EVALUATION OF HPC PAVEMENT IN NELSONVILLE, OHIO

Russ College of Engineering and Technology
Ohio Research Institute for Transportation and the Environment

Prepared in cooperation with the Ohio Department of Transportation and the U.S. Department Transportation, Federal Highway Administration

Final Report
December 2004
### Abstract
A test of concrete maturity and durability was conducted on a segment of US Route 33 during a road reconstruction project in Nelsonville, Ohio. Three different mixes were compared: Mix A had 30% blast furnace slag and used #57 aggregate; Mix B had 30% blast furnace slag and used #357 aggregate; and Mix C was a standard ODOT mix with no slag and #57 aggregate. Sections of 1000 ft (305 m) were constructed using each mix. Half of each section was cured using wet burlap and the other half was cured using a spray-on membrane. In one slab in each half section, thermocouples were installed at the center and at one corner to monitor temperatures during curing.

Small batches of each mix of concrete were also made in the laboratory and cured in a climate controlled chamber at 5°C, 20°C, and 40°C to determine the maturity function of the mix. The compressive stresses and moduli of rupture of test cylinders and beams were determined after 1, 3, 7, 14, and 28 days of curing. To study the Nurse-Saul maturity method, concrete strength was plotted against maturity (temperature-time factor). Results generally matched laboratory and field data for Mixes B and C (though the data for C was quite scattered), but the Nurse-Saul method over predicted the strength of Mix A in the field by about 30%. This may be due to field samples being cured in sunlight while the slab with the thermocouples was in the shade. The Arrhenius method was also evaluated by plotting strength versus equivalent age. The theoretical curves generally lay in the middle of the data, but the scatter in the data precludes concluding there is a good fit. In the case of Mix A’s field data, the Arrhenius method also significantly over predicted the concrete’s strength.

The other objective of this project was to determine which mix would be expected to be the most durable based on it having the least loss of support as determined by profilometer and falling weight deflectometer measurements. The profilometer measurements showed Mix B had the least warping and loss of support between morning and afternoon measurements, at 0.016 for water cured concrete and 0.019 in for membrane cured concrete. Mix C appeared to have the most warping, with 0.023 in for water cured and 0.027 for membrane cured, the latter based on only one slab, however. The falling weight deflectometer measurements at joints confirmed the profilometer measurements, as Mix B had the least deflection at 0.315 mils/kip in the afternoon. Mix A had the highest value at 0.445 mils/kip; morning values were generally 10-20% higher. Load transfer across the joints was highest for Mix B at 94.95% in the afternoon, while Mix A had the lowest value at 87.5% in the morning. Overall it appears that Mix B experienced the least loss of support.
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The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

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CHAPTER 1
Introduction

Nelsonville, Ohio, a quaint town with a population of about 4,560, is located in Athens County 60 miles southeast of Columbus. Until recently, a dilapidated two-lane road called Canal Street (US 33) was Nelsonville’s main throughway. The road was rapidly becoming inadequate to handle heavy truck loads traveling to the larger cities of Lancaster and Columbus. The Ohio Department of Transportation (ODOT) decided to reconstruct the 3.61 miles of this road passing through the heart of Nelsonville.

A plan was developed in conjunction with the Ohio Research Institute for Transportation and the Environment (ORITE) at Ohio University to study the maturity and the amount of warping and curling for three test sections, each using a different mix of concrete. Each test section was approximately 1000 feet long. Five hundred feet of each test section were cured using a spray-on membrane, while the other five hundred feet were cured using wet burlap, as shown in Figure 1.1. The new pavement consisted of a 0.5 to 6 inch asphalt layer placed on top of the preexisting base, and 9 inches of jointed plain concrete pavement.

The following parameters were monitored:

1. Temperature profile during curing with thermocouples;
2. Temperature as a function of time for the maturity test;
3. Shape of the slab using an ORITE profilometer;
4. Joint movement of the slabs;
5. Deflection during non-destructive testing.

Three different types of concrete mixes were incorporated into this project. Table 1.1 gives a summary of the different mix designs; more detailed mix design tables will be presented later in this report. Two slabs in each test section were instrumented with thermocouple sticks at the center and outside corners as shown in Figure 1.2. Figure 1.2 also illustrates the location of each test section and the location of the thermocouples.

<table>
<thead>
<tr>
<th>MIX</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate</td>
<td>No. 57</td>
<td>No. 357</td>
<td>ODOT</td>
</tr>
<tr>
<td>Slag</td>
<td>30%</td>
<td>30%</td>
<td>Normal</td>
</tr>
</tbody>
</table>

A maturity function for each experiment was established by replicating each mix and cure type at the ORITE laboratory, and then testing cylinders and beams made from the
lab batches of concrete for strength. Slab profiles were measured with the ORITE profilometer to monitor warping and curling.

Figure 1.1 Wet Burlap and Membrane Curing
1.1 Construction Sequence

In order to minimize disruption to traffic on US33 in Nelsonville, ODOT and the contractor decided that paving operation will start at 8PM and continue until 6AM. Construction on the eastbound lanes started on April 23rd 2003 at station 224+25 and ended on May 7th 2003 at station 135+05. In order to further facilitate the paving process, and eighteen foot lane was placed, which would consist of the twelve foot driving lane and six feet of the middle turning lane. A longitudinal joint would be sawed to separate the driving lane from the middle turning lane section. A 0.5 inch to 6 inch asphalt layer was placed on top of the existing base to create a bond breaker layer prior to placement of the 9 inch thick plain jointed concrete pavement.
Thermocouple sticks were installed on top of the asphalt layer prior to placement of concrete. The thermocouples were placed as shown in figure 1.2. Figure 1.3 shows the actual field installation of the thermocouple sticks. Each thermocouple stick consisted of 4 T Type thermocouples spaced evenly from top to bottom.

![Thermocouple Installation](image)

Figure 1.3  Thermocouple Installation

1.2 Maturity Methods

A maturity method is a technique for estimating the strength development of in-place concrete during its curing period by measuring the temperature history of the concrete. The strength at early stages can be estimated by the maturity method with errors in prediction not exceeding what is usually expected in the evaluation of compressive strength test results. The early stage of concrete is defined as the age at which concrete has gained strength not greater than 50 percent of its 28-day strength while curing at normal temperature. There are two methods of predicting the strength of concrete. The first is the Nurse-Saul equation (1.1), which uses simple linear integration. This is an obvious simplification since the temperatures vs. time plots have curving slopes that are
always fluctuating. The output of the equation is a temperature-time factor (TTF). The typical value of the datum temperature is 0°C for normal concrete. If the mix is a fast set, it is recommended that -10°C be used as the datum, or when using a delayed set mix, +6°C is recommended. However, the Nurse-Saul equation only works for temperatures between -5°C and 30°C. The Nurse-Saul equation is:

\[ M(t) = \Sigma (T_a - T_0) \Delta t \]  

(1.1)

Where:

- \( M(t) \) is the temperature-time factor (deg-hours).
- \( T_a \) is the average temperature during time interval.
- \( T_0 \) is the datum temperature
- \( \Delta t \) is the time interval

The second method is the Arrhenius method, which uses the reaction rate of cement to compute an equivalent age factor from the recorded temperature history of the concrete, as shown in equation (1.2). Equivalent time (\( t_e \)) is the amount of time required for a given concrete sample at a specified temperature (\( T_s \)) to attain the maturity that a tested sample has achieved. The reference temperature is most usually set equal to 20°C or 23°C, however, its selection is completely arbitrary. The Arrhenius equation is:

\[ t_e = \sum e^{\left(-\frac{Q}{T_r}\left(\frac{1}{T_a}\right)\left(\frac{1}{T_s}\right)\right)} \Delta t \]  

(1.2)

Where:

- \( t_e \) is the equivalent age at the reference temperature.
- \( Q \) is the activation energy divided by the energy constant.
- \( T_a \) is the average absolute temperature of concrete.
- \( T_r \) is the absolute reference temperature
1.3 Measuring Loss of Support

A principal factor in premature concrete pavement failure is loss of support caused by sagging or warping of the slabs in the pavement. Poured concrete will bow a bit, creating a cantilever shape that weakens the finished pavement. As heavy vehicles drive over these bowed segments they exacerbate the stresses on the concrete and the bending stress eventually causes the pavement to fail. The second major objective of this study is to measure which of the six test sections (three mixes times two curing methods) shows the least loss of support after 28 days.

Loss of support was measured using the ORITE profilometer which measured the relative elevation along a line on the concrete. Because the signal showing the warping is small relative to the fluctuations, measurements with a falling weight deflectometer (FWD) were conducted at the joints to confirm the profilometer results. The best mix would be that which has the least warp as measured by the profilometer and has the lowest deflection as measured by the FWD.
CHAPTER 2

Maturity Function: Presentation of Data and Test Results

2.1 Introduction

Concrete strength is directly related to each ingredient in a particular mix design. This means that the aggregate type and source, mix proportions and any additives have a role in the concrete strength. Because time is a major factor when placing concrete, determining when a mix has reached the desired strength so that the highway can be opened is of high importance. The current methods used include testing cylinders and beams made during the construction or taking cores from the actual pavement to test for their compressive strength. Therefore, there is a need to develop non-destructive methods to determine early age strength of concrete. The maturity method has been developed and refined to predict the early age compressive strength using time and temperature data.

The maturity method specified in ASTM C1074-93 is accepted as a means of predicting the compressive strength, but validation of this method still needs to be performed. The maturity method is a technique for estimating concrete strength that is based on the assumption that all samples of a given mixture attain equal maturity values. Using time and temperature data from the field and compressive strengths found in the lab, maturity curves can be fit to these data. The methods used to apply both maturity equations 1.1 and 1.2 and the results will be discussed in the following sections.

There are many advantages to the maturity method. It provides a means of non-destructive in-situ prediction of concrete strength. Construction time and costs can be cut because it accelerates work schedules by removing formwork earlier, shortened pre and post-tensioning times and promotes early bridge deck and pavement openings. By installing thermocouples or another type of maturity device at different locations, you can find strengths at those respective locations within a concrete structure. The maturity method also can be used to quickly alert the contractor to problems and determine saw cut times.

As with any method in testing materials, there are some disadvantages. The concrete must hydrate continuously, which will not occur if it is placed in cold weather conditions and the ambient temperature drops below 0°C. ASTM C1074 suggests supplementing the maturity method with other tests such as cylinders, which would still involve a large amount of work, which this method is trying to eliminate. Paving contractors may have difficulties using the maturity method since they would have to replicate the exact mixes to be used in the field in the laboratory up to 40 days prior to construction. This research tries to establish maturity curves that may be used by contractors and DOT personnel in the field.
To establish the maturity functions for the three different mixes used on US 33, approximately 290 cylinders and beams had to be made, cured, and monitored under controlled conditions. All mixing and testing was performed at the ORITE materials testing laboratory in Stocker Center at Ohio University.

2.2 Laboratory Instrumentation

To replicate the mixes in the field, concrete was mixed using a 9 cubic foot, gasoline powered, concrete mixer. Standard 152 millimeter (6 inch) diameter by 305 millimeter (12 inch) tall, wax coated, cardboard cylinder molds were used to make concrete cylinders using ASTM C192 standards. Concrete beams were made using 152 millimeter (6 inch) by 152 millimeter (6 inch) by 533 millimeter (21 inch) plastic beam molds to ASTM C78 standards. The samples were then cured in a temperature and moisture controlled chamber. For each batch that was being cured in the chamber, two extra cylinders were made and instrumented with one thermocouple each inserted into the center of the cylinder. Air temperature was also recorded using a Campbell Scientific model 107 temperature probe placed inside the chamber.

2.3 US33 Mix Replication Data

A beam-breaking apparatus was fabricated and mounted to a Material Testing System (MTS) compression machine where the user could capture the loads from the MTS control module. The compressive strength of the de-molded cylinders was found using a 4,448 KN (1,000,000 pound) compression machine. The compression force and strength were captured by the control panel and recorded by the user. This research project included three different mixes which included two mixes containing ground granulated blast furnace slag (GGBFS). The first mix containing slag used #357 coarse limestone is labeled mix B. The second mix containing slag used #57 coarse limestone is labeled mix A. The third mix, which is a standard Class C mix containing type I cement, is labeled mix C. The mix designs are shown in Table 2.1 through 2.3. All materials were provided by Smith Concrete of Marietta, Ohio.

Table 2.1 US33 Mix B Design

<table>
<thead>
<tr>
<th>Slag 4000 psi (#357's) – Mix B</th>
<th>SSD Weight</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement Type I</td>
<td>385 lbs</td>
<td>1.96 ft³</td>
</tr>
<tr>
<td>Slag Cement (GGBFS)</td>
<td>165</td>
<td>0.91</td>
</tr>
<tr>
<td>Coarse - #357 Limestone</td>
<td>1750</td>
<td>10.46</td>
</tr>
<tr>
<td>Sand</td>
<td>1300</td>
<td>8.07</td>
</tr>
<tr>
<td>Water</td>
<td>250</td>
<td>4.01</td>
</tr>
<tr>
<td>Admixture, Type A or D</td>
<td>22.0 oz</td>
<td></td>
</tr>
<tr>
<td>Air Entrainment (6 +/- 1%)</td>
<td>as required</td>
<td>1.62</td>
</tr>
<tr>
<td>Stump</td>
<td>4&quot; max</td>
<td></td>
</tr>
<tr>
<td>W/C Ratio</td>
<td>0.45</td>
<td></td>
</tr>
</tbody>
</table>
### Table 2.2 US33 Mix A Design

<table>
<thead>
<tr>
<th>SSD Weight</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>385 lbs</td>
<td>1.96 ft³</td>
</tr>
<tr>
<td>165</td>
<td>0.91</td>
</tr>
<tr>
<td>1750</td>
<td>10.46</td>
</tr>
<tr>
<td>1300</td>
<td>8.07</td>
</tr>
<tr>
<td>250</td>
<td>4.01</td>
</tr>
<tr>
<td>22.0 oz</td>
<td></td>
</tr>
<tr>
<td>as required</td>
<td>1.62</td>
</tr>
<tr>
<td>4&quot; max</td>
<td></td>
</tr>
<tr>
<td>0.45</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2.3 US33 Mix C Design

<table>
<thead>
<tr>
<th>SSD Weight</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>550 lbs</td>
<td>2.80 ft³</td>
</tr>
<tr>
<td>1750</td>
<td>10.46</td>
</tr>
<tr>
<td>1300</td>
<td>8.07</td>
</tr>
<tr>
<td>250</td>
<td>4.01</td>
</tr>
<tr>
<td>22.0 oz</td>
<td></td>
</tr>
<tr>
<td>as required</td>
<td>1.62</td>
</tr>
<tr>
<td>4&quot; max</td>
<td></td>
</tr>
<tr>
<td>0.45</td>
<td></td>
</tr>
</tbody>
</table>

### 2.4 Mixing and Batching

Each mix was cured at three temperatures, 5, 20, and 40°C (41, 68, and 104°F). For each mix at each temperature, samples were tested at 5 test times (1, 3, 7, 14 and 28 days). Three samples were made for each test time in case a sample was faulty and so that an average could be computed. Beams were made to ascertain flexural modulus and cylinders were made to determine compressive strength. Due to the size and number of the beams and cylinders, only two mixes could be cured at a time. For each batch made, two extra cylinders were made to be instrumented with thermocouples for temperature measurement. Using the above outlined procedure, a total of 288 samples were made as illustrated in figure 2.1. Table 2.4 shows the dates and temperature of the laboratory tests.
The mixes were made to exact proportions provided by Smith Concrete of Marietta who provided the concrete for the project. Each batch, which was approximately 0.17 m³ (6 ft³), was mixed according to ASTM C192 standards. A slump cone was used to measure the slump of each mix and an air meter was used to measure air content. The slump and air content were adjusted accordingly to meet mix design specifications by adding water or air entrainment additive, respectively. Test specimens were then molded using ASTM C470 standards for molding. Specimens were immediately smoothed off with a trowel and placed in the environmentally controlled chamber for curing.

### Table 2.4: Laboratory Mixing Dates and Temperatures

<table>
<thead>
<tr>
<th>Mix Date</th>
<th>Mix</th>
<th>Curing Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/16/2003</td>
<td>A,C</td>
<td>20ºC</td>
</tr>
<tr>
<td>2/27/2003</td>
<td>A,C</td>
<td>40ºC</td>
</tr>
<tr>
<td>4/17/2003</td>
<td>A,C</td>
<td>5ºC</td>
</tr>
<tr>
<td>5/29/2003</td>
<td>B</td>
<td>40ºC</td>
</tr>
<tr>
<td>6/26/2003</td>
<td>B</td>
<td>20ºC</td>
</tr>
<tr>
<td>7/28/2003</td>
<td>B</td>
<td>5ºC</td>
</tr>
</tbody>
</table>

### 2.5 Specimen Testing

When it was time to test the concrete specimens, they were removed from the chamber and de-molded. To ensure the tops and bottoms of the cylinders were flat, both ends were capped using capping compound. Each specimen was then tested in accordance with ASTM C39-94 and discarded appropriately. The test results for compressive strengths for the beams and cylinders can be found in Figure 2.2 through Figure 2.4 and Figure 2.5 through Figure 2.7 shows the modulus of rupture of the test specimens.
2.6 Field Data and Conditions

Mix C sections where first to be placed on April 23rd 2003. The air temperature on the evening of April 23rd and the morning of April 24th varied from 12 degrees Celsius at midnight on April 23rd to a low of 3 degrees Celsius at 6AM on April 24th. Air temperature reached 12 degrees Celsius at noon on April 24th and continued to rise. Mix A and Mix B sections where placed on May 2nd 2003. Air temperature varied between 14 and 19 degrees Celsius during placement of the concrete and subsequent 12 hour period.

Reported Mix Designs placed at station 221+00 (MixC) is shown in Table 2.5. Ninety day cylinder breaks for Mix C where reported as QC 7440 and 7610 psi and QA at 8230 psi.

Reported Mix Design placed at station 138+90 (Mix A) is shown in Table 2.6. Ninety day cylinder breaks where reported as QC 6150 psi and QA as 7720 and 7210 psi. 5 day beam breaks at station 138+90 where reported as 800 psi. Reported Mix design placed at station 144+50 (Mix B) is shown in Table 2.7. Reported 5 day beam breaks at station 144+50 where 750 psi.

Table 2.5 Mix C as placed

<table>
<thead>
<tr>
<th>Material Code Name</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand, Natural /02</td>
<td>1320 lbs</td>
</tr>
<tr>
<td>57 CR Stone 57/02</td>
<td>1675 lbs</td>
</tr>
<tr>
<td>Cement Type I</td>
<td>550 lbs</td>
</tr>
<tr>
<td>Air</td>
<td>6.0 %</td>
</tr>
<tr>
<td>Slump</td>
<td>4 inches</td>
</tr>
<tr>
<td>Water/Cement Ration</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Table 2.6 Mix A as placed

<table>
<thead>
<tr>
<th>Material Code Name</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand, Natural /02</td>
<td>1310 lbs</td>
</tr>
<tr>
<td>57 CR Stone 57/02</td>
<td>1670 lbs</td>
</tr>
<tr>
<td>Cement Type I</td>
<td>385 lbs</td>
</tr>
<tr>
<td>Granulated Slag GR100</td>
<td>165 lbs</td>
</tr>
<tr>
<td>Master Builders Admix</td>
<td>10 oz</td>
</tr>
<tr>
<td>Air</td>
<td>6.2%</td>
</tr>
<tr>
<td>Slump</td>
<td>1.5 inches</td>
</tr>
<tr>
<td>Water/Cement Ration</td>
<td>0.420</td>
</tr>
</tbody>
</table>
Table 2.7 Mix B as placed

<table>
<thead>
<tr>
<th>Material Code Name</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand, Natural 02</td>
<td>1240 lbs</td>
</tr>
<tr>
<td>357 CR Stone 57/02</td>
<td>1750 lbs</td>
</tr>
<tr>
<td>Cement Type I</td>
<td>385 lbs</td>
</tr>
<tr>
<td>Granulated Slag GR100</td>
<td>165 lbs</td>
</tr>
<tr>
<td>Master Builders Admix</td>
<td>17 oz</td>
</tr>
<tr>
<td>Air</td>
<td>8.0%</td>
</tr>
<tr>
<td>Slump</td>
<td>1.25 inches</td>
</tr>
<tr>
<td>Water/Cement Ration</td>
<td>0.469</td>
</tr>
</tbody>
</table>

2.7 Data Interpolation

Using time and temperature data collected from the lab and the field, maturity functions were plotted using Microsoft® Excel. Both the Nurse-Saul and the Arrhenius methods were evaluated to compare the results. The methods and results are presented in the following sections.

2.7.1 Nurse-Saul Maturity Method

The Nurse-Saul method is the easier of the two to use because once the reference temperature is established, it is a simple linear relation using the temperature and the time period that temperature took place. For the values of the datum temperature, it was found that 0°C worked best for the mixes containing slag, and 10°C for the standard mix. The CR7 was set up to take readings every 10 minutes from the cylinders instrumented with the thermocouples; therefore the time interval is fixed for the entire data set. Using the temperature data from the CR7, the maturity index was calculated and plotted against the ratio of the compressive strengths over the 28 day period during which the cylinders were cured in the climate chamber. With these data points, a logarithmic trend line was fitted to the experimental data set. This line is the strength versus maturity index that is used to predict the compressive strength in the field. Then using the test results from the field specimen and the temperature data, the maturity indices were calculated for both the corner and the center thermocouple sticks. Because the corners were located close to the edge, temperatures were cooler in these regions, thus producing different results from the center of the slabs. The results are shown in Figure 2.8 and Figure 2.9 for Mix B, Figure 2.10 and Figure 2.11 for Mix A, and Figure 2.12 and Figure 2.13 for Mix C.

For Mix B, which was a slag mix containing #357 aggregate, the data yielded a trend line that fit the laboratory data well and the field data very well. For Mix A, which was a slag mix containing #57 aggregate, the data gave a trend line that fit the laboratory results well but overpredicted the field data by approximately 30%. Even though the laboratory data from mix C is scattered, the maturity plot does an accurate job of predicting the strength of the field cylinders.
2.7.2 Arrhenius Maturity Method

Using the same data used for the Nurse-Saul method, the equivalent age was evaluated for each of the mixes using the Arrhenius Method. The Arrhenius maturity method is a bit more involved due to its many variables. First, a reference temperature of 23°C is established, as preferred in North American practice. Q is defined as the activation energy \( E \), divided by the universal gas constant, \( R \). The universal gas constant is equal to 8.314 g/mol K. The apparent activation energy was estimated using the following technique:

\[
E = 43.0 + 1.47 \times (20 - T_a) \text{ kJ/mol, when } T_a < 20^\circ C
\]

\[
E = 43.0 \text{ kJ/mol, when } T_a \geq 20^\circ C
\]

Using the above parameters, the compressive strengths of the specimen tested in the laboratory were plotted versus the calculated equivalent ages. Two lines were then plotted through these data for comparison. First, a logarithmic trend line was fitted to the data using the built in least squares method in Excel®. Next, a hyperbolic equation was used to estimate the strength gain up to equivalent ages of about 28 days at 23°C. This hyperbolic equation is:

\[
\frac{S}{S_{28}} = \beta \frac{k(t - t_0)}{1 + k(t - t_0)}
\]

(2.1)

Where:

\( S \) is the strength at time \( t \), psi.

\( S_{28} \) is the strength at 28 days, psi.

\( k \) is a rate constant.

\( t_0 \) is the age at the start of strength development, days.

\( \beta \) is a factor describing strength gain.

To apply equation 2.1, the following assumptions were made:

1. The strength at an equivalent age of 28 days was assumed to be 4000 psi.
2. The age at the start of strength development is the age at the time of final setting. This was found to be 0.25 days.
3. For determination of the rate constant and the value for \( \beta \), the following relationship was found:

\[
\beta = 1 + \frac{1}{28k}
\]

(2.2)
This is the key to establishing an accurate maturity function. The rate constant represents the rate at which the chemical reaction occurs at a given temperature. The value for $k$ is adjusted until the data best fits the laboratory results. The results of the rate constants and $\beta$ value determination are presented in Table 2.8.

### Table 2.8 Arrhenius Constants

<table>
<thead>
<tr>
<th>Mix</th>
<th>$\beta$</th>
<th>$k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>1.12</td>
<td>0.3</td>
</tr>
<tr>
<td>A</td>
<td>1.07</td>
<td>0.5</td>
</tr>
<tr>
<td>C</td>
<td>1.12</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The relative strength ratio $S/S_{28}$ versus equivalent age relationships estimated with equation 2.1 are shown in Figure 2.14 through Figure 2.16. Then, using the temperature data from the field, the equivalent ages were calculated using equation 2.2 and plotted with the maturity curve from equation 2.1. These data are shown in Figure 2.17 through Figure 2.22.

#### 2.7.3 Discussion of Maturity Results

All three mixes revealed similar tendencies with the Arrhenius method as the Nurse-Saul method. Again, Mix A overpredicted the strength in the field. The main reason for the discrepancies is most likely due to varying mixes between the field and the laboratory. In the field, Mix C was placed right after a small section of fast set concrete. Some of the fast set concrete could have mixed with the standard class C mix and accelerated it. With regards to Mix A, it was noted in the field that there was no shading on this section, whereas Mix B sections were placed under trees. Yet another reason could be that the cylinders cast in the field could not be placed right next to the slab, which means they, most likely experienced different temperatures then measured in the slab. Also, because less than a third of a yard was mixed in the lab compared to eight or nine yards at a time in the field, curing properties could have varied somewhat. All these reasons combined are most likely the reasons for the bad predictions from the laboratory data.

#### 2.7.4 Maturity Concept Conclusions

Two maturity methods were investigated, the Nurse-Saul and the Arrhenius methods. The Nurse-Saul method uses a time-temperature factor to measure maturity. This is simply the area under the time versus temperature plot. The results from the US33 data yielded very good results on average of predicting the strength of the cylinders in the field using the maturity curves established in the laboratory. Mix A showed a poor fit, however, which is attributed to the fact that the slabs instrumented with the thermocouples were under the shade of trees, and the test cylinders were cured across the street in direct sunlight.
The Arrhenius method, which measures maturity by its equivalent age, uses the reaction rate of cement to predict its strength based on its temperature history. When fitting curves to the laboratory data, the average fit was marginal. This is most likely attributed to the mix proportions used when replicating the mix in the laboratory and determining the constants. Again, as in the Nurse-Saul prediction, the field cylinders followed similar trends. Mix A produced a poor fit to the laboratory data, confirming the fact that the cylinders were not cured in the same conditions as the slab was.

Although the Nurse-Saul method produced better fitting results than the Arrhenius method, the fact that it uses the time-temperature factor limits its utility in real life applications. The Arrhenius method could be better applied if larger batches could be obtained from the mixing plants, rather than mixing small batches in the laboratory.

![Compressive Strengths - 5 Deg C Cure](image)

**Figure 2.2 Compressive Strengths, 5°C Cure**
Figure 2.3 Compressive Strengths, 20°C Cure
Figure 2.4 Compressive Strengths, 40°C Cure

Figure 2.5 Modulus of Rupture, 5°C Cure
Figure 2.6 Modulus of Rupture, 20°C Cure

Figure 2.7 Modulus of Rupture, 40°C Cure
MixB Nurse-Saul, Center

\[ y = 0.2095 \ln(x) - 0.3493 \]

\[ R^2 = 0.9319 \]

Figure 2.8 Nurse Saul Maturity Method Mix B, Center of Slab

MixB Nurse-Saul, Corner

\[ y = 0.2095 \ln(x) - 0.3493 \]

\[ R^2 = 0.9319 \]

Figure 2.9 Nurse Saul Maturity Method Mix B, Corner of Slab
Figure 2.10 Nurse Saul Maturity Method Mix A, Center of Slab

Figure 2.11 Nurse Saul Maturity Method Mix A, Corner of Slab
Figure 2.12 Nurse Saul Maturity Method Mix C, Center of Slab

Figure 2.13 Nurse Saul Maturity Method Mix C, Corner of Slab
Figure 2.14 Arrhenius Maturity Method Mix B Lab Data

Figure 2.15 Arrhenius Maturity Method Mix A Lab Data
Maturity for Lab Data-Mix C-Arrhenius

\[ y = 0.1632 \ln(x) + 0.3656 \]

\[ R^2 = 0.5836 \]

---

Figure 2.16 Arrhenius Maturity Method Mix C Lab Data

Maturity for Field Data-Mix B-Center-Arrhenius

\[ y = 1.12 \times \frac{(0.3 \times (x-0.25))}{1 + 0.3 \times (x-0.25)} \]

---

Figure 2.17 Arrhenius Maturity Method Mix B Field Data, Center of Slab
Figure 2.18 Arrhenius Maturity Method Mix B Field Data, Corner of Slab

Figure 2.19 Arrhenius Maturity Method Mix A Field Data, Slab Center
Figure 2.20 Arrhenius Maturity Method, Mix A Field Data, Corner of Slab

Figure 2.21 Arrhenius Maturity Method, Mix C Field Data, Center of Slab
Maturity for Field Data-Mix C-Corner-Arrhenius

\[ y = \frac{1.12 \cdot (0.3 \cdot (x-0.25))}{1 + 0.3 \cdot (x-0.25)} \]

Figure 2.22 Arrhenius Maturity Method, Mix C Field Data, Corner of Slab
CHAPTER 3

The ORITE Profilometer

3.1 Introduction

The profilometer measures pavement elevation relative to an integral guide rail every half inch of distance over a maximum travel distance of 112 inches over pavement. The elevation measurement least count is approximately 0.005 inch. The angle of the profilometer guide rail with respect to horizontal is measured for each profile using a servo inclinometer reading to 0.001 degree. This permits contiguous profiles to be concatenated virtually into one.

The elevations are measured by rolling a two inch diameter by 9/16 inch wide ball bearing “follower” over the pavement. The bearing is at the end of an arm connected to an incremental optical rotary encoder and one increment represents about 0.005 inch of change in elevation of the bearing.

An approximately 5 kilobyte ASCII disk file is produced for each profile. It records basic setup constants for the profile, the angle of the guide rail with respect to horizontal, and a variable number of observations, each consisting of an elevation and accumulated distance along the pavement. A maximum of 210 observations can be recorded, representing a 112-inch profile.

The aluminum profilometer frame is about 11 feet long. A notebook computer, used for controlling the instrument and collecting data, is supported at about waist height for convenience in reading the screen. A small 12-volt gel electrolyte battery and a 12VDC/115VAC inverter supply power to the components for a limited time of complete portability. Large, easily retractable wheels facilitate moving the instrument from place to place. The profilometer is depicted in use in Figure 3.1.
3.2 Method of Measurement, First Test Section as Example

Sets of contiguous 112-inch profiles sufficient to span each test section were recorded with the profilometer. Profiles were run as close to the outside (right) edge of the pavement slab as possible, with the outside feet of the profilometer two inches inside the slab. The positions of the beginning and ending elevations of each 112-inch profile with respect to the slab joints were recorded.

To form a continuous profile of the whole test section, the first profile was rotated about its first elevation according to its inclinometer beam angle reading. Each successive profile was translated vertically by adding a constant to all 210 elevation readings so that its beginning elevation equaled the final elevation of the previous one. Because these two elevations represented the same point on the pavement, one was discarded. Then the subsequent profile was rotated about the matched elevation point according to its beam angle reading. This was continued until the whole set of profiles was unified.

One set of profiles was run in the morning as soon as the lane was closed to traffic and a second set was run about four hours later. The pavement temperature at several points was recorded from thermocouples embedded (cast) in the pavement and the surface temperature was recorded with a Raytek infrared “gun.” During the warming period, the weather went from cool and rainy to warm and sunny.

At the fourth test section in the morning session, the profilometer failed after the first profile; therefore only 112/180 or about 2/3 of the first slab of this test section can be evaluated for warping.
Special procedures are required to minimize the drift in the inclinometer whose readings are used to concatenate adjacent profiles. Due partly to the adverse weather in the morning and partly to the need for haste, the results were imperfect, so that the beginning and ending elevations of the morning and afternoon concatenated profiles apparently do not match, i.e., the gain or loss in elevation over the whole profile is different for the pair by up to 0.15 inch over 65 feet. This effect increased as time went on during measurement. Nevertheless, it is the “fine structure” of a plot of the differences between respective elevations in the morning and afternoon profiles that reveals the warping, when the locations of the slab joints are superimposed on the plot. This will be illustrated using the first test section as an example.

![Figure 3.2](image_url)

**Figure 3.2 Morning and Afternoon Concatenated Profiles for the First Test Section**

The before and after concatenated profiles of the whole first test section are shown in Figure 3.2. This represents five slabs. Joints occur at x = 0, 15, 30, 45, 60 and 75 feet. The change (fall) in elevation from start to end of the five slabs is about two inches. No translation was needed to join the beginning elevations of the two profiles. The elevations of the two profiles at x = 75 are practically equal for this test section. One can barely detect the warping of each slab by the slight rise of the afternoon profile between the joints relative to the morning. (The vertical datum for the elevation is arbitrary. It is established by the profilometer so that no position of the ball bearing “follower” will produce a negative elevation. If a concatenated set of profiles were to describe enough descent, however, the elevations could become negative.)
To better illustrate the warping, take for example the first slab of this test section in isolation (Figure 3.3). The relative rise of the afternoon profile in the center is more obvious in this magnified representation.

Figure 3.3 also illustrates the “fine structure” revealed by the profilometer. The two-inch ball bearing follower can not follow the shape of the pavement grooves, but they are apparent in the profiles. A “spike” at about \( x = 3 \) feet was probably made by a piece of dirt.

![Figure 3.3 Morning and Afternoon Concatenated Profiles for the First Slab of the First Section](image)

3.3 Development of a Measure of Warping or Curling

The concept of warping evokes images of a smooth surface curved in one or two dimensions as a cylindrical or a spherical segment. One might imagine a spherical surface changing radius or even “oil-canning” to the opposite side as heat is absorbed, but it is of no practical use. From examination of the slab profiles presented in this report, noting in particular the shapes of the profiles between the joints, it is apparent that it is of little use trying to describe a slab as “convex upward” or “concave upward” because of the large undulations in the surface and the small amount of change due to warping.

The shape of the longitudinal profile of the slab along a line can be precisely described by the profilometer. The precision might be on the order of 0.01 inch, but that remains to be
proven by repeated measurements and some sort of control. Profiles made along closely-spaced parallel lines could be used to develop a three-dimensional surface.

The easiest way that we have found so far to visualize the warping is to plot the difference between the morning and afternoon profiles point by point along the profile. Warp will appear in the shape or curvature of this “difference function” provided that the shape is not embedded in the “noise” caused by (a) the fine structure of the pavement, (b) the 0.005 inch least count of the profilometer’s elevation sensor, and (c) the inevitable mismatch between the actual paths taken by the ball bearing follower. (The last two concepts are discussed in more detail below.)

Figure 3.4 shows the difference between the morning and afternoon profiles for the first test section. The respective morning elevations have been subtracted from the afternoon elevations so that the curvature between the joints at x = 0, 15, 30, … is convex upward, meaning that the center of the slab rose with respect to the ends as heat was absorbed by the top surface.

Figure 3.4 Difference between Morning and Afternoon Profiles for the First Test Section
The minima at the joints are obvious, and the amount of warping, taken as the difference in elevation between the peaks and lines drawn between the joints, is on the order of 0.02 inches. Recall that the least count of the profilometer elevation measurement is 0.005 inch. The reasons why the plots do not show a 0.005-inch “granularity” (i.e., do not appear as a step function with steps equal 0.005 inch) are:

1. The profilometer evaluates the elevation every half inch (approximately) by averaging ten readings of the rotary encoder. For each recorded elevation five readings are made successively over a short (1/8 to ¼ inch) distance as the ball bearing follower moves along the guide rail toward the “far” end and the process is repeated at the same place for each elevation as the follower returns to the starting end of the guide rail. The encoder produces a count for each reading, an integer, and one count represents about 0.005 inch change in elevation of the ball bearing follower. When the ten counts are averaged, a floating point number is generated representing the set of readings. For example, if five of the ten readings translate to an elevation of x.001 inch and five translate to an elevation of x.002 inch, the elevation is recorded as x.0015 inch.

2. The beginning and ending (longitudinally on the slab) of each 112-inch profile is not practically reproducible within about 1/8 inch in the field, especially when one is pressed for time. Therefore, when dirt or isolated small features of the surface are present and do not cancel each other in the difference between the morning and afternoon profiles, a “spike” results.

3. The lateral placement of the profile is not reproducible within about ¼ inch, with the same consequence as above.

3.4 Concatenated Profiles; Test Sections Two, Three and Four

The concatenated profile for the second test section is shown in Figure 3.5. Eight slabs are represented, plus about ten feet of the ninth slab. The drift in the inclinometer ran in both senses, so that the loss in elevation was the same for morning and afternoon profiles. The difference function, Figure 3.6, shows the drift as an overall rise in the middle of the curve, returning to about zero at the end of the profile. The loss of elevation for this set of slabs is about three inches. One profile was translated to match the beginning elevation of the other.
Figure 3.5 Morning and Afternoon Concatenated Profiles for the Second Test Section

Figure 3.6 Differences between Morning and Afternoon Profiles for the Second Test Section
The worst case of inclinometer drift for the day is illustrated in Figure 3.7, showing morning and afternoon profiles over the slabs of the third test section. No translation was done. The rise in elevation from the beginning to the end of the four slabs is about 2.6 inches. The ending elevations differ by about 0.15 inch. However, even though the difference drifts from zero elevation to about 0.15 inch overall (Figure 3.8), the fine structure reveals the amount of warping.

Figure 3.9 shows the data of Figure 3.7, but with the afternoon profile rotated about its first elevation so that its end elevation equals the end elevation of the morning profile. Figure 3.10 shows the resulting difference function. The difference function is easier to interpret, but the displayed amount of warp is unchanged. If time had permitted, it would have been very desirable to “close the traverse” with the profilometer by running the set of profiles in reverse to return to the beginning elevation point. The inclinometer drift could then be distributed throughout the profile. In the present case, however, weather and the need for haste made that kind of procedure impractical. The procedure has been done in the laboratory, though, and is viable.

Figure 3.7 Morning and Afternoon Concatenated Profiles for the Third Test Section
Figure 3.8 Difference between Morning and Afternoon Profiles for the Third Test Section

Figure 3.9 Third Test Section, Afternoon Profile Rotated
Figure 3.10 Third Test Section, Difference Function with Afternoon Profile Rotated

Figure 3.11 Morning and Afternoon Concatenated Profiles for the Fourth Test Section
Figure 3.12 Difference Between Morning and Afternoon Profiles for the Fourth Test Section

The concatenated profile for the fourth test section is shown in Figure 3.11. This is the test section in which the profilometer failed after the first profile, hence the shortness of the morning curve. One profile was translated to match the beginning elevation of the other. The elevation fell about 2.5 inches over the three slabs represented. As mentioned earlier, the only difference function available for this test section covers about 2/3 of the first slab. Figure 3.12 shows a definite maximum of about 0.02 inch, which could represent as much warping.

3.5 Results

Moving average trend lines (n = 20) were added to the charts of the difference functions for the four test sections in Figures 3.13 through 3.16. Table 3.1 shows the estimated “greatest displacement of the center portion of the slab profile relative to a line between the elevations at the joints,” which was defined as the measure of warp. The displacements were gauged visually along a vertical line from the maxima to a line connecting the elevations at the joints. In cases where the maximum was ambiguous or appeared spurious, the peak nearest the center of the slab was used as the maximum. The difference function for the fourth test section is a special case; the value for warp was taken as the highest elevation difference minus the lowest.
Figure 3.13 Difference Function with Trend line, First Test Section

Figure 3.14 Difference Function with Trend line, Second Test Section
Figure 3.15 Difference Function with Trend line, Third Test Section.

Figure 3.16 Difference Function with Trend line, Fourth Test Section
Table 3.1 Estimated Warp of Individual Slabs, Inches

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<th>Test Section</th>
<th>Slab Number</th>
<th>Water cure</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
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<td>0.023</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Water cure</td>
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<td></td>
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<td></td>
<td>Membrane cure</td>
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CHAPTER 4
Falling Weight Deflectometer Measurements

4.1 Introduction

Falling Weight Deflectometer (FWD) measurements were obtained on the new PCC pavement on US33 in Nelsonville to determine vertical deflection of the slab ends and load transfer across the joints in the morning and afternoon of March 24, 2004. One set of measurements was run in the morning while the pavement temperature was uniform, and a second set of measurements was run in the afternoon after the pavement surface had warmed and a positive temperature gradient had built up in the pavement. The morning run started at 8:22 am and the afternoon run started at 2:34 pm. Both runs required about two hours to complete. Infrared thermometer readings indicated the surface temperature ranged from 42º – 44º F. in the morning and from 60º – 61º F. in the afternoon.

Geophone Df1 of the FWD was at the center of the 300 mm (11.8 in.) diameter load plate, Geophone Df2 was 305 mm (12 in.) behind the center of the load plate, and Geophone Df3 was 305 mm (12 in.) in front of the center of the load plate. Table 4.1 summarizes the normalized maximum deflection (Df1) in mils/kip and load transfer (LT) in percent as the FWD load plate was placed in the approach and leave positions at five joints in each of the six test sections, each representing a different mix and curing method combination. In the approach position, the load plate was located behind the joint and load transfer was calculated as Df3/Df1. In the leave position, the load plate was located just beyond the joint and load transfer was calculated as Df2/Df1.

In general, maximum deflection and load transfer were about the same on all test sections when measured in the approach and leave positions. Data were quite consistent between the morning and afternoon runs, in that individual joints showing high or low readings in the morning showed similar trends in the afternoon. Load transfer was essentially the same on all sections and during both runs. Maximum deflection was higher on the water cured portion of Section A, about the same on both portions of Section B, and higher on the membrane cured portion of Section C. As would be expected, deflections consistently dropped in the afternoon as the surface warmed and the slab ends curled downward to increase support under the PCC slabs. The percent decrease in deflection from morning to afternoon was highest on the five water cured joints in Section A and on all ten joints in Section C. Individual joints with the most drop in deflection were Joints 8, 9 and 10 in Section A, and Joints 4, 7, 8, 9 and 10 in Section C.
### Table 4.1 ATH33-Nelsonville FWD Measurements 3/24/04

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<tr>
<th>Section</th>
<th>Curing</th>
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<tr>
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<td>(mils/kip)</td>
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CHAPTER 5

Conclusions

Three one-thousand-foot test sections were constructed on US Route 33 in Nelsonville using three different mixes of concrete. Mix A used 30% blast furnace slag cement and No. 57 limestone aggregate; Mix B used 30% blast furnace slag cement and No. 357 limestone aggregate; Mix C, a standard ODOT mix, used no blast furnace slag cement and No. 57 limestone aggregate. Half of each test section was cured using wet burlap (“water cured”), and the other half was cured using a sprayed on membrane.

5.1 Maturity Function

Two equations describing maturation of concrete were evaluated, the Nurse-Saul method and the Arrhenius method. A total of 288 test cylinders were made in the lab using the same mix proportions as in the construction and these were matured in a climate chamber at 5°C, 20°C, and 40°C, and tested at 1, 3, 7, 14, and 28 days. The tests measured compressive strength and modulus of rupture.

Using the Nurse-Saul method, Mixes A and B had a datum temperature of 0°C and Mix C had a datum temperature of 10°C. The fit of the strength ratio $S/S_{28}$ using the Nurse-Saul method varied with each mix: Mix B lab and field results both fit the curve well; Mix A’s lab results also fit well, but the field results were overpredicted by 30%; Mix C’s data were scattered, but overall the predicted strength matched those of the field cylinders. The poor fit by the field data for Mix A may be because the test cylinders were cured in the sun while the temperature sensors in the test section of the road were in the shade. It should also be noted that the Nurse-Saul method has limited applicability due to the use of a time-temperature factor.

For the Arrhenius method, the reference temperature used was 23°C. The strength at 28 days was assumed to be 4000 psi and the age of final setting and start of strength development was 0.25 days. Based on these assumptions, values of the rate constant $k$ and the strength factor $\beta$ were computed for each mix and curves were made comparing predicted strength ratios ($S/S_{28}$) using this model to measured strength ratios of field and lab samples. Again, the strength of Mix A was overpredicted by about 30%. The fits in general were not as good for each of the mixes. Some of this may be attributable to the possible differences between the small lab batch of concrete and the much larger field batch; the Arrhenius method may work better if samples were obtained from a larger batch of concrete at the mixing plant. Another possible source of discrepancy was the possible mixing of some of the Mix C with the quick set concrete used in the previous batch of concrete in the field.

5.2 Warping Measurement Using ORITE Profiler

The ORITE profiler was used to measure the warping of each test section by subtracting a morning profile from an afternoon profile. The average warps seen in slabs made of
Mix A were 0.020in for membrane cured concrete and 0.022in for water cured concrete. The average warps seen in the slabs of Mix B are 0.019in for membrane cured concrete and 0.016in for water cured concrete. The average warps seen in the slabs of Mix C are 0.027in for membrane cured and 0.023in for water cured concrete, but the former it should be noted is based on a measurement of about two-thirds of one slab because the profilometer broke down during the morning run. The water cured Mix B slabs showed the least warping, followed by the membrane cured Mix B. Mix C had the most warping, particularly the membrane cured slab, but again because of the limited data this may not be as significant as it appears.

5.3 Falling Weight Deflectometer Measurements

A falling weight deflectometer was used to measure pavement deflections and load transfers at the joints. On all sections, approaching and leaving measurements of deflection at each joint agreed very closely, to 0.01 mils/kip or less, except for the afternoon run with membrane cured Mix C. In both the morning and afternoon runs, membrane cured Mix B had the lowest deflection, 0.34 mils/kip and 0.315 mils/kip respectively, using an average of approaching and leaving values in each case. Water cured mix B had deflections that were almost as low, while water cured Mix A had the highest deflection, at 0.545 mils/kip in the morning and 0.445 mils/kip in the afternoon, followed by membrane cured Mix C. In all sections, the average deflection in the afternoon was less than that in the morning by 10-20%.

Water cured mix B had the highest load transfer across the joint at 94.5% in the morning and 94.95% in the afternoon, again using the average of approaching and leaving values. Water cured Mix A had the lowest load transfer at 87.55% in the morning and 89.0% in the afternoon. Load transfer measured in the afternoon was about the same as that measured in the morning for each section.

5.4 Loss of Support

As seen in the preceding discussion, Mix B had both the least deflection as measured by the falling weight deflectometer and the least warping as measured by the profiler. The water curing produced a lower maximum warp, but the membrane cured section had a slightly lower deflection. In both tests, the other curing method for mix B produced the second best result. Thus it appears that Mix B is the most durable mix from a standpoint of experiencing the least loss of support. Either method of curing seems to work equally well with Mix B.
CHAPTER 6

References


