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16. Abstract

Plans are currently underway for rehabilitating a heavily traveled section of Interstate Highway 10 in the El Paso, Texas, District. This section of highway is to be repaired using a bonded concrete overlay. This two-year study is investigating pavement design, traffic control, and construction methods that will yield a durable pavement at minimum cost and minimum burden to the public.

This report describes the design of a cost-effective bonded concrete overlay mix — one capable of meeting the specifications set forth by the Texas Department of Transportation (TxDOT). The design is such as to ensure that the overlay strengthens sufficiently to permit a quick return to traffic loading. The report also describes an investigation of the factors that affect the bond performance of the overlay to be constructed.

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CONCRETE BOND CHARACTERISTICS FOR A BONDED CONCRETE OVERLAY ON IH-10 IN EL PASO

by

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B. Frank McCullough

Research Report 2911-2

Research Project 7-2911
Full-Scale Bonded Concrete Overlay on IH-10 in El Paso

conducted for the

Texas Department of Transportation

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

July 1995

IMPLEMENTATION STATEMENT

The methodology and models presented in this report may be used to develop a mix design for a bonded concrete overlay that will provide adequate bond strength at early ages to allow traffic back on the pavement at minimal time without significant decrease in the life of the new pavement. Methods presented in this report may also be used to estimate the bond development between a bonded concrete overlay and its underlying substrate at early ages. Furthermore, the laboratory testing documented in this report demonstrates that bond strength may be predicted on the basis of concrete maturity.

Prepared in cooperation with the Texas Department of Transportation.

DISCLAIMERS

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SUMMARY

Plans are currently underway for rehabilitating a heavily traveled section of Interstate Highway 10 in the El Paso, Texas, District. This section of highway is to be repaired using a bonded concrete overlay. This two-year study is investigating pavement design, traffic control, and construction methods that will yield a durable pavement at minimum cost and minimum burden to the public.

This report describes the design of a cost-effective bonded concrete overlay mix — one capable of meeting the specifications set forth by the Texas Department of Transportation (TxDOT). The design is such as to ensure that the overlay strengthens sufficiently to permit a quick return to traffic loading. The report also describes an investigation of the factors that affect the bond performance of the overlay to be constructed.

CHAPTER 1. PURPOSE

1.1 PROJECT DESCRIPTION

In large metropolitan areas, many sections of the Interstate highway system are nearing the end of their useful lives. The structural performance and serviceability of these pavement sections can be improved by routine maintenance, rehabilitation, or reconstruction. Rehabilitation using bonded concrete overlays (BCOs), such as that constructed in Houston on Loop 610, proved to be a viable technical and economical solution for the rehabilitation of existing pavement (Ref 1).

Currently, rehabilitation of a heavily traveled section of Interstate Highway 10 in the Central Business District of El Paso, Texas, is being planned using a bonded concrete overlay. Pavement design, traffic control, and construction methods that will yield a durable pavement at minimum cost and minimum public burden are being investigated in a two-year study (Ref 1).

1.2 RESEARCH OBJECTIVES

The primary objective of this study is to evaluate the technical and economical feasibility of expediting BCO applications on reinforced concrete pavements in the El Paso highway district, and to monitor the subsequent performance of the overlay. Subobjectives of this study are:

1. To identify several pavement sections that represent variations in the original pavement condition and the different pavement candidate materials available for the overlay.
2. To observe and record the actual materials, construction techniques, and climatic conditions during the overlay placement.
3. To make observations on the behavior parameters before and after overlay placement activity and periodically repeat the measurements in a long-term performance monitoring procedure.
4. To statistically analyze and evaluate field data before, during, and after construction of the BCO.
5. To make final recommendations on materials, construction procedures, and construction techniques for the BCO in the El Paso highway district.

1.3 SCOPE

The scope of the research, results, and recommendations presented in this report were limited to the following:

1. Design of a cost-effective mix for the BCO that will meet specifications set forth by the Texas Department of Transportation (TxDOT) and gain sufficient strength to allow traffic back on in minimal time without significant loss of strength or durability.

2. Investigation of the factors that affect bond performance of the overlay to be constructed.
3. Determination of the optimum and adverse times to schedule the placing of the overlay and a full-scale test section.
4. Analysis of the bond development of the selected mix design at early ages.
5. Analysis of the correlation of maturity to bond strength development for the selected mix design (in order to monitor bond strength development in the field).
6. Presentation of recommendations for the construction of a full-scale test section, from which final specifications for the placement of the actual overlay will be determined.

1.4 FORMAT

This report is divided into nine chapters. A review of literature and an overview of topics related to bonded concrete overlays and the factors that affect bond are presented in Chapter 2. Chapter 3 describes the selection of a cost-effective mix design. The effects of environmental conditions that can affect the bond between the BCO and substrate pavement are discussed in Chapter 4. Overlay characteristics to be determined by the result of a full-scale test section are presented in Chapter 5. Chapter 6 discusses the results of the bond development testing of the selected mix design. Chapter 7 includes the correlation of bond and compressive strength development to maturity for the selected mix design. Chapter 8 summarizes results and preliminary construction recommendations. Finally, Chapter 9 presents conclusions and recommendations for future research.

CHAPTER 2. BACKGROUND

Before undertaking any project, one should conduct an extensive review of all pertinent literature in order to gain an understanding of the background information available on the topic being investigated. New technology, experience gained in related projects, and a knowledge of current testing procedures are all useful in organizing a testing program. The following sections briefly provide an overview of bonded concrete overlays, their construction, performance characteristics, and methods of evaluating bond strength development in the field.

2.1 BONDED CONCRETE OVERLAY CONSTRUCTION

There are three basic types of overlays that may be used in the repair of highways: (1) unbonded concrete overlays, (2) partially bonded concrete overlays, and (3) bonded concrete overlays. Unbonded concrete overlays are overlays where no bond exists between the old pavement and the new overlay. A separation layer (usually asphalt) is used to prevent bonding between the two layers of concrete. One advantage to this type of construction is that only minimal surface preparation of the existing pavement is required. The overlay thickness, however, is usually larger than that associated with bonded concrete overlays. Unbonded concrete overlays are often chosen when the expected remaining life of the pavement under rehabilitation is short (Ref 2).

Partially bonded concrete overlays are not intentionally used in current practice. This type of overlay is placed without preparation of the existing pavement. No separation layer is used. Furthermore, the strength of the bond between the overlay and the old pavement, as well as its uniformity, is uncertain (Ref 2).

Bonded concrete overlays (BCOs) are generally thinner than both unbonded and partially bonded overlays. Since the two layers are bonded, they act as one monolithic structure having a higher stiffness than would two individual layers having the same overall thickness. This type of overlay requires careful surface preparation, though, if adequate bond is to be developed.

Different types of reinforcement can be used in all three overlay types. The overlay reinforcement can consist of: (1) no reinforcement (plain concrete), (2) steel reinforcing bars, (3) welded wire mesh, and (4) fiber (steel and/or polymer) reinforcement.

The general construction of BCOs is not complex. First, the existing pavement surface is completely cleaned by one of several preparation methods. Common surface preparation methods include shotblasting, cold milling, sandblasting, and waterblasting. Shotblasting equipment impacts the surface of the pavement with steel shot, which is captured by magnets near the bottom of the equipment and is suctioned and recycled through the unit. Steel shot is slowly lost, however, especially in large cracks and in pavement discontinuities. The shotblasting method works well when removing only a thin layer of pavement, approximately 0.6-centimeters (0.25-inch) thick (Ref 3), as preparation for a bonded concrete overlay. In the cold milling process, a milling machine removes the top layer of pavement. However, this method is usually used only when a thicker layer of pavement is to be removed, usually 0.6- to 2.5-centimeters (0.25- to 1.0-inch) thick. This method has the disadvantage of fracturing the concrete and creating horizontal cracks below the surface, which may lead to delamination failure.

Sand blasting and waterblasting are generally used for secondary cleaning of the pavement to remove debris from shotblasting and cold milling just before the overlay is placed. Waterblasting is not as widely used, since the pavement must be allowed to dry before paving can begin.

Shotblasting is the preferred method of surface preparation. Whatever method is chosen to prepare the current pavement, however, numerous tests have shown that as long as the surface is free of asphalt, dirt, paint, oil, and debris, and as long as approximately 0.6 centimeters (0.25 inch) of the surface pavement has been removed, each method will provide an adequate surface on which to place the overlay (Ref 4).

After the surface of the existing pavement is prepared, overlay placement begins. One of the faster and more economical methods of placing the concrete uses expedited paving methods described later in this report. This type of paving method is sometimes incorrectly referred to as "fast track" paving by certain departments of transportation, since "fast track" implies that construction begins before the design phase is completed.

Next, the freshly placed concrete is finished and textured. In this step of overlay construction, artificial-turf drags, brooms, and steel tynes are used to obtain the desired pavement texture (Ref 5).

Finally, the overlay is allowed to cure. The curing process is critical in the construction of bonded concrete overlays. It is during this period that the pavement is most susceptible to thermal changes, drying winds, and to other adverse environmental conditions that can cause shrinkage cracking and debonding of the overlay.

The usual method of curing involves spraying the surface with a curing compound to reduce the effect of wind currents over the surface and to prevent early-age moisture loss. Sometimes, however, it is also necessary to fog the surface or cover it with wet burlap or polyethylene sheets (Ref 6), especially under such conditions as high wind and low humidity, which create a high rate of evaporation. Thermal blankets are also used when large temperature changes are anticipated.

Curing of the overlay can further be improved by placing during a period when the evaporation rate of water from the freshly placed concrete is predicted to be low. The evaporation rate of water from fresh concrete is dependent on air temperature, concrete temperature, relative humidity, and wind speed.

Of these four factors, however, evaporation rate is most heavily dependent on wind speed. From weather records and weather forecasts, an approximate evaporation rate can be predicted and an optimum time to place the overlay can be chosen. The upper limit on evaporation rate to ensure adequate curing recommended by the American Concrete Institute (ACI) is 1.0 kilograms per square meter per hour (approximately 0.2 pounds of water per square foot per hour) (Refs 5, 7).

2.2 EXPEDITED PAVING

Fast curing concrete has been used in several areas of construction for many years now. It has been only in the past decade, however, that fast curing has been applied to highway paving in what is termed "expedited paving." Using older paving methods, concrete casts for highway purposes had to be cured for 5 to 14 days before the highway could be opened to traffic. With expedited paving methods, however, the time between placement and opening lanes for traffic has been decreased to as little as 24 hours.

Expedited paving methods have been shown to have many advantages and have been used successfully in past highway projects. For example, in July 1986, a 10.1-centimeter (4.0-inch) thick concrete overlay was cast on a 17.7-centimeter (7.0-inch) thick base on U.S. Highway 71 North in Storm Lake, Iowa, over an 11.2-m (7-mile) section (Ref 8). The concrete mix used gained a compressive strength of 17,200 kPa (2,500 pounds per square inch) and a bond strength of 1,500 kPa (225 psi) in 12 hours. At 24 hours, these values were 23,700 kPa (3,400 psi) and 2,000 kPa (300 psi), respectively. It was decided that, at these 24-hour values of compressive and bond strength, the pavement would have adequate strength to allow traffic back on the highway. The repaired section was later evaluated and predicted to have an expected life of 20 to 30 years (Ref 8).

Using the expedited method on U.S. Highway 71 reduced the overall cost of the project (and even equaled the cost projections of using asphalt instead of concrete to repair the highway section). Furthermore, the burden to the public created by lane closures and detours was minimized.

Since the Highway 71 project has been completed, expedited paving methods have been used more frequently. The reduction in time and increase in automation involved in the construction process has reduced project costs to where they now rival those of asphalt construction.

However, with better technology and streamlined methods, some believe the time before traffic can be allowed back on highways repaired using expedited methods can be reduced to as little as 8 hours (Ref 9). Concrete mixes with higher early strengths and new developments in paving machinery will certainly help decrease construction time and cut costs in future projects.

2.3 FACTORS AFFECTING BOND PERFORMANCE

Loss of bond strength between an overlay and the underlying pavement is detrimental to the expected life of the new pavement. Once debonding takes place, the structure no longer performs as a monolithic slab. Stiffness is reduced and higher tensile stresses and deflections can result.

Many factors affect the performance of the bond development between concrete overlays and substrate pavement. These factors include mix design, environmental conditions (especially at early ages), overlay thickness, surface preparation, type of reinforcement, and curing.

2.3.1 Mix Design

The properties of a mix design used to place an overlay are crucial to its performance. It is desirable to place the overlay and allow traffic back on the surface in a minimal amount of time. When expedited paving methods are used, the mix must gain high strength at early ages. If the newly repaired pavement is to have a long life without needing excessive maintenance, it must be able to withstand predicted traffic volume and weights, as well as changing environmental conditions, while still remaining well-bonded to the underlying pavement.

To keep costs low, materials local to the project site should be used in mix designs that are tested for use as a proposed overlay. Component size and fineness will depend on the materials available and on the overlay design thickness. Cement type will depend on the desired characteristics of the new pavement, its availability, and its cost. Properties of a particular mix design of interest are modulus of elasticity, compressive strength development, tensile strength development, bond strength development, and coefficient of thermal expansion.

2.3.2 Environmental Conditions

The environmental conditions that exist while the concrete overlay is fresh can be critical with respect to the bond strength development of the overlay. The major environmental factors that affect plastic shrinkage, which, in turn, affect bond strength development, are air temperature, relative humidity, wind speed, and concrete temperature. Large thermal changes can cause shrinkage stresses and cracking and can lead to delamination. In past projects, shear stresses occurring between the overlay and underlying pavement have been shown to be increased by as much as 500 percent simply because the overlay was placed in the early morning, when large temperature increases can be expected (Ref 10).

All four of the factors listed above may be anticipated with the help of historical weather records and weather forecasts, but all are uncontrollable, with the exception of concrete temperature. This factor may be controlled to some extent by cooling the concrete through the use of chilled batch water or by utilizing liquid nitrogen to cool the batched concrete (Ref 11).

The effects of all four environmental factors can be combined to give the evaporation rate of water at the surface of the fresh concrete. A nomograph for calculating the evaporation rate, originally developed by C. A. Menzel and the Portland Cement Association, is shown in Figure 2.1. The evaporation rate of water, in pounds per square foot per hour, can be read from this figure when temperature, relative humidity, concrete temperature, and wind speed are known. From this figure, it is clear that wind speed is the single most important factor of the four, with respect to evaporation rate. A small increase in wind speed of just 8.0 kilometers per hour (5.0 miles per hour) can increase the evaporation rate from 50 to 100 percent. Alternatively, shading the concrete during the day in hot weather can reduce the evaporation rate by as much as 25 to 50 percent (Ref 7).

An equation for evaporation rate has been formulated in a previous study to replace the nomograph shown in Figure 2.1. This equation for evaporation rate, ER, in pounds per square foot per hour (lb/ft^2*hr) is as follows (Ref 13):

$$ER = [0.012 + 0.00484 * WS] * J \qquad [2.1]$$

where:

$$J = [0.000263 * CT^{2.2593} - \exp(-5.44 + 0.948 * \ln(RH) + 0.033 * AT)]/1.17 \qquad [2.2]$$

and

WS = wind speed (mph),

CT = concrete temperature (^{o}F),

RH = relative humidity (%), and

AT = air temperature (^{o}F).

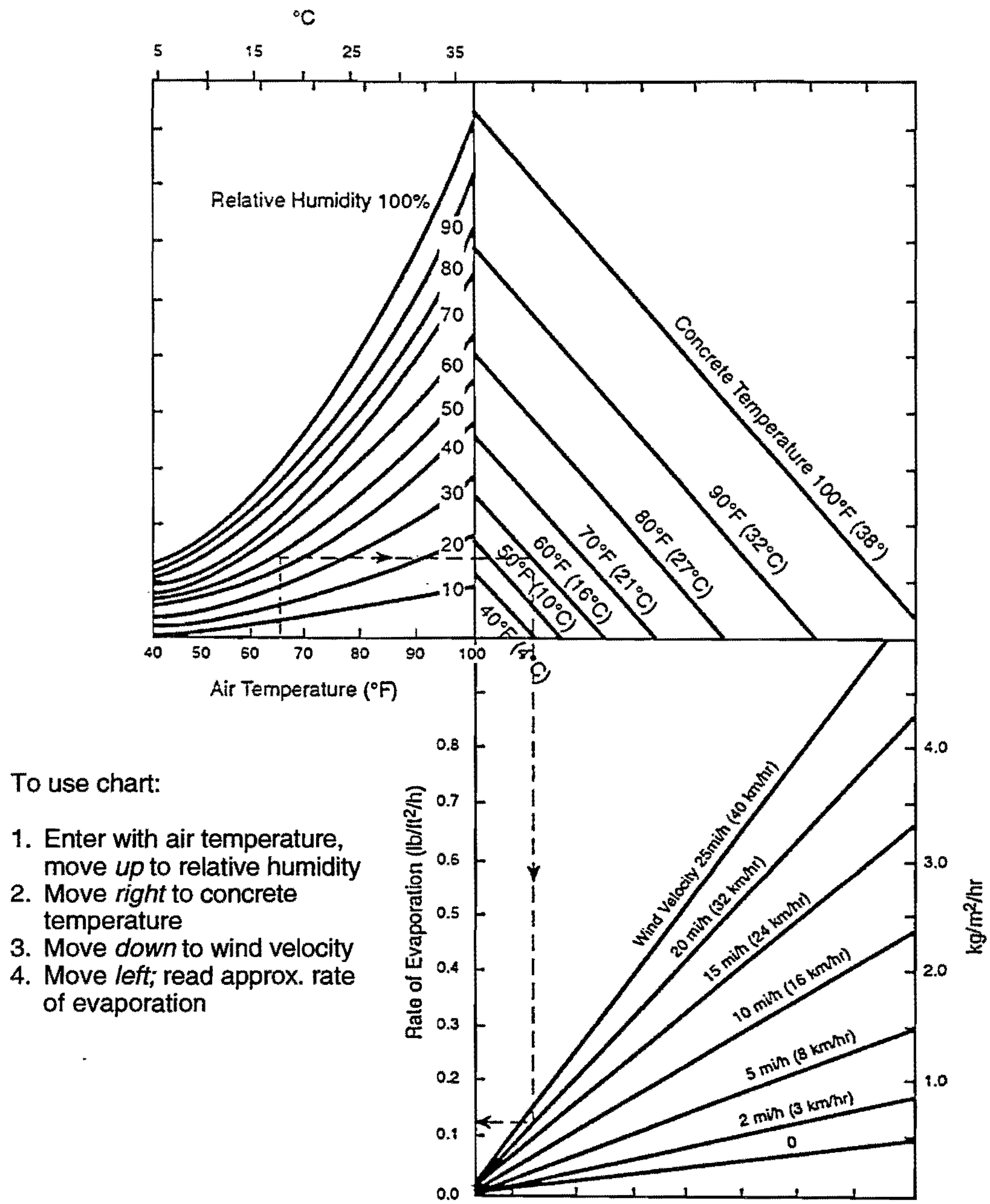

Figure 2.1. Nomograph for Calculating Evaporation Rate of Water from Freshly Placed Concrete (Ref 12).

Conversion of the resulting evaporation rate given by equations [2.1] and [2.2] to metric units of kg/m^2*hr can be easily achieved by multiplying the result by a factor of 4.9. Equations [2.1] and [2.2] are very useful in analyzing weather records to determine an optimum time to place an overlay — that is, when the evaporation rate is expected to be low (under 1.0 kg/m^2*hr or 0.2 lb/ft^2*hr).

2.3.3 Overlay Thickness

The thickness of an overlay is determined by the expected traffic load, the total thickness of the new overlay and old pavement, its expected life, and the physical limitations created by bridge and underpass clearances.

Common thicknesses for overlays placed on a typical 20.3-centimeter (8.0-inch) thick pavement range from 5.1 to 15.2 centimeters (2.0 to 6.0 inches). Current construction practices favor overlays of an approximate 10.1-centimeter (4.0-inch) thickness (Ref 10). The minimum overlay thickness allowable when using slipform paving is 5.1 centimeters (2.0 inches). There is no maximum limit to overlay thickness: overlays as thick as 25.4 centimeters (10.0 inches) have been successfully placed on airport runways and taxiways (Ref 6).

2.3.4 Surface Preparation

As stated previously, the preferred method of primary surface preparation is shotblasting. The primary preparation is usually followed by a secondary cleaning method, such as sand-blasting or waterblasting. It is important to remove the top layer of pavement (especially if the current pavement is concrete topped with a layer of asphalt) to get a clean, adequately roughened surface that is free of dirt, paint, oil, and debris. A clean, well-roughened surface will better enable the freshly placed overlay to adhere to the old pavement and ensure good bond strength development.

2.3.5 Curing

Careful and adequate curing will prevent moisture loss and reduce the evaporation rate of water from the freshly placed overlay. A properly cured overlay will not suffer as much from thermal stresses, shrinkage stresses, cracking, or delamination, and will have a longer expected life free of excessive maintenance requirements.

2.3.6 Reinforcement

The amount and type of reinforcement in an overlay (if any) and its placement can affect cracking, delamination, and deterioration of the rehabilitated pavement (Ref 2). Distribution of the reinforcement provided will affect the performance of the overlay. In the construction of thinner concrete overlays, reinforcing steel bars are often too wide in diameter to use. Distribution of such reinforcing steel would not be uniform and could result in large cracks. Better distribution of steel is obtained by using welded wire mesh or fibers to reinforce the structure.

2.4 TESTING PROCEDURES TO PREDICT BOND STRENGTH

Many test methods have been developed to obtain values for bond strength between two layers of a specimen. Most fall into the following two groups: (1) direct and indirect tension tests, and (2) shear and shear-compression tests.

2.4.1 Direct and Indirect Tension Tests

Direct tension tests involve preparing a specimen, gripping it firmly at both ends, and pulling it apart to failure (Fig 2.2). While simple in theory, accurate tension tests are difficult to perform. The load must be applied without eccentricity; otherwise a bending moment will be induced. Furthermore, gripping the specimen without slip is difficult.

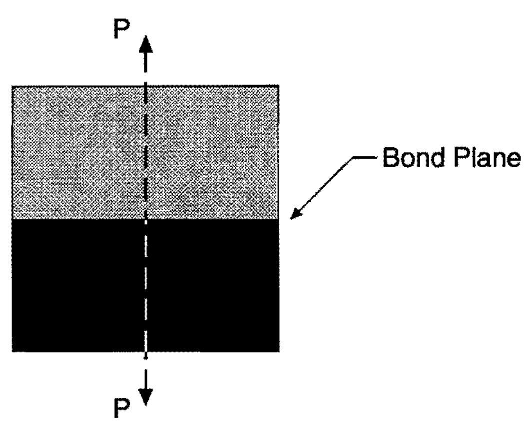

Figure 2.2. Direct Tension Test Specimen.

Indirect tension tests are somewhat simpler to perform. These tests usually involve a combination of shear and flexure, as shown in Figure 2.3. The basic shear specimen shown is loaded in shear exactly at the bonding plane. Although the application of the load in indirect tension tests is less involved, problems may still arise. For example, since the bond plane is subject to a high stress gradient at the edge, failure may be determined by a very small part of those planes submitted to the maximum stress (Ref 14). Therefore, this type of test does not have realistic applications to bonded concrete overlays.

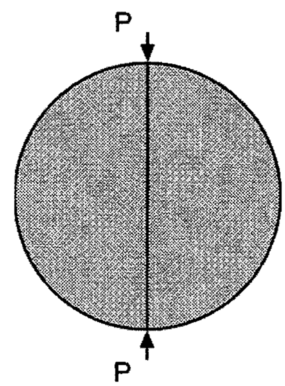

Figure 2.3. Indirect Tension Test Specimen.

2.4.2 Shear and Shear-Compression Tests

A basic shear test specimen is shown in Figure 2.4. Shear is applied at the bond line while part the specimen is held within a rigid frame. This set-up is commonly referred to as a "guillotine" test.

This particular set-up also has its drawbacks. Since a localized compressive stress is induced near the application of the load, failure is more a representation of the "average capacity" of the bond between the two halves of the specimen (Ref 14). Furthermore, it is difficult to totally eliminate bending of the specimen or to prevent small amounts of slippage within the rigid frame (Ref 4).

Shear-compression tests can be set up as shown in Figure 2.5. This set up is usually referred to as a "slant" test or "shear-slant" test. The bond plane is usually situated 60° from the horizontal (30° from the axis of applied compression). Here, the complete bond plane is stressed, without high stress gradients occurring at the level of the bond, as sometimes occurs in performing the guillotine test. However, numerous experiments performed using this set up have found considerable scatter of results (Ref 14). Furthermore, this type of test is not well-suited for bonded concrete overlay testing. The normal force component provides more friction than would ever be induced in the shear failure of an overlay (Ref 4).

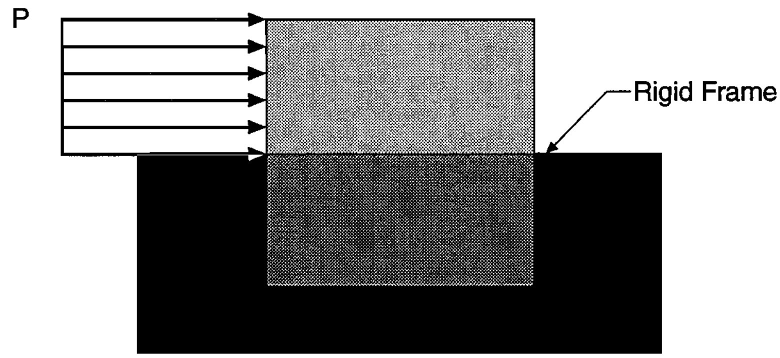

Figure 2.4. Shear Test Specimen.

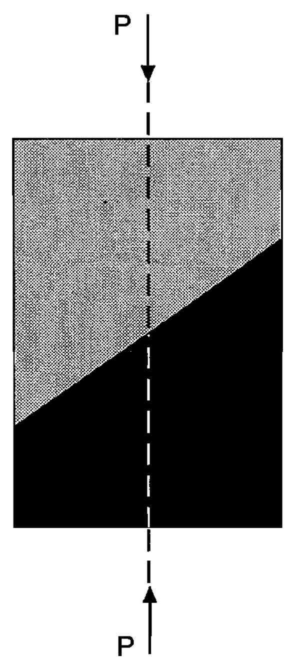

Figure 2.5. Shear-Compression Test Specimen.

2.5 MONITORING BOND DEVELOPMENT IN THE FIELD

Several methods for estimating bond strength of overlays in the field have been developed. These include destructive methods, such as core sampling and pull-out tests, and non-destructive methods, such as echo-impact tests and the use of the maturity method.

2.5.1 Analyzing Cores

Cores of concrete can be taken once the overlay has gained sufficient strength. The number of cores taken should be representative of the area under consideration. Cores should be taken randomly, but should include samples near joints and pavement edges. Once coring is completed the bond strength of the samples can be determined using the guillotine testing described earlier.

The disadvantages of this method include having to repair the cored areas, the necessity of a nearby laboratory to perform the tests, and the wait involved in letting the concrete obtain sufficient strength to withstand the force and vibration of the coring equipment.

2.5.2 Pull-Out Tests

There are a variety of pull-out tests that can be performed to estimate the bond of an overlay. Typically, inserts of a given diameter are placed in the fresh concrete to a specified depth. At a given age, these inserts are pulled out using a center-pulled hydraulic jack (Ref 15). The maximum pull-out force required to remove the insert is recorded from a pressure gauge on the jack. Calibration charts provided by the manufacturer of the jack can then be used to convert pull-out force to bond strength.

The disadvantages of this method are similar to those associated with coring. Repairs must be made on the areas where the tests are performed. Furthermore, the diameter of the inserts is typically 2.5 to 5.1 centimeters (1.0 to 2.0 inches). When the overlay is, for example, 15.2-centimeters (6.0-inches) thick, the diameter-to-depth ratio may be too small to accurately represent the bond strength of the overlay.

2.5.3 Echo-Impact Testing

The echo-impact method reveals delaminations non-destructively. This method has been used to determine not only the extent but also the position of debonded areas (Ref 16). However, some problems were encountered using this method in monitoring delaminations in a bonded concrete overlay in Houston, Texas.

In carrying out this method, a Schmidt, or Swiss, hammer is used on the pavement. Readings of the pulse velocity of the induced waves reflected back are recorded. Readings are then converted to strength values using charts provided by the manufacturer of the equipment (Ref 15).

The echo-impact method works well, as no repairs need to be made to the site after testing is completed. All work can be done at the site and many readings can be taken to map out the bond strength of the overlay and areas of delamination.

2.5.4 Maturity Method

While the maturity method offers another non-destructive, in-situ test to estimate the bond strength of the concrete overlay, it provides no insight into delaminations. Maturity of concrete can be recorded using a variety of maturity meters available on the market. Maturity readings taken over a given period can then be used to estimate the bond strength of an overlay.

Maturity monitoring is based on the chemical hydration of cement in concrete. Hydration of cement is an exothermic reaction. The heat radiating from a cement overlay can be recorded and converted to maturity values (Ref 17). Maturity (in ^{o}C*hours) at any time, t, can be expressed by following equation (Ref 18):

$$M(t) = \Sigma (T - T_o) * \Delta t \qquad [2.3]$$

where:

$M(t)$ = maturity at age t (^{o}C*hours),
Δt = time interval (hours),
T = average temperature of concrete during Δt (^{o}C), and
T_o = datum temperature (^{o}C).

The datum temperature is the temperature where the strength gain of the concrete tends to level off.

The equivalent age of the concrete at specified temperatures can be obtained from the following equation (Ref 18):

$$t_e = \Sigma \exp [-Q * (1/T_a - 1/T_s) * \Delta t] \qquad [2.4]$$

where:

t_e = equivalent age at a specified temperature, T_s (hours),
Q = activation energy divided by the gas constant (^{o}K),
T_a = average temperature of the concrete during Δt (^{o}K),
T_s = specified temperature (^{o}K), and
Δt = time interval (hours).

Maturity meters currently on the market record the temperature of the concrete continuously and calculate the values of maturity at specified intervals of time. Typically, maturity values are calculated every half hour for the first 48 hours, and then every hour until the meter is shut off or until battery power is depleted. The values at each time are stored in the memory of the unit until the test is completed; the values are then downloaded into a computer.

A plot of maturity versus time can be made using this time history. Comparison of maturity to bond development can then be made. Finally, analysis of maturity and bond development can be used to estimate the bond that has developed between the overlay and the substrate pavement with a given maturity value obtained in the field.

This method of using maturity to estimate bond development is particularly useful. The maturity wires inserted into the overlay can simply be cut once all readings have been obtained. No repairs to the pavement are necessary at the completion of testing. Furthermore, maturity meters are lightweight and portable and can record data (unsupervised) over long periods.

CHAPTER 3. MIX DESIGN

Four different mix designs for the bonded concrete overlay were evaluated and compared. The mixes considered included a standard Texas Department of Transportation (TxDOT) mix, mixes with various superplasticizers, and a mix using a high early strength cement. Shrinkage compensating cements (Type K) and rapid set cements were considered, but not tested. Owing to high cost and variability in controlling expansion when using these types of cement, both were rejected early in the mix design testing phase.

3.1 AGGREGATE CHARACTERISTICS

Aggregates were provided by Jobe Concrete Products of El Paso, Texas. Two sizes of coarse aggregate were obtained, 3.8 and 1.9 centimeter (1.5 inch and 0.75 inch) minus. Since initial calculations showed the concrete overlay would be no more than 15.2 centimeters (6.0 inches) in thickness, the larger size coarse aggregate was not utilized in any mix design testing. The maximum size aggregate for use in a slab should be less than one-third the smallest dimension of the slab (its thickness); otherwise difficulties in placement could result (Ref 19). Therefore, only the grade #67, 1.9 centimeter (0.75 inch) minus, coarse aggregate (or coarse aggregate grade #6 [Ref 20]) was used in mix design testing. The characteristics of the coarse and fine aggregate used in mix design testing were as follows:

Coarse:

Crushed, dense dolomitic Cambrian limestone	
Bulk specific gravity (BSG):	2.7
Dry rodded unit weight (DRUW):	510 kN/m^3 ($92\ lb/ft^3$)

Fine:

Bulk specific gravity (BSG)	2.6
Fineness modulus (FM)	2.8

3.2 CEMENT AND ADMIXTURES UTILIZED

Type I/II cement and a high early strength cement, Pyrament® PBC-XT 90, were used in mix design testing. Pyrament, a blended cement with a set time of 90 minutes, was provided by Lone Star Industries. The Type I/II cement was provided by Jobe Concrete.

The admixtures used in several of the test mixes included two superplasticizers: Rheobuild® 1000 High Range Water Reducer and Polyheed® 997 Medium Range Water Reducer (both produced by Master Builders). The air entraining admixture used was Grace Darex II®.

3.3 MIX DESIGNS TESTED

Originally, four mix designs were tested. Each mix was evaluated for its strength development and cost. The four mix designs tested were:

1. Standard TxDOT mix using Type I/II cement
2. High early strength mix using Type I/II cement and Rheobuild 1000 superplasticizer
3. High early strength mix using Type I/II cement and Polyheed 997 superplasticizer
4. High early strength mix using Pyrament blended cement.

While the dosage rate for Polyheed 997 was considerably greater than that for Rheobuild 1000, it yielded specimens having similar strength development characteristics. Since the cost for each product was approximately the same, the Polyheed 997 mix was dropped from further consideration.

The 1993 TxDOT specifications for overlay class concrete (Ref 21) require the following characteristics:

Minimum cement content:	9.1 sacks/m^3 (7 sacks/yd^3)
Minimum 28-day cylinder compressive strength:	31,700 kPa (4,600 psi)
Minimum 7-day flexural strength:	4,400 kPa (650 psi)
Maximum water-to-cement ratio:	0.4
Coarse aggregate grade number:	6
Desired slump for concrete pavement:	3.8 cm (1.5 inches)
Maximum slump	12.7 cm (5.0 inches)
Entrained air content:	7% ± 1 1/2%

Each of the four mixes tested was required to meet these specifications. All four mix designs were developed using the absolute volume method for selecting and proportioning concrete (Refs 20, 21).

We moist cured 1- and 3-day specimens outside under wet burlap and plastic sheets. This curing condition tended not to overestimate the early age strength characteristics of the specimens, and attempted to simulate actual site conditions. We took 7- and 28-day specimens out of their molds and cured them inside in 21°C (70°F) lime-saturated water.

Table 3.1 shows the proportions of the constituents used in each mix design tested, as well as important mix design characteristics. The Polyheed mix constituents are not shown, since the performance of this mix was similar to that for the Rheobuild mix, but more expensive It should be noted that the standard TxDOT mix had a cement content of 8.9 sacks/m^3 (6.8 sacks/yd^3 or 3719 N/m^3). This is fewer than the 9.0 sacks/m^3 (7.0 sacks/yd^3) specification. However, the concrete specimens produced with this mix did gain adequate strength. Adding more cement to the mix would only increase strength.

Table 3.1. Mix Constituents and Characteristics.

Mix *Constituents in N/m^3 (lb/yd^3):*	**Standard TxDOT Mix**	**Rheobuild Mix**	**Pyrament Mix**
Water	1484 (255)	1478 (254)	9200 (158)
Type I/II Cement	3713 (638)	5098 (876)	-
Pyrament Cement	-	-	4,377 (752)
Coarse Aggregate	10,842 (1863)	10,411 (1789)	10,988 (1888)
Fine Aggregate	6605 (1135)	6402 (1100)	8014 (1377)
Admixtures in ml/100 N (floz/100 lb) of cement):			
Rheobuild 1000	-	8.0 (1.2)	-
Darex II	-	26.6 (4.0)	-
Characteristics:			
Water/Cement Ratio	0.4	0.29	0.21
Sacks of Cement/m^3 (Sacks /yd^3)	8.9 (6.8)	12.2 (9.3)	10.5 (8.0)
Liters of Water/Sack (Gallons/Sack)	17.0 (4.5)	12.5 (3.3)	9.0 (2.4)
Slump in Centimeters (Inches)	2.5-7.6 (1.0-3.0)	2.5-7.6 (1.0-3.0)	2.5-7.6 (1.0-3.0)
Air Content	6%	4.5%	2.5%

3.3.1 Strength Development

The development of 8-hour, 1-, 3-, 7-, and 28-day compressive strengths and 8-hour, 1-, 3-, and 7-day flexural strengths is shown in Tables 3.2 and 3.3, respectively, for the mix design specimens tested. Compressive strengths were obtained using 10.2-by-20.3-centimeter (4.0-by-8.0-inch) cylinders according to ASTM C39, and a 2,700-kiloNewton (600,000-pound) capacity Forney Cylinder Testing Machine at a loading rate between 175 to 275 kiloNewtons per minute (40,000 and 60,000 lbs per minute). Flexural strengths were determined using 15.2-by-15.2-by-

53.3-centimeter (6.0-by-6.0-by-21.0-inch) beams tested according to ASTM C78 and a Reinhart Beam Tester with three-point loading.

Table 3.2 shows that the standard TxDOT mix gained compressive strength within TxDOT specifications (31,700 kPa or 4600 psi) within 28 days, although it was close to the necessary level of compressive strength at 7 days. The Rheobuild mix met compressive strength specifications within 3 days, and the Pyrament mix easily surpassed the TxDOT specification in just 1 day.

Table 3.3 shows that the standard TxDOT mix achieved flexural strength within specifications (4,400 kPa or 640 psi) soon after 7 days. The Rheobuild and Pyrament mixes, however, achieved the required flexural strength within the first 24 hours. Subsequently, these two mixes went on to develop considerable strengths necessary for a durable concrete overlay in a short period of time. Figures 3.1 and 3.2 show the compressive and flexural strength development over time for each of the three mix designs tested.

Table 3.2. Compressive Strength Development in kPa (psi).

Age (days)	Standard. TxDOT Mix	Rheobuild 1000 Mix	Pyrament Mix
0.33	1544 (224)	18,650 (2705)	24,655 (3576)
1.0	13,692 (1986)	27,124 (3934)	42,333 (6140)
3.0	22,704 (3293)	34,246 (4967)	54,978 (7974)
7.0	30,916 (4484)	39,252 (5693)[a]	60,212 (8733)
28.0	39,093 (5670)	41,631 (6038)[a]	-

[a] Improper curing in dry environment reduced compressive strengths.

Table 3.3. Flexural Strength Development in kPa (psi).

Age (days)	Standard TxDOT Mix	Rheobuild 1000 Mix	Pyrament Mix
0.33	689 (100)	3675 (533)	3792 (550)
1.0	3675 (533)	4957 (719)	5743 (833)
7.0	4137 (600)	4619 (670)[a]	7357 (1067)
28.0	4930 (715)	4137 (600)[a]	-[b]

[a] Thermocouple wires embedded in these specimens reduced flexural strengths.

[b] Flexural strength was higher than Reinhart Tester Series 416 could measure.

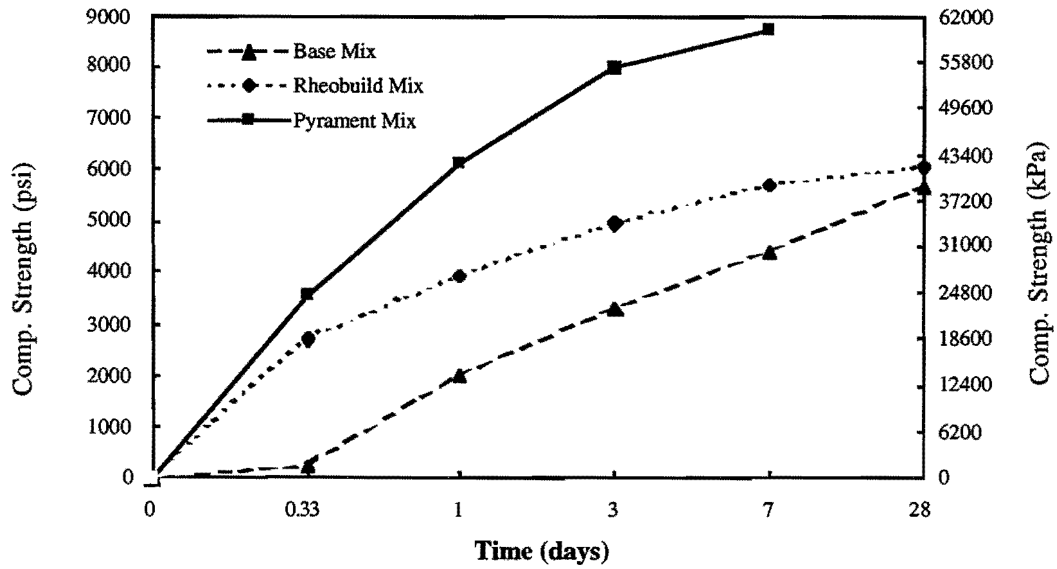

Figure 3.1. Compressive Strength Development for the Three Mixes Tested.

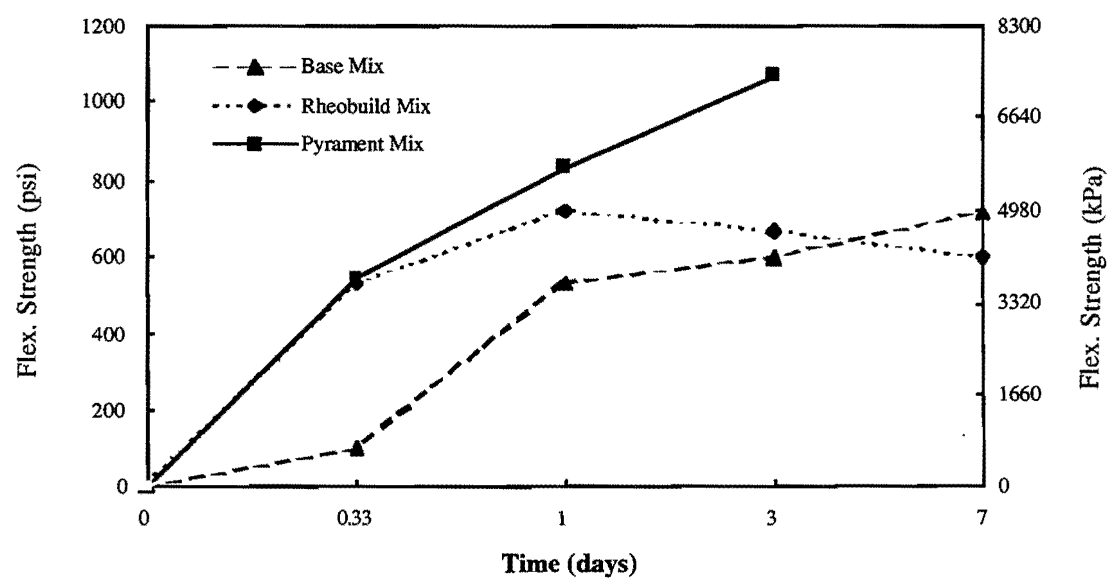

Figure 3.2. Flexural Strength Development for the Three Mixes Tested.

3.3.2 Cost Comparison

A price comparison of each mix was completed. The cost per unit volume for each of the three mixes in shown in Table 3.4. From this table, it can be seen that the Pyrament mix is considerably more expensive than either the standard mix or the Rheobuild mix (costing approximately twice as much).

Table 3.4. Cost Comparison.

Mix	Cost in $\$/m^3$ ($\$/yd^3$)
Standard TxDOT	79 (60)
Rheobuild	94 (72)
Pyrament	165 (126)

3.4 MIX DESIGN SELECTION

Both the Rheobuild and Pyrament mixes gained compressive and flexural strengths specified by TxDOT for concrete overlays much faster than did the standard TxDOT mix. However, the high cost per cubic yard (as well as the preliminary bond testing) led to the rejection of the Pyrament mix. The early age strength gain of the Rheobuild mix is considerably greater than that of the standard mix. It would be quite suitable for expedited paving, and the cost saved in reducing lane closure and construction time would more than make up for the small increase in cost. Therefore, the Rheobuild mix was selected for use in this bonded concrete overlay project and was the sole mix design considered in performance testing.

CHAPTER 4. ENVIRONMENTAL CONDITIONS AND BOND DEVELOPMENT

One of the major factors affecting the bond between a concrete overlay and the underlying substrate is the environmental conditions existing during placement and at early ages. Thermally induced stresses, high evaporation rates, and even pressure differentials caused by strong wind currents can lead to debonding of the overlay. Research has shown that delamination caused by environmental effects often occurs in the first 48 hours of the life of the pavement (Ref 4).

An investigation of weather records was undertaken to determine the times of year in El Paso, Texas, when environmental conditions should be both adverse and optimum to place the overlay. Important factors investigated included temperature, relative humidity, wind speed and direction, concrete temperature, and evaporation rate. This knowledge should play an important role in the scheduling of both the full-scale test section and the placement of the entire overlay.

4.1 TEMPERATURE

Dry bulb temperature records were obtained for the El Paso, Texas, area. This information consisted of hourly readings taken from June 1992 to May 1994. The temperature fluctuations for each month were put into spreadsheet format and charted. From these charts the average monthly temperature, average minimum monthly temperature, and average maximum monthly temperature for the 2-year period were determined. Table 4.1 shows these values.

It should be noted from Table 4.1 that the largest daily temperature differentials appear to occur during the months of June, July, and August. Placing the overlay during these months would most likely subject it to large thermal stresses. The possibility of freezing conditions should be considered during the months of November, December, January, and February.

4.2 RELATIVE HUMIDITY

Relative humidity records were also obtained for the El Paso area. Hourly readings from June 1992 to May 1994 were put into spreadsheet format and charted. Relative humidity often falls dramatically between day and night. Table 4.2 summarizes the average monthly maximum and minimum humidity values for the 2-year period studied.

The least humid months appear to be April, May, June, and July. Placing an overlay during these month may subject the fresh pavement to excessive moisture loss and cracking.

4.3 WIND SPEED

El Paso area wind speed records were also obtained. Hourly readings from June 1992 to May 1994 were put into spreadsheet format and charted. Wind speed is the environmental characteristic that most heavily affects the evaporation rate of water from fresh concrete. Table 4.3 summarizes the average monthly wind speed.

Table 4.1. Average Temperature, Average Minimum Temperature, and Average Maximum Temperature by Month.

Month	Avg. Temperature in °C (°F)	Avg. Minimum Temperature in °C (°F)	Avg. Maximum Temperature in °C (°F)	Avg. Daily Temp. Differential in °C (°F)
6/92	28 (83)	17 (63)	36 (97)	19 (34)
7/92	29 (85)	22 (72)	36 (97)	14 (25)
8/92	27 (81)	20 (68)	31 (87)	11 (19)
9/92	25 (78)	18 (65)	32 (89)	14 (24)
10/92	19 (67)	13 (55)	26 (79)	13 (24)
11/92	9 (48)	6 (43)	14 (58)	8 (15)
12/92	10 (50)	3 (37)	9 (49)	6 (12)
1/93	9 (48)	6 (42)	13 (55)	7 (13)
2/93	11 (51)	6 (43)	17 (62)	11 (19)
3/93	15 (59)	6 (43)	18 (65)	12 (22)
4/93	20 (68)	11 (52)	25 (77)	14 (25)
5/93	24 (76)	16 (61)	28 (83)	12 (23)
6/93	28 (83)	21 (69)	36 (96)	15 (27)
7/93	29 (84)	22 (71)	35 (95)	13 (24)
8/93	27 (81)	23 (73)	35 (95)	12 (22)
9/93	24 (75)	18 (65)	31 (88)	13 (23)
10/93	18 (64)	14(58)	25 (77)	11 (19)
11/93	11 (52)	6 (43)	17 (63)	11 (20)
12/93	8 (46)	4 (40)	14 (58)	10 (18)
1/94	7 (45)	2 (35)	14 (57)	12 (22)
2/94	10 (50)	4 (39)	13 (56)	9 (17)
3/94	15 (59)	7 (45)	18 (64)	11 (19)
4/94	19 (67)	11 (52)	23 (74)	12 (22)
5/94	24 (76)	16 (60)	28 (83)	12 (23)

Table 4.2. Average Monthly Maximum and Minimum Humidity.

Month	Avg. Min. Relative Humidity (%)	Avg. Max. Relative Humidity (%)
6/92	28	48
7/92	38	56
8/92	47	73
9/92	37	58
10/92	39	56
11/92	42	66
12/92	63	80
1/93	66	83
2/93	45	67
3/93	34	56
4/93	22	36
5/93	27	42
6/93	31	46
7/93	43	63
8/93	51	72
9/93	45	69
10/93	44	64
11/93	42	62
12/93	45	69
2/94	34	62
3/94	38	55
4/94	25	38
5/94	34	45

Table 4.3. Average Wind Speed by Month.

Month	Avg. Wind Speed in kph (knots)
6/92	13.5 (7.3)
7/92	13.5 (7.3)
8/92	12.2 (6.6)
9/92	12.8 (6.9)
10/92	11.8 (6.4)
11/92	13.3 (7.2)
12/92	12.6 (6.8)
1/93	13.1 (7.1)
2/93	14.4 (7.8)
3/93	15.0 (8.1)
4/93	17.0 (9.2)
5/93	15.7 (8.5)
6/93	15.6 (8.4)
7/93	14.4 (7.8)
8/93	12.2 (6.6)
9/93	12.0 (6.5)
10/93	12.2 (6.6)
11/93	12.4 (6.7)
12/93	12.2 (6.6)
1/94	12.4 (6.7)
2/94	14.0 (7.6)
3/94	14.8 (8.0)
4/94	16.4 (8.9)
5/94	13.7 (7.4)

No month stands out as having a considerably higher or lower average wind speed. It is apparent, however, that average wind speeds throughout the year are great enough to have a substantial impact on the evaporation rate of water from fresh concrete. This implies that curing procedures to be used will be critical in the strength development of the overlay.

4.4 CONCRETE TEMPERATURE

Average concrete batch temperatures (neglecting the application of any cooling measures) were obtained from Ned Finney of Jobe Concrete Products in El Paso, Texas. These temperatures are shown in Table 4.4. Evaporation rate is not as dependent on concrete temperatures as other factors (such as wind speed). It is also a moderately controllable factor, since the concrete can be cooled before placed. Lowering the concrete temperature decreases the evaporation rate, if all other factors remain the same. As such, these estimations of concrete temperature should provide an adequate approximation, if not a slight overestimation, of the concrete temperature to be expected.

Table 4.4. Estimation of Concrete Batch Temperature.

Month	Avg. Concrete Batch Temperature in °C (°F)
January	10 (50)
February	10 (50)
March	16 (60)
April	21 (70)
May	27 (80)
June	32 (90)
July	32 (90)
August	27 (80)
September	21 (70)
October	21 (70)
November	21 (70)
December	16 (60)

4.5 EVAPORATION RATE

The equation for evaporation rate (in units of pounds per square foot per hour) is as follows (Ref 13):

$$ER = [0.012 + 0.00484 * WS] * J \qquad [4.1]$$

where:

$$J = [0.000266 *(CT)^{2.2593} - \exp(-5.44+0.948 *\ln(RH)+0.033 *AT)]/1.17 \qquad [4.2]$$

and:

WS = wind speed (mph),

CT = concrete temperature (°F),

RH = relative humidity (%), and

AT = air temperature (°F).

Equations [4.1] and [4.2] were used in a statistical analysis of a bonded concrete overlay placed on a section of Interstate Highway 610 in Houston, Texas. In that study, delaminations were found to occur if the overlay was placed when the evaporation rate was 0.75 to 1.0 kg/m^2*hr (0.15 to 0.20 lb/ft^2*hr) or greater (Ref 13).

Previous research suggests concrete overlays be placed when conditions are such that the evaporation rate is less than 1.0 kg/m^2*hr (0.2 lb/ft^2*hr)[13]. Rates greater than this may lead to delaminations and require intense (and costly) curing measures.

Charts of evaporation rate fluctuation per month from June 1992 to May 1994 were generated. These charts can be found in Appendix A. Table 4.5 summarizes the average monthly evaporation rates of water from fresh concrete developed using these charts. These data were generated using equations [4.1] and [4.2], weather records, and an estimation of expected concrete temperatures.

Table 4.5. Average Monthly Evaporation Rate.

Month	**Avg. Evaporation Rate in kg/m^2*hr (lb/ft^2*hr)**
6/92	1.36 (0.28)
7/92	1.21 (0.25)
8/92	0.78 (0.16)
9/92	0.59 (0.12)
10/92	0.59 (0.12)
11/92	0.83 (0.17)
12/92	0.39 (0.08)
1/93	0.15 (0.03)
2/93	0.24 (0.05)
3/93	0.59 (0.12)
4/93	0.93 (0.19)
5/93	1.22 (0.25)
6/93	1.46 (0.30)
7/93	1.12 (0.23)
8/93	0.68 (0.14)
9/93	0.29 (0.06)
10/93	0.54 (0.11)
11/93	0.59 (0.12)
12/93	0.39 (0.08)
1/94	0.24 (0.05)
2/94	0.29 (0.06)
3/94	0.49 (0.10)
4/94	0.83 (0.17)
5/94	0.93 (0.19)

Table 4.5 shows that the months of May, June, and July give rise to the highest rates of evaporation. Placement during these months would probably provide the most adverse conditions at early ages. Excessive moisture loss combined with wind and high average daily temperature fluctuations would lead to the greatest possibility for cracking and debonding.

4.6 WIND DIRECTION

Wind direction data for the 2-year period were also analyzed. Wind direction and wind speed are of particular concern, since part of the IH-10 section to be rehabilitated is depressed.

This section runs in an east-west direction. High winds traveling parallel to this section might create a pressure differential and cause a "suction" effect on the overlay.

Average wind speeds in the El Paso area generally range from 18.5 to 27.8 kilometers per hour (10.0 to 15.0 knots). However, wind speeds between 27.8 to 37.0 kph (15.0 to 20.0 kts) are not uncommon. Wind speeds in excess of 37.0 kph (20.0 kts) have also been recorded. The predominant directions of these higher wind speeds were plotted. Analysis of weather data showed that these high winds come predominantly from the west. As such, the possibility of a "suctioning" effect on the overlay along this depressed section may be considerable.

4.7 PLACEMENT OF A FULL-SCALE TEST SECTION

One of the purposes of placing the full-scale test section will be to determine the best surface preparation, curing technique(s), and reinforcement type for the actual overlay. The full-scale test section will be comprised of areas having various reinforcement and will be subjected to different preparation and curing methods.

To judge which reinforcement, surface preparation, and curing method will perform best, the full-scale test section should be subjected to the most adverse environmental conditions that produce thermal stresses, shrinkage, cracking, and moisture loss. From the data presented in the previous sections, it is obvious that the full-scale test section should be placed in June. July and August should be considered as alternative placement months.

4.8 OPTIMUM TIME TO PLACE OVERLAY

Unlike the full-scale test section, the actual overlay should be placed under the most optimum environmental conditions. This means placing when evaporation rate and thermal stresses are expected to be low. From the data shown in the previous sections, it is recommended that the actual overlay be placed during September or October. If scheduling problems arise and the overlay must be placed during the first half of the year, it would be best to place during March. Freezing could occur during January and early February if the overlay is placed late in the evening. By late April, evaporation rates are usually very high and extensive curing precautions might be needed.

Furthermore, the overlay should be placed during the evening hours. Rapid thermal changes at early ages can cause temperature differentials in the pavement, thus producing large shear stresses. These stresses can cause curling and warping (Ref 13). Placing in the evening hours rather than in the morning has been shown to reduce shear stresses in the pavement by as much as 500 percent in past projects (Ref 7).

CHAPTER 5. OTHER FACTORS AFFECTING BOND

The major factors that affect bond strength and development include mix design, environmental conditions at the time of placement, overlay thickness, surface preparation, curing, and reinforcement. Mix design and environmental effects with respect to the design of the bonded concrete overlay to be placed on IH-10 in El Paso, Texas, have been discussed. The overlay thickness for this project has been determined in another part of this study. Surface preparation, curing method, and reinforcement will be determined from the performance of the full-scale test section to be placed.

5.1 OVERLAY THICKNESS

Using falling weight deflectometer (FWD) data, information from test cores of the current pavement, and information obtained in a visual survey of the IH-10 section to be rehabilitated, the final overlay thickness was determined. It was found that the optimum rehabilitation design for this project calls for an overlay having a 16.5-centimeter (6.5-inch) thickness.

5.2 FACTORS TO BE DETERMINED BY THE PERFORMANCE OF A FULL-SCALE TEST SECTION

The selection of surface preparation method, type of reinforcement, and curing method to be used on the actual overlay will be determined from the performance of areas of a full-scale test section. It is recommended that this test section be placed in June to subject the pavement to extreme, adverse environmental conditions, and to challenge overlay performance.

The full-scale test section will be composed of areas having different surface preparation and reinforcement. It will not only determine the performance of types of preparation and reinforcement, but will also show if any costly construction methods may be omitted without harm to the performance or durability of the overlay. An optimum curing method will be determined when the substrate of the full-scale test section is placed.

5.2.1 Surface Preparation

Two surface preparation methods of interest are shotblasting and waterblasting. Cold milling is predicted to be more expensive than shotblasting (though yielding similar results). Therefore, only shotblasting and waterblasting are recommended for use in the full-scale test section.

5.2.2 *Reinforcement*

Currently, the incorporation of Xorex™ steel fibers, Dramix® steel fibers, and polypropylene fibers in the mix design is under investigation. The use of polypropylene fibers may reduce shrinkage stresses. Owing to size considerations, however, polypropylene fibers and only one type of steel fiber may be included for use on the full-scale test section. The comparative strength and cost of the two steel fibers is currently being analyzed and will determine which will be utilized if the steel design is used.

5.2.3 *Curing Method*

The curing method to be used will be determined from the performance of various curing compounds, fogging, blankets, and sheeting that will be available when the substrate pavement for the full-scale test section is being placed. The selected method will then be used on the entire test section when the overlay portion of the test section is placed to re-verify its performance.

5.3 FULL-SCALE TEST SECTION SIZE AND PARTITIONING

The full-scale test section must be large enough to accommodate all the characteristics to be analyzed and be able to show evidence of cracking, shrinkage, debonding, etc. Increasing the length of the section, however, also increases testing costs. It is recommended that the section be divided into eight 3.6-by-15.2-meter (12.0-by-50.0-foot) test areas. This size section should be adequate for incorporating all aspects of testing, while still having test areas representative of the actual overlay. The section areas to be tested are listed in Table 5.1. It should be noted that the use of Hilti nails to provide shear reinforcement between the substrate and overlay will be considered in one the of test section areas.

Table 5.1. Test Section Areas.

Surface Prep.	**Use of Hilti Nails**	**Paving Time**	**WWF**	**Steel Fibers**	**WWF & Poly. Fibers**
Shot-blasting	Yes	Day		X	
		Night			
	No	Day		X	
		Night	X	X	X
Water-blasting	Yes	Day		X	
		Night			
	No	Day		X	
		Night			

5.4 MONITORING BOND DEVELOPMENT OF THE FULL-SCALE TEST SECTION OVERLAY

Maturity of the concrete overlay should be recorded during full-scale section testing. Pull-out tests should also be performed. This information could then be used to re-verify the results of bond and maturity testing that have been completed. If time and budget permit, echo-impact testing could also be performed to map bond development of the test section.

CHAPTER 6. BOND TESTING

Bond testing performed in the laboratory included two types of tests: shear block and guillotine. Two tests were used in order to decrease any bias one test set-up may have on results. Since expedited paving methods will be used to place the overlay, bond testing was performed only on specimens at early ages (less than 72-hours old).

6.1 SHEAR BLOCK TEST SET-UP

Shear block testing was performed using a method developed at The University of Texas at Austin. The shear block test is a type of shear-compression pull-off test. First, the substrate slab was shotblasted with Blastrac® Portable Blast Cleaning System's 1-8D Unit MK4 model loaded with S460 shot. This adequately roughened the substrate surface to ensure good bond and created a surface that adequately represents the actual substrate pavement, which will also be roughened with either shotblasting or waterblasting methods.

Next, 12.7-centimeter (5.0-inch) thick, 38.1-by-61.0-centimeter (15.0-by-24.0-inch) overlay specimens were cast on the roughened substrate. Forms created for this testing procedure allowed for casting of up to three specimens at a time. These forms also allowed for specimens having a large bonded area. A 1.0-centimeter (0.37-inch) thick foam board, with a hole in the middle for the desired area to be bonded already cut out (15.2-by-30.5-centimeter or 6.0-by-12.0-inches), was placed between the substrate and overlay. It acted as a bond breaker between the excess area of overlay and substrate. A pair of PVC pipes was also cast in the overlay outside the 15.2-by-30.5-centimeter (6.0-by-12.0-inch) area of bond development. This made room for steel bars to be inserted through the overlay specimens so that hydraulic rams could be attached to pull the specimens off the substrate pavement.

The overlay specimens were cast outside and moist-cured under wet burlap and plastic sheets. This method of curing served to approximate conditions in the field. Once cured for the desired length of time, the formwork was removed. Steel rods were then placed through the PVC pipes that were imbedded in the overlay. These rods were then connected to two hydraulic rams. Pressure required to cause the bond to fail was read and converted into shear stress. The shear block test set-up is shown in Figures 6.1 and 6.2.

The test set-up shown above induces a 2.5 centimeter (1.0-inch) eccentricity between the application of the load and the bond plane. Therefore, a bending moment is induced. Interaction of shear and bending moment produces a lower-bound estimation of the failure stress.

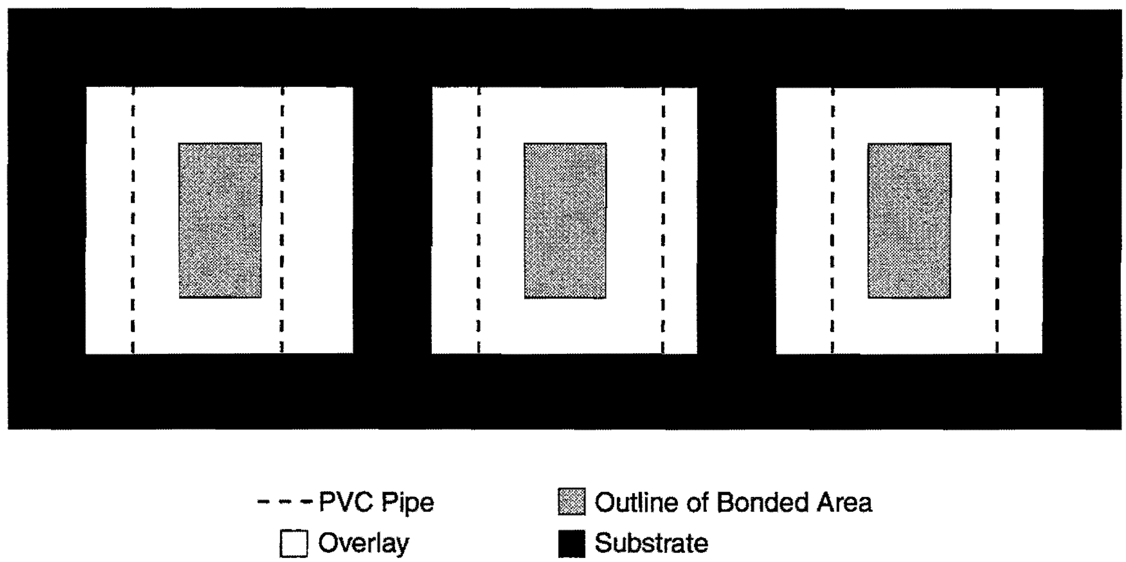

Figure 6.1. Shear Block Test Set-Up (Plan).

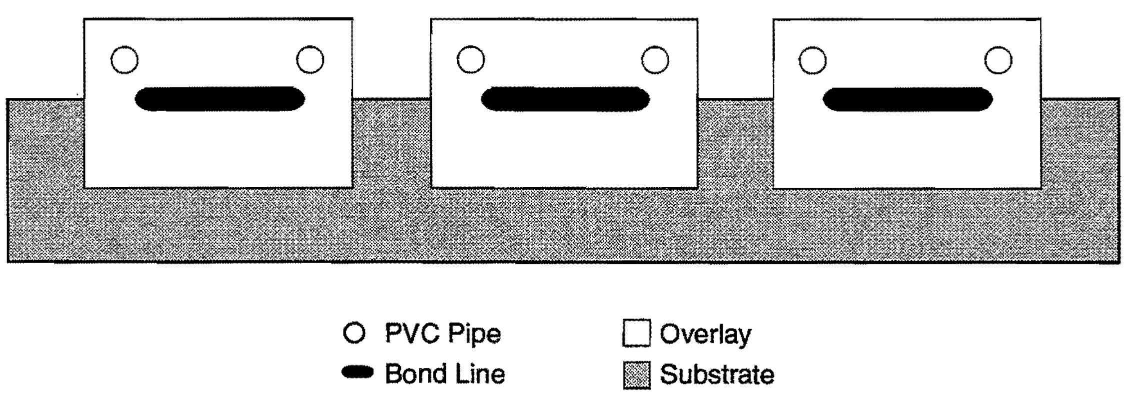

Figure 6.2. Shear Block Test Set-Up (Elevation).

6.2 SHEAR BLOCK TEST RESULTS

Shear block testing was performed at the same time mix designs were being investigated. Specimens were tested at 8 hours, 24 hours, and 72 hours. The bond results for the mixes tested are summarized in Table 6.1. Since mix design testing led to the selection of the Rheobuild mix, only bond strength results for this mix are shown.

Table 6.1. Bond Strength Results from Shear Block Testing.

Time (hours)	Bond Strength in kPa (psi)
8	852 (125)
24	3123 (458)
72	2666 (391)

Table 6.1 shows an apparent bond strength decrease between 24 and 72 hours. This unlikely decrease was probably caused by experimental error produced by environmental conditions that existed during the different concrete batches made to produce test specimens, or by the eccentricity inherent in the test set-up. Later guillotine testing verified that the bond strength does not drop between 24 and 72 hours.

Previous research has suggested that the shear stresses induced by both shrinkage and thermal stresses are on the order of 345 kPa (50 psi) (Ref 10). Shear block test results suggest that bond strength at 24 hours (3158 kPa or 458 psi) would be more than adequate to withstand these types of stresses.

6.3 GUILLOTINE TEST SET-UP

The guillotine test is a type of shear test whereby cylindrical specimens of substrate and overlay are sheared apart. In order to perform this test, it was first necessary to cast the substrate halves of the guillotine specimens. Full-length 20.3-centimeter (8.0-inch) cylinders with 10.1-centimeter (4.0-inch) diameters could have been prepared and then cut in half. However, this would have created a very smooth surface on which the overlay would have been cast. Hence, bond strength might have been considerably underestimated.

Therefore, an alternative procedure for casting the substrate halves was developed. Cylinder molds were first cut in half. After placing the substrate layer and allowing it to cure for a few hours, a wire brush was used on the top side of these half cylinders to roughen the surface. This method worked well and the surface of the finished substrate portions more accurately represented roughened substrate pavement. These half-cylinders were moist-cured for 24 hours. The molds were then taken off and the specimens were cured in 21°C (70°F) lime-saturated water for 28 days. A few full-length cylinder specimens were also cast to monitor the compressive strength gain. The 28-day compressive strength of these specimens averaged 44,815 kPa (6500 psi).

After the half-cylinder specimens were cured for 28 days, they were placed in the bottom of full-length cylinder molds with the clean, roughened sides face up. These bottom portions represented the substrate pavement. Before the "overlay" portions were cast on top of the half-cylinders, one-third were heated to 38°C (100°F), one-third were cooled to 4°C (40°F), and one-third were left at room temperature (approximately 21°C or 70°F). This was meant to simulate casting on substrate of various temperatures in order to investigate the effect of substrate temperature and, subsequently, time of placement on the development of the bond strength between the overlay and substrate pavement. The Rheobuild concrete mix was then cast on top of the heated, cooled, and room-temperature-maintained substrate cylinders.

A total of 54 guillotine specimens were cast. Half the specimens cast were moist-cured and covered with wet burlap and plastic sheets. These represented specimens curing at a low evaporation rate condition. The other half was placed in a dry room and subjected to air currents produced by a nearby fan. This was meant to represent an adverse environmental condition where the evaporation rate of water would be great. Table 6.2 shows the number of specimens prepared, their curing condition, and the temperature of the substrate layer. Three specimens were tested at 8, 24, and 72 hours. Results at each hour were then averaged. Several full-length compressive strength specimens were also cast to analyze the compressive strength development of the overlay.

Table 6.2. Guillotine Specimens Tested.

Evaporation Rate	**Substrate Temp. in °C (°F)**	**Number of Specimen Tested at 8, 24, and 72 Hours**
High	4 (40)	3
	21 (70)	3
	38 (100)	3
Low	4 (40)	3
	21 (70)	3
	38 (100)	3

Figure 6.3 shows the set-up for the guillotine tests performed. The shear plane must be carefully lined up with the plane between the frame and the plate on which the load is applied.

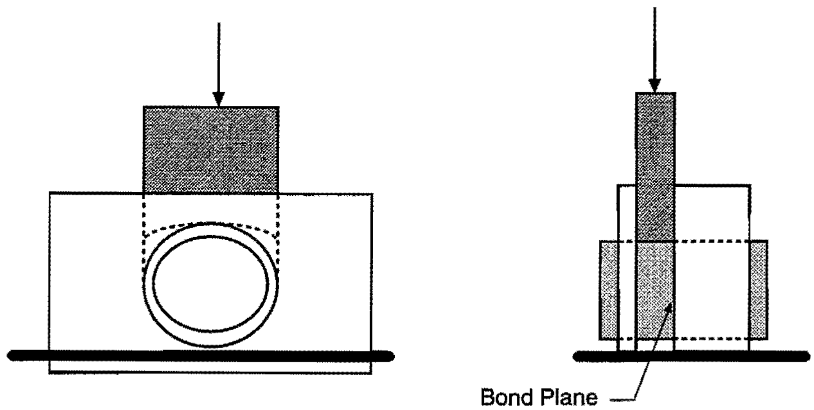

Figure 6.3. Guillotine Test Set-Up.

6.4 GUILLOTINE TEST RESULTS

The results of the guillotine tests performed are shown in Figures 6.4 and 6.5. These figures suggest that the specimens subjected to a higher evaporation rate reached bond strengths slower than the specimens subjected to a low evaporation rate condition.

On average, the low evaporation rate specimens achieved bond strengths of 2758 kPa (400 psi) at 24 hours, while the high evaporation rate specimens developed 2413 kPa (350 psi) in the same amount of time. This emphasizes the need for adequate curing conditions on the actual overlay in order to achieve the greatest bond possible at very early ages.

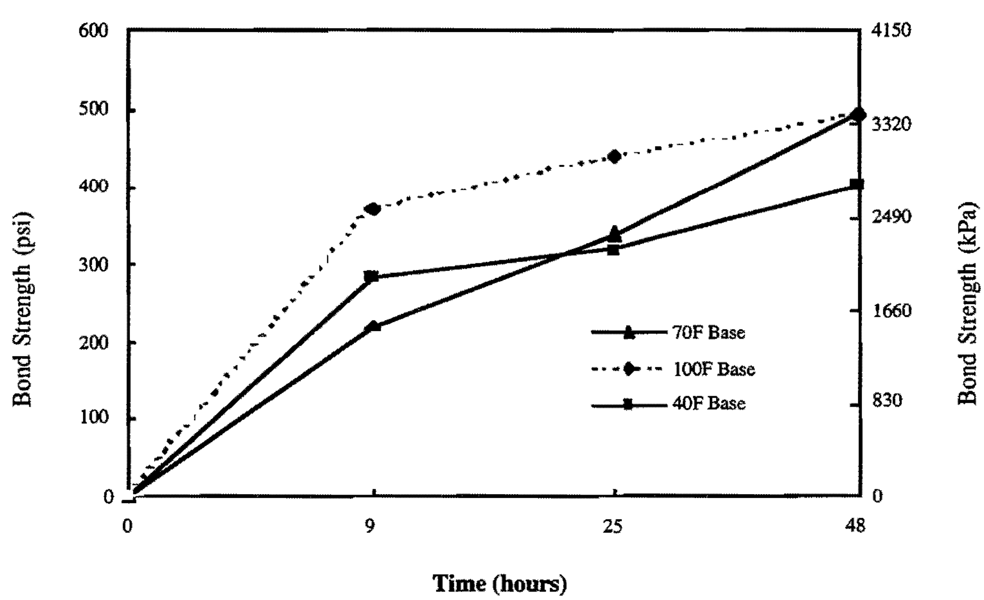

Figure 6.4. Bond Development of Guillotine Specimens (Low Evaporation Rate).

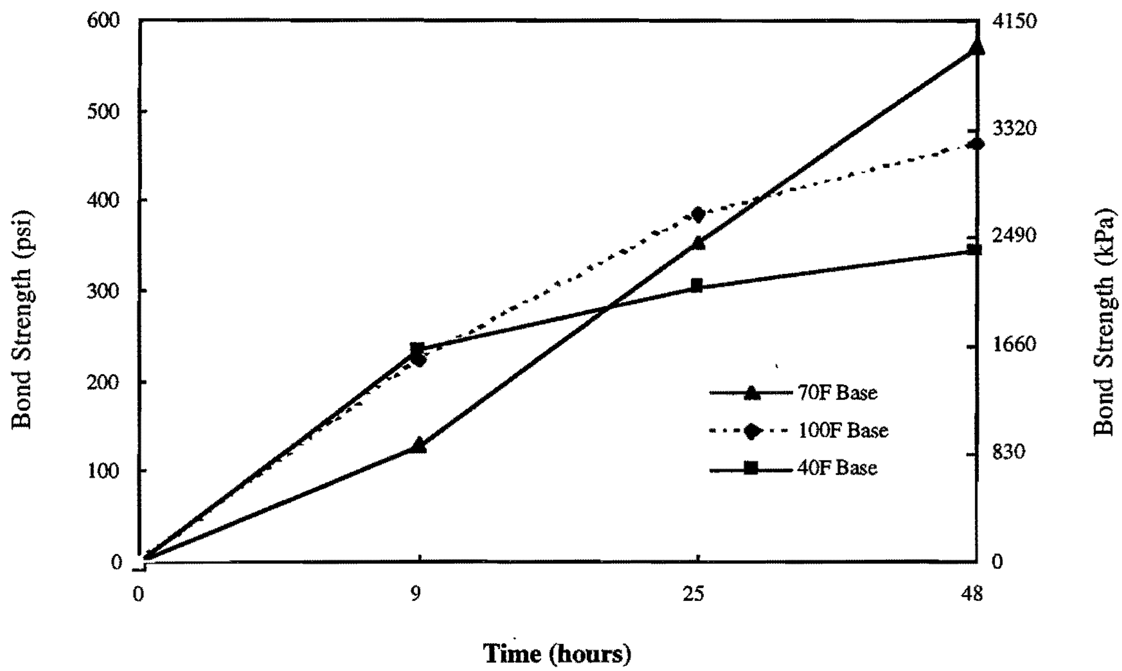

Figure 6.5. Bond Development of Guillotine Specimens (High Evaporation Rate).

The effects of substrate temperature on the development of bond are not as clear as evaporation rate, however. Specimens cast on substrates at all three temperatures gained adequate bond strength in approximately the same amount of time. No one specimen type outperformed another to any significant extent. Results indicate that when placing on substrate between 4°C and 38°C (40°F and 100°F), sufficient bond strength (approximately 2000 to 2750 kPa or 300 to 400 psi) can be obtained in 24 hours. This strength is more than adequate for overcoming the predicted 345 kPa (50 psi) necessary to offset shrinkage and thermal stresses.

Bond development of specimens at 8 hours ranged from 680 to 2585 kPa (100 to 375 psi). This emphasizes the unpredictability of bond strength development at this extremely early age. Specimens showed more consistent results after 24 hours. This finding suggests that the earliest time to put traffic back on the overlay would be 24 hours.

CHAPTER 7. MONITORING BOND DEVELOPMENT IN THE FIELD

Maturity values obtained at a given time may be used to predict the bond strength that has developed between an overlay and substrate pavement. The following sections describe the maturity curves developed for the selected mix design and their correlation to the bond and compressive strength development data obtained.

7.1 MATURITY CURVES OBTAINED FOR THE SELECTED MIX DESIGN

Two Model H-2680 System 4101 concrete maturity meters (distributed by SDS Company) were used to obtain maturity readings for the specimens cast for guillotine testing. This particular model maturity meter has four channels. It automatically reads and stores maturity values every half hour for the first 48 hours, and then hourly until the meter is turned off. The stored values of age and maturity can then be downloaded into a computer file.

Three specimens from each test group were wired to channels on the two meters. This eliminated the need to repeat tests in the event one or two wires were improperly imbedded in any test specimen. The average values of the maturity readings obtained from each channel were then plotted as a function of the age of the specimen. These curves are shown in Figures 7.1, 7.2, and 7.3.

In comparing the maturity values recorded as a function of evaporation rate, the specimens subjected to higher evaporation rates yielded higher maturity values (by as much as 700 ^{o}C*hours at the 72-hour reading).

Similarly, in comparing the maturity values recorded as a function of base temperature, it can be seen that significant differences in maturity values exist after 48 hours. At 24 hours, however, specimens cast on all three base temperatures showed maturity values between 600 and 800 ^{o}C*hours (a difference of only 200 ^{o}C*hours).

7.2 CORRELATION OF BOND STRENGTH AND MATURITY

The maturity values recorded were plotted against the bond strengths obtained during guillotine testing. Charts generated show the correlation between bond and maturity. These charts are shown in Figures 7.4 and 7.5. The three data points shown on each line plotted represent the values obtained at 8, 24, and 72 hours.

Results of bond testing have shown that the bond achieved at 24 hours will be between 2050 and 2750 kPa (300 and 400 psi); 2400 kPa (350 psi) bond strength will be taken as the predicted bond strength at 24 hours. The lowest maturity value recorded at 2400 kPa (350 psi) is

600 °C*hours. The lowest value of maturity should be used when correlating bond and maturity. If the gradient of the bond to maturity curve turns out to be greater, a bond strength higher than 2400 kPa (350 psi) at 600 °C*hours will be obtained.

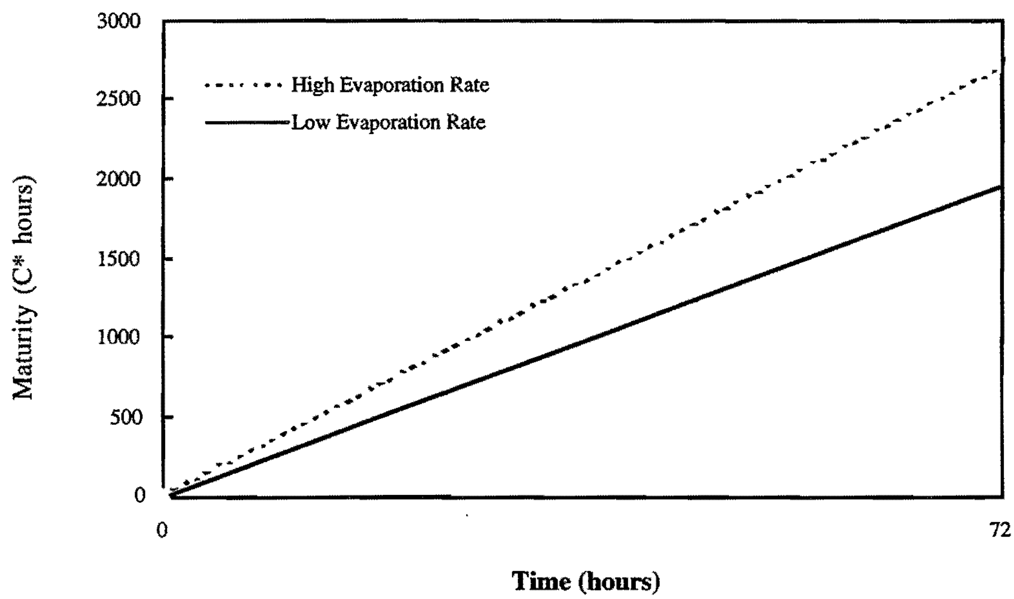

Figure 7.1. Maturity Curves (Specimens with 70°F Base).

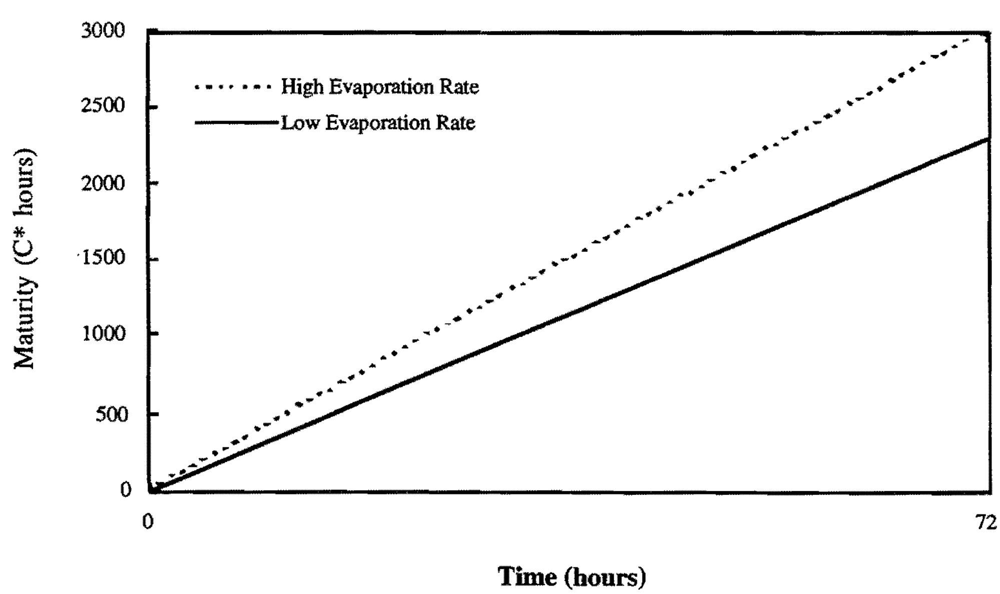

Figure 7.2. Maturity Curves (Specimens with 40°F Base).

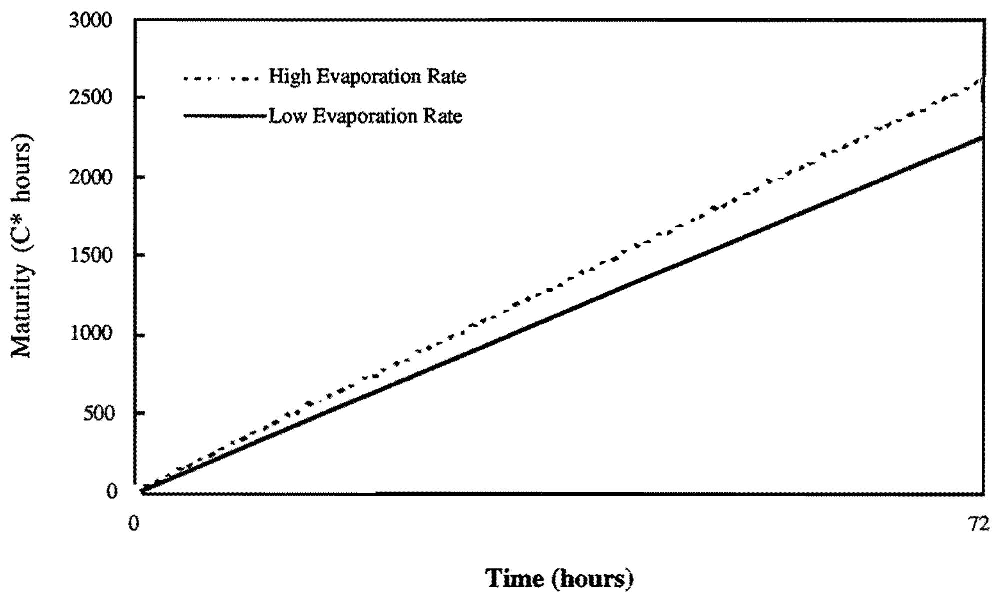

Figure 7.3. Maturity Curves (Specimens with 100°F Base).

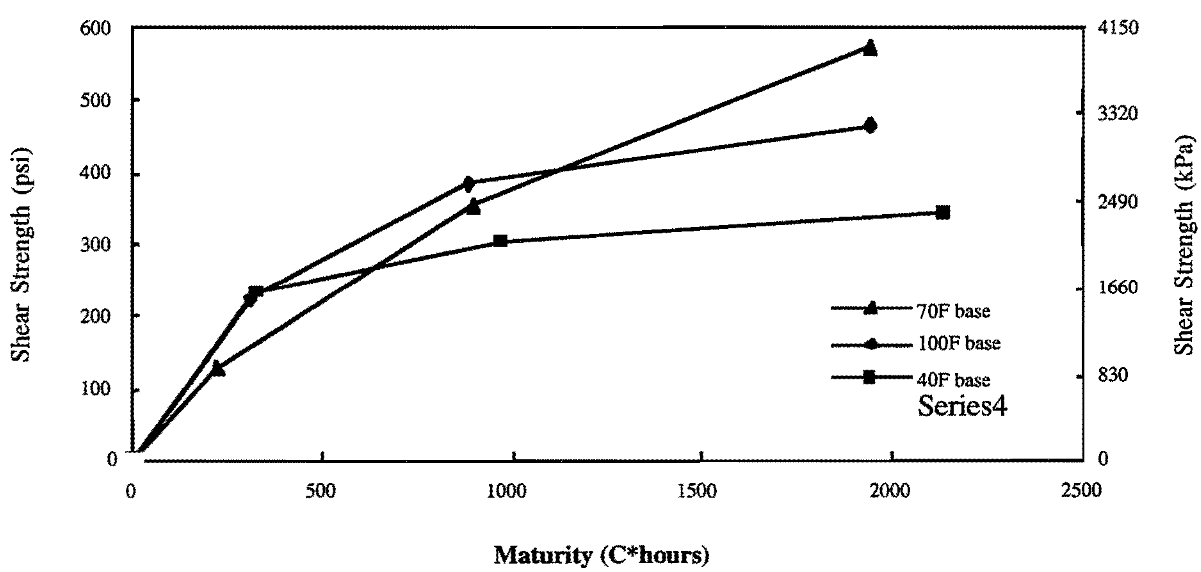

Figure 7.4. Maturity Values as a Function of Guillotine Bond Test Results (High Evaporation Rate).

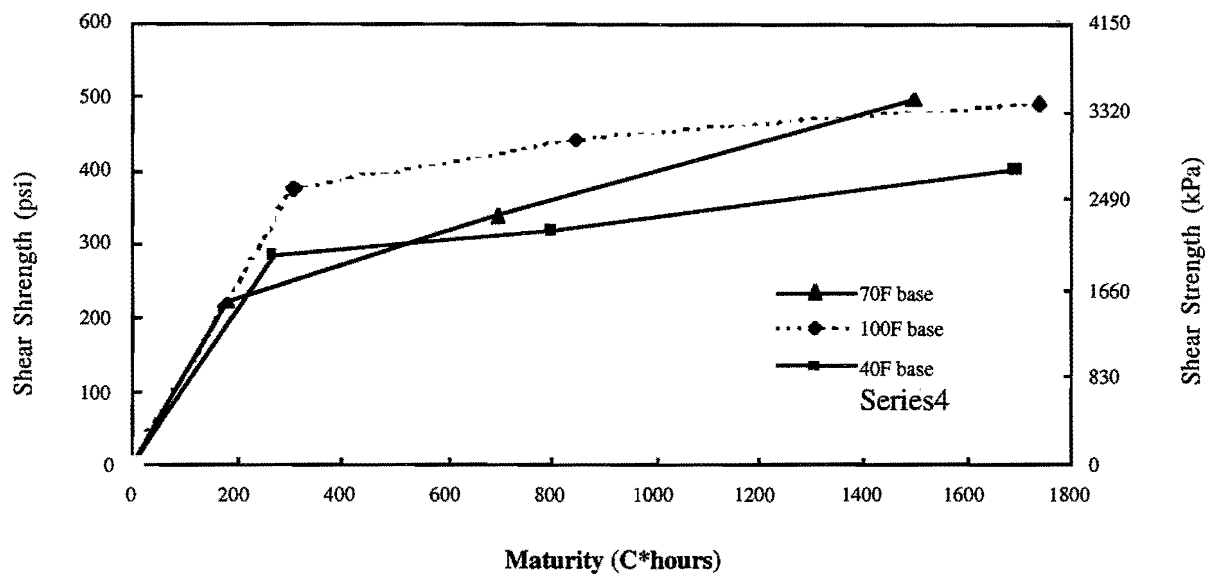

Figure 7.5. Maturity Values as a Function of Guillotine Test Bond Results (Low Evaporation Rate).

7.3 VERIFICATION OF BOND AND MATURITY CORRELATION USING SHEAR BLOCK TEST RESULTS

As stated previously, the bond at 24 hours for this pavement is estimated to be approximately 2400 kPa (350 psi). This is more than necessary to overcome the expected 345 kPa (50 psi) predicted stress induced by shrinkage and thermal effects. The highest average maturity value obtained that corresponded to a 2400 kPa (350 psi) bond strength was 600 °C*hours.

The correlation of bond and maturity was verified with shear block testing results. Table 7.1 summarizes the maturity and bond strength data obtained. At 8 hours, a bond strength of 862 kPa (125 psi) was developed, and the concrete attained a corresponding maturity of 208 °C*hours. At 24 hours, a bond strength of 3158 kPa (458 psi) bond developed, and the corresponding maturity value was 891 °C*hours. A linear interpolation between these two values indicates that at a maturity value of 600 °C*hours, the concrete bond strength would have been 4619 kPa (670 psi), 85 percent more than the conservative estimation of 2400 kPa (350 psi). Waiting for the maturity to reach 600 °C*hours would, therefore, have allowed the pavement to gain even more bond strength than necessary.

Table 7.1. Verification of Maturity and Bond Correlation with Shear Block Test Results.

Age (hours)	Bond Strength in kPa (psi)	Maturity (°C*hours)
8	852 (125)	208
24	3123 (458)	891
72	2666 (391)	2655

7.4 CORRELATION OF COMPRESSIVE STRENGTH TO MATURITY

Compressive strength specimens were created from the overlay mix and were tested at 8, 24, and 72 hours. The maturity development for each specimen was also recorded. Table 7.2 shows the average values obtained. At 24 hours, maturity values between 765 and 860 °C*hours were obtained. The corresponding compressive strengths recorded ranged from 26,500 to 31,500 kPa (3850 to 4500 psi). These compressive strengths meet or exceed the compressive strengths results obtained during the mix design phase of this project (see Chapter 3) by as much as 17 percent.

Table 7.2. Correlation of Average Compressive Strengths to Recorded Maturity Values.

Age (hours)	Compressive Strength in kPa (psi)	Maturity (°C*hours)
8	6930 (1005)	266
24	28,950 (4200)	821
72	42,270 (6131)	1676

The correlation of maturity to compressive strength development is also presented in Figure 7.6. From this information, a prediction of the compressive strength of the overlay can be made using the given maturity value of the concrete. For a required compressive strength of 31,720 kPa (4600 psi), the corresponding maturity value is approximately 850 °C*hours. This information should be re-verified during the placement of the full-scale test sections.

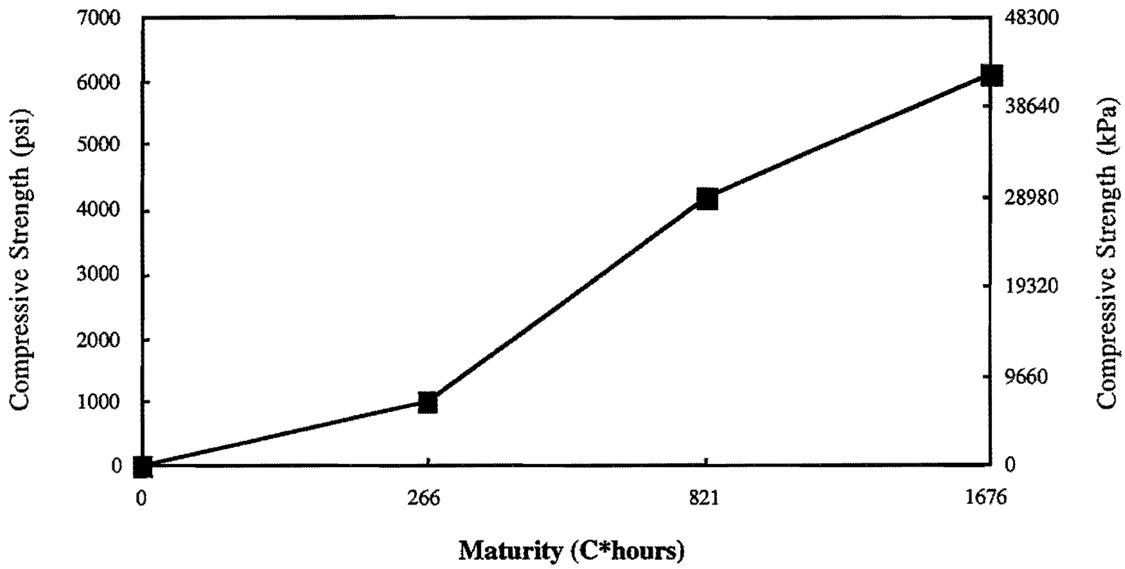

Figure 7.6. Compressive Strength as a Function of Maturity.

CHAPTER 8. SUMMARY OF CONSTRUCTION RECOMMENDATIONS

8.1 MIX DESIGN

The mix design selected meets Texas Department of Transportation specifications for overlay class concrete within 3 days. The superplasticizer, Rheobuild 1000, is included in this mix design, with the proportions of the selected mix presented in Table 8.1. The cost of this mix is estimated to be $94 per cubic meter ($72 per cubic yard).

Table 8.1. Selected Mix Design.

Constituent	Amount
Water	1478 N/m^2 (254 lb/yd^3)
Type I/II Cement	5098 N/m^2 (876 lb/yd^3)
Coarse Aggregate (3/4" minus)	10,411 N/m^2 (1789 lb/yd^3)
Fine	6402 N/m^2 (1100 lb/yd^3)
Rheobuild 1000	8.0 ml/100 N cement (1.2 floz/100 lb)
Darex II	26.6 ml/100 N cement (4.0 floz/100 lb)

Laboratory testing showed this mix design will gain 27.0 MPa (3934 psi) compressive strength in 24 hours, and 34.0 MPa (4967 psi) in 72 hours. Testing also showed this mix will gain 5.0 MPa (719 psi) flexural strength in 24 hours.

8.2 BOND DEVELOPMENT

The bond strength capability of the selected mix design was tested using two types of procedures: shear block tests and guillotine tests. Both tests predict that a conservative estimate of the bond between an overlay made with this mix and clean, roughened substrate pavement will reach 2400 kPa (350 psi) in 24 hours. This should be more than adequate to withstand the predicted 340 kPa (50 psi) stress that may be induced by shrinkage and thermal effects.

8.3 CORRELATION OF BOND AND MATURITY

Maturity readings were taken during both shear block testing and guillotine testing. Results showed that a maturity reading of 600 °C*hours should correlate conservatively to a bond strength of 2400 kPa (350 psi). This reading should be achieved approximately 24 hours after placement.

8.4 RECOMMENDATION FOR THE FULL-SCALE TEST SECTION

A full-scale test section is needed to analyze the performance of several types of surface preparation methods, curing methods, and types of reinforcement. Environmental analysis of the El Paso, Texas, area has shown that the most adverse conditions to place the overlay occur during May, June, and July. The full-scale test section should be placed during this period to fully challenge the pavement and show which construction methods and reinforcement types will work best.

Furthermore, when the full-scale test section is placed, pull-out bond tests should be performed and maturity readings should be recorded. These values can then be used to re-verify the bond testing results and maturity-bond correlation data presented in this report.

8.5 PLACEMENT OF OVERLAY

Environmental analysis has shown that the least adverse conditions for placement occur in September and October. Evaporation rate of water from the freshly placed concrete and thermal fluctuations tend to be smallest during these months. It is therefore recommended that the overlay be placed during this period.

Wind speeds and predominant wind direction may cause a suctioning effect over the depressed section of the pavement to be rehabilitated. Attention should be paid to wind conditions during the early life of the overlay. Special curing measures may be needed in this area if environmental conditions warrant. It is recommended that the evaporation rate be limited to 1.0 kg/m^2*hr (0.2 lb/ft^2*hr) to avoid extensive and costly curing measures. Furthermore, the overlay should be placed in the evening. Placing at this time rather than in the morning will serve to minimize the shear stresses induced on the pavement due to temperature differentials caused by daily temperature fluctuations.

CHAPTER 9. CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

From the research and results presented in this report, the following conclusions can be drawn:

1. The mix design selected using the Rheobuild 1000 superplasticizer (Table 8.1) will be suitable for expedited paving methods. The overlay cast using this mix should gain enough strength to allow traffic back on in 24 hours.
2. Overlay bond strengths of approximately 2050 kPa to 2750 kPa (300 psi to 400 psi) can be expected using this mix design.
3. Maturity values of 600 ^{o}C*hours have been shown to correlate with a bond strength development of 2400 kPa (350 psi).
4. The months of May, June, and July will present the most adverse environmental conditions for the overlay, especially at early ages. The full-scale test section should be placed during this period.
5. The performance of surface preparation, reinforcement, and curing methods used when placing the full-scale test section will determine these same factors that will be used in the actual overlay.
6. The months of September and October seems to present the most favorable environmental conditions for placing the overlay. March is also a suitable month if the overlay must be placed during the first half of the year.
7. The overlay should be placed during the evening to minimize shear stresses induced by large temperature increases.

9.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Although most of the bond development research for the selected mix design has been completed, the results presented in this report should still be verified through field testing. The following recommendations are made for further research:

1. Pull-out tests should be conducted on the full-scale test section overlay at 24 hours. The data obtained should be compared to the results of the shear block and guillotine testing performed.
2. Maturity values for the overlay on the full-scale test section should also be performed. The results should then be compared to results presented in this report to re-verify maturity-bond correlation.
3. If time and budget allow, echo-impact tests should be conducted on the full-scale test section to map out areas of variable bond strength and delamination.

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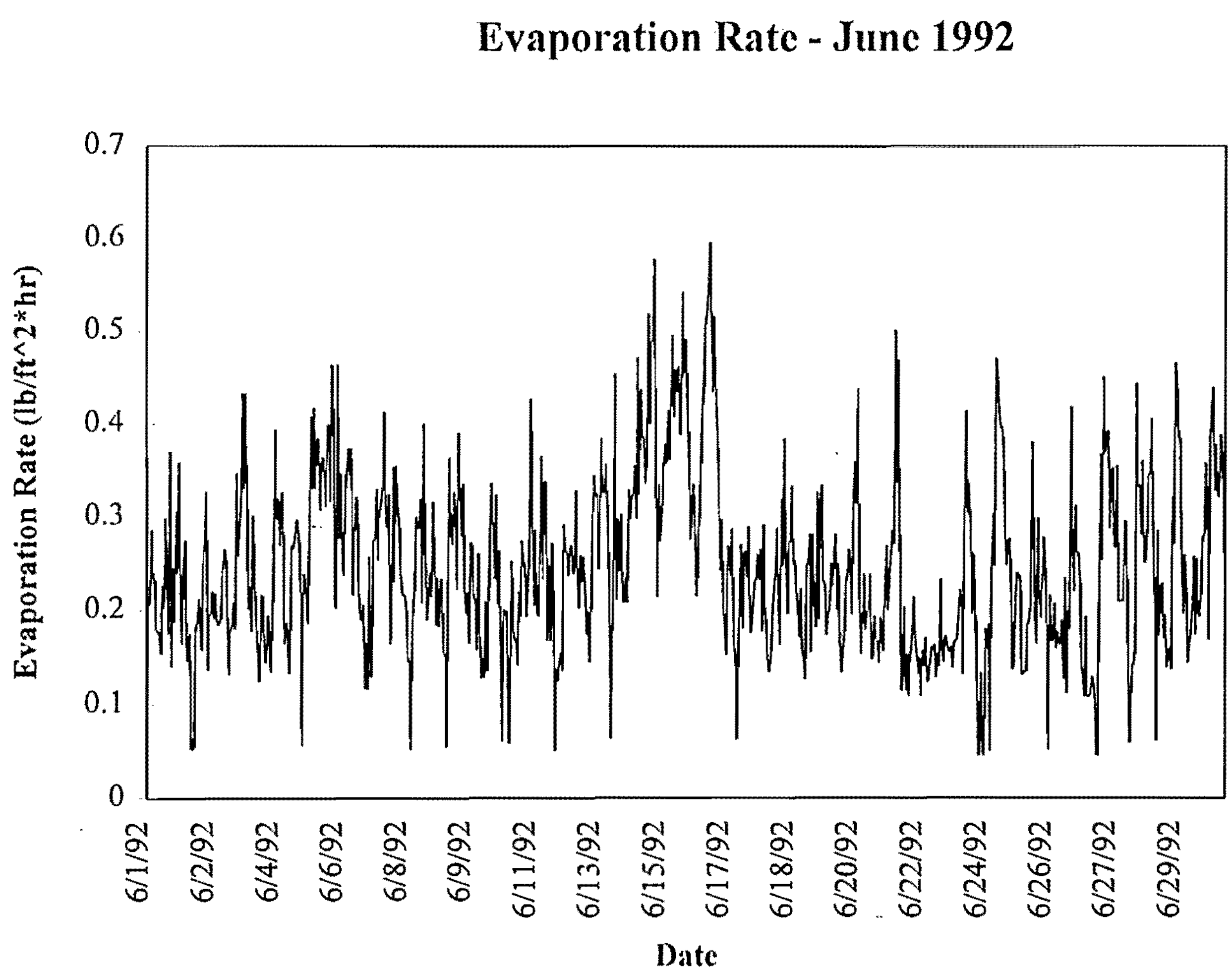
APPENDIX A:

EVAPORATION RATE DATA FOR EL PASO

(6/92-5/94)



Evaporation Rate - June 1992
Evaporation Rate (lb/ft^2*hr)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
6/1/92
6/2/92
6/4/92
6/6/92
6/8/92
6/9/92
6/11/92
6/13/92
6/15/92
6/17/92
6/18/92
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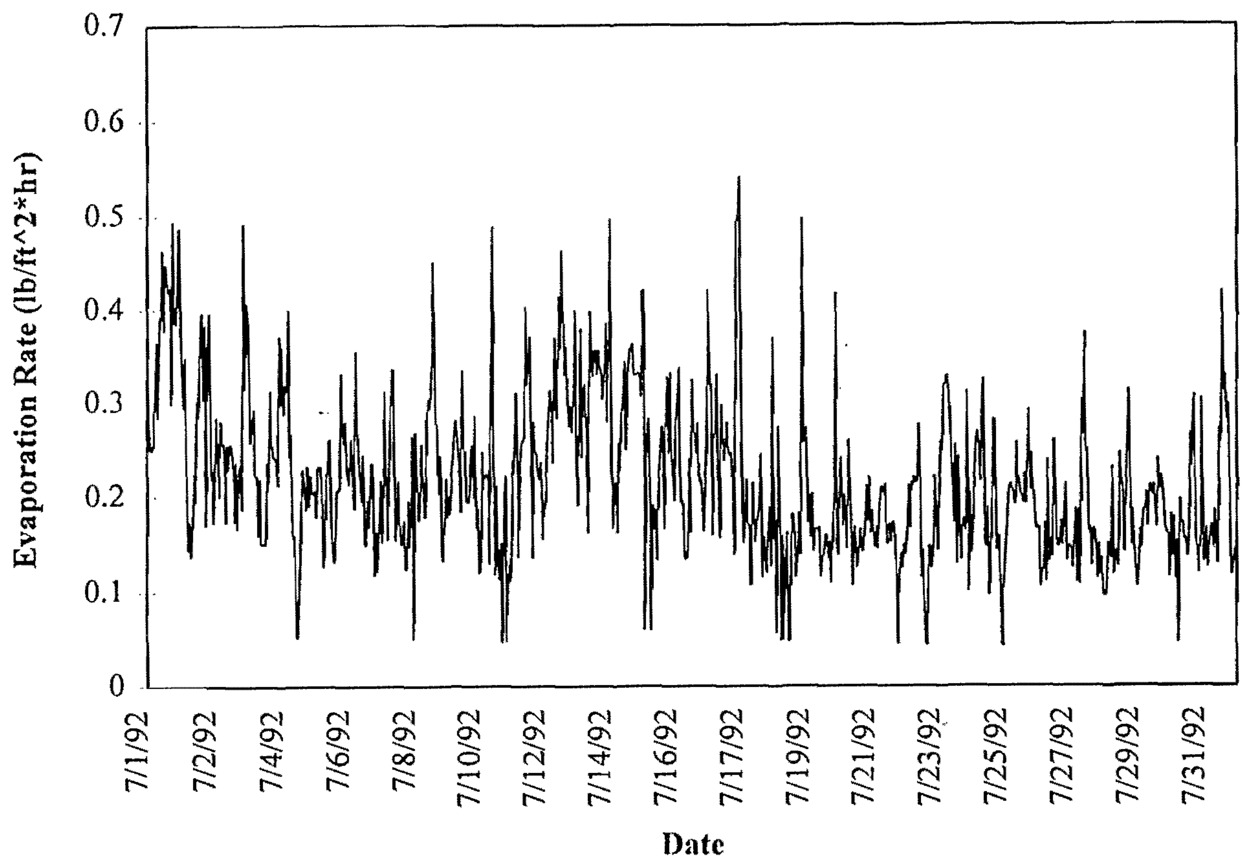
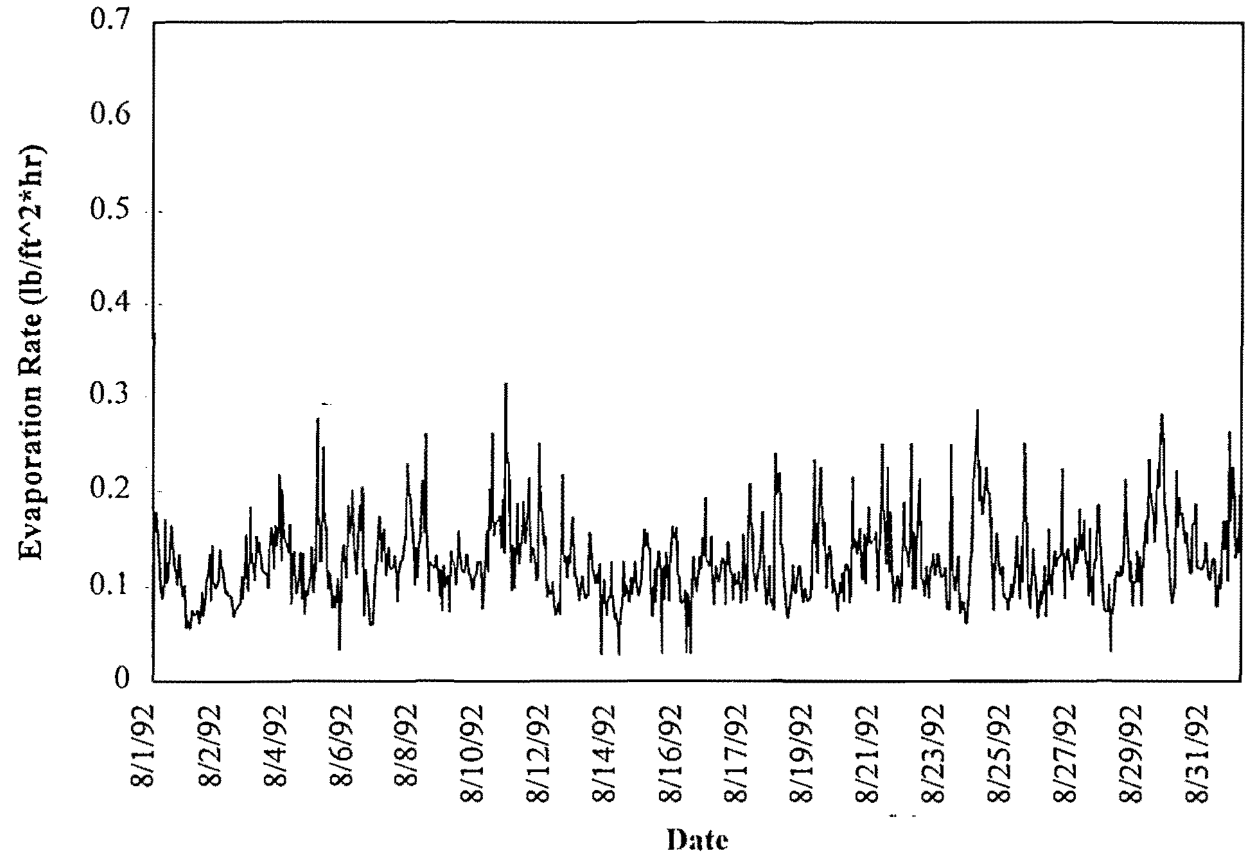
6/24/92
6/26/92
6/27/92
6/29/92
Date

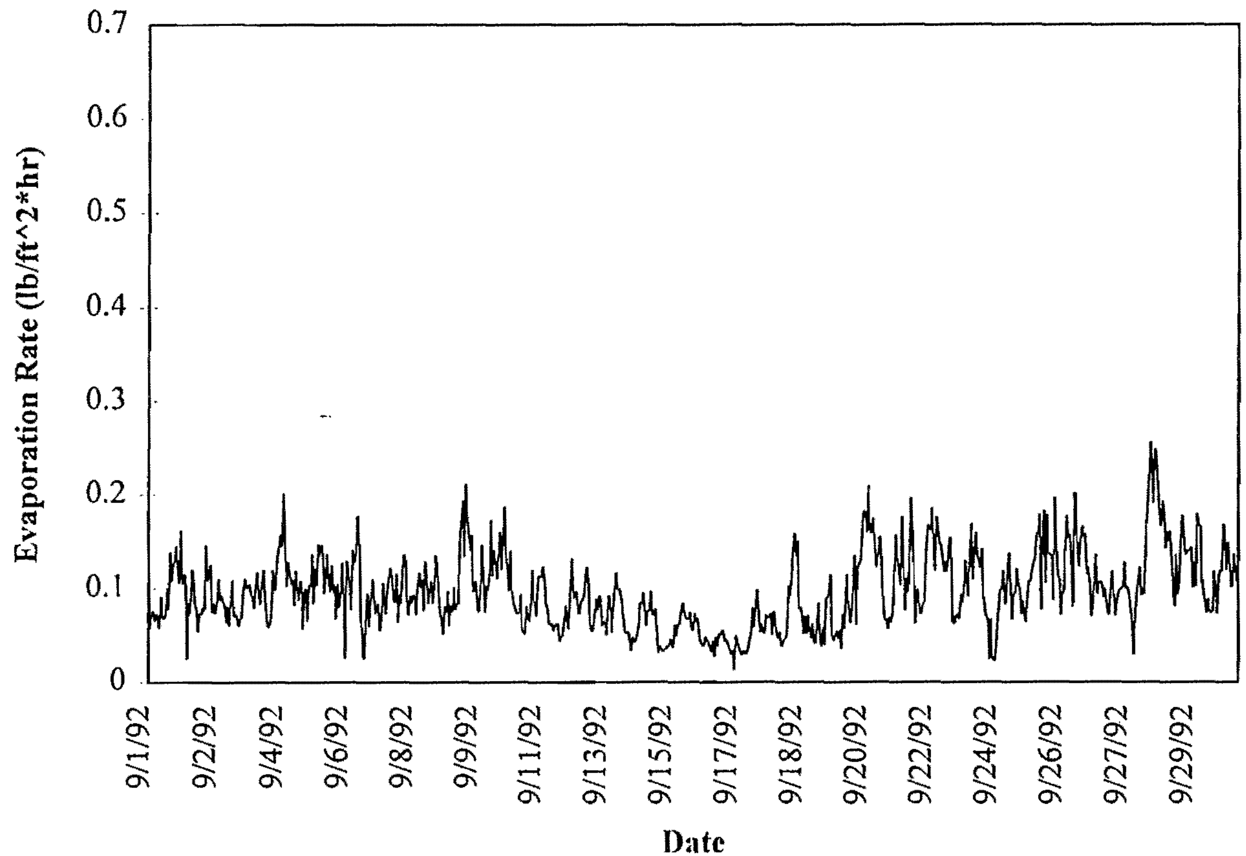
Evaporation Rate - July 1992

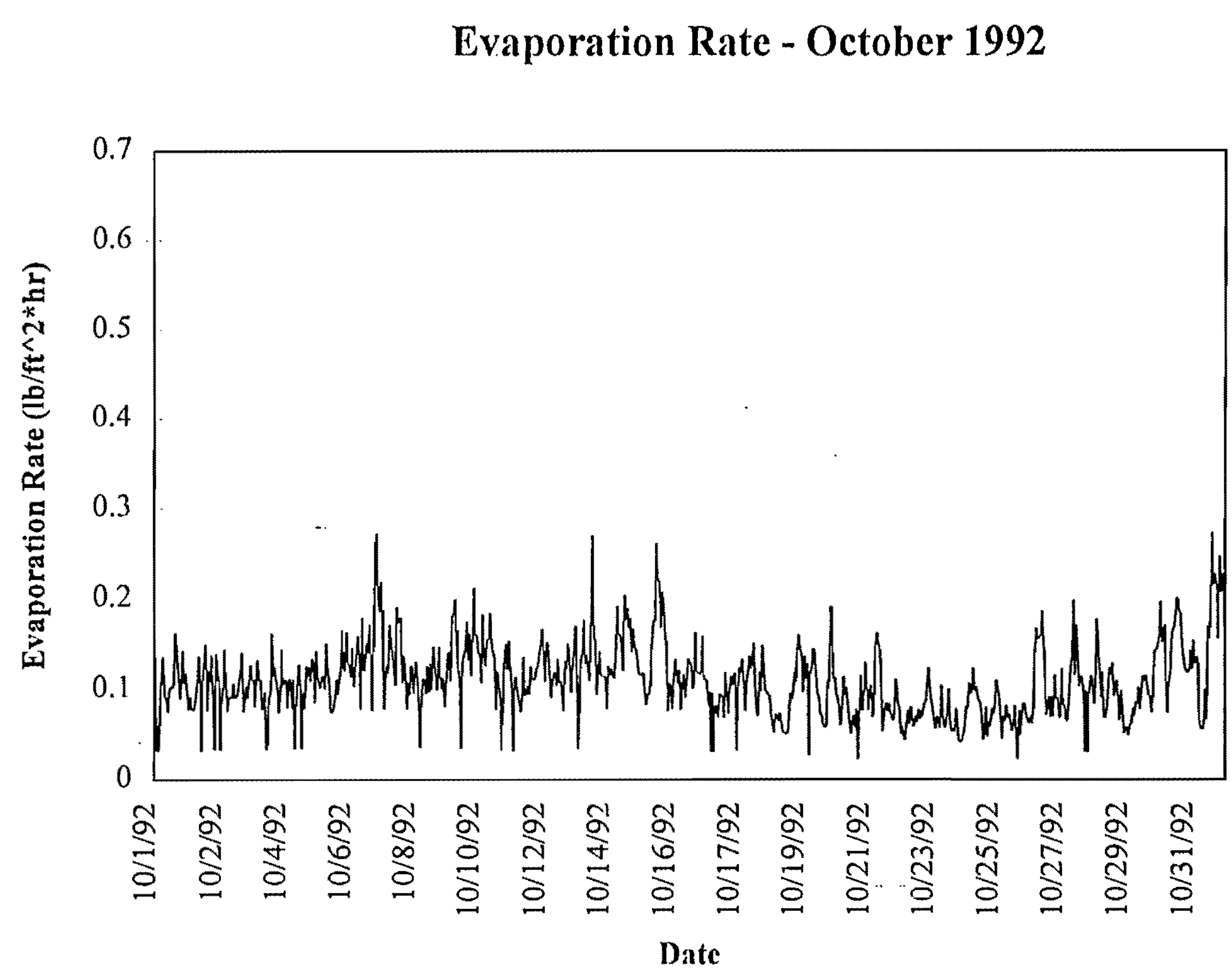


Evaporation Rate - August 1992

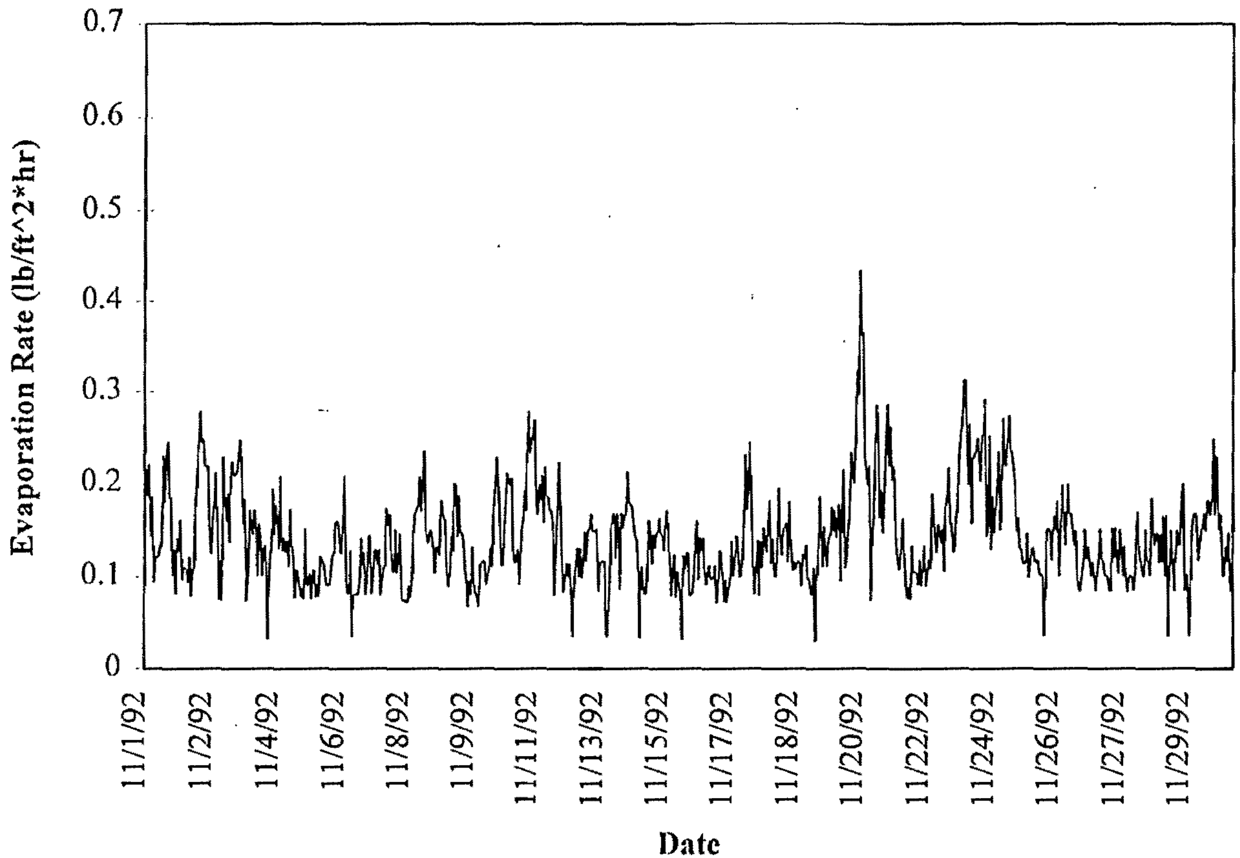


Evaporation Rate - September 1992




Evaporation Rate - October 1992
Evaporation Rate (lb/ft^2*hr)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10/1/92
10/2/92
10/4/92
10/6/92
10/8/92
10/10/92
10/12/92
10/14/92
10/16/92
10/17/92
10/19/92
10/21/92
10/23/92
10/25/92
10/27/92
10/29/92
10/31/92
Date

Evaporation Rate - November 1992



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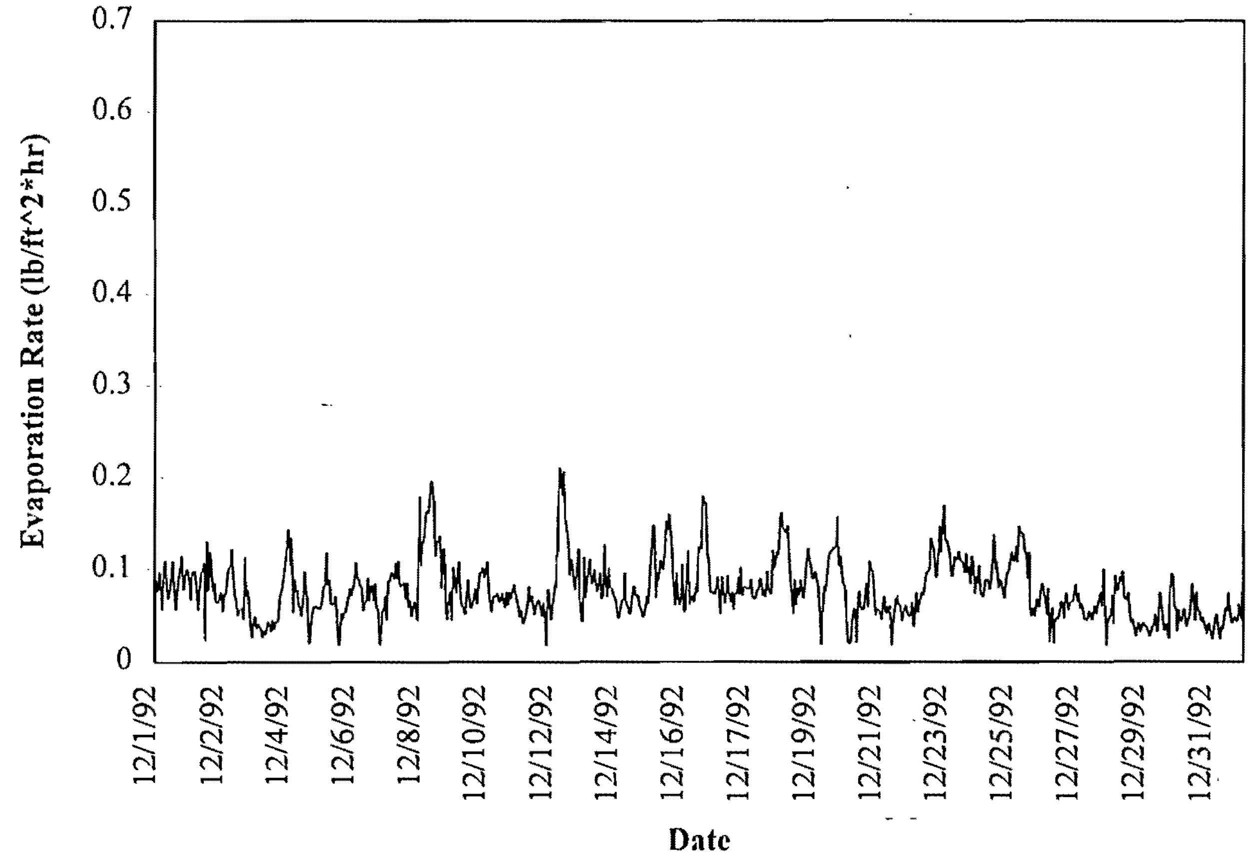

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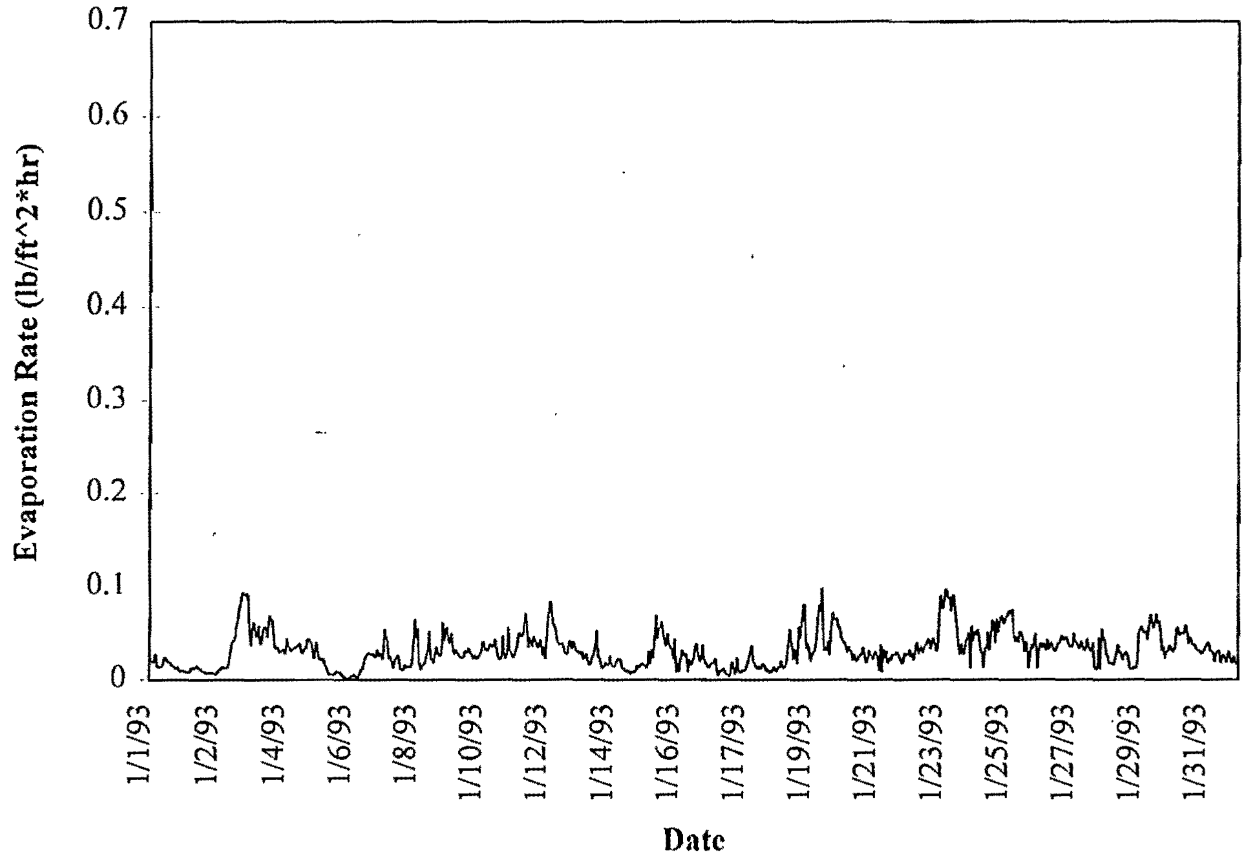

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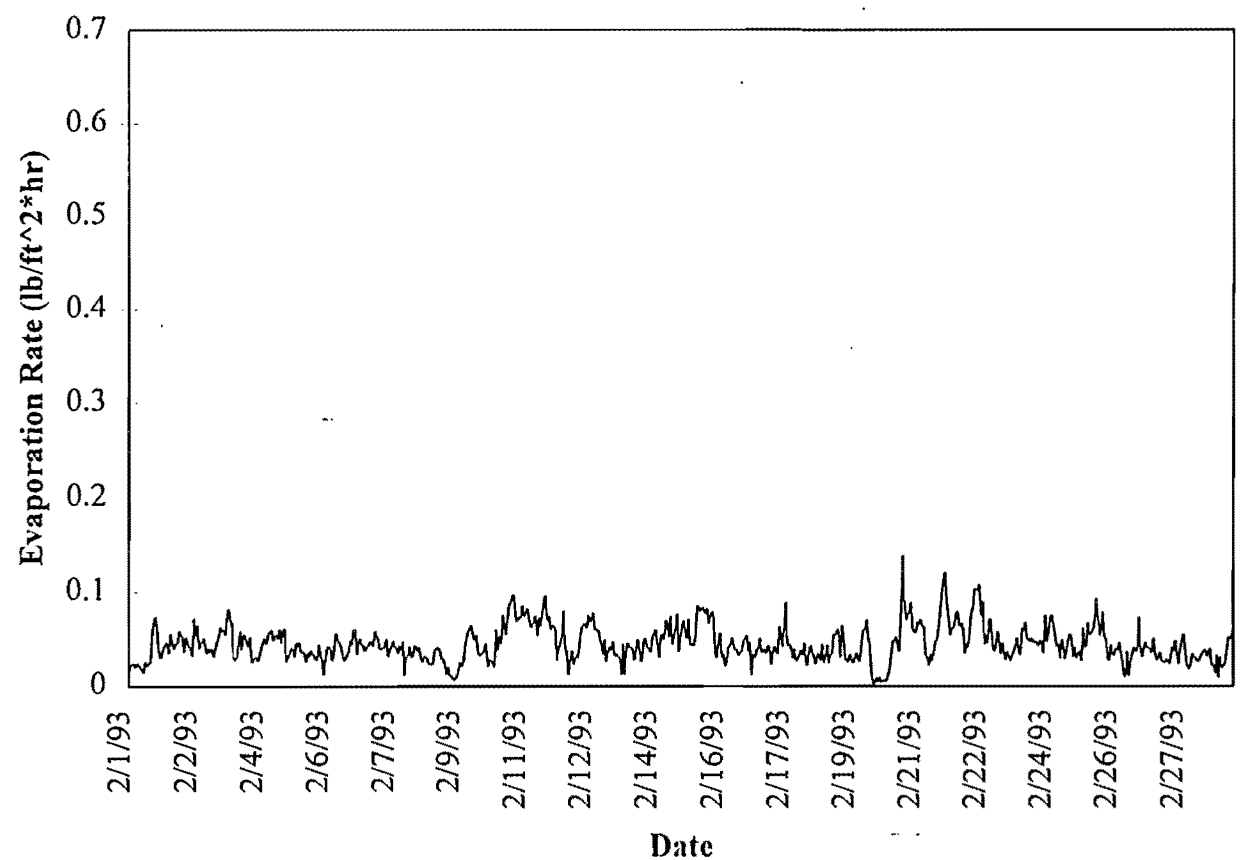

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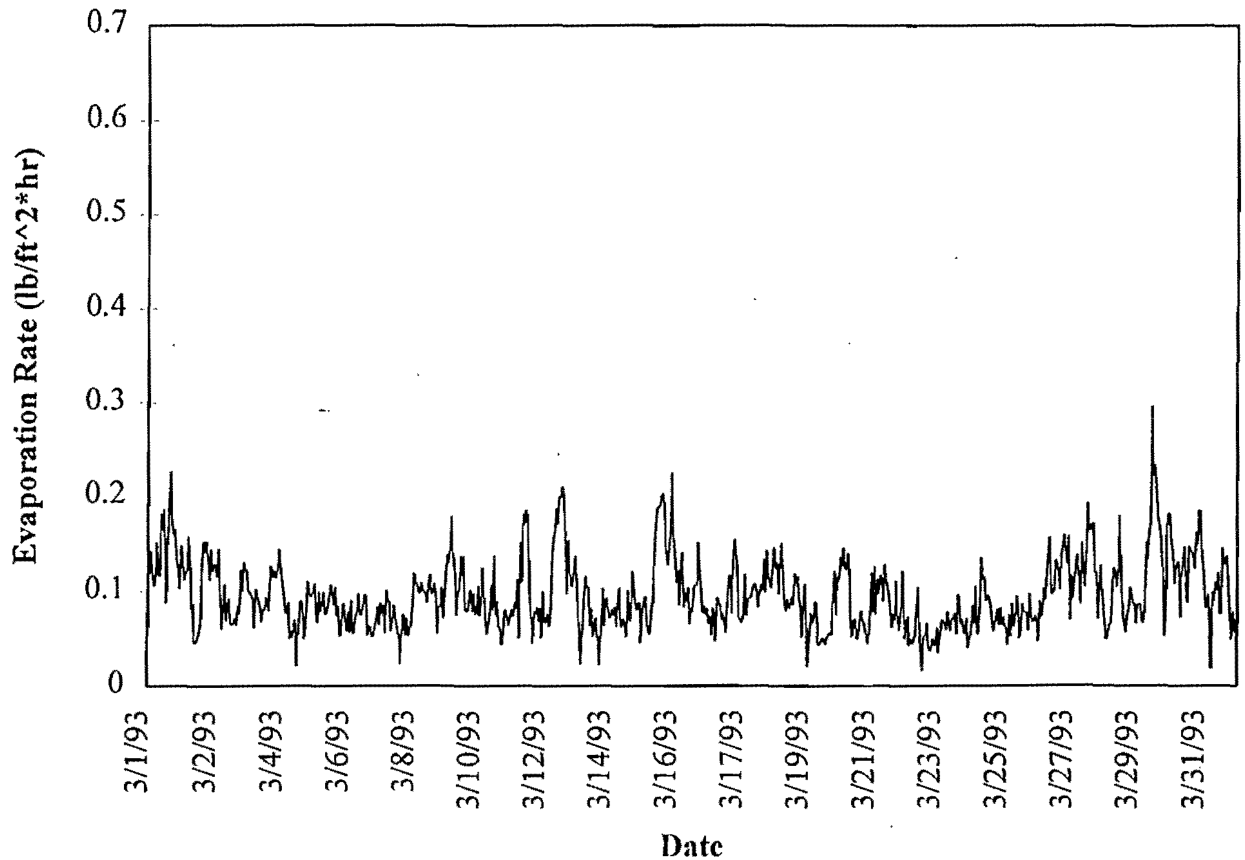
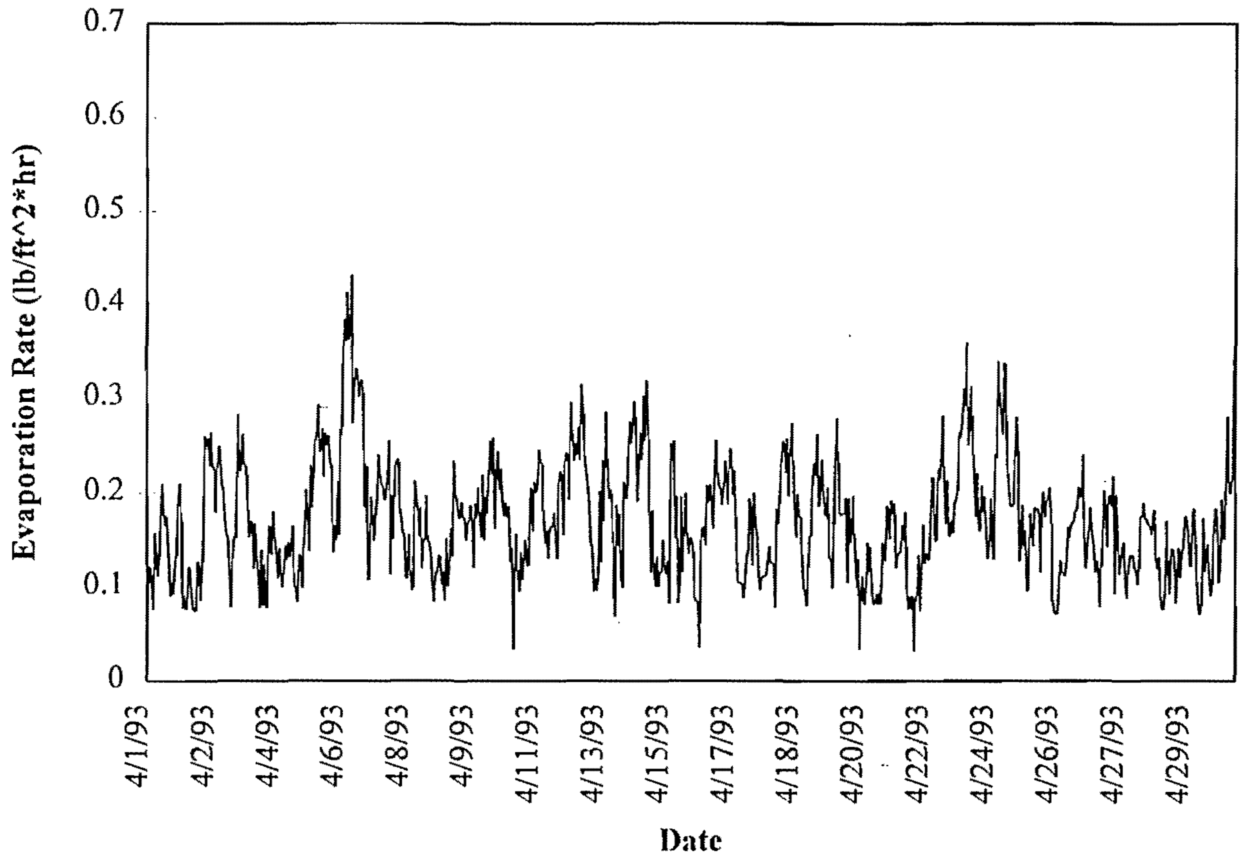
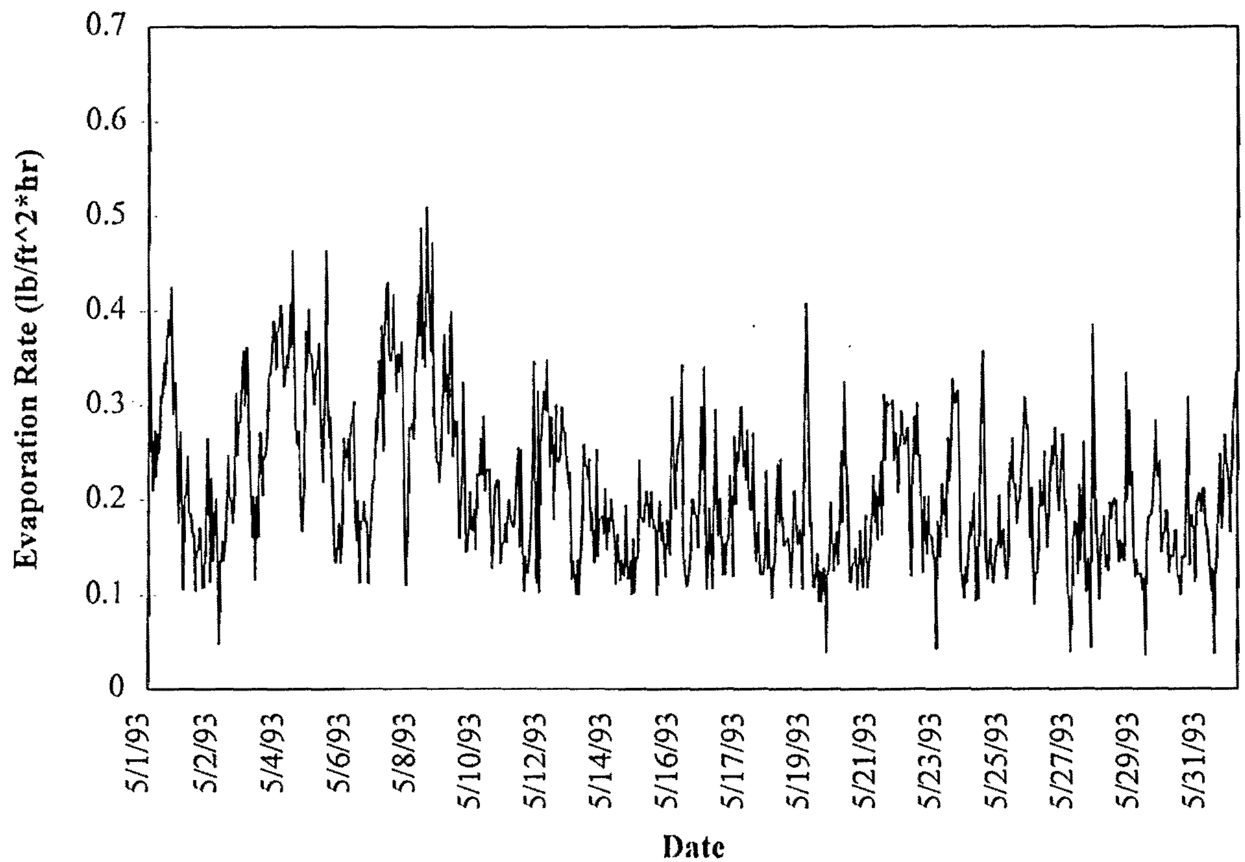


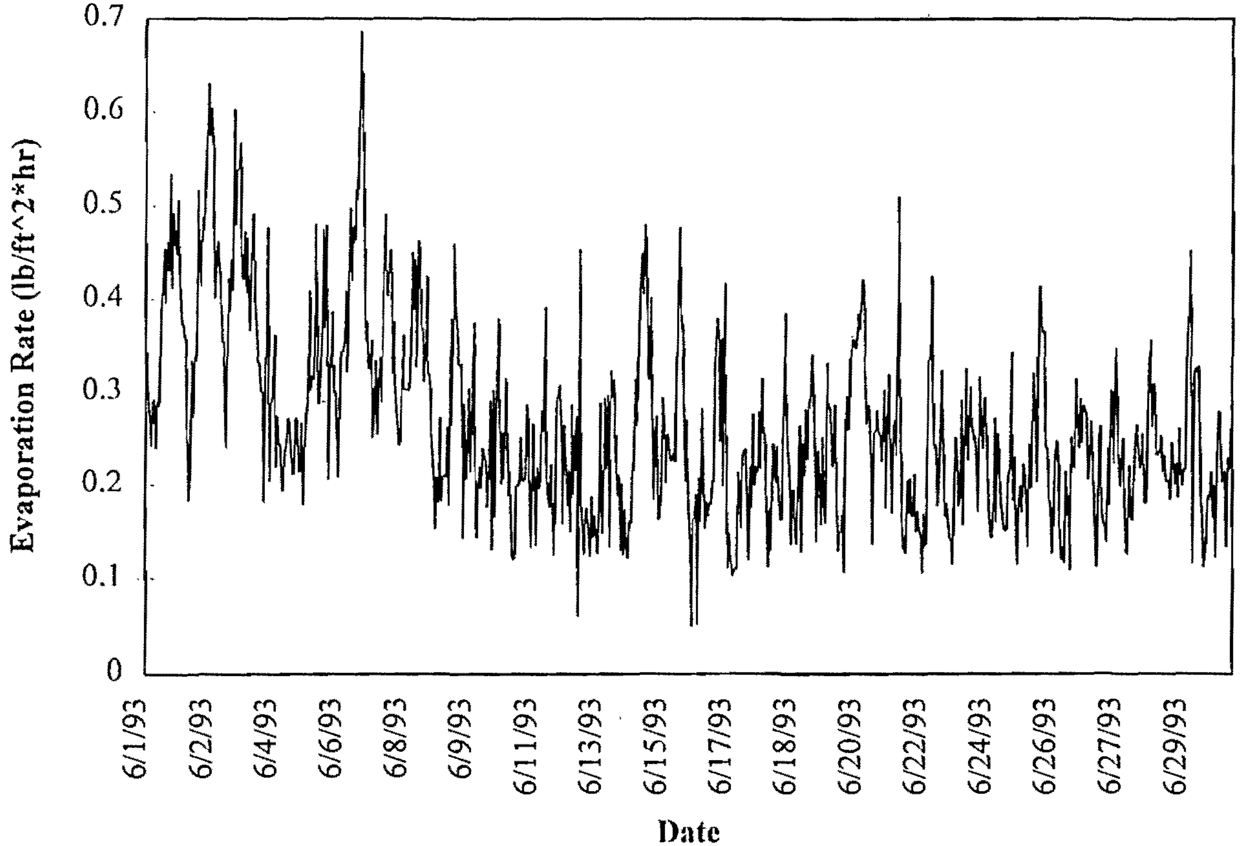
Evaporation Rate - April 1993



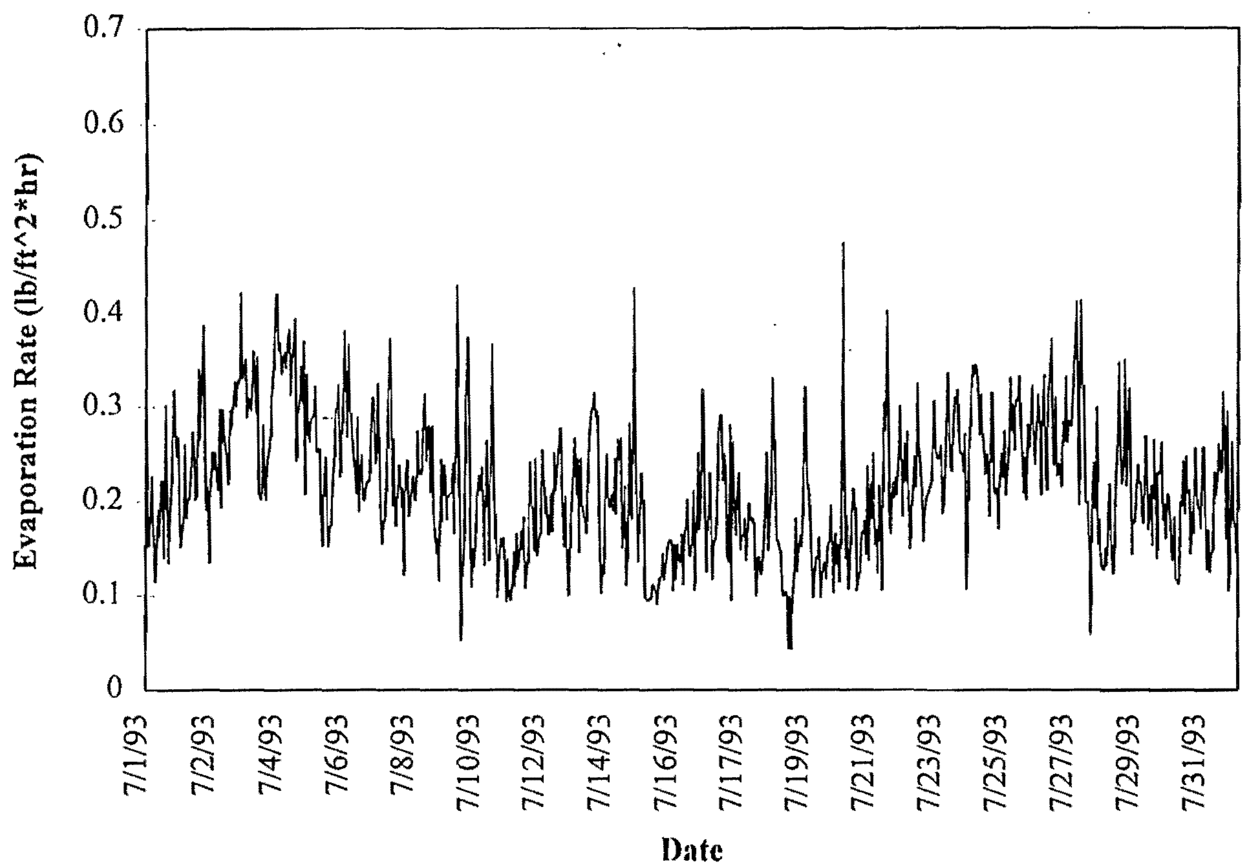
Evaporation Rate - May 1993



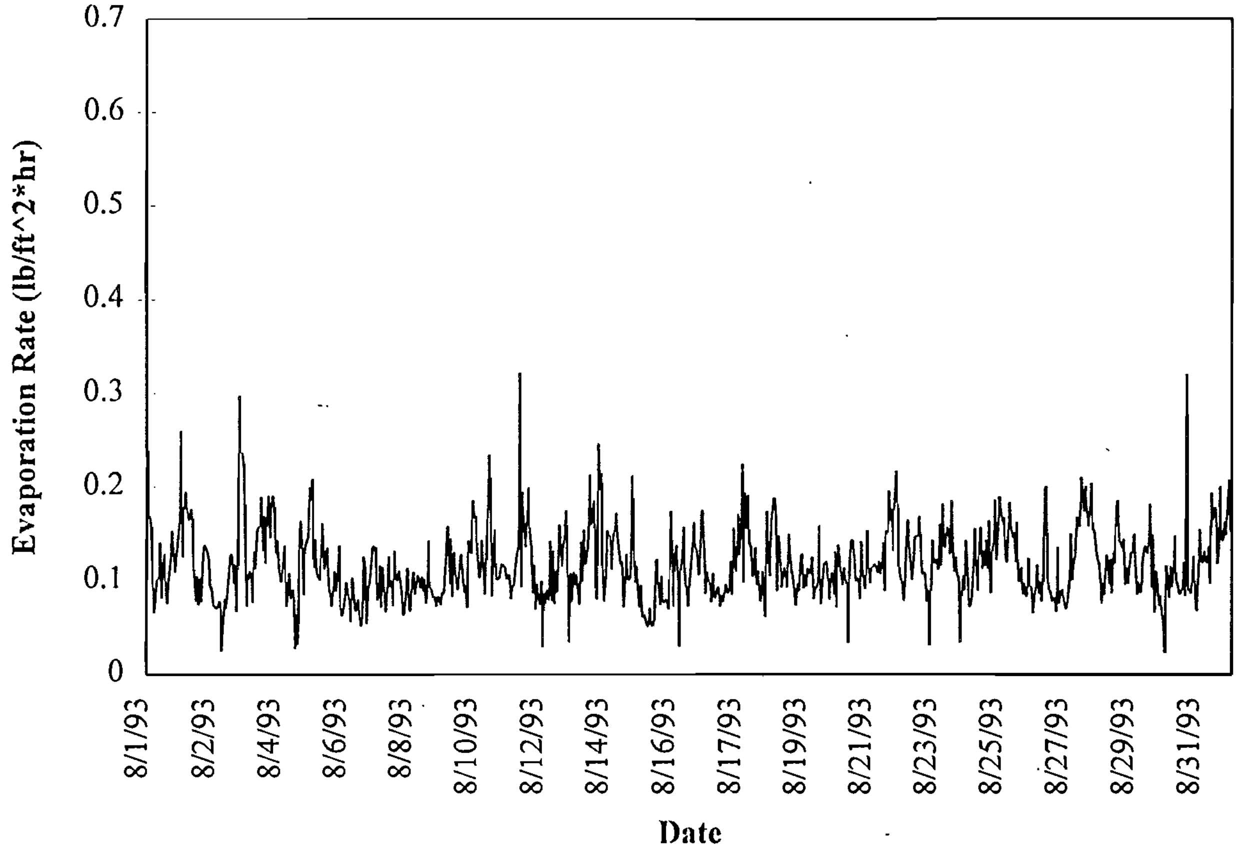
Evaporation Rate - June 1993



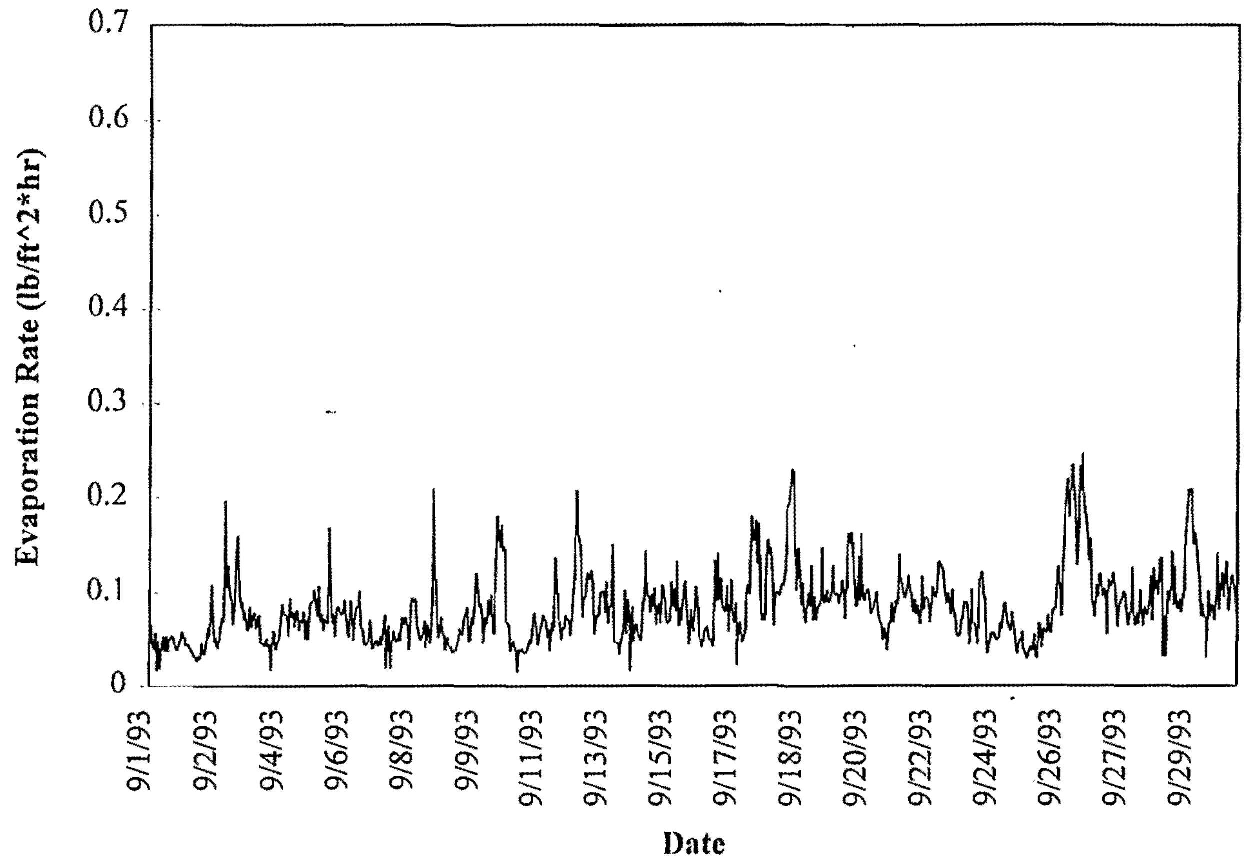
Evaporation Rate - July 1993



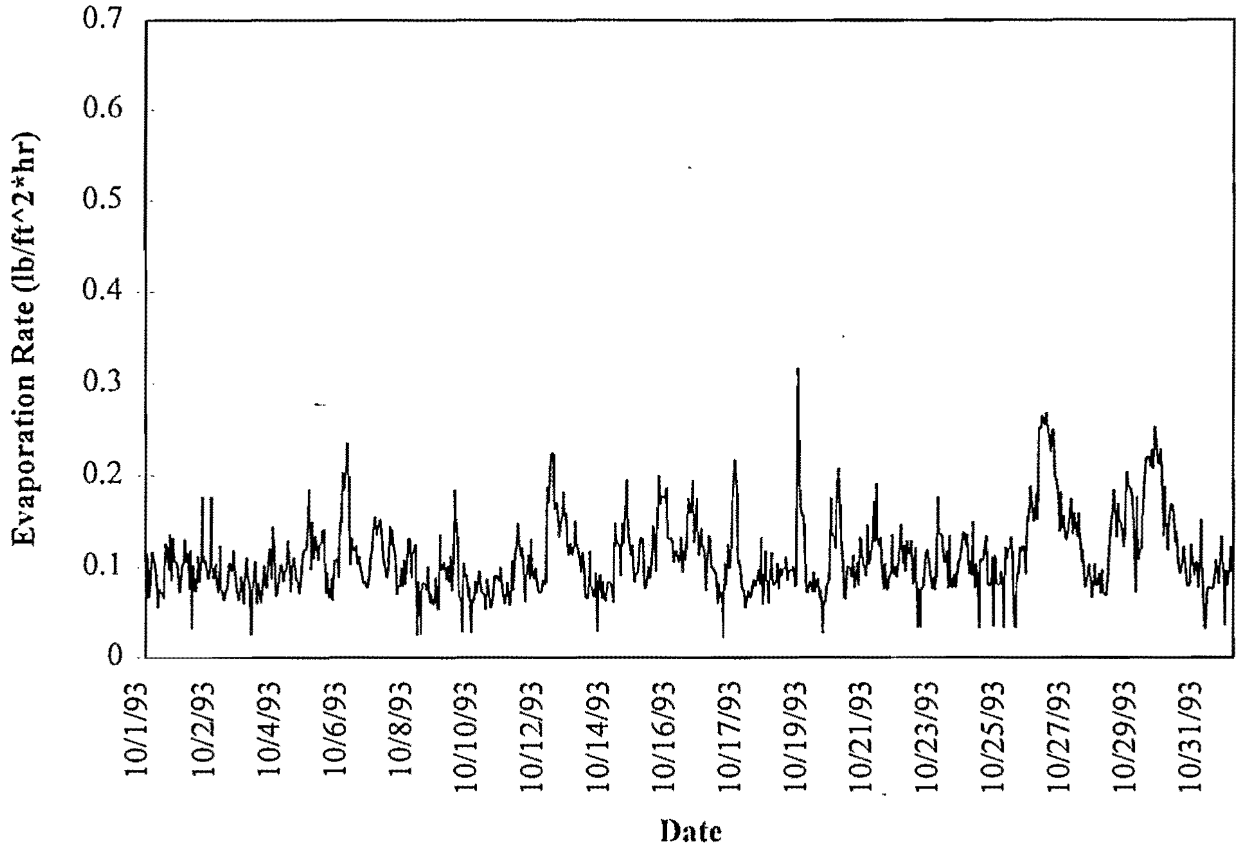
Evaporation Rate - August 1993



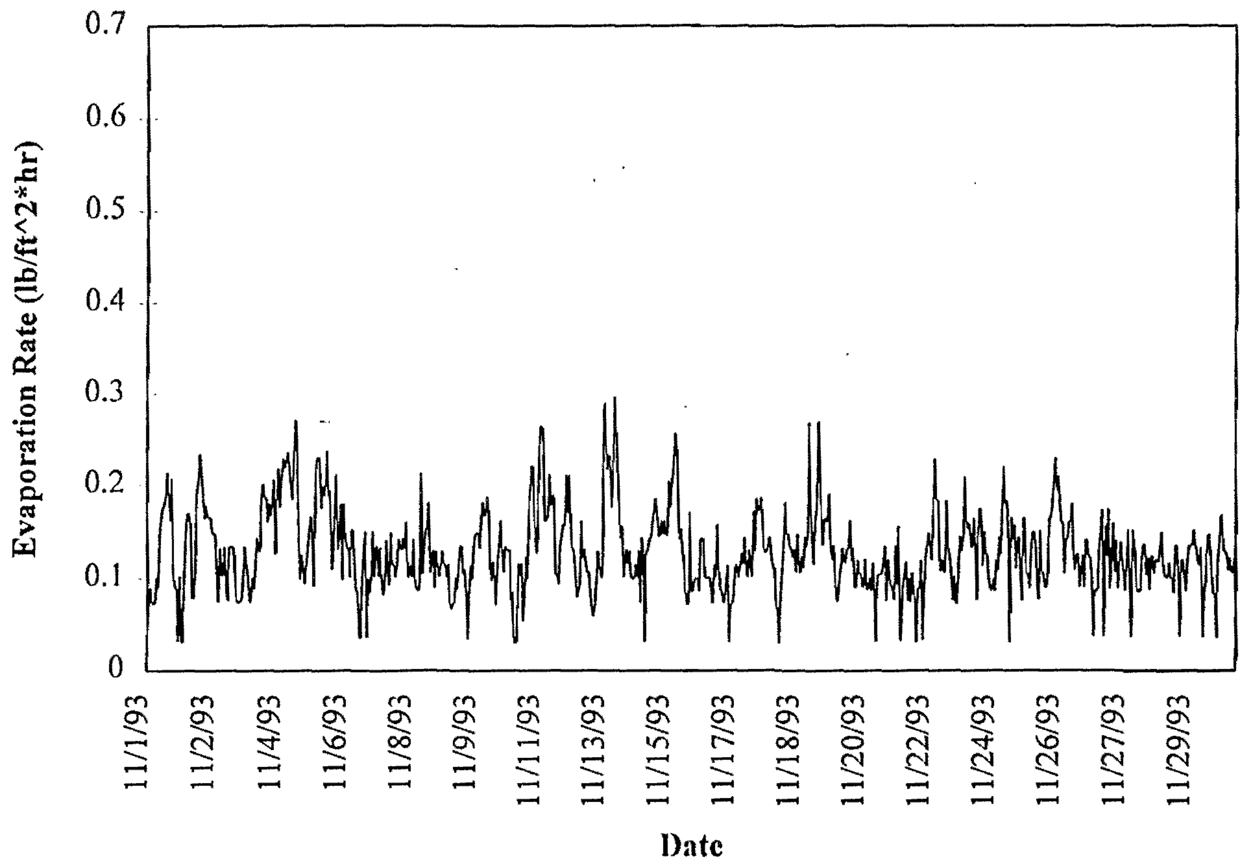
Evaporation Rate - September 1993



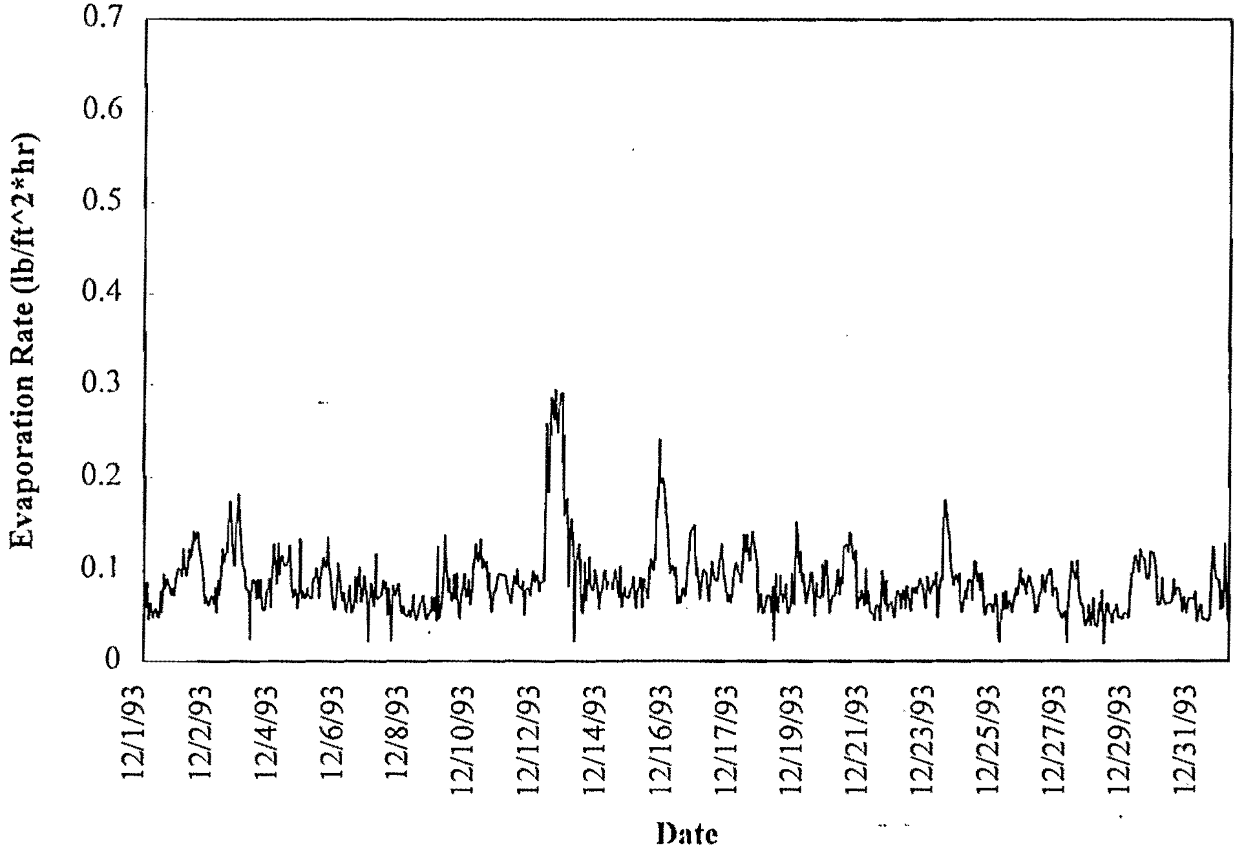
Evaporation Rate - October 1993



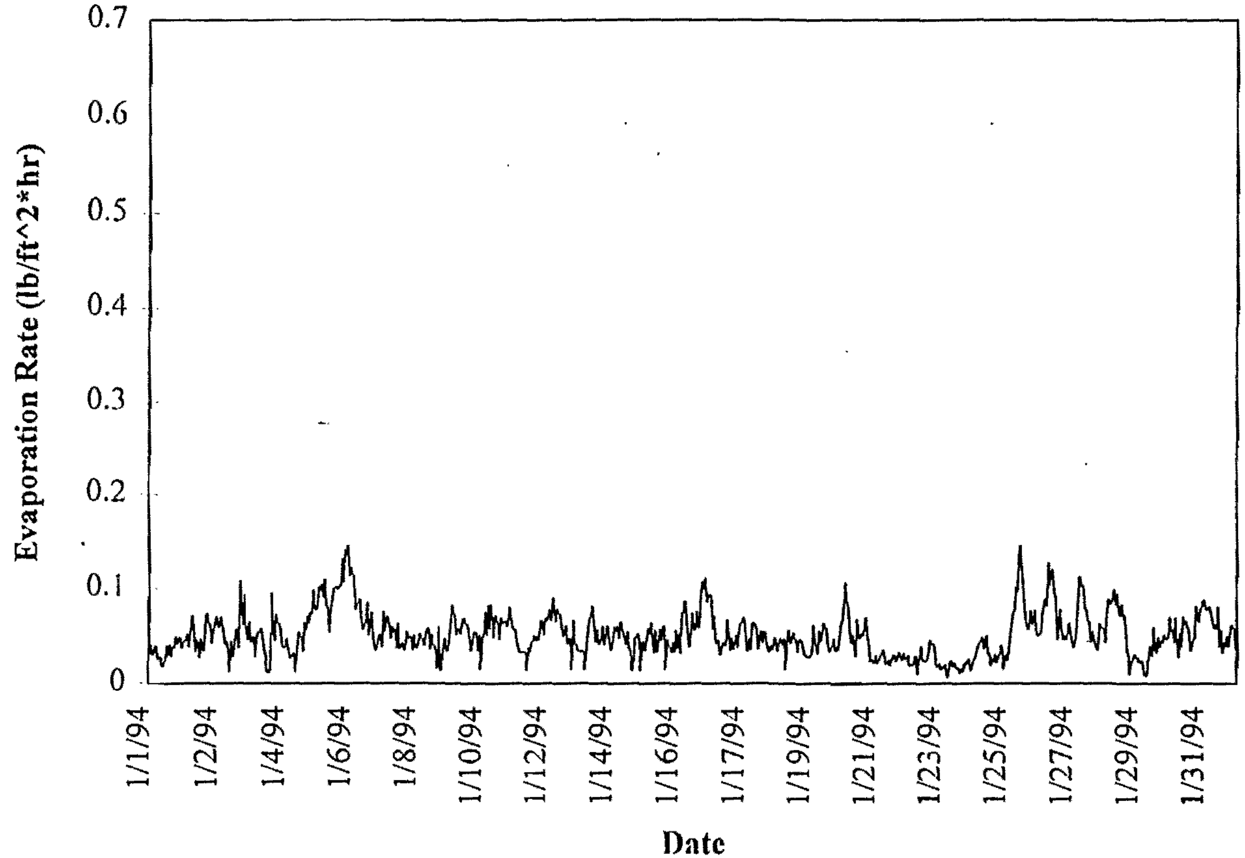
Evaporation Rate - November 1993



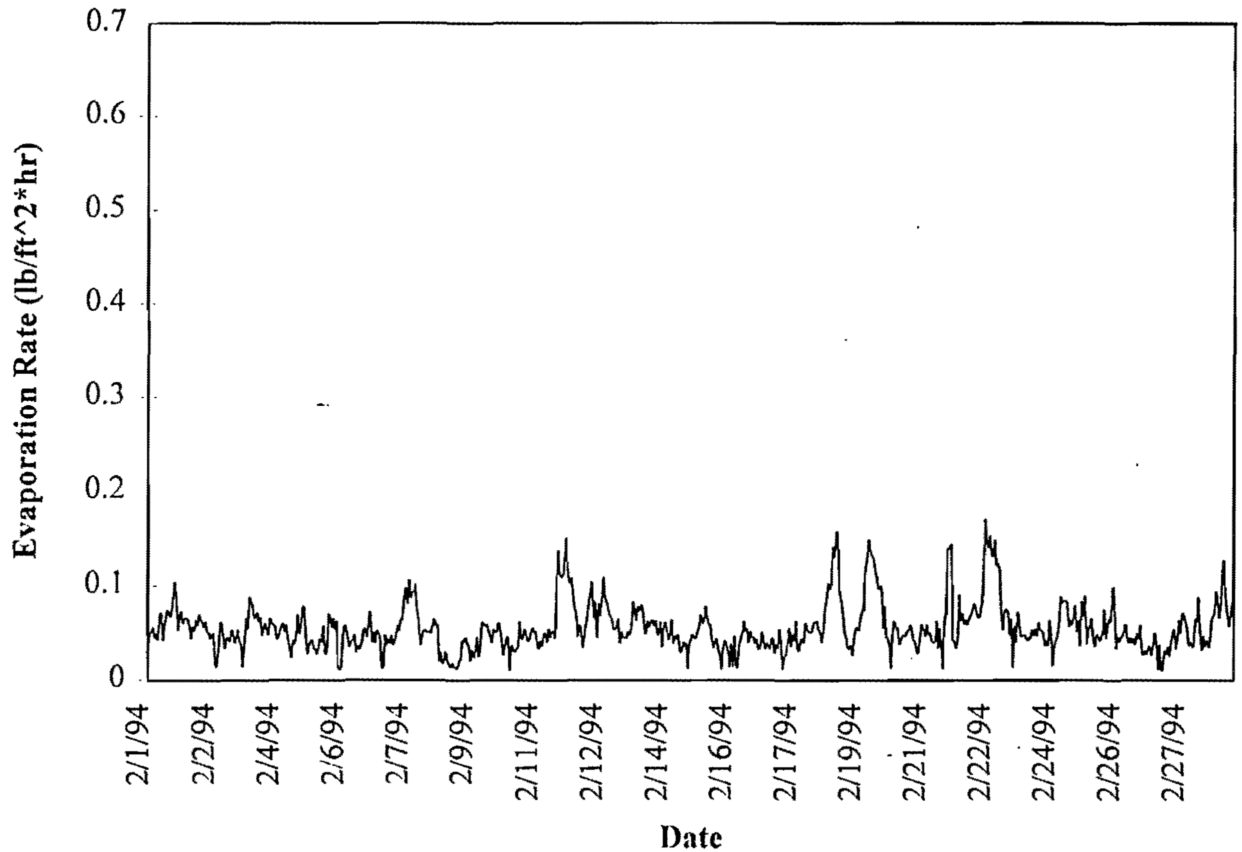
Evaporation Rate - December 1993



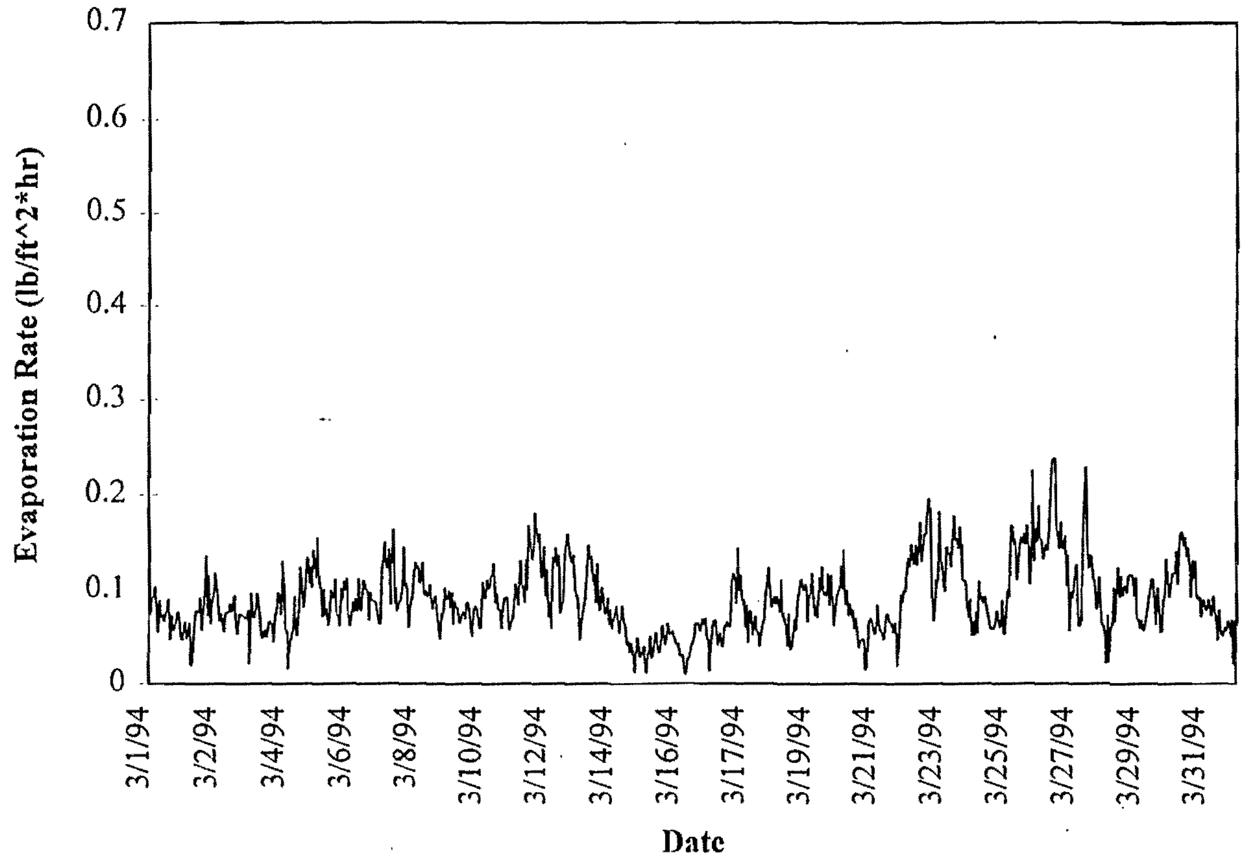
Evaporation Rate - January 1994

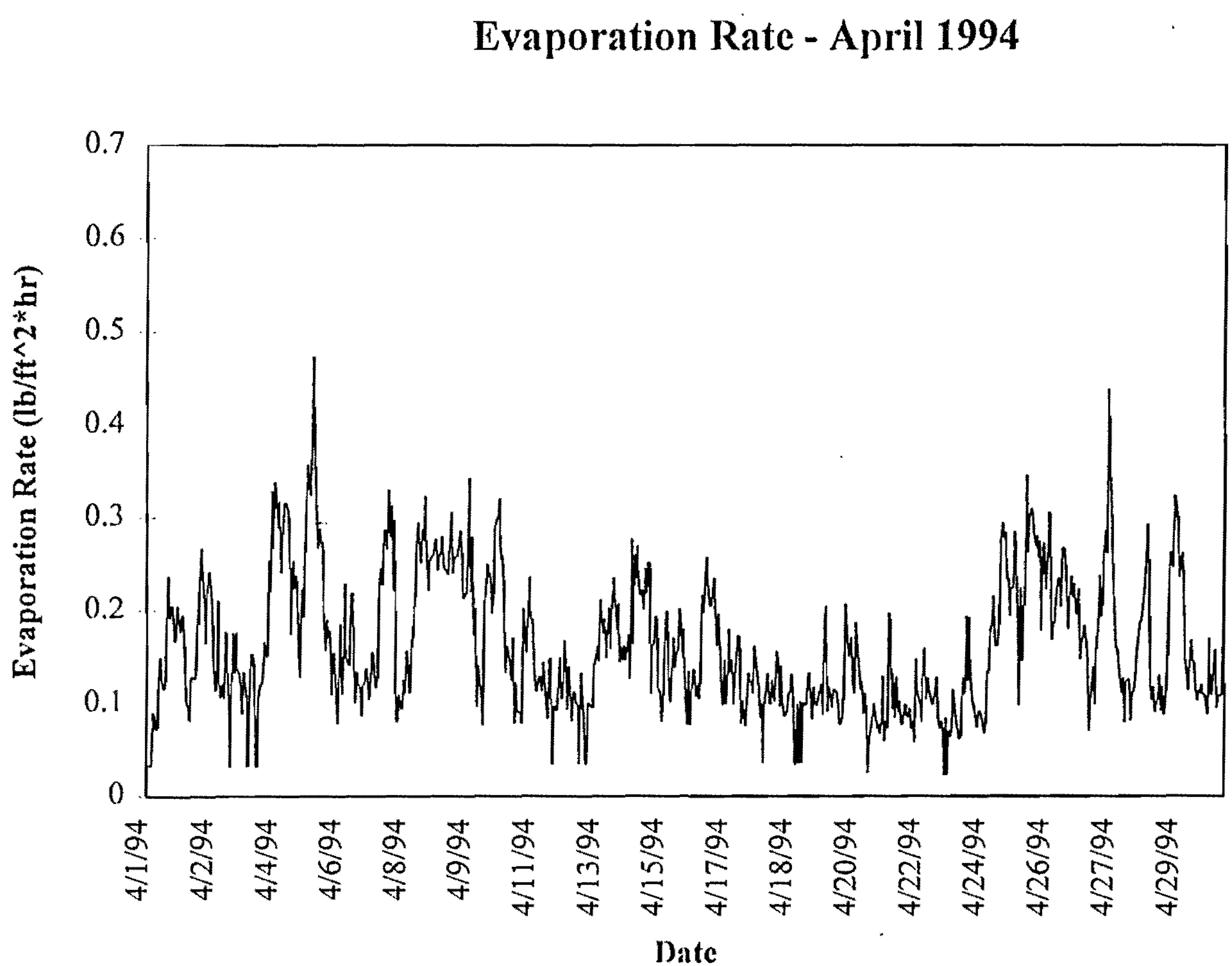


Evaporation Rate - February 1994



Evaporation Rate - March 1994




Evaporation Rate - April 1994
Evaporation Rate (lb/ft^2*hr)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
4/1/94
4/2/94
4/4/94
4/6/94
4/8/94
4/9/94
4/11/94
4/13/94
4/15/94
4/17/94
4/18/94
4/20/94
4/22/94
4/24/94
4/26/94
4/27/94
4/29/94
Date

Evaporation Rate - May 1994