Optimization of VES Concrete
Final Report

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Federal Highway Administration
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The purpose of this research study was to develop an improved very early strength (VES) concrete mix for highway construction. More than 50 concrete mixes were evaluated for strength, shrinkage, and curing rate (maturity), eventually leading to the development of an optimized VES concrete mix with improved performance characteristics. The new mix, which is detailed in the report, can gain strength more reliably than the former standard NJDOT VES mix, reaching a flexural strength of 350 psi in less than 6 ½ hours. The improved mix also exhibited 79 to 93 percent less shrinkage. The study found that maintaining an initial mix temperature of 32°C ± 5°C is crucial to attaining target strengths. A procedure is presented for applying the maturity method to help decide when roadways with VES repairs can be opened to traffic.
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PROJECT SUMMARY

The overall objective of this research study was to develop an improved very early strength (VES) concrete mix with reduced shrinkage and cracking potential. In 1996, the NJDOT began using a VES mix that was cooperatively developed by NJIT, Rutgers, NJDOT, cement and admixture manufactures and, concrete suppliers and contractors for repair of joints in concrete pavements. Since that time VES concrete has found its way into a variety of applications, including full-sized highway slabs. For these large-scale applications it was quickly discovered that transverse cracks often developed in the slabs at intervals of approximately 25 ft. Although the problem was solved in the short term by installing contraction joints, it was decided to correct the cracking problem through adjustment of the VES mix design. This formed the impetus of the current research study.

The study commenced with a thorough literature review of VES design and construction practices. This was followed by an extensive laboratory testing program during which more than 50 mixes were blended and tested using the original VES mix as a control. The effects of cement content, accelerator dosage rate, and aggregate type were studied for each test mix. In addition, shrinkage behavior was quantified with respect to the strength gain and maturity parameters. Certified NJDOT components were used for the mixes, and standard ASTM test methods were followed.

Eventually, four mixes with cement contents ranging from 611 to 799 lb/yd$^3$ were selected for more detailed evaluation. Following an extensive series of tensile and compressive strength tests as well as shrinkage and maturity measurements, the optimum VES design mix shown in Table 1 was developed.
Table 1. Proposed VES design

<table>
<thead>
<tr>
<th>Material</th>
<th>(Lb/yd³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>658</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>1,850</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>1,350</td>
</tr>
<tr>
<td>Water</td>
<td>235</td>
</tr>
<tr>
<td>Water reducer admixture Sikament 86</td>
<td>14 oz/cwt</td>
</tr>
<tr>
<td>Air entraining admixture Sika AER</td>
<td>0.75 oz/cwt</td>
</tr>
<tr>
<td>Accelerating admixture Sika Rapid1</td>
<td>38 oz/cwt</td>
</tr>
</tbody>
</table>

Test results showed that the optimum mix exhibited a 79% reduction in the free shrinkage compared with the current design, yet it still achieved a modulus of rupture of 350 psi (2.4 MPa) and a compressive strength of 2,250 psi (15.5 MPa) within 6.5 hours after finishing. The basic strategy for optimization involved reducing the amount of cement without changing the water-cement ratio, thereby reducing the total amount of water in the mix. It was also found that if larger aggregate could be used, the free shrinkage would be reduced 93%. It was further determined that the initial mix temperature needed to be at least 27 °C (81 °F) or higher in order to reliably meet the required flexural and strength requirements at 6 ½ hours.

To reduce the potential for temperature cracking, a maximum allowable temperature of 65 °C (150 °F) is recommended. Additionally, VES repairs are opened to traffic when the concrete reaches the required strength so the curing period is very limited. Procedures for limiting moisture loss and adding supplemental water are recommended to control shrinkage cracking and improve durability.
The report also recommends using the maturity method to indicate the readiness of flexural specimens for testing of sufficient pavement strength rather just waiting 6 ½ hours, as is currently done.

INTRODUCTION AND PROBLEM STATEMENT
As the most densely populated state in the nation, New Jersey is continually challenged by traffic congestion on its principal roadways and arteries. The situation is aggravated by repair operations, which can quickly bring traffic to a halt. Over the years, the New Jersey Department of Transportation (NJDOT) has tried a variety of methods to reduce the time associated with the repair of concrete pavements, to help reduce traffic congestion. For example, in 1996, the NJDOT approved the use of a very early strength very early strength concrete for roadway joint repairs. The goal was to close a highway lane in the evening, perform the required repairs and open the lane to traffic by the morning rush.

The NJDOT specifications for achieving this are as follows:

- Achieving a Modulus of Rupture of 350 psi (2.4 MPa), approximately corresponding to a compressive strength of 2,250 psi (15.5 MPa), within 6 ½ hours after finishing.
- Use of locally available materials with normal aggregate gradations.
- Use of non-chloride accelerators admixtures.
- Sufficient workability for placement and finishing operations.

This VES concrete, which was approved for use in 1996, was originally intended as a joint patching material, which was soon to be overlaid with asphalt. However, in spite of this rather restricted intent, within a year it was used in other applications. Several miles of Interstate 295 were paved using VES for regular pavement construction. Two major technical problems were quickly observed on this paving project. First, transverse cracking was observed in the 78–foot long slabs at intervals of about 25 feet. Second, the concrete curing temperatures reached a relatively high level. The “fast-track” concrete has also been used to construct exit ramps, streets and parking lots,
and its use can be expected to increase. Thus, there is a need for a VES concrete mix with a reduced potential for cracking.

The overall objective of this research study was to develop a modified VES concrete mix with reduced shrinkage and cracking potential, while maintaining or improving the rapid strength gain associated with very early strength concrete. Shrinkage cracking is primarily the result of volume changes associated with water loss, and, generally, the less water there is in a mix, the lower the tendency for cracking. By reducing the amount of cement in the mix while keeping the water-cement ratio constant, the overall effect is to reduce the overall amount of water in the mix. Another way to reduce the shrinkage is to use a larger aggregate since a larger aggregate reduces the need for cement paste, thus reducing the possibility for shrinkage. The principal question was whether a concrete with a significantly reduced cement factor could still achieve the required strength in the allotted time.

Optimization of a concrete mix is a process of balancing conflicting demands. Consideration must be given to its end use, placeability and workability, ultimate strength and durability, weight, color, and cost. For the purposes of this research, optimization of “fast-track” concrete means controlling shrinkage cracking without sacrificing rapid strength gain, while still maintaining satisfactory workability.

In view of the urgency to reopen traffic, an additional objective of the research study was to produce recommendations for a simple test method to quickly and reliably assess concrete strength. An in-place test method was desired since standard test cylinders do not include the effects of placing, compacting, and curing. The maturity method was employed for the determination of in-place strength since it is able to take these effects into account. The technique is based on the measured temperature history of concrete during the curing period. The combined effects of time and temperature lead to determination of a single parameter, the maturity index. This index is then used to correlate strengths of samples of the same concrete. The assertion is made that for a particular concrete at the same maturity, whether in cylinders, beams or in the structure, the strength will be approximately the same. More detail is provided in
appendix 1, “Literature Review,” and in appendix 3, “Applying the Maturity Method to VES concrete.”

EXPERIMENTAL PROGRAM
This section describes the experimental program conducted for the research study. The discussion is divided as follows:

- Research Approach
- Testing Program
- Results of Selected VES Mixes
- Results of Unrestrained Shrinkage Testing
- Results of Maturity Testing

At the commencement of the study an extensive literature review was conducted to develop the experimental approach. The literature review is contained in appendix 1.

Research Approach
The time required for the VES concrete to reach its target strength is a function of the amount of cement in the mix and the hardening accelerator dosage. Concrete mixes with cement contents over 600 lb/yd$^3$ can reach 2000 to 3000 psi within 8 to 12 hours. While VES mixes with a hardening accelerator can reach these strengths in 4 to 6 hours. It is the hardening accelerator admixture that differentiates VES concrete from “normal” high cement content mixes. It was found in earlier studies that dosage rates over 45 oz/cwt retarded the strength gain, counter to the intent of the accelerator’s use. Therefore, dosage rates of the hardening accelerator are varied only within a narrow range.

The first task was to see how much cement could be removed while maintaining the rapid strength gain required by very early strength concrete. A series of mixes were formulated to test the effects of the cement content, accelerator dosage rate, and aggregate type. The original 799-lb VES mix served as the control. For each mix samples were made to investigate strength, shrinkage, and maturity parameters. Mixes
with cement contents ranging from 611 lb/yd$^3$ to 705 lb/yd$^3$ were examined at increments of 47 pounds. As in the original study, the cement type remained constant.

Next, for successful or near successful mixes the maturity parameters were determined. For each mix the compressive strengths of concrete cylinders were plotted against the maturity at the time of the test using the accepted datum temperature of 6.5$^\circ$ C in order to establish a strength-maturity relationship. This relationship is used to predict the concrete strength for future field applications of that particular mix. The datum temperatures for the control mix and the selected mixes were determined using the methods recommended in ASTM C 1074$^6$ to check the use of the accepted value.

Working up the strength-maturity relationship for “fast-track” concrete involves focused activity for several hours. Since the hardening accelerator does not affect the setting time of the mix, the final set normally occurs within 3 to 4 hours. After the final set, the temperature spikes as much as 45 $^\circ$C with a strength gain of 2,000 psi in couple of hours. Since casting flexural beams is quite tedious, and only a limited number of molds are available, it is necessary to test cylinders to indicates when the beams may have reached the target strength and are ready to test. There is much activity for a couple of hours during which as many as a dozen cylinders and several beams are tested in rapid succession.

The free shrinkage characteristics of the selected mixes were also examined. The control mix and the most promising proposed mixes were evaluated for drying shrinkage under both unrestrained and restrained shrinkage tests. Companion prisms were cast to measure unrestrained shrinkage for every mix. Concrete rings were cast of only the selected mixes to evaluate restrained shrinkage. Free shrinkage was measured utilizing ASTM C 490 while the ring testing was conducted using procedures found in the literature ($^{11,12,13,15,17,19,20,\text{and 28}}$). Two stone types, #467 and #57, nominally 1½ inch and ¾ inch respectively, were utilized to investigate the shrinkage reduction potential.

Field samples of VES concrete were collected from two slabs being cast at an ongoing NJDOT construction project to verify the correlation of unrestrained shrinkage between
the laboratory and the field. In order to match the specimens, shrinkage specimens of concrete and sieved mortar were made at the construction site and then placed on boards laid across one corner on the top of the pavement slab along with the verification beams. After conducting flexural strength tests at 5 and 6½ hours, the unrestrained shrinkage specimens were removed from the molds and the initial length measured. Within 3 hours after initial measurement, the specimens had been carefully transported to NJIT and placed into the humidity controlled curing room for further evaluation.

Testing Program
More than fifty mixes were proportioned and tested during the study. Eventually, four mixes, all able to meet VES requirements, were chosen for further evaluation. The mix proportions for those mixes are summarized in table 2. Further information on testing details and results is included in appendix 2.

Table 2. Mix designs of very early strength (VES) concrete mixes

<table>
<thead>
<tr>
<th>Material / Stone Size</th>
<th>Mix No. I Control (Lb/yd³)</th>
<th>Mix No. II Proposed Mix (Lb/yd³)</th>
<th>Mix No. III (Lb/yd³)</th>
<th>Mix No. IV (Lb/yd³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement / Stone Size</td>
<td>799 #57</td>
<td>658 #57</td>
<td>658 #467</td>
<td>611 #57</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>1,840</td>
<td>1,850</td>
<td>2,050</td>
<td>1,500</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>1,090</td>
<td>1,350</td>
<td>1,250</td>
<td>1,147</td>
</tr>
<tr>
<td>Water</td>
<td>282</td>
<td>235</td>
<td>257</td>
<td>239</td>
</tr>
<tr>
<td>Water reducer admixture</td>
<td>16</td>
<td>14</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>(oz/cwt)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air entraining admixture</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>1.0</td>
</tr>
<tr>
<td>(oz/cwt)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accelerating admixture</td>
<td>32</td>
<td>38</td>
<td>40</td>
<td>45</td>
</tr>
<tr>
<td>(oz/cwt)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
For each mix twenty 4×8 in cylinders, four 6×6×22 in beams, four 1×1×11¼ in mortar bars, four 2×2×11¼ in concrete bars and seventy-two 2 in mortar cubes were cast following the procedures of ASTM C 192 and C 490 and C 109. Thermocouples were embedded in the center of two of the cylinders and two of the beams to measure the temperature for the maturity calculations.

All the beams and cylinders were placed into a 23°C, 100% relative humidity curing room meeting the standards of ASTM C 511. The cylinders were cured in an insulated chamber. The beams were packed close together outside the chamber. All were covered with a standard construction thermal blanket to reduce the heat loss and achieve semi-adiabatic temperature conditions. The cylinders were tested for compressive strength at ages of 5, 5 ½, 6, 6 ½, 7, 7 ½, 8, 8 ½ hours, one day and 28 days to develop the compressive strength-maturity relationship for that particular mix. After testing the broken samples were returned to the other curing samples to preserve as much of the heat of hydration as possible. The beams were tested in accordance with ASTM C 78 when cylinder tests indicated a compressive strength of approximately 2,250 psi or 7 hours after finishing the mixing operation, and then at 1 day and at 28 days.

When the required flexural strength had been achieved, the shrinkage bars were removed from their molds and a warm reading of the bars was made. The initial length reading was made at 24 hours as required by C 490 after cooling with the rest of the samples. The mortar cubes were also demolded at this time and placed into the required water baths following the instructions of C 1074 for the determination of the datum temperatures and activation energies.
Results of Selected VES Mixes

The fresh concrete properties of the four selected test mixes are shown in table 3.

Table 3. Fresh concrete properties

<table>
<thead>
<tr>
<th>Fresh concrete properties</th>
<th>Mix No. I</th>
<th>Mix No. II</th>
<th>Mix No. III</th>
<th>Mix No. IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial mix temperature</td>
<td>28.00 °C</td>
<td>28.00 °C</td>
<td>28.00 °C</td>
<td>28.00 °C</td>
</tr>
<tr>
<td>Slump</td>
<td>5 inches</td>
<td>4.5 inches</td>
<td>3.5 inches</td>
<td>3.0 inches</td>
</tr>
<tr>
<td>% Air content</td>
<td>5.0 %</td>
<td>4.0 %</td>
<td>5.0 %</td>
<td>5.5%</td>
</tr>
<tr>
<td>Set time</td>
<td>5.00 hrs</td>
<td>5.00 hrs</td>
<td>5.30 hrs</td>
<td>5.00 hrs</td>
</tr>
</tbody>
</table>

Mix No. I, the control mix, had the highest slump of all the mixes at 5 inches. Slumps of mix No. III and IV were somewhat lower at 3 ½ in and 3 in, respectively, but the workability was adequate. An adjustment to the water reducer dosage should bring the slump of these mixes to acceptable levels. The measured air content of the mixes ranged between 4.0 to 5.5 percent. The VES behavior of these mixes comes from the Sika Rapid-1 hardening accelerator. Since the accelerator does not start working until after the final set, the final set became a matter of some interest since it was found that the initial mix temperatures greatly affected the final set time. so the initial mix temperature for all mixes was controlled at 28°C. All four mixes reached the final set in about 5 hours. Tensile and compressive strengths for the four mix designs are summarized in table 4.
The required tensile strength of 350 psi was reached after 6 ½ to 7 hours for all the mixes. The compressive strength development of the mixes over time is seen in figure 1, which shows displays the strength development of the selected mixes up to 1 day.
Figure 1. Early strength over one day for VES concretes
All the mixes exceeded a compressive strength of 2,500 psi within 7 hours. Figure 1 also shows that Mix No. I attained a higher 6 ½ hour strength than the other mixes probably due to its higher cement content. The strength gain during the setting period is minimal, reaching a compressive strength of only about 100 psi. It was observed that the rate of compressive strength gain increases sharply after the final set for all mixes. This was attributed to the hardening admixture, which begins acting only after the final set. The rate of the strength gain after 7.5 hours for Mix No. I is lower than the other mixes. This is because the hydration of Mix No. I occurs faster but less efficiently than other three mixes at early age. Consequently, there was less potential for hydration at later ages and less additional strength gain after the first several hours. All the mixes exhibit compressive strength around 3000 psi at 7 hours. Mix No. II and Mix No. III were identical mix designs except Mix No. III used the larger type #467 stone and Mix No. II used type #57. Figure 2 compares the compressive strengths of the mixes to 7 days.
Figure 2. Early strength over one week for VES concretes
Mix No. IV developed the least strength initially, because of its lower cement content, but ultimately it gained the highest compressive strength at 28 days. In spite of its VES performance Mix No. IV was not selected as the final design mix on account of workability problems. This problem should be correctable with additional trials.

As part of the testing program, maturity related observations were made on a field application of VES to assure that the laboratory control mix exhibited properties that closely resembled that of the field mix. The test results for the field mix are shown in table 5.

Table 5. Rt.1&9 North Mix Data

<table>
<thead>
<tr>
<th>Fresh concrete properties</th>
<th>Slab No. I</th>
<th>Slab No. II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab Size</td>
<td>12x5x0.75 ft</td>
<td>12x5x0.75 ft</td>
</tr>
<tr>
<td>Initial mix temperature</td>
<td>29.00 °C</td>
<td>33.00 °C</td>
</tr>
<tr>
<td>Slump</td>
<td>6.0 inches</td>
<td>3.5 inches</td>
</tr>
<tr>
<td>% Air content</td>
<td>5.0 %</td>
<td>5.5%</td>
</tr>
<tr>
<td>Flexural strength</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0 hours</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>6.5 hours</td>
<td>387 psi</td>
<td>385 psi</td>
</tr>
<tr>
<td>Compressive strength</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0 hours</td>
<td>x</td>
<td>2,945 psi</td>
</tr>
<tr>
<td>6.5 hours</td>
<td>3,104 psi</td>
<td>3,343 psi</td>
</tr>
</tbody>
</table>

Results of Unrestrained Shrinkage Testing

The results of the unrestrained shrinkage testing are presented in figure 3, which compares the current 799 lb control mix to the 658 and 611 lb mixes all using type #57 stone cured under the same conditions.
Figure 3. Comparison of free shrinkage of 799, 658, and 611 mixes using the same coarse aggregate size.
The 799 mix is the control mix, 799F is the mix from the 1&9 project, the 658V mix was a laboratory mix that reached target strength in 6 ½ hours, referred to as mix No. 2 elsewhere, and the 658 mix was a laboratory mix that reached target strength in 7 ½ hours. The mixes with less cement and water shrank considerably less than the control mix. The 658V mix shrank 79 percent less than the 799 control. Samples of VES concrete collected from the field for the Route 1&9 North were also tested for free shrinkage. The contractor used Mix No. I, the control mix, on this project, which is labeled 799F in figure 3. Inspection of figure 3 reveals that there is reasonable correspondence between the shrinkage behavior of the laboratory control mix and field mix. Additionally, the field mix actually shrinks 10% more, but the shrinkage values reported are based on the laboratory VES mixes. The field mix was included for comparison only.

Figure 4 compares the behavior of two 658 lb. mixes, one using type #57 and the other using type #467 stone cured under the same conditions.
Figure 4. Comparison of shrinkage with same cement contents and different coarse aggregate size
The mix with the larger stone, samples CA and CB, shrank 45 percent less than the mix with the smaller stone, represented by C3 and C4. A 93 percent reduction of free shrinkage was achieved using the type #467 stone over the control mix which used the type # 56 aggregate.

**Results of Maturity Testing**

The datum temperatures determined for all the selected mixes ranged between 6.2° and 7.0° C, These values agree closely with each other and with the 6.5° C value assigned and used since 1996 for New Jersey’s VES concrete. The procedures and details for these results are found in table 6 in appendix 2, “Laboratory Testing”.

The strength-maturity relationships for the mixes also were similar. These are shown in figures 17 through 20 in appendix 2. The target flexural strength of 350 psi was reached at maturities averaging 170° C-Hr. This value, which is computed from the time of placement, is also in close agreement with the value of 160° C-Hr. found in the 1996 study. (2)

The Sika Rapid-1 strength accelerator works in such a way as not to affect the final set time. However, after the final set, strength gain progresses very rapidly. During preliminary testing considerable difficulty was experienced achieving the target strength in the required amount of time. Ultimately, the problem was traced to a low initial mix temperature which lengthened the time to final set. An initial mix temperature of 28° C (81°F) was needed to achieve the final setting in about 5 hours, then all the required strength is developed in the next 1 ½ hours.
Figure 5. Flexural strengths of VES concrete showing importance of initial mix temperature.
The initial mix temperatures, taken from actual construction records, are shown by the labeled bars, the ambient temperatures are shown as the unlabeled bars, the flexural strengths are shown by the big dots and, the required strength by the horizontal line. All mixes with initial mix temperature of 81\(^\circ\) F (28\(^\circ\) C) met the required strength at 6 ½ hours, while no mix with an initial mix temperature under 81\(^\circ\) F did so, regardless of the ambient temperature. The average strength of all the mixes at 6 ½ hours was 374 psi ± 110 psi. If the mixes with initial temperatures less than 81\(^\circ\) F are excluded, the average strength of the beams becomes 410 ± 57 psi indicating that the target strength can be reached in less than 6 ½ hours with good reliability as long as 81\(^\circ\) F can be maintained as the initial temperature. Note: not shown by the chart was the fact that all mixes met the target strength by 12 hours.

Concrete strength is a statistical expression. Due to its non-homogeneous nature samples of the same concrete can yield different strength values. Therefore, it is standard practice, recommended by ACI 318 specify strength in such a way as to achieve the required strength 90 percent of the time. This concept is depicted in figure 6.

![Figure 6 Visualization of characteristic strength](image)

Figure 6 Visualization of characteristic strength
The concrete strength is shown as a normal distribution curve with the required strength, \( f'_c \), at the peak. It is seen that \( f'_c \) is somewhat higher than the characteristic strength. The idea is to specify the strength in such a way as to get that result from 90 percent of the cylinder tests of that concrete. In this way one is reasonably assured of getting concrete with the required strength 90 percent of the time. Several methods of reaching this specification are given in ACI 228 \(^{(31)}\). The simplest of these methods is the tolerance factor method. To apply this method one selects a level of confidence, 75 percent is typical, and then based on the number of tests available, one selects a tolerance factor for the 10 percent defective level from chart 6. Table 6 presents tolerance factors for the 75 percent confidence level.

<table>
<thead>
<tr>
<th>Number of tests</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2.501</td>
</tr>
<tr>
<td>4</td>
<td>2.134</td>
</tr>
<tr>
<td>5</td>
<td>1.961</td>
</tr>
<tr>
<td>6</td>
<td>1.860</td>
</tr>
<tr>
<td>7</td>
<td>1.791</td>
</tr>
<tr>
<td>8</td>
<td>1.740</td>
</tr>
<tr>
<td>9</td>
<td>1.702</td>
</tr>
<tr>
<td>10</td>
<td>1.671</td>
</tr>
<tr>
<td>11</td>
<td>1.646</td>
</tr>
<tr>
<td>12</td>
<td>1.624</td>
</tr>
<tr>
<td>13</td>
<td>1.606</td>
</tr>
<tr>
<td>14</td>
<td>1.591</td>
</tr>
<tr>
<td>15</td>
<td>1.577</td>
</tr>
<tr>
<td>20</td>
<td>1.528</td>
</tr>
<tr>
<td>25</td>
<td>1.496</td>
</tr>
<tr>
<td>30</td>
<td>1.475</td>
</tr>
<tr>
<td>40</td>
<td>1.445</td>
</tr>
<tr>
<td>50</td>
<td>1.426</td>
</tr>
</tbody>
</table>

This tolerance factor value is multiplied by the standard error, that is, the standard deviation of the differences between the predicted strengths and the measured strengths. This product is then added to the required strength. This sum is the strength.
that needs to be specified to reach the required strength 90 percent of the time. Based on the Region Central tests above, if all the tests are used the specified strength would have to be 512 psi. If only the tests above an initial temperature of 81 °F are used, then the specified strength would need only to be 435 psi. When these values are compared to the 390 psi currently required as the proof strength by current NJDOT specifications, it is seen that the current specification would not have represented the 10th percentile of strengths that is recommended by ACI 318.

Studies of the maturity method have always utilized field observations, and this study was no exception. Even though the use of VES concrete on the Route 1&9 project was not really required since that the roadway was closed for a whole week, it did provide an opportunity to observe VES concrete under a unique circumstance. The contractor took advantage of the long closure to cure the patches for the whole week, wetting the burlap used for curing every day, more frequently on the casting days. The result was quite revealing: no cracking was observed, even in the patches exceeding 20 feet. This observation coincides with the results of the ring test undertaken as part of this study. After 90 days, none of the rings had cracked. This was attributed to sufficient curing in the initial stages before the removal of the molds. Even though the molds were removed in less than one day, that was enough curing time for the concrete to reach a tensile strength adequate to resist shrinkage cracking. Therefore, if 7 days of wet curing is available for VES concrete no change to the mix design is necessary to prevent cracking.

It has been observed in previous studies that full-sized slabs can reach temperatures approaching 65 °C before reaching the target strength. Such temperatures dry the surface of the slabs, and steam can be seen rising when curing blankets are removed. This indicates that the concrete is loosing moisture which places the slabs at higher risk of cracking. For VES concrete the curing period is limited to the amount of time needed to reach the required strength, typically less than 6 ½ hours. Therefore, it is essential that measures to minimize moisture loss should be taken during that time.
Since there is concern that temperatures in excess of 60 °C are detrimental for concrete durability on account of temperature shrinkage, the following procedure is recommended during the curing period. If the temperature of the concrete exceeds 60 °C or, if the surface of the slab curing under the thermal blankets has obviously dried, the blankets should be removed and water applied to completely wet the surface. After this, the blankets can be replaced for the remainder of the waiting period.
CONCLUSIONS

- The recommended mix reached the target strength of 350-psi flexural strength in 6.5 hours. The compressive strength at that time was 2,230 psi. The target strength was reached at a maturity of 175°C hrs using the accepted datum temperature of 6.5°C.

- The recommended mix had a measured datum temperature of 6.2°C. The datum temperatures of the four tested mixes ranged between 6°C and 7°C. Therefore, the currently utilized value of 6.5°C can be retained as giving satisfactory results.

- The concrete of the selected mix exhibits a free shrinkage reduction of 79 percent relative to the current mix. The mortar shrinkage was reduced 22 percent. Use of type # 467 aggregate in the concrete will further reduce the shrinkage by an additional 45 percent for an overall reduction of over 90 percent relative to the current 799 lb mix.

- The curing period for VES concrete is normally limited to the time required to reach the target strength, so it is very important to control moisture loss during that time to the greatest extent possible. Temperatures above 60-65°C are thought to be harmful to the durability of concrete because of inevitable temperature shrinkage. If the slab temperature exceeds 60 °C, or if the surface has dried, the insulating blankets should be pulled away and additional water sprayed onto the surface. The blankets should then be replaced for the duration of the curing period.

- Ring tests of the currently approved mix and experimental mixes did not exhibit cracks during a 90 day test. The authors believe that the failure to crack was due to removal of the outer molds after the concrete gained enough tensile strength to resist the cracking forces. The negative result of the ring tests is thought not to be critical, since consistent data from the free shrinkage testing clearly shows less shrinkage potential for the proposed mix. These results further confirm the importance of proper curing procedures.
- The verification strength of VES concrete should be increased from 390 to 410 psi.

- It is recommended that the maturity method be used to determine the testing time for the flexural beams used to authorize opening of traffic rather than simply waiting 6½ hours. Detailed instructions are included in an appendix for applying the maturity method to VES concrete.

- An initial mixing temperature of 32 °C ± 5 °C (81°F ± 7 °F) should be specified for VES concrete.

- A maximum allowable temperature of 65 °C (149 °F) should be specified for VES concrete. Procedures for cooling curing VES concrete should also be specified.

- If VES concrete can be cured in a standard manner (7 day under wet burlap), no change to the mix design is necessary to prevent cracking.

- If the verification strength of VES concrete is intended by NJDOT exceed the required strength, the value currently specified should be increased to at least 410 psi.
RECOMMENDATIONS

- A shrinkage-optimized VES mix design is presented in table 1.

Table 1. Proposed VES design

<table>
<thead>
<tr>
<th>Material</th>
<th>(Lb/yd$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>658</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>1,850</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>1,350</td>
</tr>
<tr>
<td>Water</td>
<td>235</td>
</tr>
<tr>
<td>Water reducer admixture Sikament 86</td>
<td>16 oz/cwt</td>
</tr>
<tr>
<td>Air entraining admixture Sika AER</td>
<td>0.75 oz/cwt</td>
</tr>
<tr>
<td>Accelerating admixture Sika Rapid1</td>
<td>38 oz/cwt</td>
</tr>
</tbody>
</table>

- Based on the shrinkage-optimized mix presented above and other considerations, it is recommended that “Table 914-3 Mix Design” of the current NJDOT Standard Specifications for VES concrete should read as follows:

Class Of Concrete: VES

<table>
<thead>
<tr>
<th>Class Design Strength</th>
<th>Current Values</th>
<th>Proposed Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class Design Strength</td>
<td>Mpa</td>
<td>psi</td>
</tr>
<tr>
<td>Compressive Strength (28 days)</td>
<td>26.0</td>
<td>3770</td>
</tr>
<tr>
<td>Flexural Strength (6.5 hr)</td>
<td>2.40</td>
<td>350</td>
</tr>
</tbody>
</table>

Verification Strength

| Compressive Strength (28 day) | 31.0  | 4500  |
| Flexural Strength (6.5 hrs)   | 2.70  | 390   |
| Maximum Water/Cement Ratio     | 0.370 |
| kg/kg (Note 4)                 | 0.370 |
| L/bag (Note 4)                 | 16.   |

Minimum Cement Content

| kg/m$^3$ | 390 |
| lb/cyd   | 658 |
Note 2: The maximum water/cement ratio for all classes of concrete, except VES, when a Type F, water-reducing, high-range admixture is used in accordance with Tables 914-1 and 914-2, shall be 0.40 kg/kg (17.0 L/bag).

Note 4: In order to achieve the water/cement ratio for VES concrete, an approved Type F, water-reducing, high-range admixture shall be used.

Note 5: For VES concrete, a non-chloride set or hardener accelerator in combination with Type I or Type III Portland cement shall be used.

Note 8 should be changed from:
The initial flexural strength test shall be performed at 6.5. Each individual test from the lot must meet the flexural retest limit. If any test fails to meet the flexural retest limit at 6.5 hours, a second beam shall be tested at 8 hours. The flexural beams shall be field cured in accordance with AASHTO T23, Subsection 9.
To:
The initial flexural strength test shall be performed at 6.5 hours or sooner if maturity testing indicates strength equal to the required flexural strength. Each individual test from the lot must meet the flexural test limit. If any test fails to meet the flexural test limit at 6.5 hours, a second beam shall be tested at 8 hours or sooner if maturity testing indicates strength equal to the required flexural strength. Flexural beams shall be field cured in accordance with AASHTO T23, Subsection 9, and monitored for maturity, under the thermal blankets insulating the roadway slab.

Two additional notes should be added:

Note 9: The initial concrete mix temperature shall be 32 °C ± 5 °C

Note 10: The maximum allowable curing temperature shall be 65 °C. If the curing temperature of the concrete exceeds 60 °C the curing blankets should be pulled back and the surface wet completely. After this the blankets should be replaced for the remainder of the time needed for the concrete to reach the required strength.
Measurement Of Unrestrained Shrinkage

The shrinkage of an unrestrained specimen, known as free shrinkage, can be used to estimate shrinkage potential. This test is ASTM C490, “Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete”. The objective of this test is to measure the changing length of simple concrete or mortar bars during curing.

2 in x 2 in x 11 ¼ in-concrete bar specimens and 1 in x 1 in x 11 ¼ in-mortar bar specimens are used. Steel studs are inserted into the ends of the bars so that the distance between them is 10 inches. The mortar bars are produce by sieving mortar from fresh concrete. Details of concrete and mortar prism molds are shown in figure 6.

Figure 7. Details of concrete and mortar prism mold

View of length change instrument is shown in figure 7 (ASTM C490 Standard Practice for Use of apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar and Concrete).
The gage length was taken to be 10 inches, the nominal length between the inner most ends of the gage studs. The parts of the mold were tight fitting and firmly held together when assembled and their surfaces should be smooth and free of pits. The molds were made of steel not readily attacked by the cement paste mortar or concrete. The sides of molds were sufficiently rigid to prevent spreading or warping. Each end plate of the mold was equipped to properly hold the gage studs at the required distance during the setting period. The gage studs were made of the American Iron and steel Institute type-316-stainless steel. The instrument for determining the length changes of specimens produced in the molds uses a dial gage, accurate within 0.0001-in in any 0.0010-in range and within 0.0002-in in any 0.01-in range.

Procedure to measure the length change is as following: Clean the hold at the base of the comparator into which the gage stud on the lower end of the bar fits which tends to
collect water and sand and must be cleaned after every reading. A reference bar is placed in the comparator for setting the gage zero. Take the reference bar out and then put the specimens in the device in the same position each time. Rotate specimens slowly in the measuring instrument while the comparator reading is taken. Take the comparator reading. Record the digital reading from the instrument. The length change at any age can be calculated by dividing the change in length by the gage length and multiplying by 100:

\[
L = \frac{L_x - L_i}{G} \times 100
\]  

(1)

where \(L_x\) is the comparator reading of specimen at \(x\) age in inches, 
\(L_i\) is the initial comparator reading of the specimen, and 
\(G\) is nominal gage length, 10 in.

The length change values are reported to the nearest percentage of 0.001 and report the average value to the nearest percentage of 0.01.

**Measurement Of Restrained Shrinkage**

For the measurement of restrained cracking potential, three different shapes, linear, plate, and ring have been tried for measuring the contribution of fibers to shrinkage crack reduction. However, ring specimens seem to have the best potential because they can provide the best restraint. The arrangement is also conducive to the development of mathematical models.

**Linear Specimens**

The test specimens consist of long prisms with flared ends. The lateral dimensions 0.2 in x 4.8 in. (5 mm x 120 mm) are small compared to the longitudinal dimension 60 in (1,500 mm). Restraints are applied at the flared ends, inducing cracks in the middle.
(uniform) section (see figure 8). The method was successfully used for studying the contribution of steel fibers to reducing shrinkage cracking.

Another way to provide restraint is to use reinforcing bars in the center of the matrix. The center part of the bar was debonded using a rubber tube. Hence the midsection of the specimen is subjected to tension created by the shrinkage. The specimen size was 2 in x 2 in x 12 in (50 mm x 50 mm x 300 mm) (see figure 9).

In another study, prismatic concrete specimens were glued to a stiff steel frame. The specimen dimensions were 500 mm x 80 mm x 20 mm (20 in x 3.2 in x 0.8 in.). The ends were held in position by the rigid frame. When the composite started to shrink, the reduction in length created the tensile stresses (see figure 10).

In these three types of specimens, the stress distribution at the restrained ends is rather complex. Therefore, it is difficult to formulate an analytical model for the prediction of tensile stresses and crack widths that develop because of the shrinkage strains.

Figure 9. Restrained shrinkage test: restraints applied using external grips.
Plate Specimens
Similar to the ones used for plastic shrinkage, they have also been tried for measuring cracks caused by drying shrinkage. The restraints were provided by means of stirrups attached to rigid steel frames. The primary difficulty with this kind of setup is to estimate the actual extent of restraint provided by the stirrups. Hence, the tests could be used only to make qualitative judgments among the various types of fibers.

Figure 10. Restrained shrinkage test: restraints applied using bar embedded in the specimen.

Figure 11. Test setup for linearly restrained shrinkage.
Ring specimens

Ring specimens have been used by a number of investigators for evaluating drying shrinkage of fiber-reinforced cement composites under restraint. Essentially, a ring of concrete is cast around a stiff steel ring. As the composite shrinks, it induces stresses on the steel ring (figure 11). Since the steel ring is stiff and undergoes very little deformation, the outer cement composite ring is subjected to tension. If the concrete ring is thin in relation to the internal diameter, then the stresses across the thickness can be considered uniform. The compressive stresses developed at the interface between the steel ring and the concrete ring are also negligible. The researchers used various external diameters for steel rings. The thickness of the cement composite was also varied depending on the composition of the matrix. Typically, thicker sections were used with concrete containing coarse aggregates.

Figure 12. Schematic view of a restrained ring shrinkage setup
As mentioned earlier, this setup shows the most promise because of the uniform restraint provided by the steel ring. The restraining force is imposed by the steel ring across the perimeter of the concrete, instead of two or four locations as with linear and plate specimens. The variation of stresses across the thickness of the concrete ring depends on the internal diameter of the ring. In addition to hoop stress, the concrete ring is also subjected to radial compressive stress when the steel ring exerts radial pressure. Since the diameter of the ring is relatively large, this radial compressive stress is only 20 percent of maximum hoop stress. Since cement composites are an order of magnitude stronger in compression, the maximum compressive stress in the ring is only about 2 percent of the compressive strength. Hence, the effect of compressive stresses can be neglected.
The Maturity Method

The maturity method is a non-destructive method for estimating the strength of concrete. It is sanctioned by ASTM C1074 “Standard Practice for Estimating the In-place Strength of Concrete.”\(^{(6)}\) It uses a predetermined strength-maturity relationship and the temperature history of a concrete pour to make its prediction. The strength of a given concrete mixture that has been properly placed, consolidated, and cured, is a function of its age and temperature history. The maturity method accounts for the combined effects of time and temperature on concrete strength development.

The method developed out of research on steam curing conducted by Saul. He introduced the concept and stated that “the maturity of concrete may be defined as its age multiplied by the average temperature above freezing that it has maintained.” He went on to express a Maturity Law: “Concrete of the same mix at the same maturity (reckoned in Temperature-time) has approximately the same strength whatever combination of temperature and time go to make up that maturity.”\(^{(30)}\) Over the years, Saul’s work has been confirmed and refined by other researches.\(^{(6)}\) To apply this principle samples are produced in the laboratory. The strength is periodically tested and the maturity at the time of the test noted. A plot of the strength vs. the maturity is produced that will serve as the prediction for future mixes. In the field, the temperature of the structure is measured, the maturity computed then compared to the prediction to estimate the current strength.

The maturity value is the sum of the degree-hours from initial concrete placement to the time of interest. Essentially, it is the area under the time temperature curve. The application of microelectronics and computer analysis produces a low cost method of analyzing the strength gain that is taking place in concrete structures or pavements. This is especially of interest for pavements, where it is essential to know strength at early ages in order to determine the time at which they may opened to traffic.
**Nurse-Saul Equation:**

The Nurse-Saul equation calculates the time – temperature factor (TTF) using the following equation:

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

(2)

where

- \(M(t)\) = temperature-time factor (TTF) at time \(t\), degree-days or degree-hours
- \(\Delta t\) = time interval, days or hours
- \(T_a\) = average concrete temperature during time interval, °C or °F
- \(T_0\) = datum temperature; a value of 6.5°C is used for VES concrete – 10°C is commonly used for normal concrete.

This equation is the most popular in use by state DOTs. When this equation is used, the concrete strength is related to the logarithm of temperature time factor. The datum temperature is found through a series of experiments of mortar cubes of the mix under consideration, cured at three different temperatures. The reciprocal of the strength is plotted against the reciprocal of the elapsed time since final set. Linear regression analysis of the three sets is applied to determine the equations of the best-fit lines. The intercepts of the lines are divided by their slopes to determine K values. Once the K values are known they are plotted against the curing temperature. The intercept with x-axis is the graphical solution for the datum temperature. The analytical solution is the division, again, of the y-intercept of the line by its slope. Finally, the strength-maturity relationship is determined. The compressive strengths of concrete cylinders are plotted with the maturity at the time of the test. That curve is used to predict the strength of future applications of that mix.
**Arrhenius Equation**

This equation is used to calculate the "equivalent age" maturity index. Equivalent age represents the equivalent duration of curing at the reference temperature that would result in the same value of maturity as the curing period at a given average temperature in ASTM C1074 \(^{(6)}\).

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

where

- \(t_e\) = equivalent age at standard or reference temperature, days or hours
- \(e\) = 2.718
- \(Q\) = apparent activation energy divided by the gas constant, \((E/R)\), °K
- \(E\) = apparent activation energy, J/mole
- \(R\) = universal gas constant = 8.314 J/mole °K
- \(K\) = absolute temperature, Kelvin, °K = °C + 273.15
- \(T_a\) = average concrete temperature during time interval, \(\Delta t\), °K
- \(\Delta t\) = Time interval, days or hours

With this equation, a different function (hyperbolic rather than logarithm) is used to relate concrete strength to equivalent age. The Arrhenius equation is used less commonly for concrete pavement work in the United States, though it may be more accurate. According to Carino (ASTM C1074) \(^{(6)}\), the Arrhenius relationship may be more appropriate when a wide variation in concrete temperature is expected.

**Maturity Testing Procedure**

The maturity method is a two-step process. First, a relationship is established between the maturity values and the concrete strength as measured by testing of beams or cylinders. The development of the strength-maturity curve is done at the beginning of construction using project materials. The application covers only one mixture. If there
are changes in material source, mix proportions, or mixing equipment, another correlation must be run.

Preliminary testing is necessary before technician can accurately analyze concrete in the field. Using the actual job mixture concrete materials, test specimens are prepared with thermocouples or microprocessors embedded in them. The temperature is monitored and beams or cylinders are tested to develop a relationship between the strength values and the temperature-time factor (TTF). The strength-maturity equation is developed by performing strength test at various ages, computing the corresponding temperature-time factor at the test ages, and plotting the strength as a function of the logarithm of the temperature-time factor. A best-fit is then plotted through the data. Test data from one field project indicate that the maturity curves may be more reproducible when using compressive strengths rather than flexural strengths. The second step is instrumenting and monitoring the concrete pavement. Temperature probes or microprocessors are embedded in the concrete and the temperature is measured periodically. Thermocouple wires are inserted to the desired depth in fresh concrete, shortly after placement.

**Maturity Test Equipment**

Maturity meters automatically monitor and record concrete temperature as a function of time. Acceptable devices include thermocouples or thermostats connected to strip chart recorders or digital data loggers. Commercially available devices automatically compute and display information that can be used as an index to strength, either flexural or compressive. Several maturity devices are available which continuously measure the concrete temperature and calculate the maturity automatically at least once every hour. The meter can also display the maturity value digitally at any point in time. Depending on the meter used, several different locations can be monitored simultaneously. Some maturity meters can be set to use either the Nurse-Saul or the Arrhenius equation (see Figures 13, 14, and 15).
These and similar meters are microprocessor-based, battery operated data collection systems. They typically have several channels for temperature measurement, and software to calculate the maturity value for each. The cost of the systems range from $650 - $3,000.
APPENDIX 2: DETAILS OF EXPERIMENTAL PROGRAM

Materials, Mixing and Testing Program

The components of all mixes consisted of NJDOT approved materials. Essroc Type I cement was used exclusively. The coarse aggregate was crushed granitic gneiss of type #57 and type #467 from Passaic Crushed Stone in Pompton Lakes, NJ. A natural sand, with fineness modulus ranging from 2.45 to 2.55, was used in all selected mixes. Standard sand, complying with ASTM C 778, was used as part of the investigation of variables affecting initial set time of concrete.

The VES behavior of this concrete comes principally from the use of a hardening accelerator. Rapid-1 Non-Chloride Hardening-Accelerator, manufactured by Sika Corp., was used throughout the testing program. In order to assure chemical compatibility, Sika products were used for the other admixtures, Sikament 86 High Range Water Reducer, and Sika AER Air Entraining Agent.

ASTM C 192 mixing procedures were used for the finally selected mixes, although earlier testing utilized a modified mixing procedure to allow production of sufficient mortar for shrinkage and maturity testing. ASTM C192 dictates that prior to the start of mixer rotation, the coarse aggregate, some of the mixing water, and the solution of the admixtures be loaded. The admixture is dispersed into the mixing water before addition. After starting the mixer, the fine aggregate, cement, and water are added while the mixer is running. After all ingredients are in the mixer, mixing is continued for 3-min. followed a by 3-min rest and then 2-min. of final mixing. Throughout mixing a cover is placed over the open end or top of the mixer to prevent evaporation. Upon completion of mixing, the concrete is tested for slump, air content, and unit weight in accordance with ASTM C 143 and ASTM C 231, and ASTM C 138, respectively. Cylinders and beams were cast following ASTM C192, and concrete shrinkage specimens were cast following ASTM C490.
Determining Maturity Characteristics

Maturity Values
The Nurse-Saul equation \(^{(6)}\) was used to calculate the time–temperature factor (TTF). Details of the maturity test setup are shown in figure 16. The concrete maturity is plotted versus the compressive strength to develop a strength-maturity relationship for each mix. Two of cylinders and beams were embedded with thermocouples to measure the temperature in the concrete samples for developing the strength maturity relationship under ASTM C 1074. The beginning time to calculate the maturity value was determined from the final set time test. The final set times were ensured on mortar specimens using ASTM C 403.

![Figure 17. Maturity test setup](image)

The concrete maturity versus compressive strength curves for mixes I, II, III and, IV, the key predictive result for this method, are illustrated in Figures 17 through 20. These curves are used to predict the in-place compressive strength for that concrete using the maturity method.

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Figure 18. Strength maturity curve for current VES mix
Figure 19. Strength maturity curve for Mix No. II
Figure 20. Strength maturity curve for Mix No. III
Figure 21 presents the maturity curves for Mix no. II and Mix no. III. The maturity required to reach 350-psi flexural strength (equivalent to 2,250 -psi-compressive strength) was, 152 °C-hrs for Mix no. II and 175 °C-hrs for Mix no. III. The maturity method should not be used to predict the strength of a concrete design different from the concrete from which the strength maturity relationship was derived. However, all the maturities indicate that concrete made with Essroc type I cement within the range of cement contents used in this study reached the target strength at maturity of 165, 155, 175, and 175 deg (C-hrs) for Mix no. I, II, III and IV, respectively. Previous studies reached the required flexural strength at 160 °C-hrs., quite comparable to the current study. The time needed to reach these levels was between 6.5 and 7.0 hours.
Figure 21. Maturity curve for mixes No. II and No. III
**Datum Temperature**

A datum temperature of 6.5°C has been utilized since 1996 for VES concrete in New Jersey. In order to accurately compute the maturity, the datum temperature needs be properly assigned. One task this project was to check the current value by testing the control mix. Additionally, it was needed to know if that value would apply to the proposed mix. ASTM Test Methods C 1074 and C 109 were utilized to measure the datum temperature for each mix. Twenty-four mortar cubes were cured at 33°C, twenty-four were cured at 22°C and twenty-four cubes were cured at 10°C in curing tanks of lime saturated water. The test setup is shown in figure 21. Three cubes from each temperature are tested at 1, 2, 4, 7, 14, and 28 days, extra cubes were used in resolving sometimes inconsistent tests by providing supplemental samples when needed.

The datum temperature results are shown in table 6. Mix no. I, II, III and IV had datum temperatures of 6.7, 6.2, 7.0 and 6.9 °C, respectively. All these values compare well with the 6.5 °C datum temperature that was assigned to VES concrete in 1996 and used from the outset of this project.\(^{(2)}\) so 6.5°C was kept as the datum temperature in this study and no corrections were made to the maturity measurements.

Table 6. Datum temperatures for studied mixes

<table>
<thead>
<tr>
<th></th>
<th>Mix No. I</th>
<th>Mix No. II</th>
<th>Mix No. III</th>
<th>Mix No. IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Datum temperature</td>
<td>6.7 °C</td>
<td>6.2 °C</td>
<td>7.0 °C</td>
<td>6.9 °C</td>
</tr>
</tbody>
</table>
Unrestrained Shrinkage Testing
The shrinkage of unrestrained specimens, known as free shrinkage, can be used to estimate the relative tendency of mixes to shrinkage. All developed mixes were tested for the free shrinkage.

Test Specimens And Test Setup
Four mortar bars, 1 in x 1 in x 11 ¼ in, and four concrete bars, 2 in x 2 in x 11 ¼ in were cast in accordance with ASTM C 490. All shrinkage specimens were put on the top of beam specimens in order to have them experience, as closely as possible, the early age temperatures of the test samples. All were covered with a thermal construction blanket and placed in a moist room until the concrete cylinders reached a compressive strength of about 2,250 psi.
Once the flexural strength had reached the required strength, the shrinkage bars were removed from their molds and an initial warm temperature reading was made. Initial shrinkage reading was made at one day following ASTM C 490. Two concrete and two mortar bars were moved to the 20°C, 50 percent relative humidity room. 50 percent relative humidity was chosen as the average relative humidity for the State of New Jersey. The other two concrete bars remained in the 100 percent relative humidity room. Specimens cured at 100 percent-relative humidity room experienced little shrinkage and were excluded from consideration. All bars were investigated for length change at 24, 48, 96, 168, 336 and 672 hours after initial measurement. Detail of instrument is shown in figure 22.

![Figure 22. Detail of instrument](image)

**Figure 22. Detail of instrument**

The results of this testing were summarized in figures 3 and 4 in the Experimental Results section in the main text.

**Restrained Shrinkage Testing**

This section of the report deals with evaluating the cracking potential due to restraint drying shrinkage using the ring test. A number of test setups have been developed to
measure the cracking for predicting drying shrinkage cracking potential of concrete. The ring setup was chosen to evaluate the rapid hardening concrete.

*Ring Specimens And Test Setup*

Figure 24 shows the microscope setup for measuring the cracks that develop in ring specimens subjected to restrained shrinkage. The microscope is attached to the center of the steel ring and can rotate 360°. It can also travel up and down, facilitating the crack-width measurements across the 140 mm (5.5 in.) width of the exposed concrete surface.

The variation of stresses across the thickness of the concrete ring depends on the internal diameter of the ring. For the dimensions shown in figure 23, the difference between the values of tensile hoop stress on the outer and inner surface is only 10 percent. In addition to hoop stress, the concrete ring is also subjected to radial compressive stress when the steel ring exerts radial pressure. Since the diameter of the ring is relatively large, this radial compressive stress is only 20 percent of maximum hoop stress. Since cement composites are an order of magnitude stronger in compression, the maximum compressive stress in the ring is only about 2 percent of the compressive strength. Hence, the effect of compressive stresses can be neglected.

The concrete is sealed at the top using a silicone rubber sealer, allowing it to dry evenly only at the outer edge. A relatively large ratio of the width (exposed surface) to the thickness (4 or higher) can provide uniform drying across the thickness.

The cement composite can be cast between a steel ring and an annular outer mold. The outer mold can be made of cardboard or plastic. Provisions should be made to remove the outer mold without causing disturbance to the young cement composite. Care should also be taken to place the outer ring concentrically with the inner ring to avoid non-uniform thickness of the cement composite ring. The outer mold can be removed as soon as the concrete hardens. The drying should be done in a controlled environment at a chosen temperature and relative humidity.
Figure 24 shows the microscope setup for measuring the cracks that develop because of restrained shrinkage. The microscope is attached to the center of the steel ring and can rotate 360°. It can also travel up and down, facilitating the crack-width measurements across the 140 mm (5.5 in) width of the exposed concrete surface.

![Figure 24. Dimensions of a ring specimen](image)

The strains in concrete can be measured by using strain gages. These gages should be placed along the circumference of the concrete. If cracks develop near a strain gage, then that gage reading may not be useful. The amount of stresses imposed on the concrete ring can be measured by monitoring the strains developed in the steel ring. Sensitive gages are needed to measure the strains in the steel ring because it undergoes very little deformation.
The ring setup was chosen for the experimental investigation. The primary variable was the mix proportion as shown in table 2. The following three mixes were evaluated:

- Mix no. I  Cement  799 lb/yd$^3$
- Mix no. II Cement  658 lb/yd$^3$
- Mix no. IV Cement  611 lb/yd$^3$
- Mix no. III could not be evaluated because the aggregate size exceeded the ring thickness

Since the mix volumes were small they were hand mixed and placed using rodding for consolidation. The outer ring was made of plastic which was removed after the concrete hardened. The ring made using Mix No. IV, Mix No. II, and Mix No. I are shown in figure 25, figure 26 and figure 27, respectively.
Figure 26. Rings made with concrete Mix No. IV

Figure 27. Rings made with concrete Mix No II

Figure 28. Rings made with concrete Mix No. I
Results Of Restrained Shrinkage Using Ring Test

After 90 days the ring specimens had not cracked. The authors believe that the rings did not crack because the rapid hardening concrete had gained sufficient tensile strength during the first five hours. This may have resulted from very little loss of water and hence less drying shrinkage.

Based on the performance of the rings the authors believe that, if proper care is taken during the first-6-hours to eliminate water loss from the concrete, the rapid hardening concrete can be proportioned to provide less shrinkage cracking than normal concrete.
Thermocouple Fabrication
Thermocouples are used for temperature measurements. They are simple, rugged and inexpensive. More accurate measurements can be made using thermistors or resistive temperature devices (RTDs). Thermistors are relatively easy to use but care must be taken to prevent shorting of the lead wires and they are somewhat fragile. RTDs are the most accurate temperature measuring method but also the most expensive and instrumentally the most difficult to implement, needing the use of a Wheatstone bridge circuit in very much the same way as strain gages. However, if used with care thermocouples can give reasonably accurate and precise temperature measurements. Thermocouples utilize the fact that when a junction of dissimilar metals is made a potential difference, a voltage, is generated between the other ends. When this junction is heated the voltage changes. This phenomenon is known as the Seebeck effect after Thomas Seebeck who discovered it in 1821. Although the voltage varies in a nonlinear way, it is predictable for each thermocouple type. Temperatures are correlated with voltage measurements either through look-up tables or using seventh degree (up to fifteenth degree) polynomials. A given thermocouple type at a particular temperature will generate a predictable voltage. K-type and T-type thermocouples, the type reflecting the two different metals used, are well suited for measurements in the normal temperature range and, are among the least expensive types since they use common metals, copper and constantan in the case of T-type, constantan and iron in K-type.

Thermocouples can be made by soldering, welding or simply twisting the thermocouple wires together. They can also, if necessary, be purchased from any number of suppliers. Thermocouple probes can also be used though brass tubes cast into the concrete into which a probe can be placed and recovered after testing. We find that sacrificial thermocouples are quick and easy to use. We have found that tightly twisting the wires together works very well. It was found more reliable than our welding. Loosely twisted wires can come apart inside the concrete where there is no way to correct the problem. Wire twisting is highly important. If you feel that you lack the
manual dexterity to tightly twist the wires, consider purchasing pre-made thermocouples probes

**Thermocouple Placement**

ACI 228, In-place Estimation of Concrete Strength, recommends use of five temperature measurements for the first 100 yds$^3$, and two additional measurements for each additional 20 yd$^3$. Thermocouples should be placed at the heart of the structure, the structurally most critical and the expected coolest part of the structure. Temperature measurements in the main mass of the concrete will detect temperature increases before they are noticeable in more critical areas. For a roadway slab this critical area is in the upper part of the corners. In these areas heat is lost to the air, the adjacent slab, the forms, and the ground. Two thermocouples should be placed in the most accessible corner two-inches from the top and edges of the slab. This redundancy at this point is important as insurance against thermocouple failure. Care needs to be taken that the wire is secured to whatever reinforcement is available and led-out of the slab towards the bottom of the slab to minimize the potential for future cracking. Two thermocouples should be placed into beams or cylinders, monitored either in the lab or in the field the thermocouple should be placed into the center of the specimen. If necessary, a thermocouple insertion device consisting of a stiff wire should be used to clear a path for the thermocouple wire. Care should be taken to place the thermocouple in areas that will not weaken testing of the sample. Instrument the last samples to be tested. Calculate the maturity as the average readings of the slab and the average readings of the thermocouples in the test samples. If spare thermocouple measurements are available make one measurement of the maximum temperature in the center of the slab, three or four feet from the edges. This measurement in the center gives a glimpse into the approaching behavior of the critical section of the slab.

**Data Logging**

Data loggers are used to collect and record the temperature data. For this study we have been using NJDOT’s own small, autonomous temperature loggers manufactured by ACR Co., of Vancouver, Canada, measuring from four to six temperature channels.
The units are user programmed using propriety computer software. The number of channels sampled and the frequency of sampling determine the length of time sampling can be done. ASTM C 1074 requires a temperature sample to be taken every half hour for the first 24 hours and then every hour thereafter. We tend to use sampling intervals between two and ten minutes. We usually sample at a rate that will fill the logger memory over the time period we expect to be monitoring but, very rarely less than one sample every two minutes. Other issues like thermocouple type, temperature units, delayed starting and so also need to be set. When recovering the data, complete file names need to be assigned.

**Maturity Calculation**

The temperature-time factor has been chosen to represent the maturity index. This value is the area under the temperature/time curve adjusted for the datum temperature. The datum temperature successfully used for predicting VES concrete strength is 6.5°C. For VES concrete then the maturity is calculated using equation-2 formula. So, for VES concrete the formula becomes: 

\[ M(t) = \sum (T_a - 6.5) \Delta t \]

This procedure computes the area under the temperature/time curve using the trapezoidal method. ASTM C 1074 shows an example of how to apply this formula to temperature data.

In addition to setting up the data collection, the ACR proprietary software can be used to implement the above expression. The following program needs to be written into a custom equation. The apostrophes indicates remarks.

```plaintext
'Maturity equation processes temperature data to maturity values for ACR loggers
'temp computes average temperature over time increment
temp = (Source0 + prev) / 2
'datum is the datum temperature, change as necessary
'Use 6.5 for VES, 0 for normal concrete
datum = 6.5
'Following condition prevents apparent strength loss
If temp <= datum Then temp = datum
'srate is the number of minutes between samples
srate = 2
```
'k is sampling rate in hours for computation in degC-hrs.
k=srate/60

'Answer0 is the accumulated maturity up to the current time increment
Answer0=Answer0+(temp-datum)*k

'prev is previous temperature measurement for temperature averaging in line 3
prev=temp

If a ten minute sampling rate is chosen then a simpler version without the comments is:

Answer0=Answer0+(Source0-6.5)*0.16667 for maturity in degree C hours

or

Answer0=Answer0+(Source0-6.5)*0.00694 for maturity in degree C days

(If you have the ACR software installed then open a “New Equation” from the Equation menu, assign a number (101 works if you have no others), enter deg C hr or deg C days into the units box, then copy the text of the maturity equation given above and paste it into the new equation.)

To apply this equation to a chart of temperatures, choose “Equation” from the menu then add compound line to graph. Select the maturity equation number (101), tab, select Source0, tab, select the temperature channel for maturity calculation, usually, the lowest curve in concrete, click the “Accept” box. The maturity at any given time, up to the current time, can then be read off the graph or picked off the graph viewed as a table after conversion from the menu.

**Develop Strength/maturity Relationship**

Application of the maturity method begins by determining the strength/maturity relationship. Following procedures of ASTM C 192 cylinders and beam specimens are made. Thermocouples are placed in the center of representative samples. Typically, testing starts just after the final set and proceeds every half an hour or less until the required strength is reached. At the time of the test, the current maturity index is recorded. Alternatively, several tests can be done and the index read off the file at the end of the testing. Testing proceeds at convenient time or maturity increments, every half an hour starting at the final set, 3-5 hours, until about 2250 -psi, at which a beam
can be tested to confirm reaching required 350-psi flexural strength. Testing of duplicate specimens is required but, because the strength is rising so quickly be sure to mark the exact time of the test for matching with the corresponding maturity. A curve plotting the maturity index on the x-axis and compressive strength on the y-axis is made. From this plot the strength at a given maturity can be predicted.

It should be noted that ASTM C 1074 starts the maturity calculations at the final set, in other words, the maturity at the final set is zero. Without this condition, it is possible for VES concrete to reach a target maturity without a final set. To date we have neglected this provision. Experience has shown, data is being collected to show, that the performance of VES can be predicted from the time to the final set. The temperature curve can be used to mark the time of the final set. When the temperature rises two to three degrees above the initial temperature trend, the concrete will have set. If a VES mix has not set within four hours it is unlikely that the target strength will be reached in 6½ hours. Incidentally, data reviewed to date shows that all VES mixes, regardless of initial mixing temperature and set times reached the required strength within ten hours.

**Initial Mixing Temperature Requirements**

The initial concrete temperature has a tremendous effect on VES concrete. It is extremely important that the initial mixing temperature be between 81°F (27°C) and 95°F (35°C). The probability of success in the prescribed 6½ hours is greatly enhanced. Figure 5 shows that all mixes with initial mixing temperatures greater than 81°F meet the required strength at 6½ hours. All mixes with initial mixing temperatures less than 81°F fail to make the required strength at 6½ hours.

**Curing**

The maturity method assumes that sufficient water for complete hydration of the cement is present. This requirement makes curing all the more important. In the case of VES concrete, the time to the target strength is all the curing that the concrete will get. It is therefore required that as soon as the finishing has been completed wet burlap needs be applied. Once that is in place the thermal blankets need to cover the concrete pour.
as soon as possible. To as great an extent as possible, the beams should be placed under the blankets as well. After the blankets have been removed, the surface should be kept wet as long as possible. Again, this will be all the curing this concrete will get. Give it as much curing as possible, is should be wet when it is open to traffic.

**Field Strength Prediction**

Because the maturity method is predicated on two assumptions, 1) the concrete being tested is the same concrete from which the strength-maturity relationship was derived and 2) there is sufficient moisture for complete hydration and, because many variables can affect temperature measurements, and thereby the maturity calculations, it is suggested by ACI 228, In-place Methods to Estimate Concrete Strength, that the maturity method alone is not adequate for reliable strength prediction. It needs to be combined with other testing to confirm its prediction. This testing could be in the form of another nondestructive test like a Schmidt Hammer, ASTM C 805, or ultrasonic pulse velocity, ASTM C 597, or some other convenient method. However, we recommend the continued testing of beams in accordance with T97, contained in the New Jersey Concrete specifications, currently used to authorize opening of traffic be retained with a difference. The maturity of the highway slab and the beams will be used to time the testing of beams kept under conditions of T23, as close to those of the highway slab as possible, that is, kept under the thermo blankets. When the maturity of the slab reaches the prescribed value, 175 °C-hrs. in the current study, the beams would be tested, to assess the strength of the slab to the same level of confidence currently enjoyed. The advantage of this method over the current one is that it is quite possible that this could happen before the now specified 6½ hours. Data shows some beams approaching 500 psi in that much time. The road could be opened a half-an-hour or even an hour earlier in favorable conditions. At the same time, if there is insufficient maturity for testing, the beam need not be sacrificed except as proof that sufficient strength has not been achieved in the required time. A chart like figure 28 would be used to determine the maturity required reaching a specified strength. Experience with actual field specimens would refine that value.
Another issue is the determination of the specified or characteristic strength. The characteristic is that strength that will be exceeded by a certain percentage of tests. We expect that 90 percent of the beam strength predictions will exceed the required 350 psi. A look at figure 29 will show that for this to be so, the specified strength will have to be greater than the actual required strength by some nontrivial amount as shown in figure 6.
The procedure, called the General Tolerance Factor Method, is outlined in ACI 228R1. This amount depends on the size of the test population, the standard deviation and, the level of confidence desired. Analysis of the field data shown in figure 5 in the main text where 32 beam tests averaged 374 ± 110 psi shows about 82 percent of samples exceeding target strength at 6.5 hours. The required strength needed to be 512 psi. Where the requirements for an initial mix temperature of 81 °F were met the beams averaged 410 ± 57 psi. In that case the required strength would need to be 435 psi.
References


