236.8	777	Pyramid	Yes	Inner	block repair
	236.8	777	Pyramid	Yes	Middle	3
33b	239	784	Pyramid	Yes	Middle	2
33c	239.9	787	Pyramid	Yes	Middle	3
34	243.2	798	Pyramid	Yes	Inner	5
	243.2	798	Pyramid	Yes	Middle	3
34b	247.5	812	Pyramid	Yes	Middle	1
34c	253.3	831	Pyramid	Yes	Middle	3
34d	257.9	846	Pyramid	Yes	Middle	3
35	281.6	924	Pyramid	Yes	Inner	4
	281.6	924	Pyramid	Yes	Middle	2
36	284.4	933	Pyramid	Yes	Inner	4
37	287.7	944	Pyramid	Yes	Inner	4
38	294.4	966	Pyramid	Yes	Inner	block repair
39	296.6	973	Pyramid	Yes	Inner	2
40	301.1-304.5	988-999	Pyramid	Yes	Inner	block repair
41	319.7	1,049	Pyramid	No	Middle	5
42	328.3	1,077	Pyramid	No	Inner	2
43	333.5	1,094	Pyramid	No	Inner	3
	333.5	1,094	Pyramid	No	Middle	2
44	363.9	1,194	Pyramid	No	Inner	4
45	356.3-380.4	1169-1248	Pyramid	No	Inner	block repair
46	389.8	1,279	Pyramid	No	Inner	5
47	392.9	1,289	Pyramid	No	Inner	6

48	424.3	1,392	Pyramid	No	Inner	4
	424.3	1,392	Pyramid	Yes	Middle	3
49	474.3	1,556	Pyramid	No	Inner	2
	474.3	1,556	Pyramid	No	Middle	3
50	479.8	1,574	Pyramid	No	Inner	3
	479.8	1,574	Pyramid	No	Middle	2
51	516.6	1,695	Pyramid	No	Inner	2
52	610.2	2,002	Pyramid	No	Inner	3
	610.2	2,002	Pyramid		Middle	2
53	622.4	2,042	Rapid Set	Yes	Outer	4
54	627	2,057	Rapid Set	No	Outer	4
55	631.5	2,072	Rapid Set	No	Outer	4
56	639.5	2,098	Pyramid	Yes	Inner	2
	639.5	2,098	Rapid Set	Yes	Outer	3
57	641.9	2,106	Rapid Set	Yes	Outer	4
58	645.3	2,117	Rapid Set	No	Outer	4
59	650.1	2,133	Pyramid	No	Inner	2
	650.1	2,133	Rapid Set	No	Outer	4
60	662	2,172	Rapid Set	No	Outer	4
61	679.1	2,228	Rapid Set	No	Outer	2
62	682.4	2,239	Rapid Set	No	Outer	4
63	685.5	2,249	Rapid Set	Yes	Outer	4
64	691.9	2,270	Rapid Set	No	Outer	4
65	696.8	2,286	Rapid Set	Yes	Outer	4
66	707.4	2,321	Rapid Set	No	Outer	1
67	710.2	2,330	Rapid Set	No	Outer	1
68	713.2	2,340	Rapid Set	Yes	Outer	4
69	715.4	2,347	Rapid Set	No	Outer	4
70	727.6	2,387	Rapid Set	No	Outer	1
71	736.7	2,417	Rapid Set	Yes	Outer	1
72	755.6	2,479	Pyramid	No	Inner	5
	755.6	2,479	Rapid Set	No	Outer	1
73	773.6	2,538	Rapid Set	No	Inner	5
74	780.6	2,561	Rapid Set	No	Inner	2

75	788.2	2,586	Pyramid	No	Inner	3
	788.2	2,586	Pyramid	No	Middle	3
	788.2	2,586	Rapid Set	No	Outer	4
76	796.7	2,614	Pyramid	No	Inner	2
	796.7	2,614	Rapid Set	No	Outer	3
77	801.3	2,629	Pyramid	No	Inner	4
	801.3	2,629	Pyramid	No	Middle	3
78	811.7	2,663	Pyramid	No	Inner	4
	811.7	2,663	Pyramid	No	Middle	3
	811.7	2,663	Rapid Set	No	Outer	3
79	818.4	2,685	Pyramid	No	Inner	3
	818.4	2,685	Rapid Set	No	Outer	3
80	823.6	2,702	Pyramid	No	Inner	2
	823.6	2,702	Pyramid	No	Middle	2
81	831.5	2,728	Rapid Set	No	Outer	4
82	834.8	2,739	Rapid Set	No	Outer	3
83	838.2	2,750	Pyramid	No	Inner	4
	838.2	2,750	Pyramid	No	Middle	3
	838.2	2,750	Rapid Set	No	Outer	4
84	844.3	2,770	Rapid Set	No	Outer	4

Note: Repairs made with Pyramid were placed on May 5 or 13, 1993. Shaded rows record repairs made with Rapid Set in 1992, for which the exact repair date is unknown.

Table A.2. Spall Repairs with Flamcoat Products in the Westbound Frontage of BW 8 North.

Patch series number	Distance (m)	Distance (ft.)	Repair material	Lane
1	0	0	PF113-H101	Inner
2	0.6	2	PF113-H101	Inner
3	7.9	26	PF113-H101	Inner
4	8.5	28	PF113-H101	Inner
5	10.4	34	PF113-H101	Inner
6	15.2	50	PF113-H101	Inner
7	25.3	83	PF113-H101	Inner
8	41.5	136	PF113-H101	Inner
9	61.9	203	PF113-H101	Inner
10	32.3	106	PF113-H101	Inner
11	88.4	290	PH101	Inner
12	106.1	348	PH101	Inner
13	109.7	360	PH101	Inner
14	110.6	363	PH101	Inner
15	114.3	375	PH101	Inner
16	119.5	392	PH101	Inner
17	124.1	407	PH101	Inner
18	133.5	438	PH101	Inner
19	135.6	445	PH101	Inner
20	138.4	454	PH101	Inner
21	139.3	457	PR111-H101	Inner
22	141.1	463	PR111-H101	Inner
23	142.6	468	PR111-H101	Inner
24	145.7	478	PR111-H101	Inner
25	146.3	480	PR111-H101	Inner
26	151.8	498	PR111-H101	Inner
27	153.3	503	PR111-H101	Inner
28	156.4	513	PR111-H101	Inner
29	160	525	PR111-H101	Inner
30	161.2	529	PR111-H101	Inner
31	164.9	541	PR111-H101	Inner

Table A.3. Distresses in Patches Repaired with Pyramid.

Patch series No.	Distance (m)	Repair material	Sawcut	Types of distresses observed in October 1993	Types of distresses observed in June 1994	Types of distresses observed in January 1995
1	4.3	Pyramid	Yes			1, 2
2	6.4	Pyramid	Yes			2, 3
3	25.3	Pyramid	Yes			3
4	32.6-36.6	Pyramid	Yes			3
	32.6-36.6	Pyramid	Yes			3
5	43.9-44.8	Pyramid	Yes	2	2, 3	2, 3
6	49.7	Pyramid	Yes		3	3
7	53	Pyramid	Yes		3	3
8	63.4	Pyramid	Yes		3	3
9	68.6	Pyramid	Yes		3	3
10	74.7	Pyramid	Yes		3	3
11	78.9	Pyramid	Yes		3	3
12	89.6	Pyramid	Yes			3
13	102.4-105.1	Pyramid	Yes			3
14	109.1	Pyramid	Yes	2		2, 3
15	115.2	Pyramid	Yes	1		1
16	138.7	Pyramid	Yes			1, 3
17	153	Pyramid	Yes			No
18	160.6	Pyramid	Yes	1		1
19	162.8	Pyramid	Yes	1		1
	162.8	Pyramid	Yes			No
20	168.2	Pyramid	Yes			No
21	170.4	Pyramid	Yes			No
22	175.3	Pyramid	Yes			No
23	180.1	Pyramid	Yes			3
24	187.8	Pyramid	Yes			No
25	189	Pyramid	Yes			3
	189	Pyramid	Yes			3
26	193.2	Pyramid	Yes			3
	193.2	Pyramid	Yes			3

27	197.5	Pyramid	Yes	2	2	2
28	207.3	Pyramid	Yes			3
	207.3	Pyramid	Yes			No
29	218.2	Pyramid	Yes			No
30	223.4	Pyramid	Yes	2	2	2, 3
	223.4	Pyramid	Yes			3
31	227.7	Pyramid	Yes			4
	227.7	Pyramid	Yes			3
32	232	Pyramid	Yes			3
33	236.8	Pyramid	Yes			3
	236.8	Pyramid	Yes			3
33b	239	Pyramid	Yes			3
33c	239.9	Pyramid	Yes			3
34	243.2	Pyramid	Yes			3
	243.2	Pyramid	Yes			No
34b	247.5	Pyramid	Yes			3
34c	253.3	Pyramid	Yes	2	2	2
34d	257.9	Pyramid	Yes			3
35	281.6	Pyramid	Yes			2 (severe)
	281.6	Pyramid	Yes			2
36	284.4	Pyramid	Yes			2
37	287.7	Pyramid	Yes			2
38	294.4	Pyramid	Yes			2
39	296.6	Pyramid	Yes			3
40	301.1-304.5	Pyramid	Yes			3
41	319.7	Pyramid	No			3
42	328.3	Pyramid	No			3
43	333.5	Pyramid	No	3	3	3, 4
	333.5	Pyramid	No			3, 4
44	363.9	Pyramid	No	2	2	2, 3
45	356.3-380.4	Pyramid	No			3
46	389.8	Pyramid	No	3	3	3
47	392.9	Pyramid	No	3	not inspected	3
48	424.3	Pyramid	No	4	not inspected	3, 4

	424.3	Pyramid	Yes	4	not inspected	3, 4
49	474.3	Pyramid	No		not inspected	3
	474.3	Pyramid	No		not inspected	3
50	479.8	Pyramid	No	3	not inspected	4
	479.8	Pyramid	No		not inspected	4
51	516.6	Pyramid	No	4	not inspected	3
52	610.2	Pyramid	No		not inspected	3
	610.2	Pyramid	No		not inspected	3
53	622.4	Rapid Set	Yes	2	not inspected	2 (severe)
54	627	Rapid Set	No		not inspected	3
55	631.5	Rapid Set	No		not inspected	3
56	639.5	Pyramid	Yes		not inspected	3
	639.5	Rapid Set	Yes		not inspected	3
57	641.9	Rapid Set	Yes		not inspected	2
58	645.3	Rapid Set	No	2	not inspected	2 (severe)
59	650.1	Pyramid	No		not inspected	3
	650.1	Rapid Set	No	2	not inspected	2
60	662	Rapid Set	No		not inspected	2
61	679.1	Rapid Set	No		not inspected	2
62	682.4	Rapid Set	No	2	not inspected	2
63	685.5	Rapid Set	Yes		not inspected	2
64	691.9	Rapid Set	No	3	not inspected	3
65	696.8	Rapid Set	Yes		not inspected	2
66	707.4	Rapid Set	No		not inspected	2
67	710.2	Rapid Set	No	2	not inspected	2
68	713.2	Rapid Set	Yes		not inspected	2
69	715.4	Rapid Set	No		not inspected	2
70	727.6	Rapid Set	No	2	not inspected	2
71	736.7	Rapid Set	Yes		not inspected	2
72	755.6	Pyramid	No	3	not inspected	3
	755.6	Rapid Set	No	3	not inspected	2, 3
73	773.6	Rapid Set	No	3	not inspected	2, 3
74	780.6	Rapid Set	No	3	not inspected	2, 3
75	788.2	Pyramid	No	3	not inspected	2, 3

	788.2	Pyramid	No	3	not inspected	2, 3
	788.2	Rapid Set	No	3	not inspected	2, 3
76	796.7	Pyramid	No	3	not inspected	2, 3
	796.7	Rapid Set	No	3	not inspected	2, 3
77	801.3	Pyramid	No	1	not inspected	2, 3
	801.3	Pyramid	No	2, 3	not inspected	2, 3
78	811.7	Pyramid	No		not inspected	2, 3
	811.7	Pyramid	No		not inspected	2, 3
	811.7	Rapid Set	No		not inspected	2, 3
79	818.4	Pyramid	No		not inspected	2, 3
	818.4	Rapid Set	No	2	not inspected	2, 3
80	823.6	Pyramid	No		not inspected	2, 3
	823.6	Pyramid	No		not inspected	2, 3
81	831.5	Rapid Set	No		not inspected	2, 3
82	831.5	Rapid Set	No		not inspected	2, 3
83	838.2	Pyramid	No	3	not inspected	2, 3
	838.2	Pyramid	No	3	not inspected	2, 3
	838.2	Rapid Set	No	3	not inspected	2, 3
84	844.3	Rapid Set	No	2	not inspected	2, 3

Note: Repairs made with Pyramid were placed on May 5 or 13, 1993. Shaded rows record repairs made with Rapid Set in 1992, for which the exact repair date is unknown.

Table A.4. Spall Repairs on BW 8 West.

Patch series No.	Distance (m)	Distance (ft.)	Repair material	Saw cut	Lane	Number of patches
1	19.8	65	Rapid Set	No	Outer	1
2	50.6	166	Rapid Set	Yes	Outer	1
3	56.4	185	Rapid Set	Yes	Outer	1
4	59.7	196	Rapid Set	Yes	Outer	1
5	64	210	Rapid Set	Yes	Outer	1
6	68.9	226	Rapid Set	Yes	Outer	1
7	73.8	242	Rapid Set	Yes	Outer	1
8	78.3	257	Rapid Set	Yes	Outer	1
9	86	282	Rapid Set	Yes	Outer	1
10	87.5	287	Rapid Set	Yes	Outer	2
11	91.4	300	Rapid Set	No	Outer	1
12	112.2	368	Rapid Set	No	Outer	1
13	115.8	380	Rapid Set	No	Outer	1
14	117.3	385	Rapid Set	No	Outer	2
15	119.8	393	Rapid Set	No	Outer	1
16	121	397	Rapid Set	No	Outer	1
17	124.1	407	Rapid Set	No	Outer	2
18	124.7	409	Rapid Set	No	Outer	1
19	128.6	422	Rapid Set	No	Middle	1
20a	131.7	432	Rapid Set	No	Middle	1
20b	131.7	432	Rapid Set	No	Outer	1
21	143.9	472	Rapid Set	No	Outer	1
22	147.5	484	Rapid Set	No	Outer	1
23	151.2	496	Rapid Set	No	Middle	1
24	154.8	508	Rapid Set	No	Middle	1
25a	157	515	Rapid Set	Yes	Middle	1
25b	157	515	Rapid Set	Yes	Outer	1
26	163.1	535	Rapid Set	No	Middle	1
27	166.1	545	Rapid Set	No	Middle	1
28a	170.4	559	Quikrete	Yes	Middle	1
28b	170.4	559	Quikrete	No	Outer	1

29a	177.4	582	Quikrete	Yes	Outer	1
29b	177.4	582	Quikrete	Yes	Middle	1
30	179.8	590	Quikrete	No	Middle	1
31	181.4	595	Quikrete	No	Middle	2
32a	183.5	602	Quikrete	Yes	Outer	1
32b	183.5	602	Quikrete	Yes	Outer	1
33	184.7	606	Quikrete	Yes	Outer	1
34a	188.4	618	Quikrete	No	Middle	2
34b	188.4	618	Quikrete	No	Outer	1
35	194.8	639	Quikrete	No	Outer	1
36a	198.1	650	Quikrete	No	Middle	1
36b	198.1	650	Quikrete	No	Outer	1
37	200.6	658	Quikrete	No	Middle	1
38a	206.3	677	Quikrete	Yes	Outer	1
38b	206.3	677	Quikrete	No	Middle	2
39	208.5	684	Quikrete	No	Outer	2
40a	211.8	695	Quikrete	No	Middle	1
40b	211.8	695	Quikrete	No	Outer	1
41a	213.1	699	Quikrete	No	Outer	2
41b	213.1	699	Quikrete	No	Middle	1
42a	216.4	710	Quikrete	Yes	Middle	1
42b	216.4	710	Quikrete	Yes	Outer	1
43a	218.5	717	Quikrete	No	Outer	1
43b	218.5	717	Quikrete	No	Outer	1
44	220.1	722	Quikrete	No	Outer	1
45	221	725	Quikrete	No	Middle	1
46	221.3	726	Quikrete	No	Middle	1
47	224	735	Quikrete	No	Outer	1
48	224.3	736	Quikrete	No	Middle	2
49a	224.9	738	Quikrete	No	Middle	1
49b	224.9	738	Quikrete	No	Outer	2
50a	228	748	Quikrete	No	Middle	2
50b	228	748	Quikrete	No	Outer	1
51a	228.6	750	Quikrete	No	Middle	1

51b	228.6	750	Quikrete	No	Outer	1
52a	233.5	766	Quikrete	No	Middle	1
52b	233.5	766	Quikrete	No	Outer	1

Table A.5. Distresses in Patches Placed with Rapid Set in October 1993.

Patch series No.	Distance (m)	Distance (ft.)	Saw cut	Distress types observed in June 1994	Distress types observed in January 1995
1	19.8	65	No	No	No
2	50.6	166	Yes	No	2
3	56.4	185	Yes	No	2
4	59.7	196	Yes	No	No
5	64	210	Yes	No	2
6	68.9	226	Yes	No	2
7	73.8	242	Yes	No	No
8	78.3	257	Yes	4	2, 4
9	86	282	Yes	No	2, 4
10	87.5	287	Yes	4	2
11	91.4	300	No	No	3
12	112.2	368	No	No	3
13	115.8	380	No	No	3
14	117.3	385	No	3	3
15	119.8	393	No	3	3
16	121	397	No	No	3
17	124.1	407	No	No	3
18	124.7	409	No	3, 4	3, 4
19	128.6	422	No	3	3
20a	131.7	432	No	3	3
20b	131.7	432	No	3	3
21	143.9	472	No	3	3
22	147.5	484	No	3	3
23	151.2	496	No	3	3
24	154.8	508	No	3	3
25a	157	515	Yes	2	2
25b	157	515	Yes	No	No
26	163.1	535	No	3	3
27	166.1	545	No	No	3

Table A.6. Distresses in patches placed with Quikrete in October 1993.

Patch series No.	Distance (m)	Distance (ft)	Saw cut	Types of distresses observed in June 1994	Types of distresses observed in January 1995
28a	170.4	559	Yes	1, 2	1, 2
28b	170.4	559	No	No	No
29a	177.4	582	Yes	1, 2	1, 2
29b	177.4	582	Yes	1, 2	1, 2
30	179.8	590	No	3	3
31	181.4	595	No	3	3
32a	183.5	602	Yes	1, 2	1, 2
32b	183.5	602	Yes	1, 2	1, 2
33	184.7	606	Yes	1, 2	1, 2
34a	188.4	618	No	3	3
34b	188.4	618	No	3	3
35	194.8	639	No	3	3
36a	198.1	650	No	3	3
36b	198.1	650	No	3	3
37	200.6	658	No	3	3
38a	206.3	677	Yes	1, 2	1, 2
38b	206.3	677	No	3	3
39	208.5	684	No	3	3
40a	211.8	695	No	3	3
40b	211.8	695	No	3	3
41a	213.1	699	No	3	3
41b	213.1	699	No	3	3
42a	216.4	710	Yes	1, 2	1, 2
42b	216.4	710	Yes	1, 2	1, 2
43a	218.5	717	No	3	3
43b	218.5	717	No	3	3
44	220.1	722	No	3	3
45	221	725	No	3	3
46	221.3	726	No	3	3
47	224	735	No	3, 4	3, 4
48	224.3	736	No	3	3

49a	224.9	738	No	3	3
49b	224.9	738	No	3	3
50a	228	748	No	3	3
50b	228	748	No	3	3
51a	228.6	750	No	3	3
51b	228.6	750	No	3	3
52a	233.5	766	No	3	3
52b	233.5	766	No	3	3

Table A.7. Test data for Test 1 (Quikrete on Slab E).

Date	Time	Elapsed time (hours)	Temperature (°C)		R.H. (%)	Shear strength (MPa)	
			ambient	repair material		at edge	at center
8/22/95	16:45	0	36.7	39.2	93.2	-	-
8/22/95	17:45	1	35	40.7	83.2	0.387	0.557
8/23/95	19:45	3	31.6	36.9	82.1	0.42	0.563
8/23/95	00:45	8	28.9	31.6	67.2	0.612	0.756
8/23/95	04:45	12	24.4	29	70.7	0.623	0.47
8/24/95	15:45	24	36.9	44.1	44.7	0.536	0.653
8/24/95	16:45	48				-	0.525

Note: R.H. designates the pore relative humidity.

Table A.8. Test data for Test 2 (Quikrete on Slab P).

Date	Time	Elapsed time (hours)	Temperature (°C)		R.H. (%)	Shear strength (MPa)	
			ambient	repair material		at edge	at center
8/20/95	10:00	0	29	31.8	-	-	-
8/20/95	11:00	1	32.4	27.6	95.4	0.416	0.381
8/20/95	13:00	3	40.7	47.1	60.5	0.616	0.481
8/20/95	18:00	8	37.2	41.6	57.3	0.699	0.506
8/20/95	22:00	12	31.1	33.6	68.6	0.556	0.539
8/21/95	10:00	24	35.3	39.1	58.3	0.914	0.518
8/22/95	10:00	48	30	31.8	rain	0.786	0.522

Note: R.H. designates the pore relative humidity.

Table A.9. Test data for Test 3 (Quikrete on Slab O).

Date	Time	Elapsed time (hours)	Temperature (°C) ambient	Temperature (°C) repair material	R.H. (%)	Shear strength (MPa) at edge	Shear strength (MPa) at center
8/21/95	15:00	0	39	40.3	-	-	-
8/21/95	16:00	1	39	44.3	-	0.094	0.212
8/21/95	19:00	4	34.4	40.1	93.7	0.522	0.578
8/21/95	23:00	8	29.2	30.1	wet	0.479	0.69
8/22/95	03:00	12	27.4	28.9	wet	0.513	0.819
8/22/95	15:00	24	36.7	43.8	58.6	0.505	0.614
8/23/95	15:00	48	37.7	42.9	65.4	0.514	0.561

Note: R.H. designates the pore relative humidity.

Table A.10. Test data for Test 4 (Quikrete on Slab A).

Date	Time	Elapsed time (hours)	Temperature (°C) ambient	Temperature (°C) repair material	Shear strength (MPa) at edge	Shear strength (MPa) at center
8/4/95	8:45	0	26.7	32.2	-	-
8/4/95	9:45	1	30.6	35.6	0.197	0.178
8/4/95	11:45	3	30.9	39.3	0.368	0.467
8/4/95	17:45	9	40.6	43.8	0.504	0.557
8/4/95	22:45	14	31.9	39.8	0.479	0.51
8/5/95	8:45	24	28.6	29.8	0.521	0.387
8/6/95	8:45	48	28.3	29.1	0.516	0.461

Table A.11. Test data for Test 5 (Rapid Set on Slab F).

Date	Time	Elapsed time (hours)	Temperature (°C)		Shear strength (MPa)	
			ambient	repair material	at edge	at center
8/26/95	22:00	0	-	-	-	-
8/26/95	23:00	1	37.1	42.4	0.363	-
8/26/95	13:00	3	45.3	44	0.55	0.252
8/26/95	18:00	8	34	36.3	0.709	0.654
8/26/95	22:00	12	30.1	31.8	0.685	0.734
8/27/95	14:00	24	40.6	40.8	0.696	0.505
8/28/95	24:00	48	39.3	38.1	0.723	-

Table A.12. Test data for Test 6 (Rapid Set on Slab D).

Date	Time	Elapsed time (hours)	Temperature (°C)		Shear strength (MPa)	
			ambient	repair material	at edge	at center
8/26/95	22:00	0	32.5	35.1	-	-
8/26/95	23:00	1	33.4	36.2	0.422	-
8/26/95	13:00	3	36.1	41.3	-	0.441
8/26/95	18:00	8	34.4	35.9	0.756	0.577
8/26/95	22:00	12	32.3	31.6	0.63	0.72
8/27/95	14:00	24	40.7	42	0.685	0.741
8/28/95	24:00	48	39.3	39.3	0.848	0.807

Table A.13. Test data for Test 7 (Rapid Set on Slab N).

Date	Time	Elapsed time (hours)	Temperature (°C)		R.H. (%)	Shear strength (MPa)	
			ambient	repair material		at edge	at center
8/21/95	15:30	0	39	42.4	-	-	-
8/21/95	16:30	1	40	42.3	-	0.306	-
8/21/95	19:00	3.5	34.4	40.3	89.7	0.44	0.47
8/21/95	23:30	8	29.2	31.3	wet	0.469	0.611
8/22/95	03:30	12	27.4	28.9	wet	0.579	0.68
8/22/95	15:30	24	36.7	43.8	54.8	0.634	0.657
8/23/95	15:30	48	41.6	42.1	51.1	0.603	0.651

Note: R.H. designates the pore relative humidity.

Table A.14. Test data for Test 8 (Rapid Set on Slab C).

Date	Time	Elapsed time (hours)	Temperature (°C)		Shear strength (MPa)	
			ambient	repair material	at edge	at center
8/13/95	08:30	0	28.2	33.7	-	-
8/13/95	09:30	1	30.8	36.8	0.377	0.368
8/13/95	12:30	3	36.1	46.3	0.53	0.69
8/13/95	16:30	8	30.8	39.7	0.609	0.527
8/13/95	20:30	14	28	33.4	0.628	0.477
8/1495	08:30	24	27.2	29.4	0.659	0.647
8/15/95	08:30	48	26.1	26.6	0.623	0.77