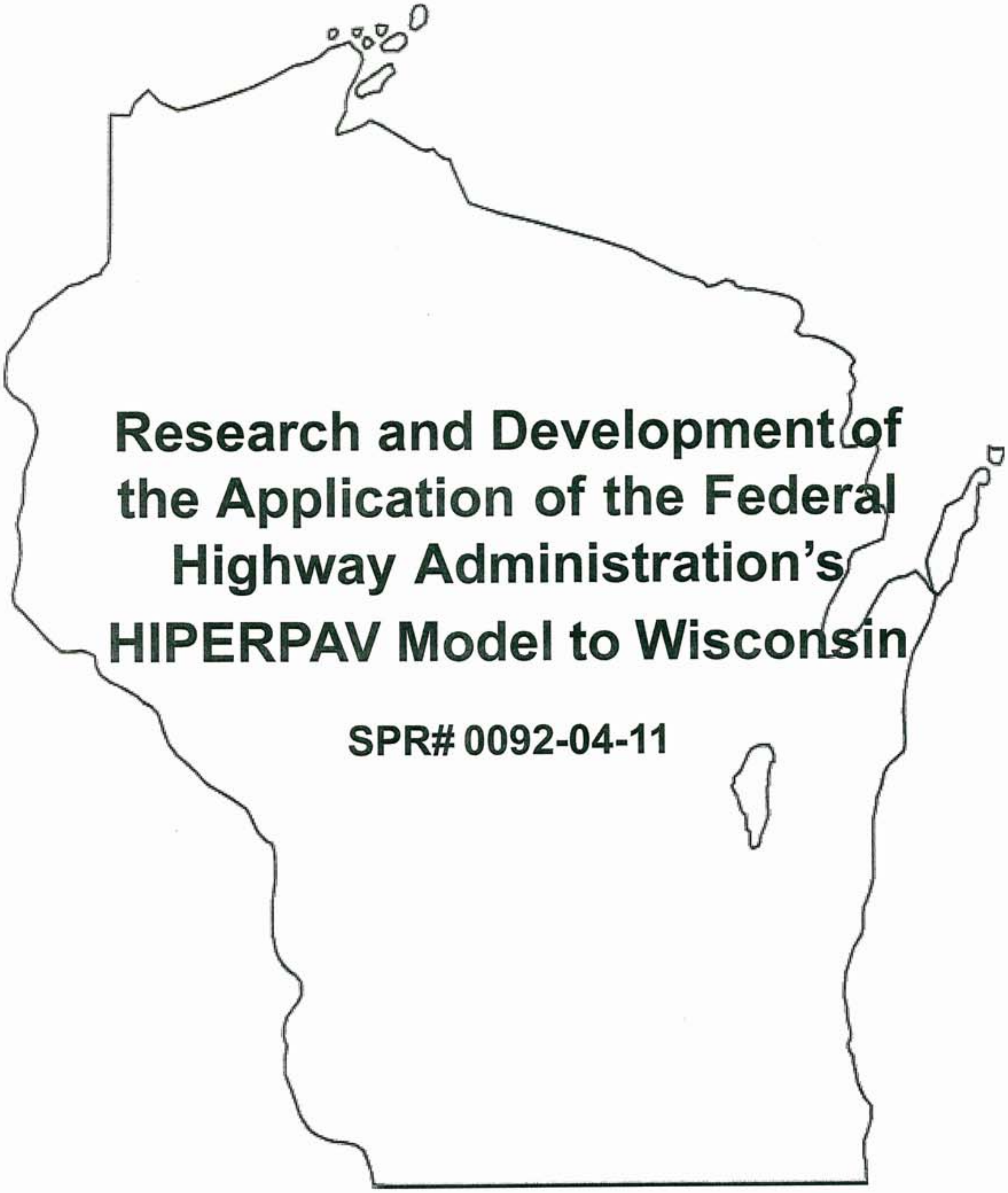
Wisconsin Highway Research Program



# Research and Development of the Application of the Federal Highway Administration's HIPERPAV Model to Wisconsin

**SPR# 0092-04-11**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April 2006

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# RESEARCH AND DEVELOPMENT OF THE APPLICATION OF THE FEDERAL HIGHWAY ADMINISTRATION'S HIPERPAV MODEL TO WISCONSIN

***FINAL REPORT***

***Submitted to***

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16. Abstract

This report summarizes the work involved in customizing the (HIgh PERformance PAVing) HIPERPAV® software for the state of Wisconsin. Under this research project, HIPERPAV was customized to use the same terminology and designations currently employed by the Wisconsin Department of Transportation (WisDOT) and the Wisconsin concrete pavement industry. Technical documentation describing the proper use of HIPERPAV and selection of input values was produced under this research to further improve the implementation process within the State.

In order to accomplish the above, information was obtained from the Wisconsin Highway Research Program (WHRP) oversight committee and Wisconsin stakeholders in the paving industry. In addition, an information search of Wisconsin typical design standards and construction procedures was also performed. Dr. Hani Titi of the University of Wisconsin-Milwaukee produced a report on the investigation of typical input values and terminology on concrete pavements commonly used in Wisconsin.

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## EXECUTIVE SUMMARY

### *Project Summary*

HIPERPAV is a computer program that allows users to evaluate the effect of design, materials, environment, and construction factors on the early-age behavior of concrete pavements. HIPERPAV has been widely recognized by planners, designers, and contractors as a useful tool to simulate the first 72 hours after placement. Under this research project, HIPERPAV was customized to use the same terminology and designations currently employed by the Wisconsin DOT (WisDOT) and the Wisconsin concrete pavement industry. In addition, technical documentation describing the proper use of HIPERPAV and selection of input values was produced under this research to further improve the implementation process within the State. Better management tools for interpretation of results and enhanced capabilities were also incorporated.

### *Background*

Within the State of Wisconsin, HIPERPAV has been used for the analysis and optimization of design and construction alternatives. It is believed that proper customization and implementation of HIPERPAV to Wisconsin conditions will encourage its use by WisDOT and Wisconsin's pavement contractors. Because experienced staff from Wisconsin DOT, consultants, and contractors are retiring, implementation of a tool such as HIPERPAV for optimization of pavement design and construction options will be of particular significance. Under this scenario, a tool like HIPERPAV could be particularly useful in the field.

### *Process*

During the early phases of the project, a meeting was conducted to obtain information on desirable features to incorporate in the HIPERPAV Wisconsin System from the Wisconsin Highway Research Program (WHRP) oversight committee and Wisconsin stakeholders in the paving industry. In addition to the committee's input, an information search of Wisconsin typical design standards and construction procedures was also performed. Dr. Hani Titi of the University of Wisconsin-Milwaukee produced a report on the investigation of typical input values and terminology on concrete pavements commonly used in Wisconsin.

From the above information search, a list of typical default input values and input ranges were developed. In addition to default input values, enhanced functionality of the HIPERPAV-Wisconsin System was identified in several areas.

## *Findings and Conclusions*

HIPERPAV is a proven tool used widely by planners, designers, and contractors helping them to ensure success with their concrete projects. Our customizations of the software for the State of Wisconsin will enable officials, engineers and contractors build and maintain concrete structures with more precision and confidence.

## *Recommendations for Further Action*

It is anticipated that additional implementation of the HIPERPAV-Wisconsin model outside of the scope of this project will be needed in order to fully integrate it into routine practice. To assist in forming a vision for full implementation, a number of additional phases could be considered in the future, including specification development, testing, database development, validation, workshops and technology transfer.

OUTLINE

# 1 INTRODUCTION

HIgh PERformance concrete PAVing (HIPERPAV) is a computer program that allows users to evaluate the effect of design, materials, environment, and construction factors on the early-age behavior of concrete pavements. HIPERPAV has been widely recognized by planners, designers, and contractors as a useful tool to simulate the first 72 hours after placement. The simulation includes the critical curing period after construction, predicting the development of strength and stresses in a concrete pavement. Practical applications where HIPERPAV has proven useful include identification of potential risk during hot and cold weather concreting, identification of base restraint problems, determination of saw cutting windows, and strength prediction for opening to traffic.

The Transtec Group has developed HIPERPAV in cooperation with the Federal Highway Administration as well as hundreds of individuals and institutions representing the private industry, public agencies, and academia. After nearly a decade of development, the software has been calibrated and validated throughout the United States. Today, HIPERPAV is the first choice of contractors, State DOTs, and the concrete pavement industry for the analysis and optimization of concrete pavement design and construction decisions.

Within the State of Wisconsin, HIPERPAV has been used for the analysis and optimization of design and construction alternatives. However, because it had been developed under FHWA sponsorship, HIPERPAV included only "typical" material types and properties representing the nation as a whole. In other words, only generic base types, concrete mix constituents, and curing methods were provided. To further the possibility of successful implementation in the State of Wisconsin, HIPERPAV was customized under this study to use the same terminology and designations currently employed by the Wisconsin DOT (WisDOT) and the Wisconsin concrete pavement industry. In addition, technical documentation describing the proper use of HIPERPAV and selection of input values was produced under this project to further improve the implementation process within the State. Better management tools for interpretation of results and enhanced capabilities were also incorporated.

## *1.1 Background and Significance of Work*

It is believed that by customizing the HIPERPAV models to include terminology used by WisDOT and contractors as well as guidelines for proper input selection, better acceptance and confidence in the results will be obtained.

Implementation of a tool such as HIPERPAV for optimization of pavement design and construction options will be of particular significance. This is especially true in the current situation where experienced staff from Wisconsin DOT, consultants, and contractors are retiring. Under this scenario, a tool like HIPERPAV could be particularly useful in the field. HIPERPAV can provide critical assistance to better understand the impact of the different design, materials, climatic, and construction factors on concrete pavement behavior during the critical first 72 hours after placement.

It is believed that proper customization and implementation of HIPERPAV to Wisconsin conditions will encourage its use by WisDOT and Wisconsin's pavement contractors. In turn, this will provide the State with a real systems approach to maximize quality, optimize pavement construction procedures, control cost, increase productivity, and enhance long-term pavement performance.

The benefits of the HIPERPAV program to the State of Wisconsin can be realized in nearly every phase of the concrete paving process. Examples of benefits in some of the different phases are as follows:

***Pavement Design:*** The interaction between the unique climatic conditions in the State, along with commonly used concrete mixture proportions, can be evaluated objectively in order to prevent early-age distresses such as transverse cracking and plastic shrinkage cracking. Better recommendations of design features can result, even allowing the selection of design features to reflect unique aspects of a project construction. For example, a custom joint spacing can be selected to reflect the use of a given mix design. Although this may seem unconventional by today's thinking, this ability may be of particular interest as part of a design-build or warranty job.

***Construction Planning:*** Prior to construction, the contractor can evaluate the implications of using different concrete constituents such as various cementitious materials or coarse aggregate types, again considering the climatic conditions unique to Wisconsin. Under any placement conditions, the use of various concrete-making constituents can be optimized to ensure adequate strength development characteristics, without experiencing potentially high slab stresses that can lead to mid-panel cracking. Time is money, but "better" mixes often cost more too. Having a tool to predict the tradeoffs can improve the planning process.

***Pavement Construction:*** A Wisconsin HIPERPAV can aid the contractor in evaluating their sawcutting operations, opening times to traffic, and their risk of mid-slab cracking. Recent advancements in concrete maturity and on-site weather monitoring, allow this to be done under near real time. Short of real time, the "5-day" weather forecast can be used, allowing the contractor to identify the most appropriate curing strategy or concrete materials for the day's placement. For example, this may include taking additional measures to have the necessary equipment, labor, and slab protection on site during placement. The result is an objective measure of the potential of adverse paving conditions. This contrasts to "guesses" that are commonly used today, which can lead to differences of opinion between stakeholders in the concrete paving process.

***Forensic Evaluation:*** HIPERPAV has successfully been used to evaluate the most probable cause of concrete pavement failures that have been experienced on various projects nationwide. Through the use of climatic data from weather stations within Wisconsin, along with concrete material properties typical to the State, parameters can be identified that may have contributed to the observed distresses. Answering the question "what went wrong" can help us to improve the way things are done in the future, and HIPERPAV can help us in this process.

## 1.2 Research Objectives

Four primary objectives were identified to properly customize the HIPERPAV model for a successful implementation in the State of Wisconsin. These include:

1. Research of the HIPERPAV model and determination of proper inputs for Wisconsin;
2. Modification of HIPERPAV to accommodate Wisconsin conditions;
3. Documentation of the proper use of HIPERPAV; and
4. Training of WisDOT and contractor staff on the proper use of HIPERPAV and its incorporation into construction operations.

## 1.3 Scope of the Report

This report documents the work done during this project to customize HIPERPAV to conditions commonly found in the State of Wisconsin in terms of input values and terminology as well as enhanced features to facilitate its use.

HIPERPAV solutions (sample case studies) for proactive and post-mortem concrete paving scenarios with step-by-step instructions for adequate selection of inputs and interpretation of results are documented herein.

Finally, conclusions from the work addressed in this project and recommendations for integration of the HIPERPAV Wisconsin system into normal design and construction practice are provided.

# 2 WORK CONDUCTED TO CUSTOMIZE HIPERPAV

In this session, the work conducted to customize HIPERPAV for the State of Wisconsin is described.

## 2.1 Investigation for Determination of Proper Inputs

During the early phases of the project, a meeting was conducted to obtain information on desirable features to incorporate in HIPERPAV Wisconsin from the Wisconsin Highway Research Program (WHRP) oversight committee and Wisconsin stakeholders in the paving industry. During this meeting, valuable information was obtained with respect to the type of inputs and software functionality that required customization.

In addition to the committee's input, an information search of Wisconsin typical design standards and construction procedures was also performed. Dr. Hani Titi of the University of Wisconsin-Milwaukee produced a report on the investigation of typical input values and terminology on concrete pavements commonly used in Wisconsin (see Appendix A).[1] The information collected was obtained through a number of interviews with Wisconsin Department of Transportation (WisDOT) personnel, contractors, and the Wisconsin Concrete Paving Association (WCPA). In addition, various official documents including WisDOT standard concrete pavement specifications, the Facility Development Manual (FDM), and other sources were consulted. [2-8]

## 2.2 HIPERPAV-Wisconsin Customization

From the above information search, a list of typical default input values and input ranges were developed. Whenever values for any given input were not available or currently used in the State, the national default values currently present in the software were included in HIPERPAV-Wisconsin.

In addition to default input values, enhanced functionality of the HIPERPAV-Wisconsin System was identified in several areas. The following sections describe the enhancements made to the software:

### 2.2.1 General Enhancements

- The HIPERPAV-Wisconsin system has the capability to import files from the FHWA HIPERPAV II version 3.0 file format (*.hp3) and previous versions (*.h25, *.hpv). This can be done by selecting “File→Open→Files of type” from the main menu. With this capability, users in Wisconsin that have used the software will be able to read HIPERPAV files from previous versions.

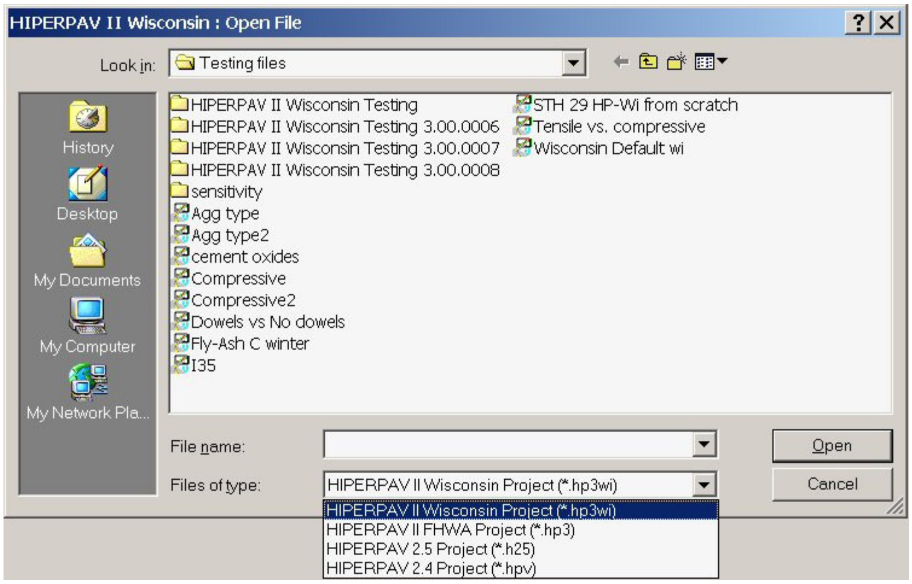

Figure 1. Screenshot of FHWA HIPERPAV II

- The URL (root directory) of the WisDOT website was added as a link under the “Websites” section of the “Help” menu (see Figure 2).

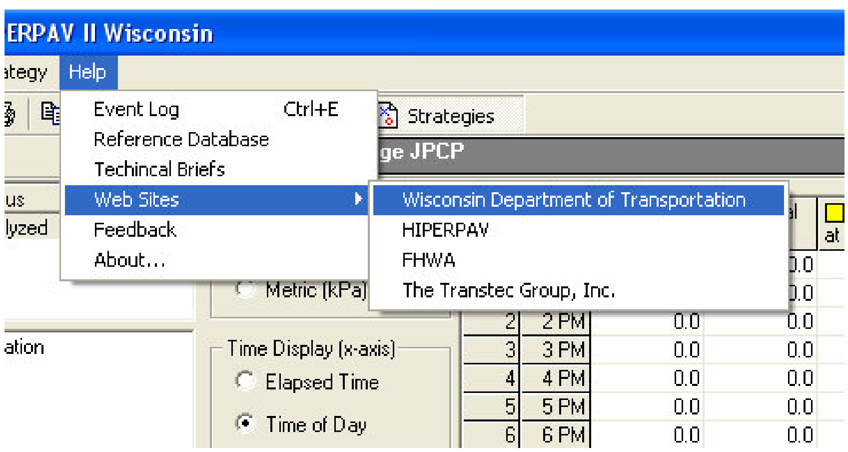

Figure 2. Screenshot of WisDOT website location in HIPERPAV Wisconsin

- The input checks feature in HIPERPAV for unrealistic values was updated with input ranges typical to Wisconsin identified during the information search. A tool tip shows on the validation window by hovering the mouse over the flagged input.

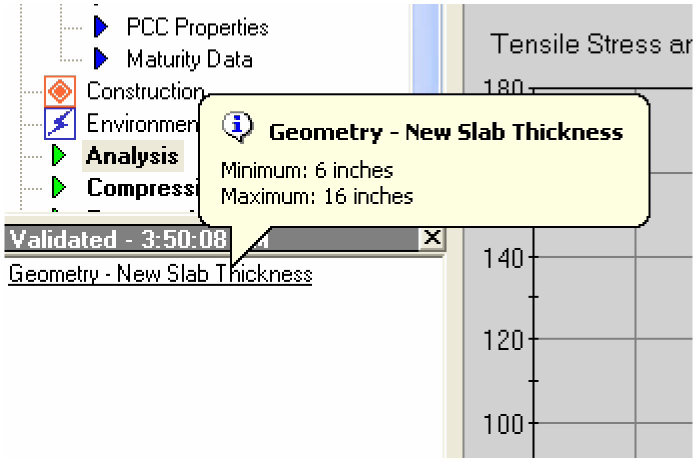


Figure 3. Input checks feature

- In addition, the content of this document was converted to HTML and PDF formats which would be suitable either (compiled) as a Windows Help File, or could be put on the HIPERPAV.com, WisDOT, or other web pages for review by interested parties.

### *2.2.2 Geography*

- The geography map under Project Information now automatically zooms in on Wisconsin - but leaving it ready to zoom out as seen in Figure 4.

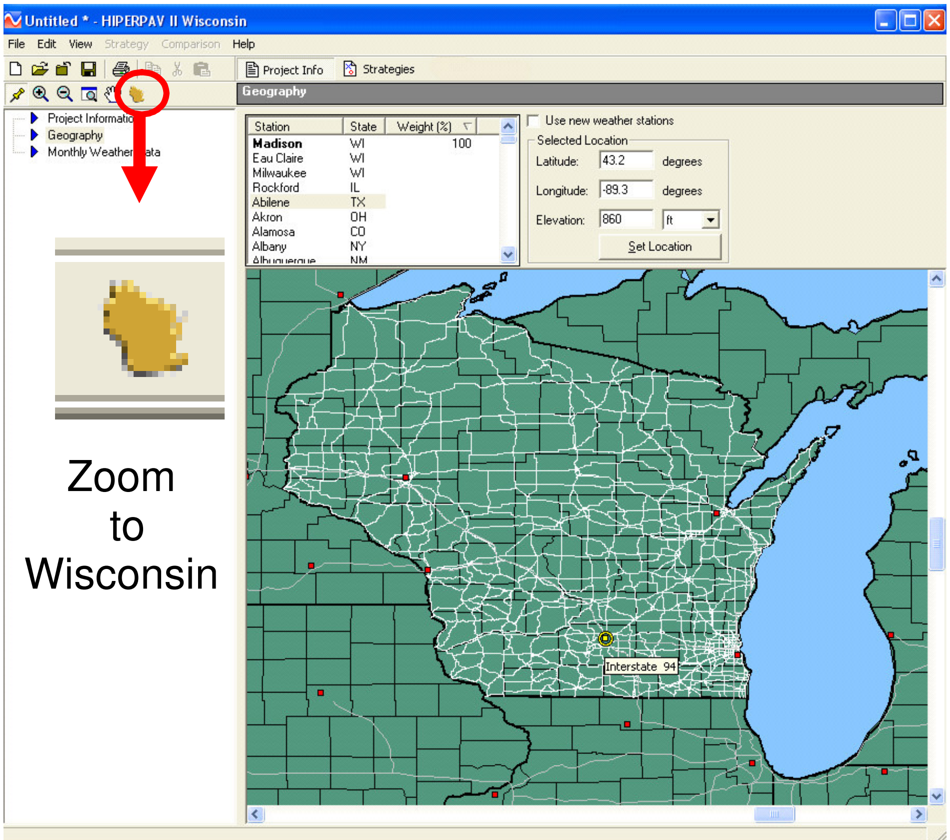

Figure 4. Zoom-to-Wisconsin feature

- Geographic features such as additional highways were included for ease in identifying project location (see Figure 5).

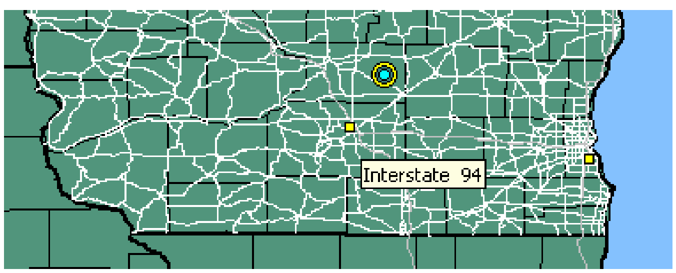

Figure 5. Screenshot of geographic features example

The latest version of HIPERPAV includes an extensive environmental database linked to a sophisticated Geographic Information System (GIS) based interface. When the project location is selected in HIPERPAV, the environmental database is queried for weather data from weather stations near the specified location. Using an intelligent algorithm, the most relevant weather stations are selected, and the weather information for the specified location is calculated based on a weighted interpolation scheme. The weather database in HIPERPAV contains mean hourly readings for the entire year (based on 30 years of data) for a number of weather stations distributed nationwide. Additional weather stations available in Wisconsin were added with the use of the current National Oceanic and Atmospheric Administration (NOAA) weather database. These newly added weather stations provided unreliable weather information since weather data for some of these weather stations is not as comprehensive as for the weather stations previously included in the FHWA HIPERPAV II software. The user can see that the weather trends using the additional weather stations are not as invariable as compared to the weather stations included in the FHWA software. The "jagged" trends using the additional weather stations are due to insufficient historical data. Therefore, the use of these additional weather stations was left as optional as seen in Figure 6. Figure 6 also illustrates the "jagged" trends when using the additional weather stations.

See Appendix B for additional information on the additional weather stations.

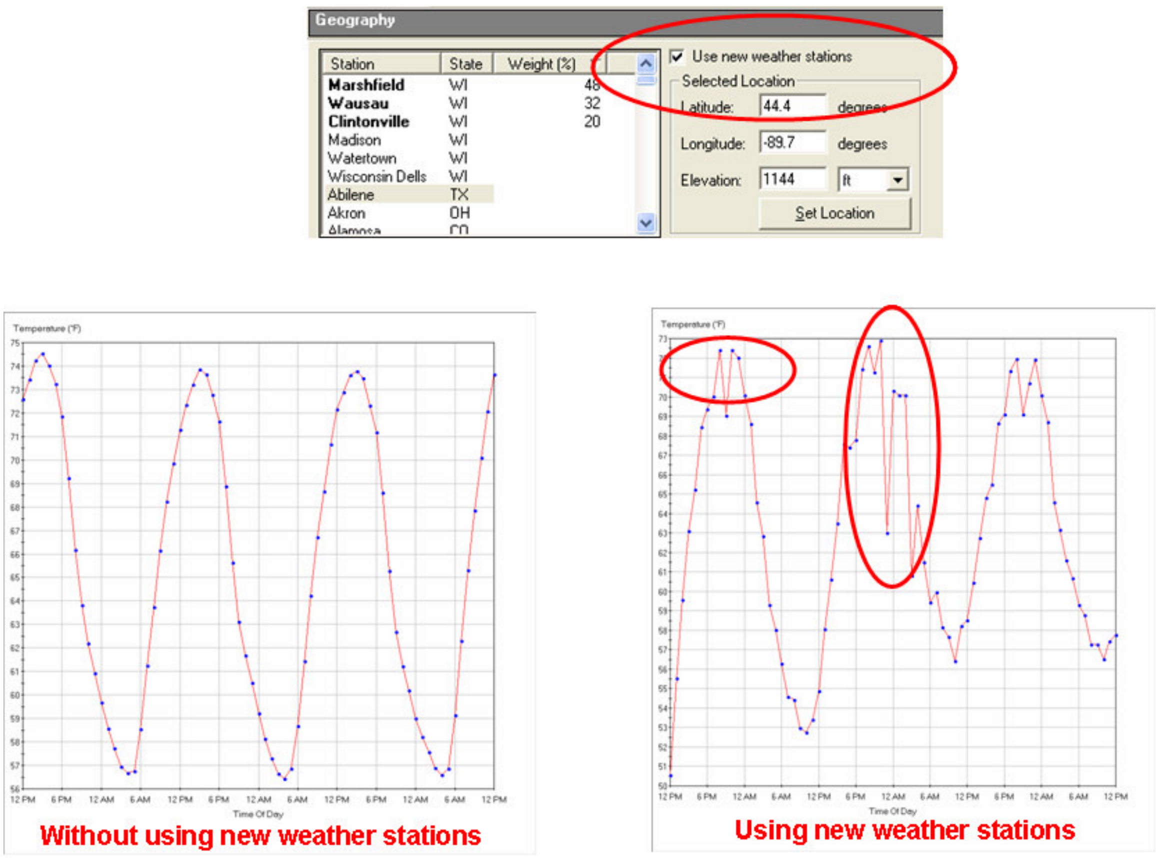


Figure 6. Difference of using additional weather stations

### 2.2.3 Design

- Typical values for joint spacing, slab thickness, and slab width used in Wisconsin were included as default in the software as shown in Figure 7.

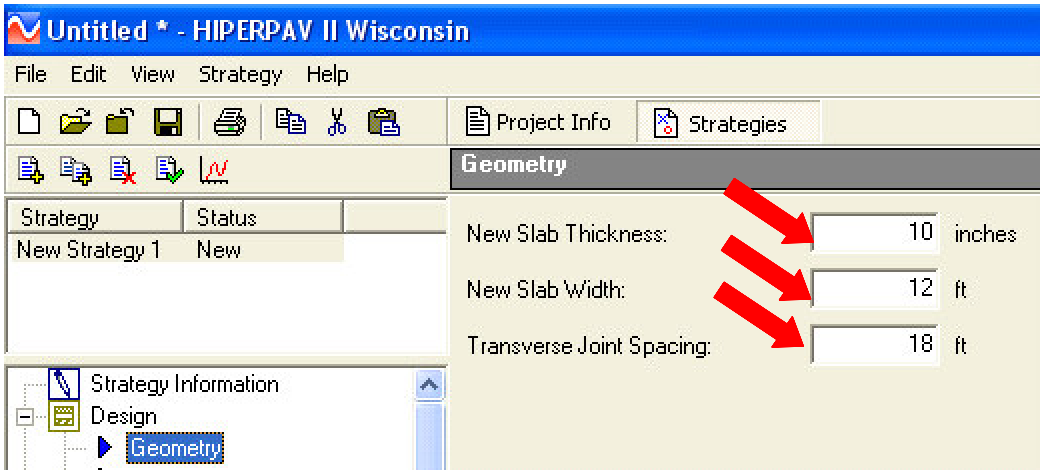


Figure 7. Default geometry values

- The “Unbounded Aggregate Subbase" was replaced for the "Dense Graded Base (unbounded)" which is the most commonly used base type under concrete pavements in Wisconsin. In addition, "Open Graded Base" was also included as an option (see Figure 8).

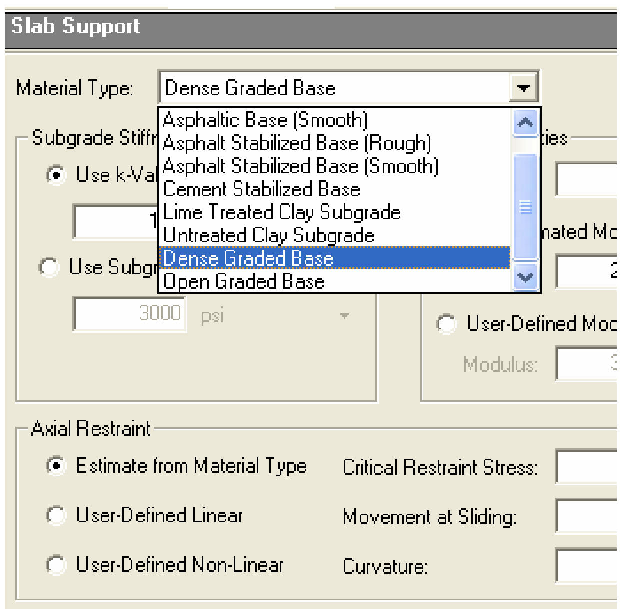


Figure 8. Slab support terminology

- Typical values of stiffness and restraint for local base and subgrade types were also included as defaults (see Figure 9).

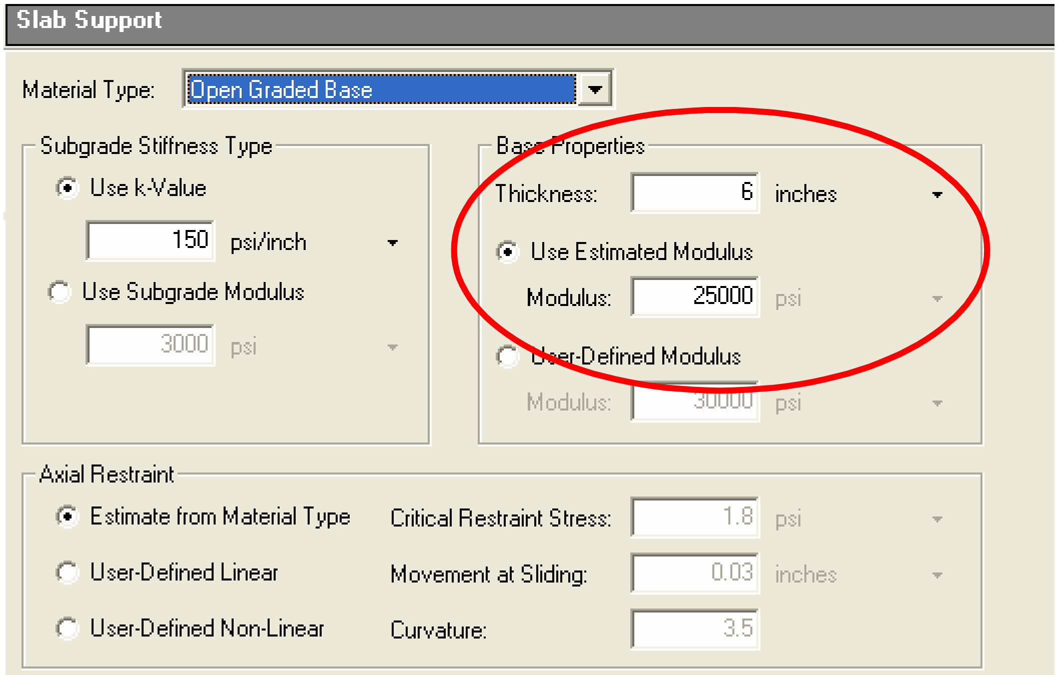


Figure 9. Typical modulus values for base and subgrade types

- The HIPERPAV-Wisconsin system now has the ability to update the base stiffness as a function of the base type selected.
- The default *k* value in the software reflects typical values in Wisconsin. Because higher k values lead to higher early stresses (due to the curling component), the *k* value is required as an input to the software.

### *2.2.4 Materials and Mix Design*

- A library of approved cements with the cement chemical composition from different manufacturers was developed as part of the HIPERPAV-Wisconsin customization (Figure 10). This library can be updated from a central location and the information can be downloaded as it becomes available. It is believed that keeping control of the cement library in a central location saves time in entering the data and is less prone to having discrepancies between different copies of the software. Cements are identified by manufacturer and plant location in the cement library. It is believed that use of this library with updated cement information will provide for a better characterization of the concrete heat of hydration.

- Similar to the FHWA HIPERPAV version, air entraining and water reducing admixtures are not included in the software because no significant effects to early-age strength/stresses have been found with the use of these admixtures.

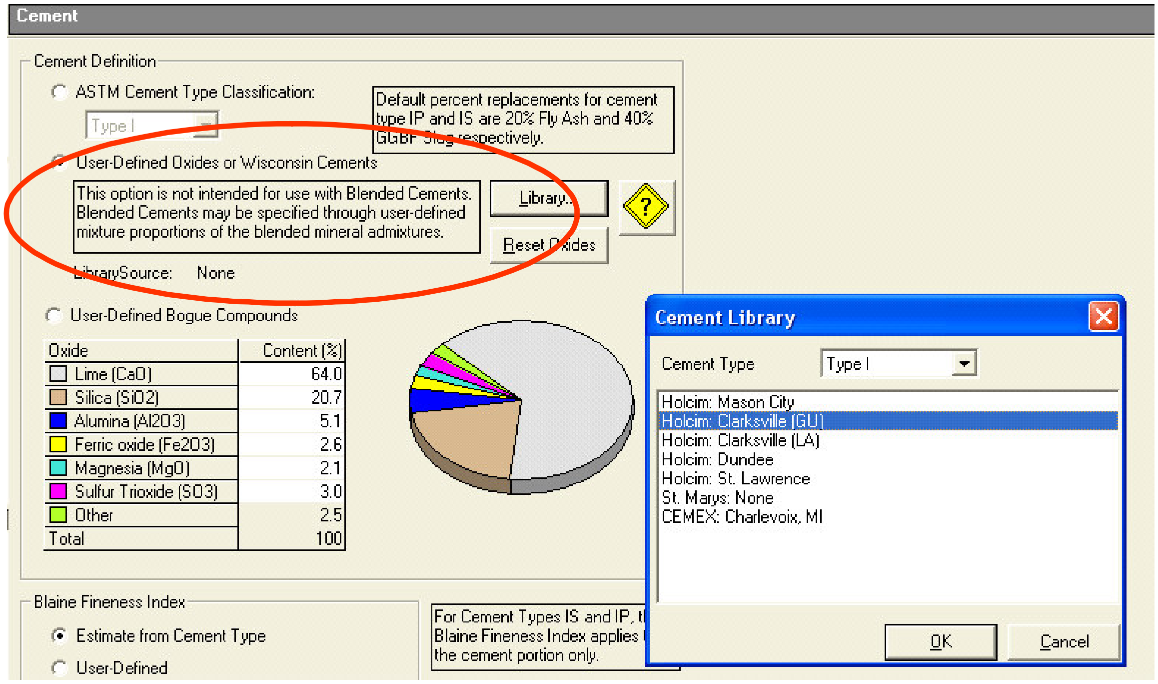


Figure 10. Cement library

- Dolomite was included in the software with its corresponding thermal properties since this is a common aggregate type used in Wisconsin (Figure 11).

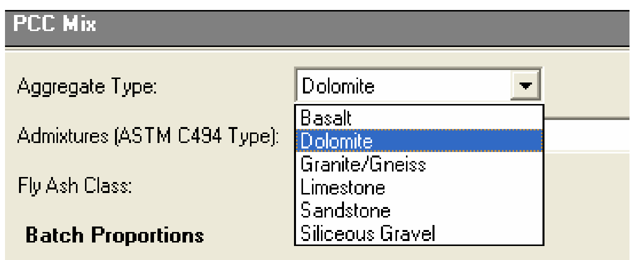


Figure 11. Aggregate addition

- Under the screen for mix proportions, a calculated "%" was included next to the mass column for better interpretation of concrete proportions (Figure 12). It should be noted that concrete proportions in HIPERPAV should be in the form of saturated surface dry weights.

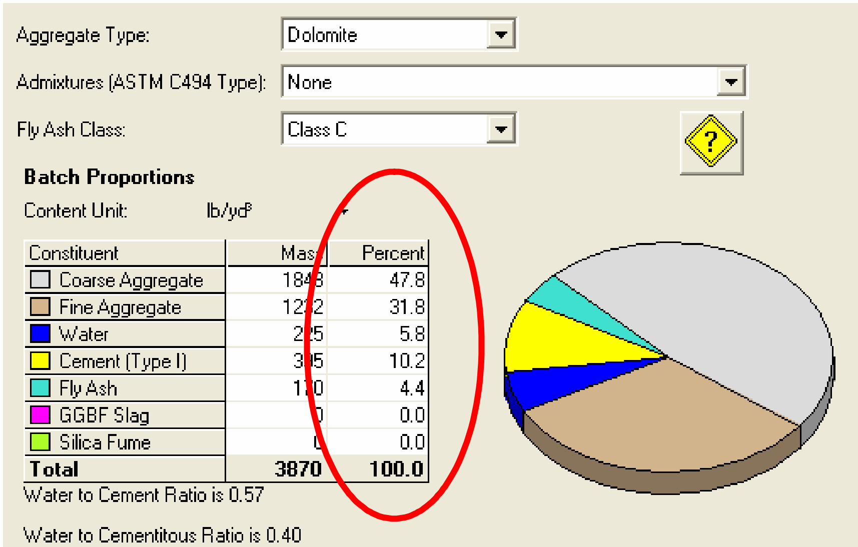


Figure 12. Calculated percent located next to the mass column

- Initially, a library of Concrete Grades was planned for incorporation into the software. However, this library was not included since it was believed that, due to the flexibility allowed in mix proportions, the use of this library could have posed confusion rather than functionality in the use of the software.
- Under the PCC Properties screen the strength type was changed to compressive and typical default values for strength were changed to reflect what is used in Wisconsin.
- No significant changes were made to the Maturity Data screen.

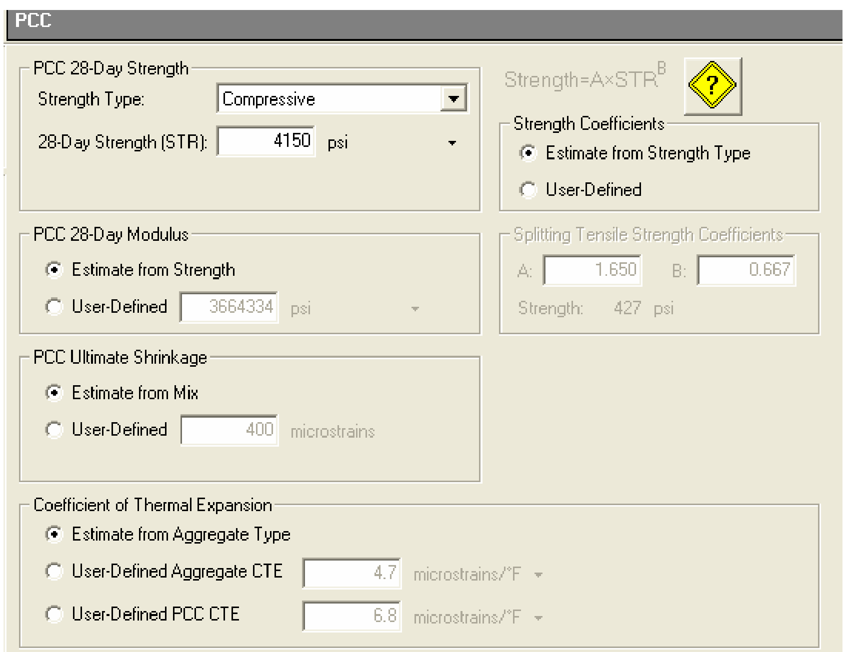


Figure 13. PCC properties.

### *2.2.5 Environment*

- Initially, it had been contemplated to look into the possibility of downloading weather data from Intellicast® weather forecast service based on the zip code corresponding to the project location (see Figure 13). However, this option requires extensive maintenance since the weather data has to be updated daily and maintained at a central location at the Wisconsin DOT where it could be distributed to HIPERPAV users. Therefore, this option was not included.

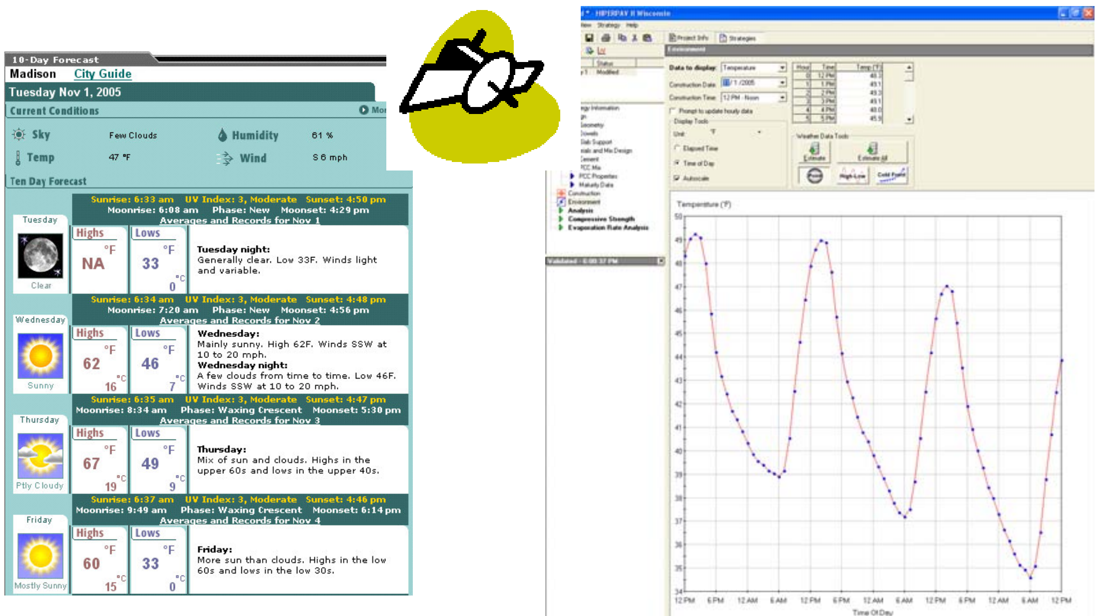


Figure 14. Intellicast® weather data and HIPERPAV Wisconsin

### *2.2.6 Construction*

- Although typical curing methods used in Wisconsin are available in HIPERPAV, terminology was changed according to WisDOT standard construction specifications from “Cotton mats or burlap” and “Polyethylene sheet and cotton mats” to "Burlap or Cotton Mats" and "Polyethylene-coated burlap" (see Figure 14).

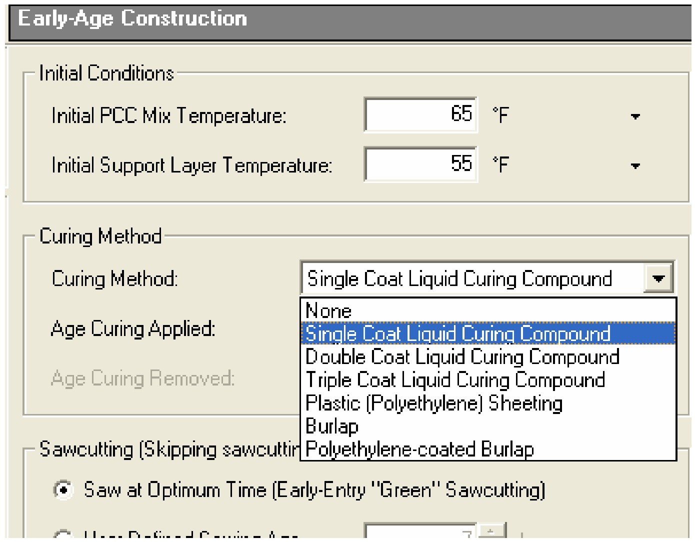


Figure 15. Curing method terminology

### 2.2.7 Analysis

- For better interpretation of results and since compressive strength is more commonly used in Wisconsin according to standard construction specifications, an option to show the compressive strength in a different plot than that to predict early-age cracking behavior was included (see Figure 15).

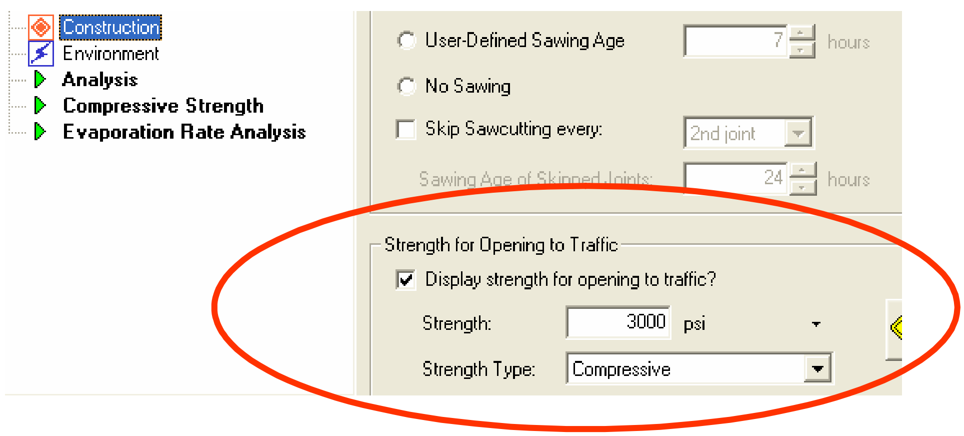


Figure 16. Compressive strength analysis option

- The HIPERPAV-Wisconsin system now shows whether the specified 28-day strength is expected to be met or not within the 72-hour analysis (see Figure 16).

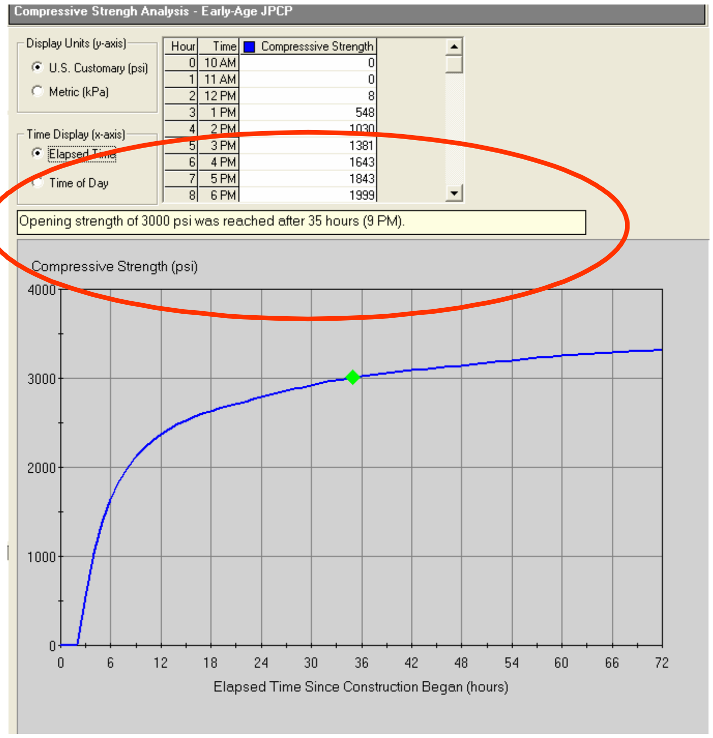


Figure 17. Compressive strength analysis screenshot

- For the evaporation analysis, the wind speed curves were left as an optional plot (with the use of a checkbox) for better interpretation of evaporation results (see Figure 17). In addition, the user can now enter user-defined values for evaporation thresholds. This can be done by selecting "File→Options" from the main menu. (see Figure 18).

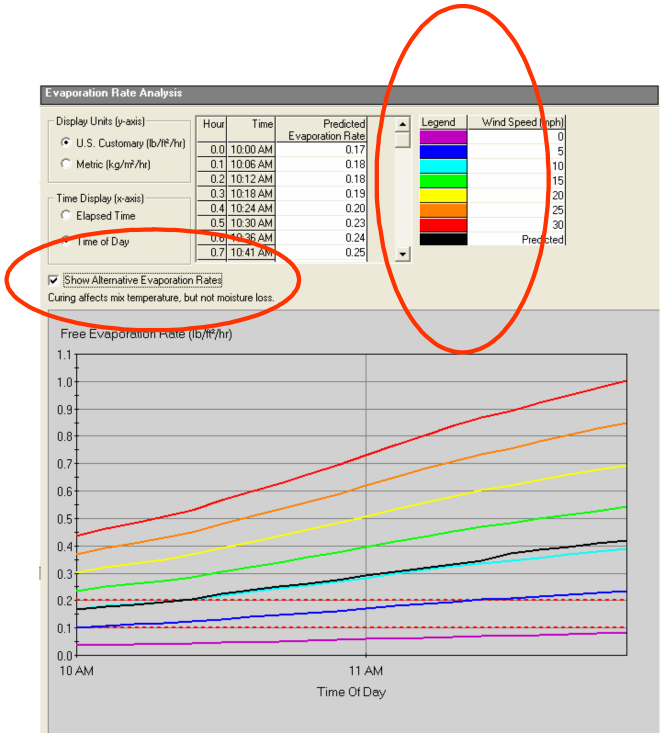


Figure 18. Evaporation rate analysis screenshot

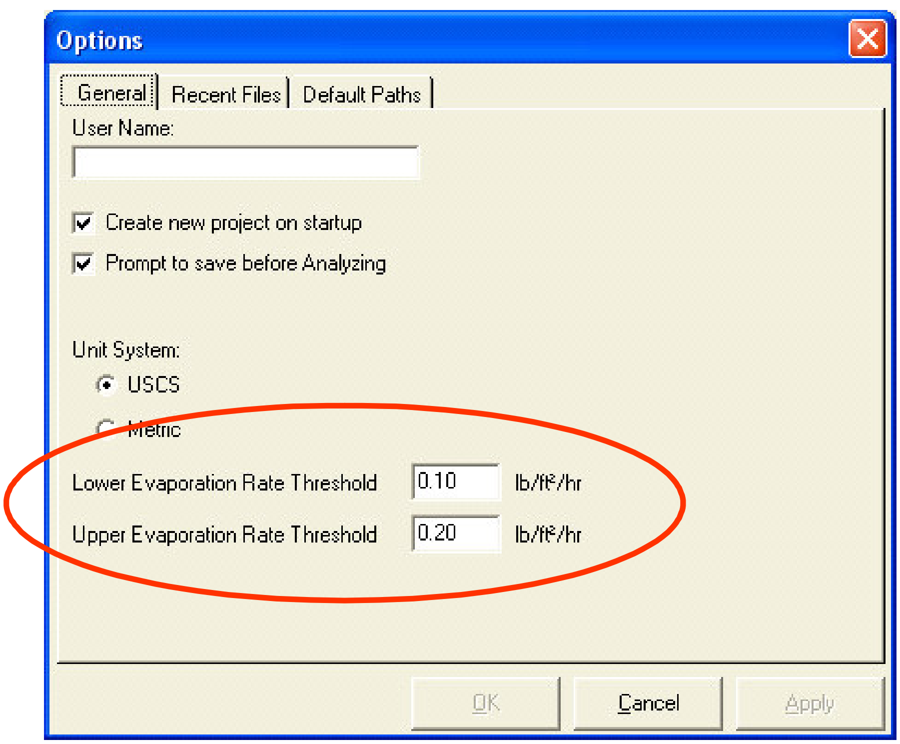


Figure 19. User-defined values for evaporation rates

The HIPERPAV Wisconsin customization was completed before the release of the FHWA HIPERPAV II (The HIPERPAV II version includes the long-term JPCP and CRCP analysis).

Significant efforts were made to develop HIPERPAV Wisconsin with the new software interface; unfortunately, the inclusion of the long-term JPCP and CRCP analysis was out of the scope for this project.

## 3 DESIGN AND CONSTRUCTION GUIDELINES

The reader is referred to the Federal Highway Administration publication FHWA-HRT-04-122 for detailed design and construction guidelines to optimize early-age concrete pavement behavior and for a comprehensive HIPERPAV user's manual.(8) This publication can be accessed within the HIPERPAV software as an electronic PDF document. Frequently asked questions (FAQ) sheets are also included in Appendix C.

## 4 CASE STUDIES

Development of HIPERPAV solutions (sample case studies) for proactive and post-mortem concrete paving scenarios were developed along with step-by-step instructions for adequate selection of inputs and interpretation of results. The case study material was developed for the HIPERPAV Wisconsin Workshop as part of the implementation program. The following four case studies considered were:

1. **Post-Mortem Case Study**. In this case study, a forensics analysis is required for a recently constructed concrete pavement. During the first placement, mid-panel cracking was observed, and the base was a rough Open Graded Hot Mix Asphalt (OG-HMA). In the second placement, white curing compound was applied over the base, yet cracks were also observed. The user must determine possible causes of cracking for this case study.

2. **Cold Front Case Study**. In this case study, a section of a concrete pavement construction has been recently placed and a cold front is forecasted to occur that evening. As a result, the minimum air temperature is expected to decrease drastically. The user must evaluate the impact that the cold front will have and determine what measures can be used to minimize the risks of cracking.

3. **Sawcutting Case Study**. In this case study, the latest time for joint sawing will be analyzed, as well as the possibility of temporarily skipping designated cuts to minimize the risk of cracking.

4. **Aggregate Selection Case Study**. In this case study, a contractor is experiencing an aggregate shortage, and he can only get enough aggregate to complete the project by using aggregate from two different pits. The aggregates possess different coefficient of thermal expansion (CTE) properties, and since the project will take a year to complete, the contractor must determine what would be the

best time to use the aggregates from each pit. The user will use HIPERPAV to determine the best time to use both aggregates.

The case study documents are included in Appendix D.

# 5 CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Summary

Within the state of Wisconsin, HIPERPAV had been used as a tool to help analyze and optimize pavement design and construction alternatives. However, since the software had been developed under FHWA sponsorship, only "typical" materials types and properties were included in HIPERPAV to represent the entire nation. In order for the WisDOT and contractor staff to gain more confidence and acceptance in the results generated by HIPERPAV, the software has been customized to better represent the design and construction practices of the state. Additionally, since many of the experienced staff from Wisconsin DOT, as well as consultants, and contractors, are retiring, the implementation of the Wisconsin version of HIPERPAV will prove to be an extremely useful tool in the office and in the field.

In order to ensure HIPERPAV's successful implementation in the State of Wisconsin, numerous customizations to the software and documentation have been completed. These customizations include the addition of inputs related to geography, design, materials and mix design, environment, construction, analysis and weather conditions appropriate for Wisconsin. With these customizations, HIPERPAV can provide the state with a real systems approach to maximize the state's design and construction practices. In addition, HIPERPAV documentation and training for WisDOT and contractor staff is provided.

## 5.2 Conclusions

HIPERPAV is a proven tool used widely by planners, designers, and contractors helping them to ensure success with their concrete projects. [9-11] Our customizations of the software for the State of Wisconsin will enable officials, engineers and contractors build and maintain concrete structures with more precision and confidence.

## 5.3 Recommendations (Future tasks)

It is anticipated that additional implementation of the HIPERPAV-Wisconsin model outside of the scope of this project will be recommended in order to fully integrate it into routine practice. To assist in forming a vision for full implementation, a number of additional phases are outlined below that could be considered in the future:

### 5.3.1 Phase II – Specification Development

Once the HIPERPAV-Wisconsin model gains acceptance by Wisconsin concrete paving stakeholders, various WisDOT policies, specifications, and operating procedures may be impacted as a result. In this phase, changes to WisDOT policy manuals and Standard Specifications could be identified and developed to accommodate the changes in practice. This process may include developing language for Special Provisions, which can be tried on test projects. It may also include identification and documentation of additional laboratory or field tests to collect the inputs used by HIPERPAV that are not currently measured.

### 5.3.2 Phase III – Testing

Additional work with the goal of full customization of HIPERPAV to local conditions in the State of Wisconsin includes a more detailed characterization of locally available materials. To meet this objective, a laboratory and field testing program could be developed and executed. Examples of specific evaluation techniques include:

> *Calorimetry Testing:* This task would include a study of the effects on the heat of hydration for commonly used concrete paving mixtures in Wisconsin. This type of testing would account for the effects of chemical and mineral admixtures commonly used in the State.
>
> *Slab-Base Restraint Testing:* A number of push-off tests could be performed on commonly used bases in the State of Wisconsin. This would assist by better characterizing the frictional restraint at the slab-base interface.
>
> *Modulus of Elasticity and Indirect Tensile Strength Correlations:* Since the modulus of elasticity and indirect tensile strength are not commonly performed tests, correlations to flexural strength for the materials locally available in Wisconsin could be performed.

### 5.3.3 Phase IV – Database development

Information on available materials and their characterization as well as common mix designs are sometimes available in the DOT record. This information is always valuable, and as part of this phase, it could be formatted electronically and made available to designers and contractors within HIPERPAV-Wisconsin. Along with the results of the tests performed in Phase III, the following information can be catalogued, if available:

- Base types and properties;
- Cement and supplementary cementitious materials (ideally including heat of hydration characteristics); and
- Common mix designs (ideally including heat fingerprint characteristics derived from adiabatic calorimetry).

Available information in the Materials Reporting System (MRS) database could also be linked to the HIPERPAV-Wisconsin System within this phase.

### 5.3.4 Phase V - Validation

Although nationwide validation of HIPERPAV has been performed in the past [12, 13], to ensure full implementation and acceptance by the Wisconsin pavement community, local validation of the models may be performed.  For this stage, construction sites within the State of Wisconsin can be instrumented to verify the predictive accuracy of the HIPERPAV-Wisconsin system.  By comparing the HIPERPAV-Wisconsin predictions with real measured pavement data, assurance in the prediction under local conditions can be made.

#### *5.3.5 Phase VI – Workshops and Technology Transfer*

Additional workshops covering the eight Transportation Districts in Wisconsin could be conducted in this phase.  Training of WisDOT employees, consultants, and contractor's staff could be conducted to better meet full implementation of the HIPERPAV-Wisconsin System.

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## Appendix A

## Parameters of Jointed Plain Concrete Pavements for Customization of the HIPERPAV-Wisconsin System

**Introduction**

This report presents a summary of information and data on the variables affecting design and construction of Jointed Plain Concrete Pavements (JPCPs) used in Wisconsin Department of Transportation (WisDOT) projects. The report is focused on design, materials, environment, and construction factors affecting the early-age behavior of JPCPs for customization of the HIPERPAV-Wisconsin system.

**Design Features**

The Facility Development Manual (FDM) identifies the Jointed Plain Concrete Pavement with dowels as the standard type of concrete pavement to be used on highways in Wisconsin. Details of WisDOT JPCP with dowels are presented in Appendix A.

*Transverse Contraction Joints*

The spacing of transverse contraction joints of JPCPs is specified based on the location of the highway (rural versus urban) and the concrete slab thickness. Spacing of transverse contraction joints for rural and urban Wisconsin highways are given in Table 1.

Table 1: Spacing of transverse contraction joints for urban and rural Wisconsin Highways

| **Pavement Thickness, D (in)** | **Transverse Contraction Joint Spacing (ft)** | | **Dowel Bar Diameter (in)** | |
|---|---|---|---|---|
| | Rural Areas | Urban Areas | Rural Areas | Urban Areas |
| D ≤ 9½ | 15 | – | 1¼ | – |
| D > 9½ | 18 | – | 1½ | – |
| D = 6 and 6½ | – | 12 | – | 1¼ |
| D = 7 and 7½ | – | 14 | – | 1¼ |
| D = 8 and 8½ | – | 15 | – | 1¼ |
| D = 9 and 9½ | – | 15 | – | 1¼ |
| D ≥ 10 | – | 18 | – | 1½ |

Lane and shoulder width data for rural highways are given in Table 2 below.

Table 2: JPCP Width for Rural Wisconsin Highways

| **Highway Cross Section** | **Rural Areas** | | | |
|---|---|---|---|---|
| | **Lane width (ft)** | **Traveled way width (ft)** | **Shoulder width (ft)** | **Total Paved width (ft)** |

| | | | | |
|---|---|---|---|---|
| 2-lane 2-way Highway | 12 | 24 | 3 | 30 |
| Divided Highway | 12 | 24 | 2 | 26 |

For rural doweled JPCPs, the dowel bar length is 18″ spaced at 12″ centerline to centerline. WisDOT specifies the joint saw cut depth to be ⅓ of the slab thickness (D) with a maximum cut width of ¼ inch. The orientation of transverse contraction joints is specified at right angle ($90^o$) to the highway centerline. WisDOT requires that these joints to be left unsealed.

*Longitudinal Joints*

Details of the concrete pavement longitudinal joints of JPCPs used in WisDOT projects are presented in Appendix A. These joints are left unsealed. The depth of the saw cut is given as function of the pavement thickness as shown in Table 3.

Table 3: Details of the longitudinal joints of JPCPs used in WisDOT pavement projects*

| Pavement Thickness "T" | Clear Depth "D" | Saw Cut Groove "G" | Maximum Tie Bar Spacing "S" Pavement Width | |
|---|---|---|---|---|
| | | | 24′ or 26′ | 30′ |
| 6, 6½″ | 3″ ± ½″ | 2″ | 48″ | 42″ |
| 7, 7½″ | 3¼″ ± 1″ | 2¼″ | 45″ | 36″ |
| 8, 8½″ | 3¾″ ± 1″ | 2½″ | 39″ | 30″ |
| 9, 9½″ | 4¼″ ± 1″ | 3″ | 33″ | 27″ |
| 10, 10½″ | 4¾″ ± 1″ | 3¼″ | 30″ | 24″ |
| 11, 11½″ | 5¼″ ± 1″ | 3¾″ | 27″ | 21″ |
| 12 | 5¾″ ± 1″ | 4″ | 24″ | 21″ |

* See Appendix A for details

*Base/Subbase*

The typical subbase thickness used in JPCPs is 6″. In some cases, additional 4″ of open graded base course (OGBC) is used, which will result in a total thickness of 10″ for the subbase/base course layer.  Subbase/base course layers used in JPCP projects in Wisconsin are typical made of unbound materials. Treated subbase/base course layers (such as asphalt treated base, ATB, or cement treated base, CTB) are rarely used. According to WCPA, there was only one project that was constructed on treated base in the last 20 years.

The material type of the 6-inch subbase/base course layers depends on the location of the project and availability of local materials. Crushed limestone (quarried limestone) is used for projects located in the eastern part of the state (areas include Green Bay, Oshkosh, and Milwaukee). In the southern part of the state (Madison area), dolomitic gravel is used, while igneous gravel is used if the project is located in the northern part of the state.

Resilient modulus test was conducted on 38 types of crushed aggregate base course materials from Wisconsin (Eggen and Brittnacher, 2004). The test was conducted according to the procedure described in SHRP Protocol P46. Test results showed that the average resilient modulus of aggregates is 23,405 psi with a minimum value of 15,995 psi and a maximum value of 31,090 psi. Table 4 present the results of resilient modulus test conducted by Eggen and Brittnacher (2004).

Table 4: Resilient modulus of aggregates from various sources in Wisconsin (after Eggen and Brittnacher, 2004)

| **Source Name** | **P (Pit) or Q (Quarry)** | **Conditions During Mr Testing** | | | | | **Average Resilient Modulus (psi)** |
|---|---|---|---|---|---|---|---|
| | | **Dry Dense (pcf)** | **Compaction (%)** | **Moisture%)** | **Void Ratio** | **Degree of Saturation** | |
| 19th Hole | Q | 132.1 | 96.1 | 8.3 | 0.257 | 67.3 | 24,766 |
| Begin | P | 139.8 | 95.5 | 6.2 | 0.211 | 68.1 | 19,569 |
| Boone | Q | 128.9 | 97.1 | 7.9 | 0.240 | 72.8 | 16,546 |
| Bracket | Q | 119.2 | 96.4 | 7.9 | 0.394 | 45.5 | 23,849 |
| Brooks | P | 131.8 | 95.6 | 5.0 | 0.264 | 43.1 | 31,090 |
| Cepress | Q | 131.8 | 95.2 | 8.0 | 0.227 | 81.2 | 15,995 |
| Cisler | Q | 129.8 | 96.6 | 7.0 | 0.238 | 59.8 | 17,498 |
| Clockmaker | Q | 136.1 | 96.7 | 7.4 | 0.234 | 75.3 | 22,403 |
| Crooked Lake | P | 142.3 | 96.5 | 5.6 | 0.210 | 60.0 | 20,987 |
| Emerald | Q | 135.5 | 96.0 | 6.8 | 0.225 | 62.1 | 23,873 |
| Glenmore | Q | 138.8 | 96.9 | 6.4 | 0.247 | 62.8 | 20,472 |
| Globe | P | 126.7 | 97.2 | 9.6 | 0.265 | 69.8 | 19,598 |
| Harry's/Schmidt | P | 133.5 | 97.6 | 6.6 | 0.247 | 58.3 | 22,107 |
| Householder | Q | 131.1 | 97.0 | 7.6 | 0.265 | 68.4 | 23,081 |
| Kiehnau | Q | 130.9 | 95.3 | 4.9 | 0.326 | 35.4 | 28,712 |
| Kings Bluff | Q | 135.8 | 97.1 | 8.8 | 0.210 | 87.9 | 22,242 |
| Knight | Q | 132.2 | 96.7 | 8.0 | 0.253 | 66.3 | 21,951 |
| Kohlhoff | Q | 143.0 | 96.9 | 5.6 | 0.203 | 62.7 | 29,675 |
| Krueger | Q | 137.1 | 97.0 | 6.0 | 0.212 | 60.3 | 21,892 |
| Lutze | P | 140.0 | 95.5 | 6.4 | 0.236 | 69.1 | 22,245 |
| Mackville | Q | 127.7 | 95.8 | 4.3 | 0.343 | 26.7 | 29,002 |
| Marsalek | Q | 133.6 | 95.6 | 7.5 | 0.219 | 61.6 | 20,714 |
| Moser (Meyer) | Q | 134.8 | 96.8 | 7.6 | 0.215 | 68.2 | 24,703 |
| Myklbust | P | 141.1 | 96.6 | 6.4 | 0.216 | 71.3 | 27,986 |
| Spruce | P | 138.2 | 95.0 | 5.5 | 0.217 | 55.4 | 21,563 |
| Rudinger | Q | 140.0 | 96.0 | 5.8 | 0.237 | 62.0 | 25,924 |
| Sussex | Q | 132.8 | 95.7 | 7.8 | 0.267 | 65.0 | 23,939 |
| Thies | P | 141.2 | 97.8 | 6.1 | 0.198 | 72.0 | 19,626 |
| Tork | Q | 129.1 | 97.1 | 7.9 | 0.255 | 72.8 | 20,403 |
| Wetzel | Q | 135.3 | 97.9 | 7.7 | 0.252 | 76.2 | 19,081 |
| Dennis Johnson | Q | 130.6 | 96.3 | 7.4 | 0.264 | 53.7 | 25,204 |
| Elmwood | Q | 133.3 | 97.2 | 8.1 | 0.282 | 72.4 | 26,841 |
| Faulks | P | 137.9 | 96.0 | 5.0 | 0.199 | 53.0 | 20,382 |
| Haverland | Q | 131.2 | 96.2 | 8.6 | 0.231 | 63.9 | 27,094 |
| Johnson | P | 138.4 | 96.2 | 5.1 | 0.213 | 49.0 | 28,649 |
| Johnson Creek | Q | 135.9 | 97.1 | 8.0 | 0.225 | 72.7 | 25,349 |
| Crobar | P | 135.9 | 95.7 | 5.6 | 0.202 | 47.3 | 25,488 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Scott | P | 135.6 | 97.9 | 6.3 | 0.227 | 60.9 | 28,900 |
| **Max.** | - | 143.0 | 97.9 | 9.6 | 0.394 | 87.9 | 31,090 |
| **Min.** | - | 119.2 | 95.0 | 4.3 | 0.196 | 26.7 | 15,995 |
| **Ave.** | - | 134.4 | 96.5 | 6.9 | 0.243 | 62.7 | 23,405 |

_Subgrade_

Typical values for the modulus of subgrade reaction (*k*), used in the design of JPCPs, range from 150 to 175 pci (psi/in). The value *k*=150 pci is recommended and used for JPCPs by WisDOT engineers.

The value of modulus of subgrade reaction (*k*) for different types of subgrade is given in Table 5 below.

Table 5: Soil Parameters for Pavement Design (After WisDOT FDM, 2004)

| **Material** | **AASHTO Classification** | **Soil Support Value (SSV)** | **Wisconsin Design Group Index** | **Subgrade *k* (pci)** | **Resilient Modulus $M_R$ (psi)** |
|---|---|---|---|---|---|
| I – well sorted | A-1-a | 5.5 – 5.4 | 0 – 2 | 300 | 7,000 |
| | A-1-b | 5.3 – 5.2 | 3 – 4 | 275 | 6,000 |
| | A3 | 5.1 – 5.0 | 5 – 6 | 250 | 5,000 |
| | A-2-4 | 4.9 – 4.7 | 7 – 8 | 225 | 4,300 |
| | A-2-4/A-4 | 4.6 – 4.5 | 9 – 10 | 200 | 3,600 |
| | A-4/A-6 | 4.4 – 4.2 | 11 – 12 | 175 | 3,300 |
| II – poorly sorted | A-4 | 4.2 | 12 | 150 | 3,000 |
| | A-4/A-6 | 4.1 – 3.8 | 13 – 15 | 125 | 2,800 |
| | A-7-6 | 3.7 – 3.5 | 16 – 17 | 100 | 2,600 |
| | A-7-5 | 3.3 – 3.0 | 18 – 20 | 75 | 2,500 |

Communications with WisDOT and WCPA engineers indicated that there is no data and information available on the restraint conditions and slab/subbase restraint stresses. Data and information available in the literature on similar materials/conditions can be used herein.

**Material Properties**

The 1972 version of the AASHTO guide for design of pavement structures is used by WisDOT to design rigid pavements. The design is conducted using the computer program WisPAVE. Material properties needed for pavement design using the AASTHO 1972 guide include: the working stress of concrete ($f_t$), modulus of elasticity of concrete (*E*), and modulus of subgrade reaction (*k*). Typical values for these parameters are given by the FDM as: $f_t$=490 psi and *E*=4,200,000 psi. The modulus of subgrade reaction is determined from the soil report through correlation with other soil properties as presented in Table 5.

The average compressive strength of the concrete used in JPCPs in Wisconsin ranges between 4,050 and 4,150 psi (WCPA). The minimum values vary from 3,560 to 3,750 psi. The following relationship can be used to estimate the modulus of elasticity of the concrete (psi) from compressive strength:

$$E = 57{,}000\sqrt{f_c^{'}} \tag{1}$$

where $f_c^{'}$ is the compressive strength of the concrete in psi. The modulus of elasticity values, for the average concrete mixes used in JPCPs in Wisconsin, are given in Table 6 below.

Table 6: Modulus of elasticity values for the average concrete mixes used in JPCPs in Wisconsin (calculated using Equation 1)

| **Compressive Strength $f_c^{'}$ (psi)** | **Modulus of Elasticity *E* (psi)** |
|---|---|
| 4,150 | 3,671,968 |
| 4,050 | 3,627,458 |
| 3,750 | 3,490,522 |
| 3,560 | 3,400,947 |

The most common concrete grade used in concrete pavements in Wisconsin is A-FA where approximately 80% of the pavements are constructed using this grade. Concrete grades A and A-S are also used with about 10% each. Proportions per cubic yard for the three concrete grades are given in Table 7 below.

Table 7: Quantities for a nominal cubic yard of concrete types used in rigid pavement construction.

| **Concrete Grade** | **Cement (lb)** | **Class C Fly Ash (lb)** | **Slag (lb)** | **Total Aggregate (lb)** | **Fine Aggregate (lb)** | **Design water (gal.)** | **Max. Water (gal.)** |
|---|---|---|---|---|---|---|---|
| A | 565 | - | - | 3,120 | 936 – 1248 (1404*) | 27 | 32 |
| A-FA** | 395 | 170 | - | 3,080 | 924 – 1232 (1386*) | 27 | 32 |
| A-S*** | 395 | - | 170 | 3,100 | 930 – 1240 (1395*) | 27 | 32 |

* According to WisDOT Specifications, this amount of fine aggregate may be used if crushed stone or recycled concrete aggregate are used in the coarse aggregate fraction (see page 23)
** Past practice was to use 20 to 22% fly ash; using 30% (the max allowed) fly ash is becoming common practice (WCPA)
** *For slipform paving, up to 50% (282.5 lb) slag is allowed (WCPA)

*Chemical Composition of Cement*

Different companies produce the cement that is used in JPCPs in Wisconsin. The following is a list of the major five companies along with the cement type produced:

1. Lafarge (Types I/II, III)
2. Holcim (Types I, I/II, GU, ISM)
3. St. Marys Cement (Type I)
4. Cemex (Type I)
5. Dixon- Marquette Cement (Types I, II, III, ISM)

Data on the chemical composition of the cement type produced by these companies and used in JPCPs were collected, summarized, and presented in Tables 8-25.

Table 8: Chemical composition of Type I/II cement from Lafarge North America, Sugar Creek, MO for the year 2003

| **Month** | **CaO** (%) | **$SiO_2$** (%) | **$Al_2O_3$** (%) | **$Fe_2O_3$** (%) | **MgO** (%) | **$SO_3$** (%) | **Other** (%) |
|---|---|---|---|---|---|---|---|
| January | 62.60 | 20.30 | 5.10 | 3.60 | 1.30 | 3.10 | 4.00 |
| January | 63.00 | 20.60 | 5.10 | 3.40 | 1.40 | 2.70 | 3.80 |
| February | 62.70 | 20.20 | 5.20 | 3.50 | 1.50 | 3.10 | 3.80 |
| February | 62.90 | 20.40 | 5.20 | 3.50 | 1.50 | 3.00 | 3.50 |
| March | 62.90 | 20.50 | 5.20 | 3.30 | 1.50 | 3.20 | 3.40 |
| March | 62.90 | 20.40 | 5.20 | 3.50 | 1.50 | 3.00 | 3.50 |
| April | 63.20 | 20.40 | 5.10 | 3.30 | 1.50 | 2.90 | 3.60 |
| April | 63.10 | 20.40 | 5.10 | 3.30 | 1.50 | 3.00 | 3.60 |
| May | 63.10 | 20.30 | 5.10 | 3.30 | 1.50 | 2.90 | 3.80 |
| May | 63.10 | 20.40 | 5.10 | 3.30 | 1.50 | 2.80 | 3.80 |
| June | 63.10 | 20.50 | 5.10 | 3.30 | 1.50 | 2.80 | 3.70 |
| June | 63.00 | 20.40 | 5.10 | 3.30 | 1.50 | 3.00 | 3.70 |
| July | 63.10 | 20.50 | 5.10 | 3.50 | 1.50 | 2.90 | 3.40 |
| August | 63.90 | 20.70 | 5.10 | 3.40 | 1.50 | 2.80 | 2.60 |
| September | 63.30 | 20.70 | 5.00 | 3.40 | 1.60 | 2.80 | 3.20 |
| October | 63.30 | 20.80 | 5.00 | 3.40 | 1.70 | 2.80 | 3.00 |
| November | 63.20 | 20.60 | 5.00 | 3.40 | 1.80 | 2.80 | 3.20 |
| December | 63.20 | 20.60 | 5.00 | 3.40 | 1.70 | 2.80 | 3.30 |
| **Average** | **63.09** | **20.48** | **5.10** | **3.39** | **1.53** | **2.91** | **3.68** |

Table 9: Chemical composition of Type I/II cement from Lafarge North America, Davenport, IA for the year 2003

| **Month** | **CaO** (%) | **$SiO_2$** (%) | **$Al_2O_3$** (%) | **$Fe_2O_3$** (%) | **MgO** (%) | **$SO_3$** (%) | **Other** (%) |
|---|---|---|---|---|---|---|---|
| January | 62.90 | 20.40 | 4.50 | 3.10 | 3.30 | 2.70 | 3.10 |
| February | 62.70 | 20.40 | 4.40 | 3.30 | 3.30 | 2.70 | 3.20 |
| March | 62.60 | 20.50 | 4.50 | 3.30 | 3.40 | 2.80 | 2.90 |
| April | 62.30 | 20.60 | 4.70 | 3.20 | 3.50 | 2.70 | 3.00 |
| May | 62.30 | 20.50 | 4.90 | 3.10 | 3.40 | 2.70 | 3.10 |
| June | 61.80 | 20.40 | 5.00 | 3.50 | 3.20 | 2.70 | 3.40 |
| July | 61.90 | 20.30 | 4.90 | 3.60 | 3.40 | 2.80 | 3.10 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| August | 62.10 | 19.70 | 5.20 | 3.70 | 3.00 | 2.80 | 3.50 |
| September | 62.20 | 19.80 | 5.20 | 3.30 | 3.10 | 2.80 | 3.60 |
| October | 62.30 | 20.20 | 5.10 | 3.20 | 2.80 | 2.70 | 3.70 |
| November | 62.20 | 20.20 | 5.00 | 3.20 | 2.90 | 2.70 | 3.80 |
| **Average** | **62.30** | **20.27** | **4.85** | **3.32** | **3.21** | **2.74** | **3.26** |

Table 10: Chemical composition of Type I/II cement from Lafarge North America, Joppa, IL for the year 2003

| **Month** | **CaO** (%) | **$SiO_2$** (%) | **$Al_2O_3$** (%) | **$Fe_2O_3$** (%) | **MgO** (%) | **$SO_3$** (%) | **Other** (%) |
|---|---|---|---|---|---|---|---|
| January | 63.80 | 20.90 | 4.60 | 2.70 | 2.90 | 2.60 | 2.50 |
| February | 63.50 | 20.90 | 4.80 | 2.70 | 3.10 | 2.60 | 2.40 |
| March | 63.80 | 20.70 | 4.50 | 2.70 | 3.20 | 2.60 | 2.50 |
| April | 63.60 | 20.70 | 4.60 | 2.70 | 3.20 | 2.60 | 2.60 |
| May | 63.60 | 20.80 | 4.70 | 2.80 | 3.00 | 2.60 | 2.50 |
| June | 63.80 | 20.80 | 4.60 | 2.80 | 2.90 | 2.60 | 2.50 |
| July | 63.90 | 20.90 | 4.60 | 2.90 | 2.80 | 2.60 | 2.30 |
| August | 63.40 | 20.60 | 4.60 | 3.00 | 3.50 | 2.60 | 2.30 |
| September | 63.60 | 20.80 | 4.50 | 2.90 | 3.30 | 2.60 | 2.30 |
| October | 63.40 | 20.50 | 4.50 | 2.80 | 3.30 | 2.70 | 2.80 |
| November | 63.10 | 20.40 | 4.50 | 2.80 | 3.40 | 2.70 | 3.10 |
| **Average** | **63.59** | **20.73** | **4.59** | **2.80** | **3.15** | **2.62** | **2.47** |

Table 11: Chemical composition of Type I/II cement from Lafarge North America, Alpena, MI for the year 2003

| **Month** | **CaO** (%) | **$SiO_2$** (%) | **$Al_2O_3$** (%) | **$Fe_2O_3$** (%) | **MgO** (%) | **$SO_3$** (%) | **Other** (%) |
|---|---|---|---|---|---|---|---|
| February | 64.90 | 20.80 | 4.70 | 2.60 | 2.30 | 2.40 | 2.30 |
| March | 65.40 | 20.50 | 4.90 | 2.70 | 2.40 | 2.80 | 1.30 |
| April | 65.30 | 20.40 | 4.70 | 2.70 | 2.30 | 2.40 | 2.20 |
| May | 65.30 | 20.40 | 4.80 | 2.80 | 2.20 | 2.50 | 2.00 |
| June | 65.50 | 20.40 | 4.80 | 2.70 | 2.20 | 2.50 | 1.90 |
| July | 65.70 | 20.70 | 4.70 | 2.60 | 2.20 | 2.50 | 1.60 |
| August | 65.60 | 20.70 | 4.70 | 2.60 | 2.30 | 2.60 | 1.50 |
| September | 65.70 | 20.60 | 4.70 | 2.60 | 2.20 | 2.50 | 1.70 |
| October | 65.70 | 20.70 | 4.70 | 2.60 | 2.20 | 2.50 | 1.60 |
| November | 65.60 | 20.90 | 4.80 | 2.70 | 2.30 | 2.50 | 1.20 |
| December | 65.70 | 21.10 | 4.70 | 2.60 | 2.10 | 2.50 | 1.30 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Average** | **65.49** | **20.65** | **4.75** | **2.65** | **2.25** | **2.52** | **1.73** |

Table 12: Chemical composition of Type III cement from Lafarge for the year 2003

| Month | CaO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | MgO (%) | $SO_3$ (%) | Other (%) |
|---|---|---|---|---|---|---|---|
| January | 63.90 | 20.00 | 4.60 | 2.50 | 2.30 | 3.50 | 3.20 |
| February | 63.80 | 20.20 | 4.60 | 2.60 | 2.30 | 3.50 | 3.00 |
| March | 63.50 | 19.90 | 4.50 | 2.60 | 2.30 | 3.70 | 3.50 |
| April | 63.50 | 19.90 | 4.50 | 2.60 | 2.30 | 3.70 | 3.50 |
| May | 64.10 | 20.20 | 4.60 | 2.70 | 2.40 | 3.50 | 2.50 |
| June | 64.30 | 19.90 | 4.60 | 2.70 | 2.40 | 3.50 | 2.60 |
| July | 64.30 | 19.90 | 4.60 | 2.70 | 2.40 | 3.50 | 2.60 |
| August | 64.50 | 20.40 | 4.60 | 2.50 | 2.20 | 3.60 | 2.20 |
| September | 64.70 | 20.00 | 4.70 | 2.70 | 2.40 | 3.40 | 2.10 |
| **Average** | **64.07** | **20.04** | **4.59** | **2.62** | **2.33** | **3.54** | **2.80** |

Table 13: Chemical composition of Hydraulic Cement, Portland Cement-Type I from Holcim, Mason City Plant for the year 2003

| Month | CaO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | MgO (%) | $SO_3$ (%) | Other (%) |
|---|---|---|---|---|---|---|---|
| January | 65.00 | 20.40 | 5.20 | 2.20 | 2.40 | 2.80 | 2.00 |
| February | 64.90 | 20.10 | 5.30 | 2.20 | 2.40 | 2.80 | 2.30 |
| March | 65.60 | 20.50 | 5.40 | 2.10 | 2.20 | 2.80 | 1.40 |
| April | 65.10 | 20.50 | 5.20 | 2.20 | 2.40 | 2.90 | 1.70 |
| May | 65.60 | 20.60 | 5.20 | 2.10 | 2.10 | 2.80 | 1.60 |
| June | 64.60 | 20.40 | 5.20 | 2.10 | 2.60 | 2.80 | 2.30 |
| July | 65.00 | 20.60 | 5.30 | 2.20 | 2.20 | 2.90 | 1.80 |
| August | 64.90 | 20.70 | 5.30 | 2.20 | 2.10 | 2.80 | 2.00 |
| September | 65.60 | 20.60 | 5.50 | 2.10 | 1.90 | 2.70 | 1.60 |
| November | 65.30 | 20.40 | 5.40 | 2.20 | 2.10 | 2.70 | 1.90 |
| December | 65.30 | 20.70 | 5.30 | 2.20 | 2.30 | 2.80 | 1.40 |
| **Average** | **65.17** | **20.50** | **5.30** | **2.16** | **2.25** | **2.80** | **1.82** |

Table 14: Chemical composition of Hydraulic Cement, Portland Cement-Type I, GU from Holcim, Clarksville for the year 2003

| Month | CaO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | MgO (%) | $SO_3$ (%) | Other (%) |
|---|---|---|---|---|---|---|---|
| April | 63.60 | 19.90 | 4.90 | 2.40 | 3.90 | 2.70 | 2.60 |
| July | 63.50 | 19.50 | 4.80 | 2.50 | 3.90 | 2.90 | 2.90 |
| August | 63.40 | 19.50 | 4.80 | 2.50 | 3.90 | 3.00 | 2.90 |
| September | 63.30 | 19.60 | 4.80 | 2.50 | 3.90 | 3.00 | 3.30 |
| October | 63.00 | 19.50 | 4.80 | 2.50 | 3.90 | 3.00 | 3.30 |
| November | 63.20 | 19.60 | 4.80 | 2.30 | 3.80 | 3.00 | 3.30 |
| December | 62.50 | 19.70 | 4.70 | 2.50 | 3.50 | 3.00 | 4.10 |
| **Average** | **63.21** | **19.61** | **4.80** | **2.46** | **3.83** | **2.94** | **3.20** |

Table 15: Chemical composition of Hydraulic Cement, Portland Cement-Type I LA Low Alkali from Holcim, Clarksville for the year 2003

| Month | CaO (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | MgO (%) | $SO_3$ (%) | Other (%) |
|---|---|---|---|---|---|---|---|
| January | 63.80 | 20.30 | 5.10 | 2.40 | 3.70 | 2.50 | 2.20 |
| February | 63.80 | 20.00 | 5.00 | 2.50 | 4.00 | 2.70 | 2.00 |
| March | 63.60 | 19.90 | 4.90 | 2.70 | 3.90 | 2.70 | 2.30 |
| April | 63.80 | 20.00 | 4.90 | 2.50 | 3.90 | 2.70 | 2.20 |
| May | 63.80 | 19.70 | 4.90 | 2.50 | 4.00 | 2.70 | 2.40 |
| June | 63.60 | 19.80 | 5.00 | 2.50 | 3.90 | 2.80 | 2.40 |
| July | 63.40 | 19.30 | 5.00 | 2.50 | 4.00 | 2.90 | 2.90 |
| August | 63.40 | 19.50 | 4.70 | 2.50 | 3.90 | 3.00 | 3.00 |
| September | 63.40 | 19.50 | 4.70 | 2.50 | 4.00 | 3.00 | 2.90 |
| October | 63.30 | 19.50 | 4.80 | 2.50 | 3.80 | 3.00 | 3.10 |
| November | 63.40 | 19.50 | 4.80 | 2.30 | 3.80 | 3.00 | 3.20 |
| December | 62.50 | 19.80 | 4.60 | 2.70 | 3.50 | 3.10 | 3.80 |
| **Average** | **63.48** | **19.73** | **4.87** | **2.51** | **3.87** | **2.84** | **2.70** |

Table 16: Chemical composition of Hydraulic Cement, Portland Cement-Type I from Holcim, Dundee Plant for the year 2003

| **Month** | **CaO** (%) | **$SiO_2$** (%) | **$Al_2O_3$** (%) | **$Fe_2O_3$** (%) | **MgO** (%) | **$SO_3$** (%) | **Other** (%) |
|---|---|---|---|---|---|---|---|
| January | 63.10 | 20.30 | 4.90 | 2.50 | 3.50 | 3.00 | 2.70 |
| February | 62.70 | 20.50 | 5.10 | 2.50 | 3.40 | 3.00 | 2.80 |
| March | 62.70 | 20.50 | 4.90 | 2.60 | 3.50 | 3.00 | 2.80 |
| April | 62.80 | 20.40 | 4.90 | 2.60 | 3.50 | 3.10 | 2.70 |
| May | 62.90 | 20.30 | 5.10 | 2.60 | 3.50 | 3.00 | 2.60 |
| June | 62.90 | 20.40 | 5.00 | 2.60 | 3.50 | 3.00 | 2.60 |
| July | 62.20 | 20.20 | 5.10 | 2.60 | 3.60 | 3.00 | 3.30 |
| August | 62.10 | 20.20 | 5.00 | 2.60 | 3.60 | 3.00 | 3.50 |
| September | 62.10 | 19.90 | 5.00 | 2.60 | 3.50 | 3.10 | 3.80 |
| October | 61.90 | 20.00 | 5.00 | 2.40 | 3.40 | 3.00 | 4.30 |
| November/December | 61.90 | 19.90 | 5.20 | 2.40 | 3.50 | 3.00 | 4.10 |
| **Average** | **62.48** | **20.24** | **5.02** | **2.55** | **3.50** | **3.02** | **3.20** |

Table 17: Chemical composition of Hydraulic Cement, Portland Cement-Type I from Holcim, St. Lawrence Cement Plant for the year 2003

| **Month** | **CaO** (%) | **$SiO_2$** (%) | **$Al_2O_3$** (%) | **$Fe_2O_3$** (%) | **MgO** (%) | **$SO_3$** (%) | **Other** (%) |
|---|---|---|---|---|---|---|---|
| March | 63.80 | 20.70 | 5.60 | 2.20 | 2.60 | 3.50 | 1.60 |
| June | 63.50 | 20.60 | 5.50 | 2.30 | 2.50 | 3.30 | 2.30 |
| July | 63.50 | 20.40 | 5.50 | 2.30 | 2.50 | 3.30 | 2.50 |
| August | 63.30 | 20.20 | 5.40 | 2.30 | 2.60 | 3.70 | 2.50 |
| September | 62.50 | 19.60 | 5.40 | 2.20 | 2.60 | 3.80 | 3.90 |
| October | 63.10 | 20.30 | 5.50 | 2.30 | 2.60 | 3.90 | 2.30 |
| November | 63.00 | 20.10 | 5.50 | 2.30 | 2.50 | 4.10 | 2.50 |
| December | 63.30 | 20.00 | 5.40 | 2.20 | 2.50 | 4.30 | 2.30 |
| **Average** | **63.25** | **20.24** | **5.48** | **2.26** | **2.55** | **3.74** | **2.49** |

Table 18: Chemical composition of Hydraulic Cement, Portland Cement-Type I, II from Holcim-Theodore, Alabama Plant for the year 2003

| **Month** | **CaO** (%) | **$SiO_2$** (%) | **$Al_2O_3$** (%) | **$Fe_2O_3$** (%) | **MgO** (%) | **$SO_3$** (%) | **Other** (%) |
|---|---|---|---|---|---|---|---|
| January | 64.50 | 20.80 | 4.80 | 3.50 | 1.70 | 2.80 | 1.90 |
| February | 64.40 | 20.80 | 4.90 | 3.40 | 1.60 | 2.80 | 2.10 |
| March | 64.60 | 20.70 | 4.90 | 3.30 | 2.00 | 2.80 | 1.70 |
| April | 64.40 | 20.80 | 4.90 | 3.40 | 1.60 | 2.80 | 2.10 |
| May | 65.00 | 21.30 | 4.90 | 3.20 | 1.40 | 3.20 | 1.00 |
| June | 64.20 | 20.70 | 4.60 | 3.20 | 1.80 | 3.30 | 2.20 |
| July | 64.50 | 20.50 | 4.80 | 3.20 | 1.90 | 3.20 | 1.90 |
| August | 64.50 | 20.60 | 4.80 | 3.20 | 1.90 | 3.30 | 1.70 |
| September | 64.60 | 20.60 | 5.10 | 3.40 | 1.50 | 3.30 | 1.50 |
| October | 64.50 | 20.50 | 4.90 | 3.30 | 1.30 | 3.30 | 2.20 |
| November | 64.50 | 20.50 | 4.90 | 3.30 | 1.30 | 3.30 | 2.20 |
| December | 64.30 | 20.80 | 4.80 | 3.30 | 1.50 | 3.30 | 2.00 |
| **Average** | **64.50** | **20.72** | **4.86** | **3.31** | **1.63** | **3.12** | **1.88** |

Table 19: Chemical composition of Hydraulic Cement, Blended Cement-Type GU, ISM from Holcim-Mason City Plant for the year 2003

| **Month** | **CaO** (%) | **$SiO_2$** (%) | **$Al_2O_3$** (%) | **$Fe_2O_3$** (%) | **MgO** (%) | **$SO_3$** (%) | **Other** (%) |
|---|---|---|---|---|---|---|---|
| October | - | - | - | - | 2.20 | 2.70 | 95.10 |

Table 20: Chemical composition of Type I Cement, St. Marys Cement for the year 2003

| **Month** | **CaO** (%) | **$SiO_2$** (%) | **$Al_2O_3$** (%) | **$Fe_2O_3$** (%) | **MgO** (%) | **$SO_3$** (%) | **Other** (%) |
|---|---|---|---|---|---|---|---|
| January | 62.81 | 19.77 | 5.32 | 2.53 | 2.78 | 3.97 | 2.82 |
| February | 62.90 | 19.57 | 5.30 | 2.54 | 2.80 | 3.96 | 2.93 |
| March | 62.67 | 19.48 | 5.18 | 2.53 | 2.78 | 3.96 | 3.40 |
| April | 62.75 | 19.43 | 5.13 | 2.49 | 2.73 | 4.01 | 3.46 |
| May | 62.72 | 19.33 | 5.11 | 2.55 | 2.73 | 4.08 | 3.48 |
| June | 62.77 | 19.62 | 5.21 | 2.55 | 2.76 | 4.03 | 3.06 |
| July | 62.83 | 19.65 | 5.24 | 2.58 | 2.80 | 4.01 | 2.89 |
| August | 62.55 | 19.46 | 5.26 | 2.76 | 2.81 | 4.09 | 3.07 |
| September | 62.58 | 19.37 | 5.20 | 2.71 | 2.84 | 4.20 | 3.10 |
| October | 62.70 | 19.51 | 5.21 | 2.74 | 2.85 | 4.14 | 2.85 |
| November | 62.70 | 19.57 | 5.17 | 2.80 | 2.91 | 4.13 | 2.72 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| December | 62.49 | 19.42 | 5.11 | 2.78 | 2.93 | 4.23 | 3.04 |
| **Average** | **62.71** | **19.52** | **5.20** | **2.63** | **2.81** | **4.07** | **3.07** |

Table 21: Chemical composition of Type I Cement, CEMEX Charlevoix Plant, MI, for the year 2003

| **Month** | **CaO (%)** | **$SiO_2$ (%)** | **$Al_2O_3$ (%)** | **$Fe_2O_3$ (%)** | **MgO (%)** | **$SO_3$ (%)** | **Other (%)** |
|---|---|---|---|---|---|---|---|
| January | 63.20 | 19.33 | 5.49 | 2.68 | 4.26 | 3.31 | 1.73 |
| February | 62.47 | 19.31 | 5.62 | 2.76 | 4.03 | 3.29 | 2.52 |
| March | 62.31 | 19.15 | 5.64 | 2.78 | 4.02 | 3.33 | 2.77 |
| April | 62.19 | 19.31 | 5.64 | 2.74 | 3.87 | 3.28 | 2.97 |
| May | 62.47 | 19.36 | 5.66 | 2.59 | 3.91 | 3.18 | 2.83 |
| June | 63.28 | 19.60 | 5.67 | 2.44 | 3.72 | 2.89 | 2.40 |
| July | 63.34 | 19.90 | 5.55 | 2.36 | 3.68 | 2.90 | 2.27 |
| August | 63.32 | 19.81 | 5.47 | 2.38 | 3.88 | 2.88 | 2.26 |
| September | 62.83 | 19.59 | 5.42 | 2.27 | 3.86 | 2.91 | 3.12 |
| October | 62.64 | 19.89 | 5.40 | 2.25 | 3.68 | 2.88 | 3.26 |
| November | 62.90 | 20.14 | 5.36 | 2.16 | 3.66 | 2.90 | 2.88 |
| December | 63.06 | 20.17 | 5.33 | 2.15 | 3.72 | 3.15 | 2.42 |
| **Average** | **62.83** | **19.63** | **5.52** | **2.46** | **3.86** | **3.08** | **2.62** |

Table 22: Chemical composition of Type I Cement, Dixon-Marquette Cement for the year 2002

| **Oxide** | **Average Content (%)** |
|---|---|
| Lime (CaO) | 62.47 |
| Silica ($SiO_2$) | 20.43 |
| Alumina ($Al_2O_3$) | 4.56 |
| Ferric oxide ($Fe_2O_3$) | 3.28 |
| Magnesia (MgO) | 3.62 |
| Sulfur Trioxide ($SO_3$) | 3.53 |
| Other | 2.11 |

Table 23: Chemical composition of Type II Cement, Dixon-Marquette Cement for the year 2002

| **Oxide** | **Average Content (%)** |
|---|---|
| Lime (CaO) | 63.00 |
| Silica ($SiO_2$) | 20.78 |
| Alumina ($Al_2O_3$) | 4.33 |

| | |
|---|---|
| Ferric oxide ($Fe_2O_3$) | 3.43 |
| Magnesia (MgO) | 3.72 |
| Sulfur Trioxide ($SO_3$) | 3.32 |
| Other | 1.42 |

Table 24: Chemical composition of Type III Cement, Dixon-Marquette Cement for the year 2002

| Oxide | Average Content (%) |
|---|---|
| Lime (CaO) | 62.20 |
| Silica ($SiO_2$) | 20.26 |
| Alumina ($Al_2O_3$) | 4.56 |
| Ferric oxide ($Fe_2O_3$) | 3.24 |
| Magnesia (MgO) | 3.77 |
| Sulfur Trioxide ($SO_3$) | 4.23 |
| Other | 1.74 |

Table 25: Chemical composition of Type ISM Cement, Dixon-Marquette Cement for the year 2002

| Oxide | Average Content (%) |
|---|---|
| Lime (CaO) | 58.93 |
| Silica ($SiO_2$) | 22.83 |
| Alumina ($Al_20_3$) | 3.93 |
| Ferric oxide ($Fe_2O_3$) | 2.84 |
| Magnesia (MgO) | 5.33 |
| Sulfur Trioxide ($SO_3$) | 2.90 |
| Other | 3.24 |

*Chemical Composition of Supplementary Cementitious Materials*

Cementitious materials used in JPCPs in Wisconsin include ground granulated blast furnace slag (GGBFS) and fly ash. Lafarge and Holcim produce the slag. Tables 26 to 29 summarize the chemical composition of Lafarge and Holcim slag.

Table 26: Chemical composition of Slag from Lafarge, NewCem Cement, South Chicago for the year 2002

| Month | Sulfide (S) (%) | $SO_3$ (%) |
|---|---|---|
| November | 1.06 | 0.02 |
| December | 1.00 | 0.00 |

| | | |
|---|---|---|
| **Average** | **1.03** | **0.01** |

Table 27: Chemical composition of Slag from Lafarge, NewCem Cement for the year 2003

| Month | Sulfide (S) (%) | $SO_3$ (%) |
|---|---|---|
| March | 1.00 | 0.00 |
| May | 1.00 | 0.00 |
| June | 1.00 | 0.00 |
| August | 1.00 | 0.00 |
| September | 1.00 | 0.00 |
| October | 1.00 | 0.00 |
| November | 1.00 | 0.00 |
| **Average** | **1.00** | **0.00** |

Table 28: Chemical composition of Slag from Lafarge, NewCem Cement, Joppa, IL for the year 2003

| Month | Sulfide (S) (%) | $SO_3$ (%) |
|---|---|---|
| January | 0.98 | 0.20 |
| February | 0.98 | 0.20 |
| March | 0.98 | 0.20 |
| April | 0.98 | 0.20 |
| June | 0.95 | 0.20 |
| July | 0.97 | 0.13 |
| August | 1.00 | 0.12 |
| September | 0.93 | 0.22 |
| October | 0.91 | 0.21 |
| November | 0.96 | 0.16 |
| **Average** | **0.98** | **0.18** |

Table 29: Chemical composition of Slag from Holcim, SkyWay GranCem Cement for the year 2003

| Month | Sulfide (S) (%) | $SO_3$ (%) |
|---|---|---|
| February | 1.00 | 0.60 |
| March | 1.00 | 0.70 |
| April | 1.00 | 0.50 |
| May | 1.00 | 0.40 |
| June | 1.00 | 0.30 |
| July | 1.00 | 0.20 |
| August | 1.00 | 0.00 |
| September | 1.02 | 0.18 |

| | | |
|---|---|---|
| October | 1.10 | 0.12 |
| December | 1.00 | 0.20 |
| **Average** | **1.01** | **0.32** |

Fly ash type C is used in JPCPs with a maximum of 30% of the cementitious materials. Fly ash types C and F are produced by the power industry (e.g., WE Energies). The chemical composition of the fly ash is summarized in Tables 30 to 32.

Table 30: Chemical composition of WE fly ash (Personal Communication with Bloom Consultants, 2004)

| Source | ASTM C 618 Class F | ASTM C 618 Class C | OCPP Units 5-6 | OCPP Units 7-8 | PIPP Units 1-4 | PIPP Units 5-6 | PIPP Units 7-9 | PPPP | VAPP |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ % | - | - | 36.1 | 34.3 | 40.4 | 36.9 | 37.0 | 41.4 | 39.27 |
| $Al_2O_2$ % | - | - | 19.5 | 19.4 | 18.5 | 18.1 | 18.6 | 21.8 | 15.93 |
| $Fe_2O_3$ % | - | - | 6.0 | 5.7 | 4.2 | 3.6 | 5.5 | 5.6 | 4.57 |
| $SiO_2+Al_2O_3+Fe_2O_3$ % | 70.0 Min | 50.0 Min | 61.6 | 59.4 | 63.1 | 58.6 | 61.1 | 68.8 | 59.77 |
| $SO_3$ % | 5.0 Max | 5.0 Max | 1.6 | 1.4 | 0.6 | 0.7 | 2.4 | 1.4 | 1.11 |
| CaO % | - | - | 24.3 | 25.8 | 3.0 | 2.9 | 19.5 | 19.3 | 3.31 |
| Moisture Content % | 3.0 Max | 3.0 Max | 0 | 0 | 0 | 0.1 | 0 | 0.0 | 0.00 |
| LOI % | 6.0 Max* | 6.0 Max | 0.1 | 0.3 | 28.0 | 33.2 | 0.9 | 0.8 | 31.31 |
| Available Alkali as $Na_2O$ % | AASHTO M 295-00 1.5 Max | | 1.3 | 1.4 | 0.7 | 0.7 | 1.8 | 1.3 | -0.6 |

Legend: OCPP: Oak Creek Power Plant, PIPP: Presque Isle Power Plant, PPPP: Pleasant Prairie Power Plant VAPP: Valley Power Plant.

*The use of class F Pozzolan containing up to 12.0% loss on ignition may be approved by the user if either acceptable performance records or laboratory test results are made available.

Table 31: Chemical composition of WE fly ash, Ramme and Tharaniyil (1999)

| Source | ASTM C618 Class F | ASTM C618 Class C | OCPP Unit 8 | PIPP Units 1-6 | PIPP Units 7-9 | PPPP | PWPP Units 2-3 | VAPP |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ % | - | - | 37.77 | 56.93 | 34.61 | 35.4 | 45.41 | 42.62 |
| $Al_2O_2$ % | - | - | 19.5 | 28.2 | 21.3 | 18.9 | 23.60 | 18.36 |
| $Fe_2O_3$ % | - | - | 5.79 | 4.7 | 5.85 | 5.94 | 11.96 | 5.71 |
| $SiO_2$+$Al_2O_3$+$Fe_2O_3$ % | 70.0 Min | 50.0 Min | 63.06 | 89.83 | 61.76 | 60.24 | 80.97 | 66.69 |
| $SO_3$ % | 5.0 Max | 5.0 Max | 1.19 | 0.58 | 2.14 | 1.96 | 0.54 | 0.73 |
| CaO % | - | - | 23.56 | 3.12 | 20.03 | 26.9 | 2.48 | 2.26 |
| Moisture Content % | 3.0 Max | 3.0 Max | 0.05 | 0.10 | 0.16 | 0.08 | 0.23 | 0.29 |
| LOI % | 6.0 Max * | 6.0 Max | 0.42 | 13.60 | 0.62 | 0.37 | 11.86 | 26.00 |
| Available Alkali as $Na_2O$ % | 1.5Max | 1.5 Max | - | 1.38 | 2.51 | 0.97 | - | - |

Legend: OCPP: Oak Creek Power Plant, PIPP: Presque Isle Power Plant, PPPP: Pleasant Prairie Power Plant, PWPP: Port Washington Power Plant, VAPP: Valley Power Plant

*The use of class F Pozzolan containing up to 12.0% loss on ignition may be approved by the user if either acceptable performance records or laboratory test results are made available.

Table 32: Typical chemical composition of fly ash, Ramme and Tharaniyil (1999)

| Compounds | Class F Fly Ash | | Class C Fly Ash | | Portland Cement | |
|---|---|---|---|---|---|---|
| | Typical* | ASTM C-618 | Typical** | ASTM C-618 | Typical*** | ASTM C-150 |
| $SiO_2$ | 51.00 | - | 35.40 | - | 20.25 | - |
| $Al_2O_2$ | 22.63 | - | 18.90 | - | 4.25 | - |
| $Fe_2O_3$ | 4.50 | - | 5.94 | - | 2.59 | - |
| $SiO_2+Al_2O_3+Fe_2O_3$ | 78.13 | 70.0 (min%) | 60.24 | 50.0 (min%) | - | - |
| CaO (Lime) | 2.71 | - | 26.9 | - | 63.6 | - |
| MgO | 1.49 | - | 4.46 | - | 2.24 | 6.0 (max%) |
| $SO_3$ | 0.52 | 5.0 (max%) | 1.96 | 5.0 (max%) | - | 3.0 (max%) |
| Loss on Ignition | 12.91 | 6.0 | 0.37 | 6.0 | 0.55 | 3 (max%) |
| Moisture Content | 0.21 | 3.0 (max%) | 0.08 | 3.0 (max%) | - | - |
| Insoluble Residue | - | - | - | - | - | 0.75 (max%) |
| Available Alkalies as Equivalent $Na_2O$ | 1.38 | 1.50 (max%) | 0.97 | 1.50 (max%) | 0.20 | - |

*Class F Fly Ash from PIPI Units 5-6
**Class C Fly Ash from PPPP
***Type 1 Portland Cement from Lafarge Corporation

*Aggregates*

The most common aggregate type in Wisconsin is obtained from limestone (calcium carbonate) and dolomite (carbonate with calcium and magnesium carbonate). There is high variability of the properties of aggregates obtained from hard rock (basalt and granite). High variability in properties is also associated with gravel of igneous rock origin and from limestone dolomite. Figure 1 show the distribution of bedrock in Wisconsin. (see page 5 for base/subbase materials).

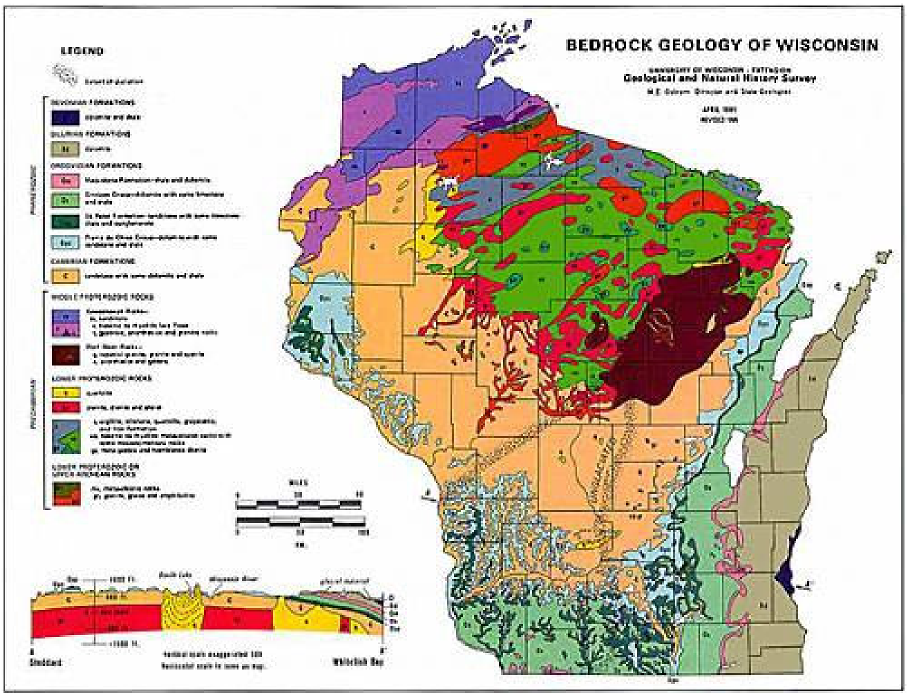



Figure 1: the distribution of bedrock in Wisconsin.

Wisconsin DOT specifications require the use of fine and coarse aggregates in concrete mixes for pavements. Fine aggregate can be a combination of sand with fine gravel, crushed gravel, or crushed stone. Size requirements for well graded fine aggregate specified by WisDOT are given in Table 33 below:

Table 33: Size requirement for fine aggregates

| **Sieve Size** | **% Passing** |
|---|---|
| $\frac{3}{8}$ (9.5 mm) | 100 |
| No. 4 (4.75 mm) | 90 – 100 |
| No. 16 (1.18 mm) | 45 – 85 |
| No. 50 (300 μm) | 5 – 30 |
| No. 100 (150 μm) | 0 – 10 |

Table 34 presents a summary of the composition of fine aggregate samples obtained from different locations in Wisconsin. Majority of these samples consist of high percentage of carbonate.

The use of the recycled concrete in the coarse aggregate fraction for concrete pavements is allowed by WisDOT specifications. However, the concrete pavement contractors in Wisconsin have not used it during the last 10 years. The reason is that the recycled concrete aggregate usually fails the soundness and wear test. The common practice is to blend the recycled concrete aggregate with the available local materials and used it in the subbase/base course layers.

Table 34: Composition of fine aggregate samples obtained from different locations in Wisconsin (after Eggen and Brittnacher, 2004).

| Source Name | Pit or Quarry | Fine Fraction (passing sieve #4) Composition (%) | | | |
|---|---|---|---|---|---|
| | | Quartz | Carbonate | Feldspar | Other Lithics |
| 19th Hole | Q | 4 | 94 | - | 2 |
| Begin | P | 52 | 12 | 12 | 24 |
| Boone | Q | 37 | - | 47 | 16 |
| Bracket | Q | - | - | - | 100 |
| Brooks | P | 58 | - | 7 | 35 |
| Cepress | Q | 70 | - | 20 | 10 |
| Cisler | Q | 48 | 4 | 39 | 9 |
| Clockmaker | Q | 18 | 78 | - | 4 |
| Crooked Lake | P | 42 | - | 5 | 53 |
| Emerald | Q | 17 | 82 | - | 1 |
| Glenmore | Q | - | 100 | - | - |
| Globe | P | 30 | - | - | 70 |
| Harry's/Schmidt | P | 51 | - | 12 | 37 |
| Householder | Q | 36 | 53 | - | 11 |
| Kiehnau | Q | 1 | 98 | - | 1 |
| Kings Bluff | Q | 12 | 87 | - | 1 |
| Knight | Q | 12 | 83 | - | 5 |
| Kohlhoff | Q | 1 | 98 | - | 1 |
| Krueger | Q | 26 | 69 | - | 5 |
| Lutze | P | 19 | 72 | 2 | 7 |
| Mackville | Q | 5 | 83 | - | 12 |
| Marsalek | Q | 22 | 78 | - | 1 |
| Moser (Meyer) | Q | 10 | 89 | - | 1 |
| Myklbust | P | 52 | 19 | 5 | 24 |
| Spruce | P | 28 | 59 | 2 | 11 |
| Rudinger | Q | 1 | 99 | - | - |
| Sussex | Q | 1 | 94 | - | 4 |
| Thies | P | 37 | - | 13 | 50 |
| Tork | Q | 42 | - | 48 | 10 |
| Wetzel | Q | 6 | 88 | - | 6 |
| Dennis Johnson | Q | - | 95 | - | 5 |
| Elmwood | Q | 1 | 99 | - | - |
| Faulks | P | 38 | 22 | 27 | 13 |
| Haverland | Q | 1 | 98 | - | 1 |
| Johnson | P | 45 | - | 12 | 43 |
| Johnson Creek | Q | 1 | 98 | - | 1 |
| Crobar | P | 40 | 48 | 4 | 8 |
| Scott | P | 70 | - | 10 | 20 |

Coarse aggregate used in concrete pavements can be durable gravel, crushed gravel, crushed stone or crushed concrete free of an excess of thin or elongated pieces, frozen lumps, vegetation, deleterious substances or adherent coatings considered injurious. The size requirements for coarse aggregate specified by WisDOT are presented in Table 35.

Table 35: Size requirement for coarse aggregates

| **Sieve Size** | **% Passing** | |
|---|---|---|
| | Size No. 1 AASHTO No. 67 | Size No. 2 AASHTO No. 4 |
| 2 inch (50 mm) | – | 100 |
| 1½ inch (37.5 mm) | – | 90 – 100 |
| 1 inch (25 mm) | 100 | 20 – 55 |
| ¾ inch (19 mm) | 90 – 100 | 0 – 15 |
| ⅜ (9.5 mm) | 20 – 55 | 0 – 5 |
| No. 4 (4.75 mm) | 0 – 10 | – |
| No. 8 (2.36 mm) | 0 – 5 | – |

Table 36 presents a summary of the composition of coarse aggregate samples obtained from different locations in Wisconsin. Majority of these samples consist of high percentage of carbonate.

Table 36: Composition of coarse aggregate samples obtained from different locations in Wisconsin (after Eggen and Brittnacher, 2004)

| Source Name | WDOT District | County | Coarse Fraction (retained on #4 sieve) Composition (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Feslic Plutonic | Mafic Plutonic | Feslic Volcanic | Mafic Volcanic | Sili-clastic | Car-bonate | Chert | Non foliated Meta-morphic | Foliated Meta-morphic |
| 19th Hole | 1 | Iowa | - | - | - | - | - | 98 | 2 | - | - |
| Begin | 7 | Langlade | 18 | 14 | 4 | 24 | 16 | 20 | - | 4 | - |
| Boone | 6 | Clark | 93 | - | - | - | 2 | - | - | 15 | - |
| Bracket | 7 | Iron | - | - | - | - | 100 | - | - | - | - |
| Brooks | 7 | Forest | 23 | 31 | 1 | 17 | 8 | 2 | - | 15 | 3 |
| Cepress | 4 | Wood | 93 | 7 | - | - | - | - | - | - | - |
| Cisler | 4 | Marathon | 86 | - | - | - | 10 | - | - | 4 | - |
| Clockmaker | 5 | Vemon | - | - | - | - | - | 99 | 1 | - | - |
| Crooked Lake | 8 | Bayfield | 3 | 34 | 10 | 27 | 23 | - | - | 3 | - |
| Emerald | 6 | St. Croix | - | - | - | - | 1 | 99 | - | - | - |
| Glenmore | 3 | Brown | - | - | - | - | - | 100 | - | - | - |
| Globe | 7 | Iron | - | 12 | 36 | 27 | 25 | - | - | - | - |
| Harry's/ Schmidt | 7 | Vilas | 21 | 5 | 8 | 31 | 10 | - | - | 22 | 3 |
| Householder | 5 | Richland | - | - | - | - | 2 | 97 | 1 | - | - |
| Kiehnau | 3 | Door | - | - | - | - | - | 100 | - | - | - |
| Kings Bluff | 5 | LaCrosse | - | - | - | - | - | 100 | - | - | - |
| Knight | 1 | Green | - | - | - | - | - | 95 | 5 | - | - |
| Kohlhoff | 1 | Dodge | - | - | - | - | - | 100 | - | - | - |
| Krueger | 3 | Oconto | - | - | - | - | - | 100 | - | - | - |
| Lutze | 3 | Manitowoc | - | 4 | - | 1 | - | 95 | - | - | - |
| Mackville | 3 | Outagamie | - | - | - | - | - | 99 | 1 | - | - |
| Marsalek | 5 | Buffalo | - | - | - | - | - | 100 | - | - | - |
| Moser (Meyer) | 5 | Monroe | - | - | - | - | - | 99 | 1 | - | - |
| Myklbust | 1 | Sauk | 6 | 28 | 3 | 5 | 4 | 50 | - | 4 | - |
| Spruce | 3 | Oconto | 1 | 3 | - | 4 | 5 | 87 | - | - | - |
| Rudinger | 2 | Fond du Lac | - | - | - | - | - | 91 | 9 | - | - |
| Sussex | 2 | Waukesha | - | - | - | - | - | 100 | - | - | - |
| Thies | 7 | Lincoln | 9 | 28 | - | 31 | 15 | - | - | 17 | - |
| Tork | 4 | Wood | 96 | 4 | - | - | - | - | - | - | - |
| Wetzel | 5 | Crawford | - | - | - | - | - | 96 | 4 | - | - |
| Dennis Johnson | 1 | Lafayette | - | - | - | - | - | 100 | - | - | - |
| Elmwood | 6 | Pierce | - | - | - | - | - | 100 | - | - | - |
| Faulks | 4 | Waupaca | 34 | 7 | - | 16 | 3 | 34 | - | 6 | - |
| Haverland | 1 | Grant | - | - | - | - | - | 100 | - | - | - |
| Johnson | 8 | Polk | 9 | 18 | 11 | 41 | 15 | - | - | 6 | - |
| Johnson Creek | 2 | Jefferson | - | - | - | - | - | 100 | - | - | - |
| Crobar | 2 | Waukesha | - | 9 | - | 3 | 1 | 85 | - | 2 | - |

Table 37 presents the values of specific gravity of the coarse aggregates described in Table 36.

Table 37: Specific gravity of coarse aggregate.

| **Source Name** | **Coarse Aggregate Bulk Specific Gravity** |
|---|---|
| 19th Hole | 2.596 |
| Begin | 2.723 |
| Boone | 2.542 |
| Bracket | 2.665 |
| Brooks | 2.694 |
| Cepress | 2.614 |
| Cisler | 2.538 |
| Clockmaker | 2.655 |
| Crooked Lake | 2.831 |
| Emerald | 2.606 |
| Glenmore | 2.720 |
| Globe | 2.538 |
| Harry’s/Schmidt | 2.708 |
| Householder | 2.670 |
| Kiehnau | 2.773 |
| Kings Bluff | 2.549 |
| Knight | 2.567 |
| Kohlhoff | 2.755 |
| Krueger | 2.656 |
| Lutze | 2.777 |
| Mackville | 2.740 |
| Marsalek | 2.554 |
| Moser (Meyer) | 2.572 |
| Myklbust | 2.779 |
| Spruce | 2.687 |
| Rudinger | 2.764 |
| Sussex | 2.749 |
| Thies | 2.745 |
| Tork | 2.570 |
| Wetzel | 2.699 |
| Dennis Johnson | 2.532 |
| Elmwood | 2.701 |
| Faulks | 2.669 |
| Haverland | 2.488 |
| Johnson | 2.724 |
| Johnson Creek | 2.646 |
| Crobar | 2.680 |
| Scott | 2.688 |

**Construction**

Slip form paving is the predominant construction method of JPCPs in Wisconsin. The following are major points that characterize JPCP construction in Wisconsin:

*Curing Compounds*: Oil-based curing compounds are not allowed in concrete pavements in Wisconsin. Only water-based pigmented curing compounds are allowed. This type is beneficial in summer time. The disadvantage of using the water-based type arises in spring and fall since it delays curing by reflecting the sunlight.

*Cementitious Materials*: Use of slag and fly ash is allowed in concrete pavements while the use of silica fume rarely if ever used.

*Admixtures:* In 90% of the JPCP projects in Wisconsin, type A water reducing admixture is used. In rare cases, type D water reducing and retarding admixture is used. Air entrainer is also used in the concrete mixes for JPCPs. The required air content is 7% ± 1.5% when the concrete is tested in front of the slip form paver.

*Concrete Mixing and Delivery*: For main line paving, most contractors use central batch plant for mixing concrete and dump trucks for delivery. For handwork and extras (turn lanes and intersections), the delivery is usually done by ready mix trucks provided by a second party. The ready mixes are considered inferior when compared to central batch plant mixes. The variability of the ready mixes is about two times the variability of central batch plants. In addition, central batch plants have the capability of using slag and fly ash, which is not the case for ready mix plants.

*Type of Slip form Paving Machine*: The type of paving machine is one of the factors affecting the quality of constructed pavement. Heavy machines with dowel bar inserter are preferred. The level/amount of vibration depends on the machine type. For mixes with fly ash and slag, less vibration is needed since higher vibration levels will reduce the amount of entrained air at the pavement surface.

*Saw Cutting*: Saw cutting is very important since it is the mechanism to control random cracking. Two methods are used, the conventional wet cut and the early entry dry cut. The latter is picking up popularity in Wisconsin. The cut depth is also important in this case. In 90% of the projects in Wisconsin, the conventional wet cutting method is used. In about 10% of the projects (during hot weather), the early-entry dry cut is used. In this case 3 to 4 joints are skipped during the sawing process.

*Cold Weather*: Pavement construction during cold weather requires special care to protect the pavement. Protective covering should be used as soon as concrete is finished and sets sufficiently to prevent excessive surface marring. If the air temperature ranges from less than 28 to 22 $^{o}$F, then single layer of polyethylene should be used to cover the pavement surface. If the air temperature falls below 22 to 17 $^{o}$F, then double layer of polyethylene should be used. If the air temperature falls below 17 $^{o}$F, then 6" of loose dry straw or hay between 2 layers of polyethylene should be used. In JPCP projects in Wisconsin, the curing cover is usually applied within ½ hour and kept until the compressive strength of 3,000 psi is achieved. The curing cover is temporarily removed within 24 to 48 hours for saw cutting.

It should be noted that construction during extreme weather conditions is not common practice in Wisconsin. According to WCPA, the 6" loose dry straw or hay between 2 layers of polyethylene was used in two projects in the last 20 years.

**Limitations**

Some of the requested information and data on materials used for WisDOT projects are not available. The investigator discussed this issue with David Larson and Steven Krebs of WisDOT who agree that values for similar materials available in the literature can be used at this time. Testing on Wisconsin materials will be conducted in the future and the input parameters can be adopted. This includes the following:

1. Information on critical slab/subbase restraint stress and movement at sliding for local subbase and subgrade types

2. Coefficient of thermal expansion (CTE), thermal conductivity, and specific heat properties for coarse aggregate types available in Wisconsin.

3. Information on CTE of typical Wisconsin paving concrete

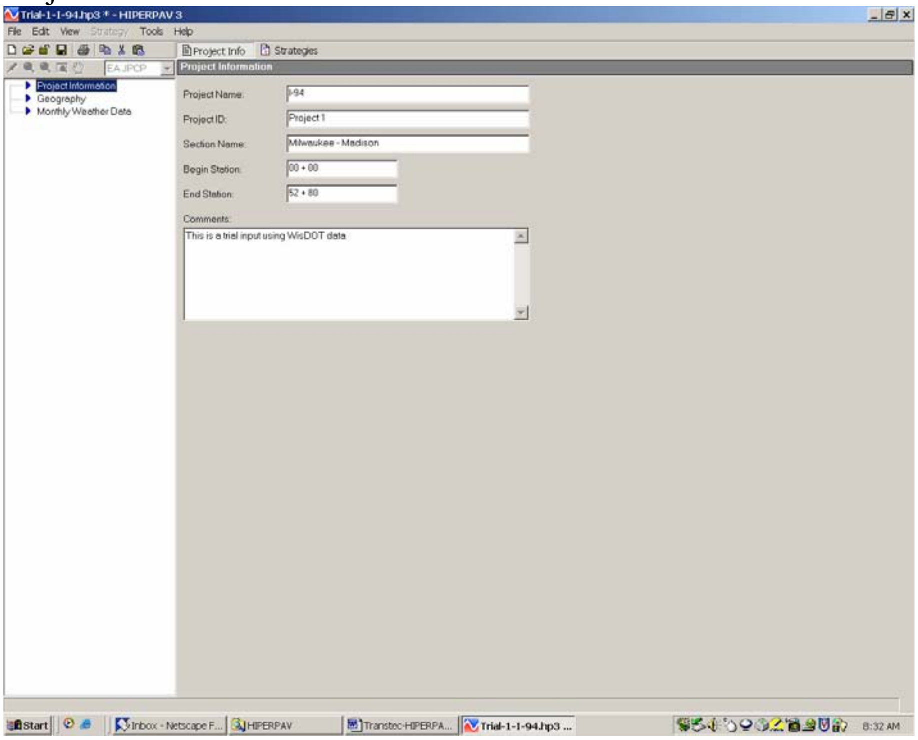
4. Information on strength conversion correlations between compressive and splitting tensile tests for Wisconsin materials

5. Information available on typical maturity relationships for Wisconsin concrete mixtures

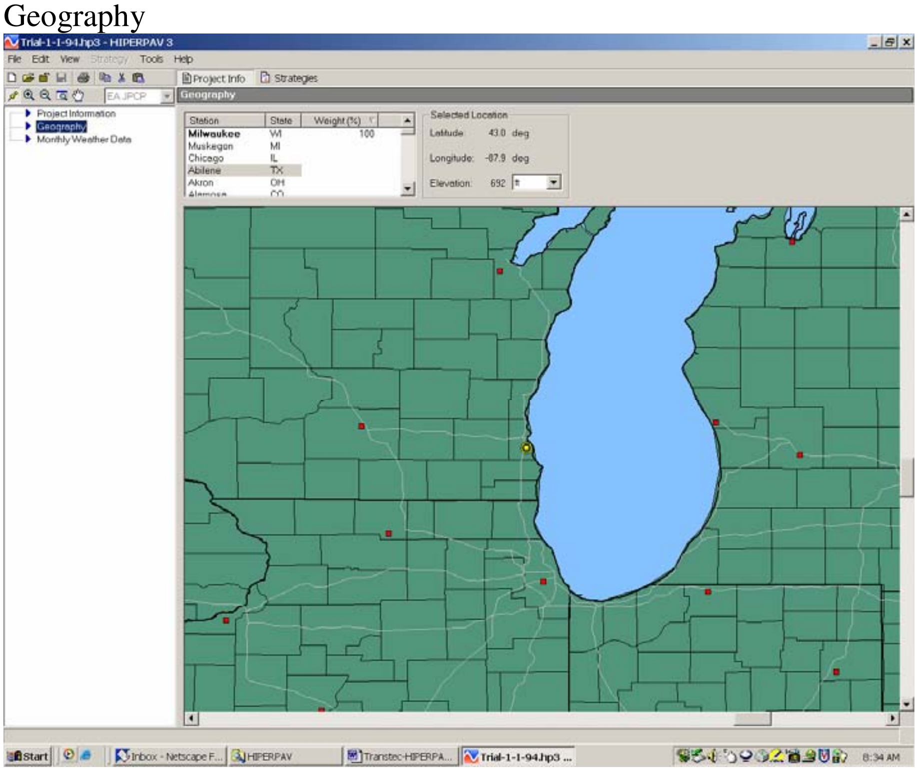
**HIPERPAV-Wisconsin Input Parameters**

The following is a presentation of typical input parameters for JPCPs in Wisconsin:

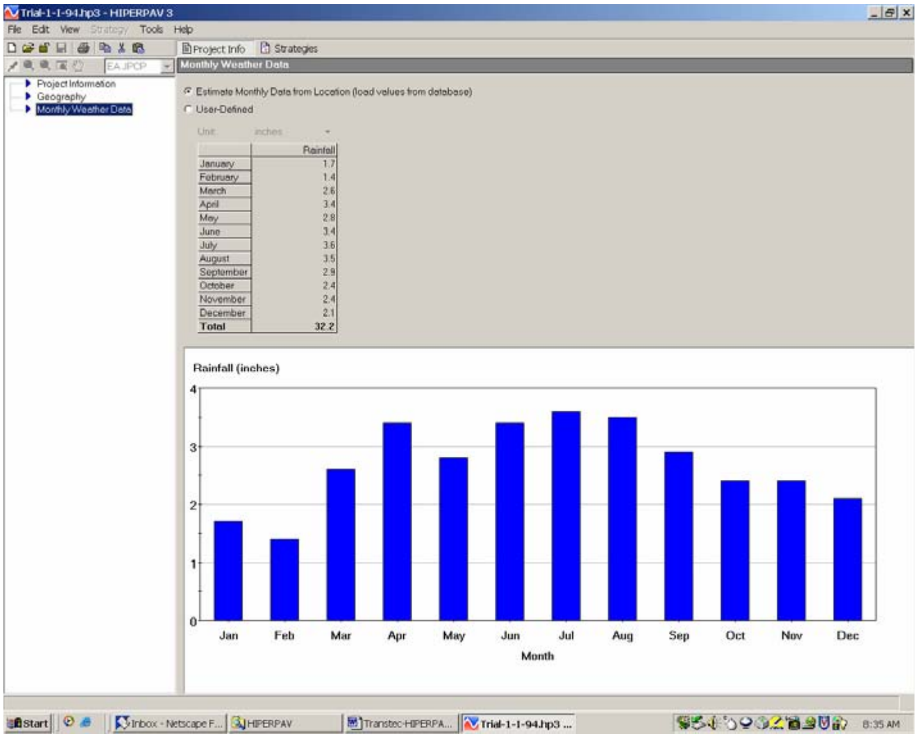
Project Information



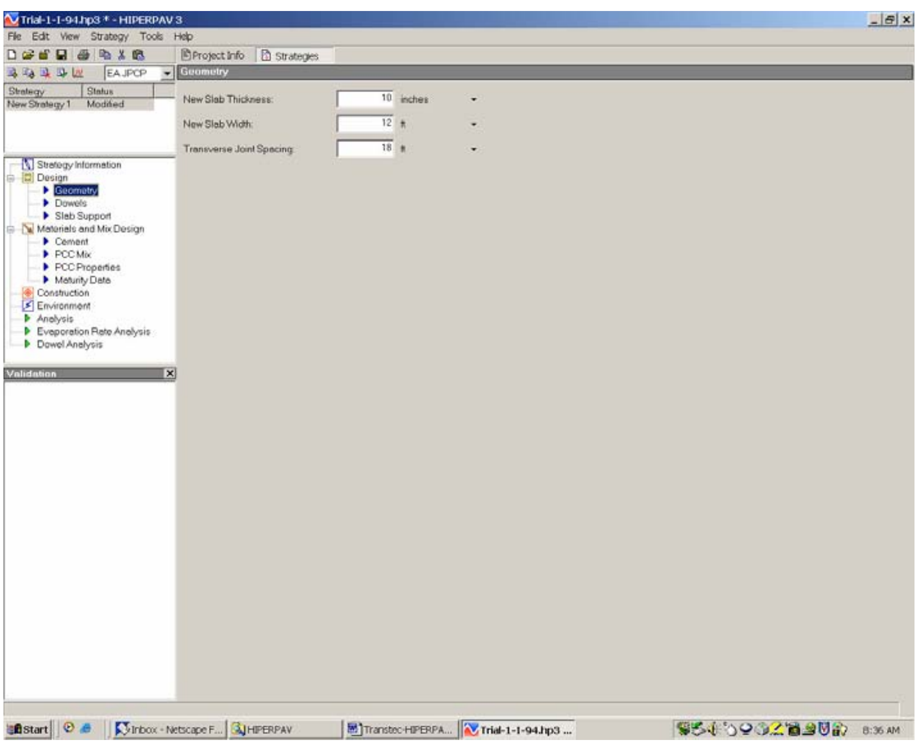

Geography



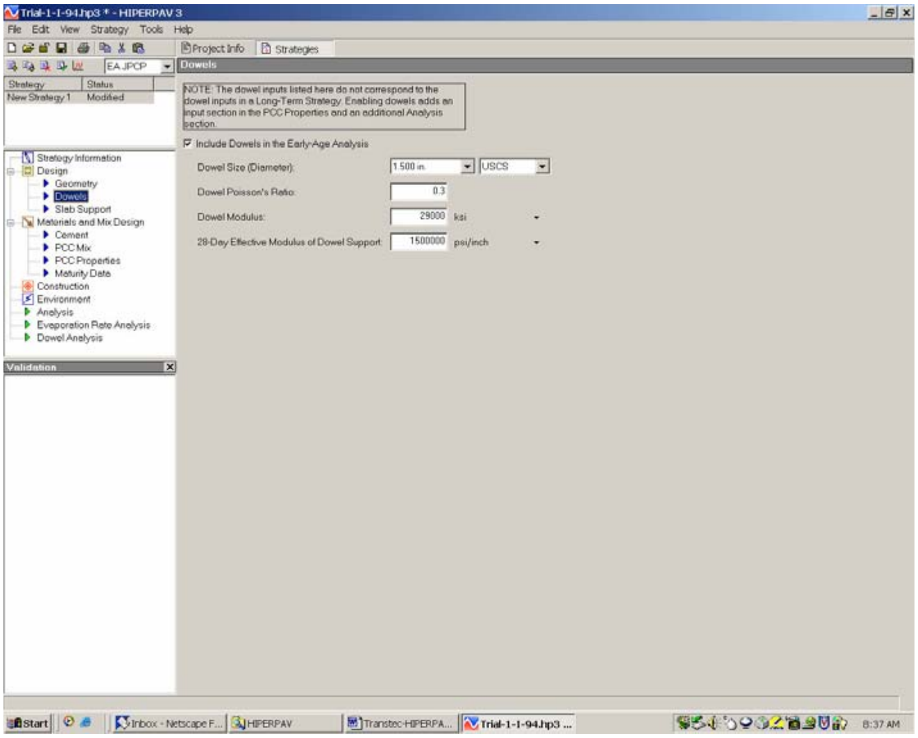
Monthly Weather Data:



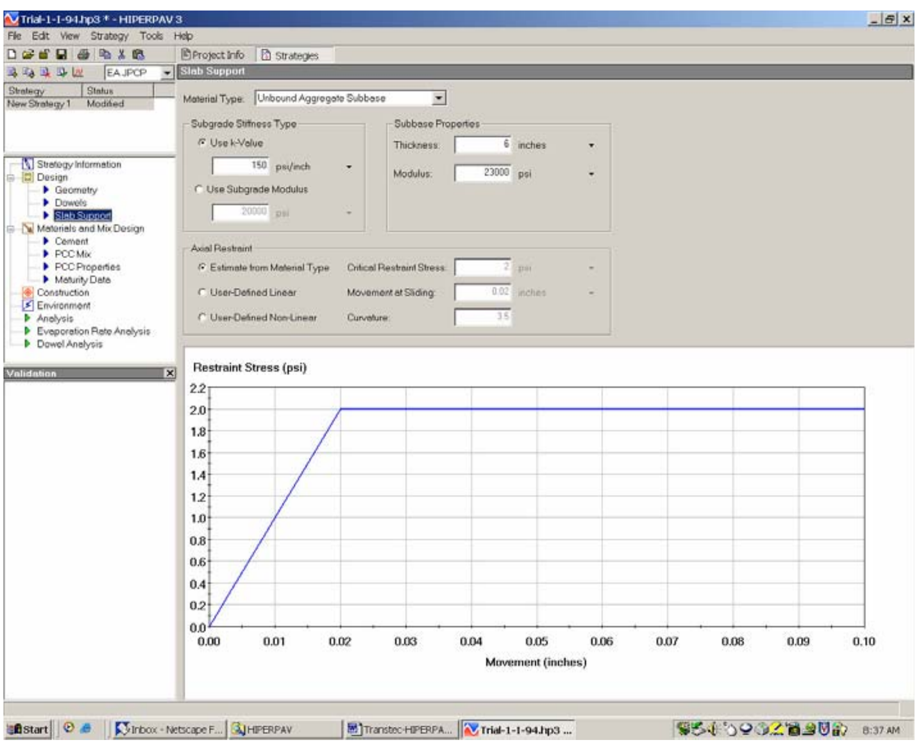

Design: Geom0etry



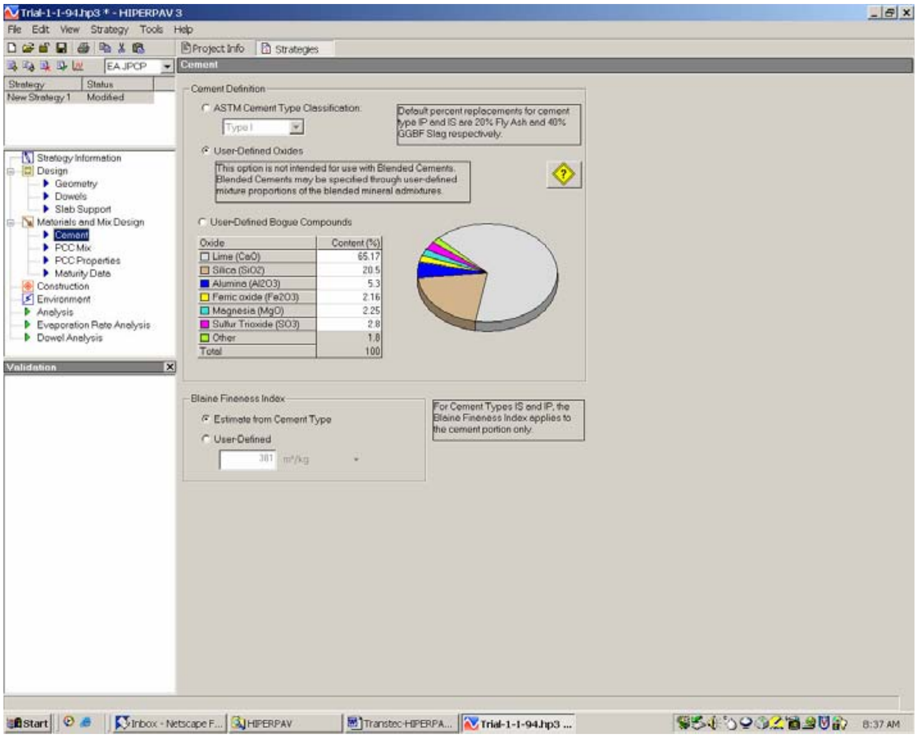
Design: Dowels



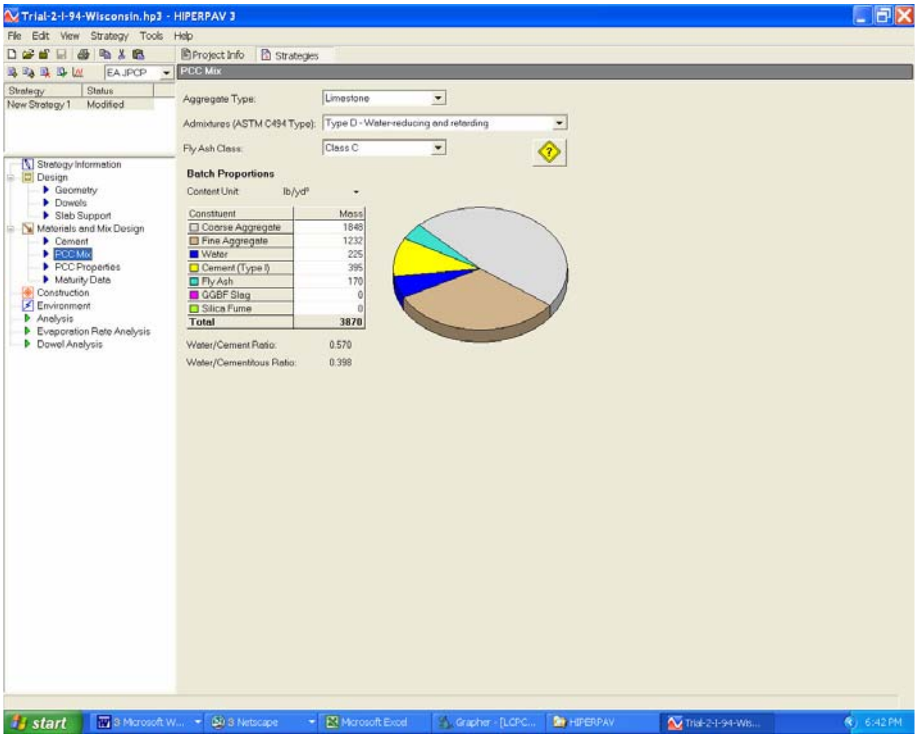

Design: Slab Support



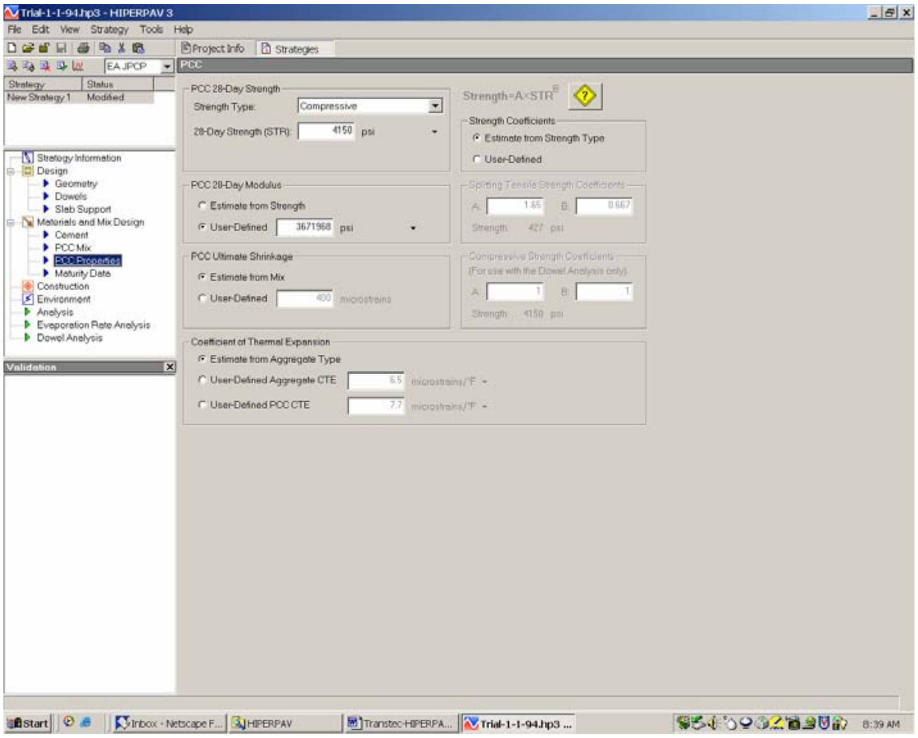
Materials and Mix Design: Cement



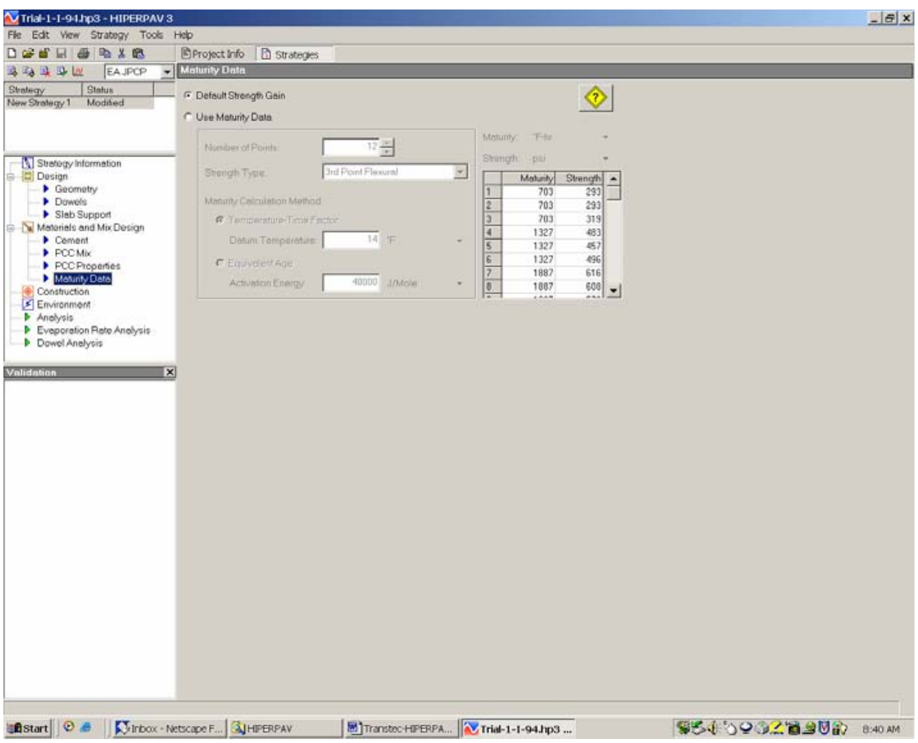

Materials and Mix Design: PCC Mix



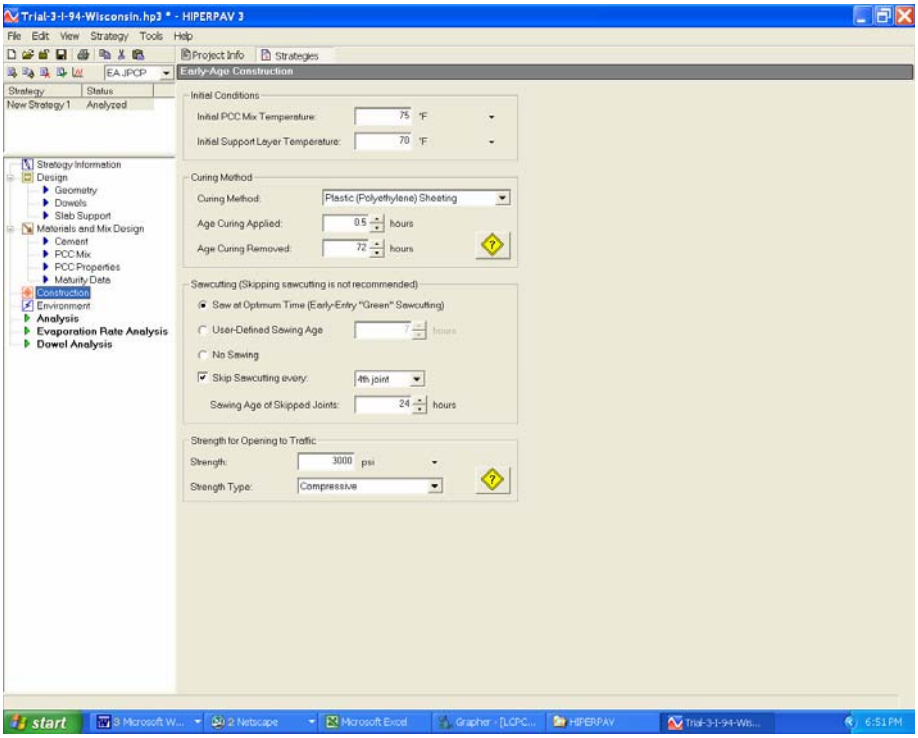
Materials and Mix Design: PCC Properties



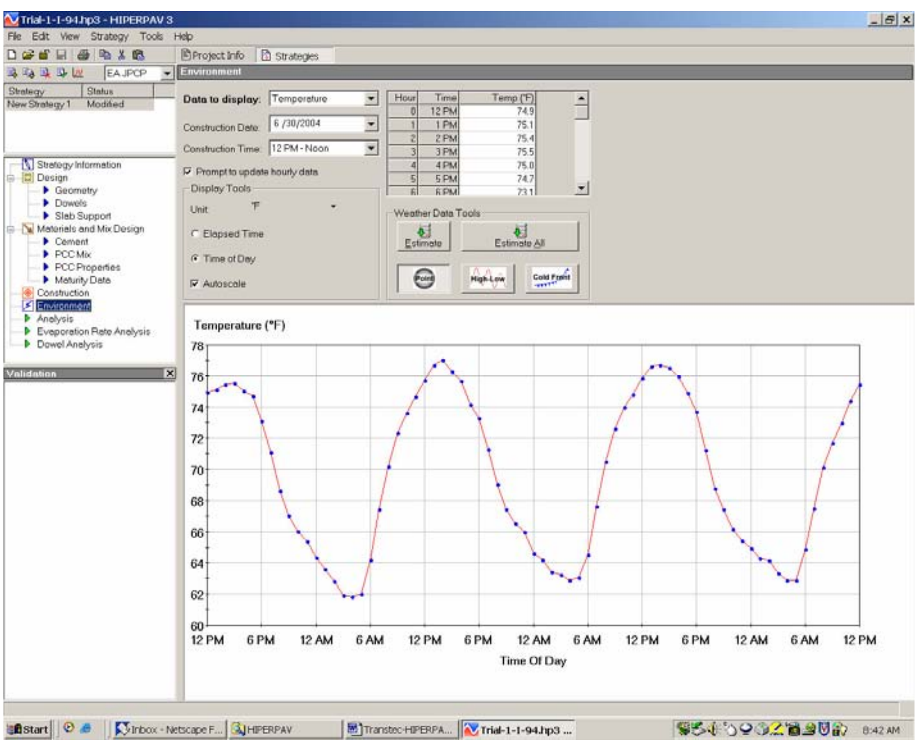

Materials and Mix Design: Maturity Data



Construction:




Environment:



The following is a summary of the cement chemical composition needed as input for HIPERPAV:

Table 38: Average chemical composition of Type I cement

| Company | $CaO$ (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $MgO$ (%) | $SO_3$ (%) | Other (%) |
|---|---|---|---|---|---|---|---|
| Holcim | 65.17 | 20.50 | 5.30 | 2.16 | 2.25 | 2.80 | 1.82 |
| Holcim | 63.21 | 19.61 | 4.80 | 2.46 | 3.83 | 2.94 | 3.20 |
| Holcim | 63.48 | 19.73 | 4.87 | 2.51 | 3.87 | 2.84 | 2.70 |
| Holcim | 62.48 | 20.24 | 5.02 | 2.55 | 3.50 | 3.02 | 3.20 |
| Holcim | 63.25 | 20.24 | 5.48 | 2.26 | 2.55 | 3.74 | 2.49 |
| St. Mary's | 62.71 | 19.52 | 5.20 | 2.63 | 2.81 | 4.07 | 3.07 |
| CEMEX | 62.83 | 19.63 | 5.52 | 2.46 | 3.86 | 3.08 | 2.62 |
| Dixon-Marquette | 62.47 | 20.43 | 4.56 | 3.28 | 3.62 | 3.53 | 2.11 |

Table 39: Average chemical composition of Type I/II cement

| Company | $CaO$ (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $MgO$ (%) | $SO_3$ (%) | Other (%) |
|---|---|---|---|---|---|---|---|
| Lafarge | 63.09 | 20.48 | 5.10 | 3.39 | 1.53 | 2.91 | 3.68 |
| Lafarge | 62.30 | 20.27 | 4.85 | 3.32 | 3.21 | 2.74 | 3.26 |
| Lafarge | 63.59 | 20.73 | 4.59 | 2.80 | 3.15 | 2.62 | 2.47 |
| Lafarge | 65.49 | 20.65 | 4.75 | 2.65 | 2.25 | 2.52 | 1.73 |
| Holcim | 64.50 | 20.72 | 4.86 | 3.31 | 1.63 | 3.12 | 1.88 |

Table 40: Average chemical composition of Type II cement

| Company | $CaO$ (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $MgO$ (%) | $SO_3$ (%) | Other (%) |
|---|---|---|---|---|---|---|---|
| Dixon-Marquette | 63.0 | 20.78 | 4.33 | 3.43 | 3.72 | 3.32 | 1.42 |

Table 41: Average chemical composition of Type III cement

| Company | $CaO$ (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $MgO$ (%) | $SO_3$ (%) | Other (%) |
|---|---|---|---|---|---|---|---|
| Lafarge | 64.07 | 20.04 | 4.59 | 2.62 | 2.33 | 3.54 | 2.80 |
| Dixon-Marquette | 62.2 | 20.26 | 4.56 | 3.24 | 3.77 | 4.23 | 1.74 |

Table 42: Average chemical composition of Hydraulic Cement, Blended Cement-Type GU, ISM

| Company | $CaO$ (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $MgO$ (%) | $SO_3$ (%) | Other (%) |
|---|---|---|---|---|---|---|---|
| Holcim | - | - | - | - | 2.20 | 2.70 | 95.10 |

Table 43: Average chemical composition of Type ISM Cement

| Company | $CaO$ (%) | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | $MgO$ (%) | $SO_3$ (%) | Other (%) |
|---|---|---|---|---|---|---|---|
| Dixon-Marquette | 58.93 | 22.83 | 3.93 | 2.84 | 5.33 | 2.9 | 3.24 |

**References**


Eggen, P, and Brittnacher, D., (2004). Determination of Influence on Support Strength of Crushed Aggregate Base Due to Gradational, Regional, and Source Variations, Draft Report, OMNNI Associates, Madison, WI.

Haifang Wen (2004). “Personal Communications,” Bloom Consultants, Milwaukee, WI

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# Appendix B

## HIPERPAV Wisconsin Weather Data

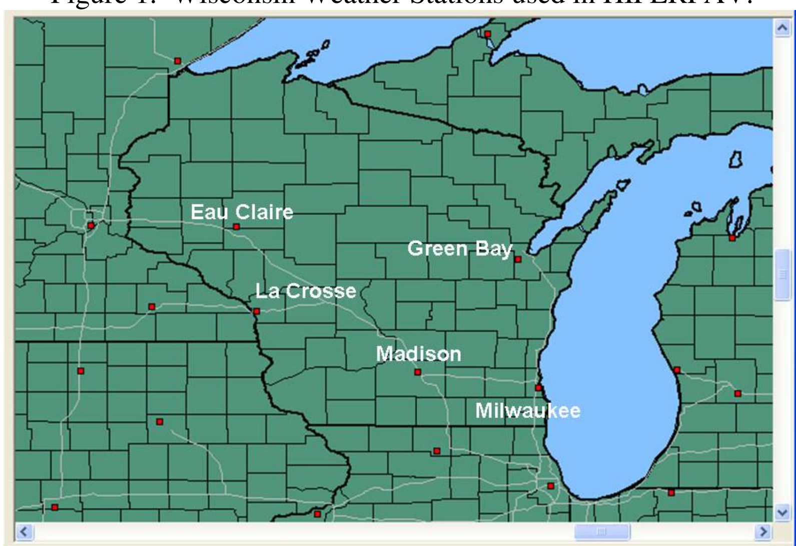
## INTRODUCTION

To increase accuracy in HIPERPAV's prediction of weather conditions across the state of Wisconsin, more weather data is needed than is currently contained in the software program. This technical memorandum discusses how more weather data across the state of Wisconsin can be obtained, and how it can be incorporated into the customized version of HIPERPAV Wisconsin.

### WISCONSIN WEATHER STATIONS IN HIPERPAV

In the current version of HIPERPAV, five weather stations are used to estimate the weather data in Wisconsin. These weather stations are located in Eau Claire, La Cross, Madison, Green Bay and Milwaukee, WI (Figure 1).

Figure 1. Wisconsin Weather Stations used in HIPERPAV.




The weather data currently contained in HIPERPAV II is from the Samson database (1961-1990 and 1990-1995) developed by the NCDC (National Climatic Data Center). HIPERPAV uses the following hourly data from this database:

1. Dry bulb (air) temperature – average value
2. Global horizontal radiation (or solar radiation) – average and standard deviation
3. Relative humidity – average value
4. Wind speed – average
5. Total sky cover – average value in percent
6. Precipitation
7. Station Pressure

From this hourly data, HIPERPAV also calculates the daily low and high dry bulb temperatures and the monthly precipitation data. The Samson database only contained this information for the five weather stations listed above. To better approximate the weather across the state of Wisconsin in HIPERPAV, the same weather data needs to be obtained at more weather stations across the state.

## NCDC INTEGRATED SURFACE HOURLY OBSERVATIONS DATABASE

The National Weather Service has recently developed a new database that contains the above information (except for solar radiation and relative humidity data) for more weather stations in Wisconsin. This database – Integrated Surface Hourly Observations – is a compilation of global surface hourly observations from the NCDC and Navy surface hourly data, NCDC precipitation data, and Air Force DATSAV3 surface hourly data. Hourly and synoptic type data for approximately 12,000 global stations are available in the database from 1995 to 2002. This translates to a total of 42 weather stations in Wisconsin (Table 1). However, data is not available at all of the stations from 1995 to 1999. Some of them (22 stations) have limited data. It will have to be decided how much data is enough to develop the average weather data for each site.

Table 1. NCDC Integrated Surface Hourly Database Station History (October 2003).

| USAF | WBAN | STATION NAME | CTRY | | ST | CALL | LAT | LON | ELEV(.1M) | Data |
|---|---|---|---|---|---|---|---|---|---|---|
| 726400 | 14839 | MILWAUKEE MITCHELL INTL AP | US | US | WI | KMKE | +42950 | -087900 | +02048 | 1995-99 |
| 726404 | 99999 | MINOCQUA/WOODRUFF | US | US | WI | KARV | +45933 | -089733 | +04960 | 1995-99 |
| 726405 | 94869 | MILWAUKEE TIMMERMAN | US | US | WI | KMWC | +43117 | -088050 | +02240 | 1995-99 |
| 726406 | 99999 | KENOSHA (CGS) | US | US | WI | K16C | +42583 | -087750 | +01786 | 1995-96 |
| 726407 | 99999 | MILWAUKEE (CGLS) | US | US | WI | K15C | +43017 | -087950 | +01814 | 1995-96 |
| 726408 | 99999 | SHEBOYGAN (CGS) | US | US | WI | K21C | +43750 | -087700 | +00010 | 1995-96 |
| 726409 | 99999 | WAUKESHA | US | US | WI | KUES | +43033 | -088233 | +02840 | 1998-99 |
| 726410 | 14837 | MADISON DANE CO REGIONAL ARPT | US | US | WI | KMSN | +43133 | -089350 | +02615 | 1995-99 |
| 726415 | 99999 | JANESVILLE/ROCK CO. | US | US | WI | KJVL | +42617 | -089033 | +02460 | 1995-99 |
| 726416 | 14921 | LONE ROCK FAA AP | US | US | WI | KLNR | +43200 | -090183 | +02192 | 1995-99 |
| 726417 | 99999 | MEDFORD | US | US | WI | KMDZ | +45100 | -090300 | +04480 | 1999 |
| 726418 | 99999 | OSCEOLA | US | US | WI | KOEO | +45317 | -092683 | +02750 | 1999 |
| 726424 | 99999 | RACINE | US | US | WI | KRAC | +42767 | -087817 | +02050 | 1999 |
| 726425 | 99999 | SHEBOYGAN | US | US | WI | KSBM | +43783 | -087850 | +02280 | 1999 |
| 726426 | 99999 | STEVENS POINT | US | US | WI | KSTE | +44550 | -089533 | +03380 | 1999 |
| 726427 | 99999 | SUPERIOR | US | US | WI | KSUW | +46683 | -092100 | +02060 | 1999 |
| 726430 | 14920 | LA CROSSE MUNICIPAL ARPT | US | US | WI | KLSE | +43867 | -091250 | +01984 | 1995-99 |
| 726435 | 14991 | EAU CLAIRE COUNTY AP | US | US | WI | KEAU | +44867 | -091483 | +02713 | 1995-99 |
| 726436 | 94930 | VOLK FIELD ANG | US | US | WI | KVOK | +43933 | -090267 | +02801 | 1995-99 |
| 726450 | 14898 | GREEN BAY AUSTIN STRAUBEL INT | US | US | WI | KGRB | +44483 | -088133 | +02094 | 1995-99 |
| 726452 | 99999 | WISCONSIN RAPIDS | US | US | WI | KISW | +44350 | -089833 | +03080 | 1997-99 |
| 726454 | 99999 | TWO RIVERS (CGS) | US | US | WI | KC58 | +44133 | -087550 | +01820 | 1995-96 |
| 726455 | 99999 | MANITOWAC MUNI AWOS | US | US | WI | KMTW | +44133 | -087683 | +01980 | 1995-99 |
| 726456 | 99999 | OSHKOSH/WITTMAN FLD | US | US | WI | KOSH | +43967 | -088550 | +02460 | 1995-99 |
| 726457 | 99999 | APPLETON/OUTAGAMIE | US | US | WI | KATW | +44250 | -088517 | +02800 | 1995-99 |
| 726458 | 99999 | STURGEON BAY | US | US | WI | KSUE | +44850 | -087417 | +02210 | 1995-99 |
| 726459 | 99999 | STURGEON BAY | US | US | WI | K0Y2 | +44783 | -087317 | +01760 | 1995-96 |
| 726463 | 14897 | WAUSAU MUNICIPAL ARPT | US | US | WI | KAUW | +44917 | -089633 | +03658 | 1995-99 |
| 726464 | 99999 | WATERTOWN | US | US | WI | KRYV | +43167 | -088717 | +02540 | 1995-99 |
| 726465 | 99999 | MOSINEE/CENTRAL WI | US | US | WI | KCWA | +44783 | -089667 | +03890 | 1995-99 |
| 726467 | 99999 | RICE LAKE MUNICIPAL | US | US | WI | KRPD | +45483 | -091717 | +03470 | 1995-99 |
| 726468 | 99999 | PHILLIPS/PRICE CO. | US | US | WI | KPBH | +45700 | -090400 | +04490 | 1995-99 |
| 726502 | 99999 | CLINTONVILLE MUNI | US | US | WI | KCLI | +44617 | -088733 | | 1997-99 |
| 726503 | 99999 | WISCONSIN DELLS | US | US | WI | KDLL | +43517 | -089767 | | 1997-99 |
| 726504 | 99999 | EAGLE RIVER UNION | US | US | WI | KEGV | +45933 | -089267 | +05000 | 1997-99 |
| 726505 | 99999 | KENOSHA REGIONAL | US | US | WI | KENW | +42600 | -087933 | +02260 | 1997-99 |
| 726506 | 99999 | FOND DU LAC CO. | US | US | WI | KFLD | +43767 | -088483 | +02460 | 1997-99 |
| 726507 | 99999 | MINERAL POINT | US | US | WI | KMRJ | +42883 | -090233 | | 1997-99 |
| 726508 | 99999 | HAYWARD MUNI ARPT | US | US | WI | KHYR | +46033 | -091450 | +03700 | 1997-99 |
| 726509 | 99999 | JUNEAU\DODGE CO | US | US | WI | KUNU | +43433 | -088700 | +02850 | 1997-99 |
| 727410 | 99999 | PARK FALLS MUNI | US | US | WI | KPKF | +45933 | -090450 | +04690 | 1995-96 |
| 727415 | 99999 | RHINELANDER/ONEIDA | US | US | WI | KRHI | +45633 | -089467 | +04950 | 1995-99 |

with:
- USAF = Air Force Datsav3 station number
- WBAN = NCDC WBAN number
- CTRY = WMO historical country ID, followed by FIPS country ID
- ST = State for US stations
- CALL = ICAO call sign
- LAT = Latitude in thousandths of decimal degrees
- LON = Longitude in thousandths of decimal degrees

```
ELEV = Elevation in tenths of meters
```

It will be possible to incorporate this new data into HIPERPAV since it has a similar database structure to the Samson database. Any inconsistencies in the data will be identified after the data is obtained from the NCDC. It may not be necessary to include all of the data from all of these weather stations in HIPERPAV because of their close proximity. This will have to be assessed at a later stage in the project.

### *Calculation of Relative Humidity*

It will be possible to calculate the relative humidity data from the dry bulb temperature and dew point data contained in the new database using the following formula from NCDC (shown in Fortran notation):

RH=NINT((((173.-(.1*DB)+DP)/(173.+.9*DB))**8.)*100.)

where, RH = relative humidity
DB = dry bulb temp in whole degrees Fahrenheit
DP = dew point temp in whole degrees Fahrenheit
* = multiply
** = raise to power of

### *Total Sky Cover Data*

From the Samson database to the Integrated Surface Hourly Observations database, there was a change in the method of observation for the total sky cover. In July 1996, the National Weather Service agreed to follow the METAR format. Only clouds lower than 12,000 ft were recorded. Clouds greater than 12,000 ft were not. This means that a ‘clear’ sky is noted when clouds are not present at less than 12,000 ft, even if there are clouds at an elevation greater than 12,000 ft. The total sky cover data from the Samson database will not correlate to the data contained in the newer database.

## SOLAR RADIATION DATA

In the Samson database, the solar radiation data from 1991 to 1990 and from 1990 to 1995 was either modeled or measured directly for the five stations in Wisconsin. ‘Solar radiation is the driving energy for the geophysical and biochemical processes that control weather and life on earth.’ (ISIS website) Solar radiation data from 1995 to 2001 is available at the following website from the ISIS (Integrated Surface Irradiance Study) project: www.srrb.noaa.gov/isis/index.html. The ISIS program has only 9 solar radiation measuring sites across the United States (Figure 2). One of them is in Madison, WI. This site was selected because it produces regionally representative solar radiation data. Data from 2002 to 2004 can be freely downloaded from this site.

Figure 2. ISIS network across the United States.


In 2002, the Surface Radiation Research Branch (SURFRAD) incorporated the ISIS program (www.srrb.noaa.gov/surfrad/index.html). In the SURFRAD program, there are an additional seven sites throughout the US, none in Wisconsin.

In HIPERPAV, it will be possible to use to solar radiation data currently in HIPERPAV and the updated Madison, WI solar radiation data and extrapolate it to the increased number of weather stations identified in the Integrated Surface Hourly Observations database. We will let the user know that measured solar radiation is only available at the Madison, WI station and modeled data at the Eau Claire, La Cross, Green Bay and Milwaukee, WI weather stations.

# Appendix C

# Frequently Asked Questions

# HIPERPAV F.A.Q.'s

## ❖ Questions on Design Inputs

1. ***What should I use for the slab width and joint spacing inputs?***
   - A schematic of the geometry input entered in HIPERPAV is shown below in Figure 1. The slab width that should be input into HIPERPAV is the widest spacing between adjacent longitudinal joints. In Figure 1, the slab width would be 16 feet which includes the width of the left lane plus the left shoulder since only a paint stripe (with no joint) separates these two segments.

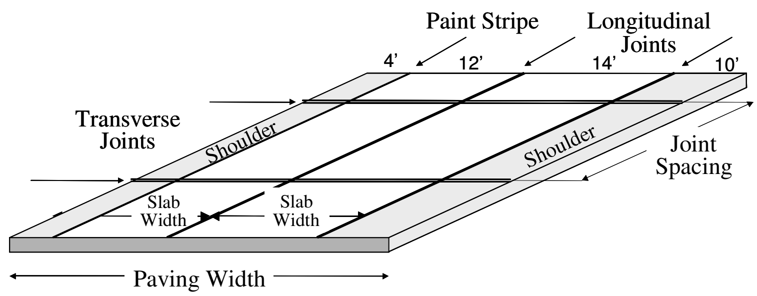



**Figure 1.** Schematic of the Geometry Input in HIPERPAV.

   - The transverse joint spacing corresponds to the largest spacing between transverse joints. If random joint spacing is used, use the longest joint spacing expected. Alternatively, you can perform an analysis for each joint spacing used and compare the solutions.

2. ***What effect does slab width have on the results?***
   - The slab width is used to determine the stress state on the transverse direction. Joint spacing is used to determine the stress state on the longitudinal direction. The stress in both directions affects the overall "critical" stress as a result of the Poisson effect.

3. ***Can I use a variable value for subbase thickness across the section?***
   - To maintain simplicity in the software, variable subbase thickness is not considered. However, the user can evaluate the sensitivity of subbase thickness using different values. This can be done by running multiple strategies with a range of subbase thicknesses. The thickness that shows the most critical condition can be used as input in the final analysis.

4. ***How do I measure slab-base restraint?***
   - By performing a push-off test (see the next question).

5. ***What is a push-off test?***
   - A push-off test is a procedure to measure the friction, bearing, adhesion, and bonding conditions at the slab-subbase interface. Although this test is not officially standardized, it has been performed for nearly a century in various forms. This most recently used procedure consists of casting a slab of the designed thickness on top of the same subbase type to be used on the job. A range of slab sizes have been used in the past, but generally good numbers can be found when using a 3 × 5' slab. A horizontal force is applied on one side of the slab with a hydraulic jack, and a load cell is used to measure the applied load. Dial gages are installed at the opposite side to measure the slab movement. The restraint stress is determined from the applied force divided by the area of the test slab. The testing history of restraint stress and slab movement during the push off procedure is recorded and the restraint stress at free sliding is evaluated. The most current specification for this test can be obtained by contacting the HIPERPAV Support Team (www.hiperpav.com).

6. ***What value of subbase thickness and stiffness do I use for multiple layers?***
   - It is recommended that the selection of the base thickness and stiffness to simulate the effect of a multiple layer base system be made with guidance from the most current AASHTO pavement design guidelines.

## ❖ Questions on Materials and Mix Design Inputs

7. ***Can we handle several aggregates – for example, from multiple stockpiles?***
   - It is currently assumed that there are only coarse and fine aggregate sources. Aggregate blends can be considered by separating these into coarse and fine components. With respect to the CTE, a weighted value can be used if more than one coarse aggregate is used.

8. ***Does the program check for mixture proportions?***
   - The current version does not verify the accuracy of the mixture proportioning. Therefore, the user must ensure that the mixture proportions entered will yield the design strength entered in the "Design Inputs". Future versions of HIPERPAV may include a Mix Design Module for mix proportioning.

9. ***How are chemical admixtures accounted for since there are no inputs for dosage rates?***
   - Only moderate adjustments to the hydration of the cement are considered in HIPERPAV when chemical admixtures are selected. These adjustments are based on average dosage rates.

10. ***Can differences in cement chemistry from the default cement types be modeled?***
    - Yes, HIPERPAV allows the user to enter a different chemistry in terms of the Bogue compounds by selecting the cement "User-Defined Bogue Compounds." Alternatively, they can enter this information in terms of the chemical oxide composition by selecting the cement "User-Defined Oxides" option. Both of these features are found within the "Cement" inputs.

11. ***Does the program consider cement grind (fineness)?***
    - Yes, the Blaine fineness index is an input to HIPERPAV. For blended cements, this input applies to the cement portion only.

12. ***Why is cement type IV not included in the default cement types?***
    - Type IV cement is not considered as a common cement type for paving applications, although it may be easily included in a future version if a potential demand for this cement type is found to exist.

13. ***Does the software consider blended cements like cement type IS?***
    - Yes, the current version of HIPERPAV considers the use of blended cement type IP and IS. Percent replacements considered for type IP and IS are 20% and 40% respectively. Entering the percent of admixture replacement under the PCC Mix Screen can simulate other percent replacements or blended cement types. As more information on the hydration of other cement types is available, it will be incorporated into HIPERPAV.

14. ***Are the chemical properties of the fly ash considered?***
    - Only the CaO content is considered in the current model. The database used to develop the model was limited. It would be possible to consider various fly ash chemistries in a future version, as new models become available.

15. ***Could concrete heat of hydration information from adiabatic calorimetry tests be used as input for the software?***
    - Not in its current form. However, a more advanced user input screen may be incorporated in a future version of HIPERPAV once standard tests for cement adiabatic calorimetry are developed. Adiabatic calorimetry testing is becoming more widely accepted, and additional information on

current testing options can be found by contacting the HIPERPAV Support Team (www.hiperpav.com).

***16. Is air entrainment considered in HIPERPAV?***

- Not in the current form, however, it may be added in a later version of HIPERPAV.

***17. Can the program consider shrinkage-compensating cements?***

- The models in HIPERPAV can be adapted to virtually any cement type. However, in its current form, only cement types I, IP, IS, II, III and V are considered. As more information is gathered on the properties and performance of other cement types, they can be included in HIPERPAV.

***18. What value of strength do I use? Can I use the "spec" value?***

- HIPERPAV requires the mean values of strength and modulus of elasticity (as is commonly required in pavement thickness design). The 28-day laboratory measured values should be input in HIPERPAV. Construction specification values should not be used here since they are often much lower than mean values at 28 days. ASTM specifications C 31 or C 192 should be used in defining the curing conditions for the 28-day strength and modulus values required by HIPERPAV.

***19. What if I have only flexural or compressive strength?***

- Many correlations for estimating the tensile strength from flexural or compressive strength are available and may be used with caution in HIPERPAV. However, given that the primary mode of failure during early-age behavior is tensile stress, consideration for implementation of tensile strength tests is highly desired since it would yield significantly more reliable results.
  A good correlation from a number of studies is that the tensile strength may be predicted by taking 72% of the third-point flexural strength or 62% of the center point flexural strength. Also, tensile strength ($f_t$) can be estimated from compressive strength ($f_c$) by using the following relationship: $f_t = 0.72 \times 2.3 \times (f_c)^{2/3}$. These conversion coefficients are the default coefficients in the HIPERPAV strength conversion module.
- Many engineers use the ACI Building Code Formula for predicting the tensile strength from the compressive strength, but this conversion should not be used in HIPERPAV since it commonly under-predicts the strength due to the probabilistic considerations in the formula.

***20. What if I don't have information on the modulus of elasticity?***

- The sensitivity of the stress calculations due to the modulus of elasticity is relatively low as compared to other variables (for most concrete coarse aggregates used in the field). Coarse aggregates such as lightweight, or those containing higher than normal calcium or silica contents may have significantly different values. If the modulus of elasticity used in HIPERPAV is higher than the actual modulus of elasticity of the concrete, the stresses calculated would be slightly higher than the actual stresses developing in the concrete. Thus, a conservative high value of modulus of elasticity (i.e. 5,000,000 psi) may be used if a preliminary analysis is desired. Another option is to let HIPERPAV predict the modulus of elasticity as a function of the concrete strength based on hard-coded correlations.

***21. Is the strength automatically adjusted in HIPERPAV when I modify my proportions?***

- No, the mix proportions are independent of the 28-day strength. The strength input and other concrete properties need to be modified accordingly by the user.

***22. Is the coefficient of thermal expansion (CTE) for the concrete considered in the inputs?***

- Yes, you can enter either the CTE for either the concrete (user-defined PCC CTE) or for the coarse aggregate (user-defined aggregate CTE) under the "PCC Properties" screen.

***23. How do I measure ultimate shrinkage?***

- Currently, the Japan Concrete Institute (JCI) test for unrestrained shrinkage shows the most promise as becoming an industry standard for measuring shrinkage potential of concrete. More information on this test can be obtained by contacting the HIPERPAV Support Team (www.hiperpav.com).

## ❖ Questions on Environmental Inputs

***24. Where should wind speed be measured?***

- It is recommended to measure wind speed as close to the surface of the concrete as possible. The height and location where wind speed is measured is important since it varies significantly depending on height from the pavement surface and proximity with obstacles to wind patterns. However, the weather information provided by local weather stations may be used with reasonable results. The user should recognize that the weather service generally measures the wind speed approximately 10 feet (or more) above the ground.

***25. Can I override the temperatures and other weather conditions from the database?***

- Yes, clicking "Estimate" or "Estimate All", within the "Environment" inputs, updates hourly-data based on the geographic location selected. The "prompt to update hourly-data" check box can be unchecked to automatically update weather data as a function of changes in construction time or construction date.

***26. Is monthly rainfall used in the early-age modelling?***

- No, rainfall data is used only in the long-term performance predictions. It does not affect early-age predictions.

***27. If a cold front occurs and the stresses are high, what do we do now?***

- You can try other construction procedures such as cotton mats. Other options could include the use of other mix designs with different cement types.

***28. How do I know the average climatic conditions for the month?***

- Choose the middle of the month (e.g. the 15th) and update the hourly-data from the database. This should give a good estimate for the average climatic conditions for that month.

***29. Can I override the temperatures and other weather conditions from the database?***

- Yes, user-defined data can be entered by typing the hourly data in the gridlines or by dragging the points on the screen. Another option is to copy the 73 hourly values from an Excel (or similar) spreadsheet, select the first gridline cell under each of the climatic inputs, and using the "Paste" Icon to paste the information in HIPERPAV.

## ❖ Questions on Construction Inputs

***30. What would be the best time of placement based on ambient temperature conditions, noting that early placement during the day might be a dangerous time for hot weather concreting?***

- The answer depends on the specific value for all the inputs including cement type, thickness, subbase type, etc. HIPERPAV has the ability to integrate all these concepts for specific situations. Multiple strategies can be run with the specific site information and analyzing for different construction times. Care should be taken in modifying time of day dependant inputs such as the temperature of the mix, temperature of the subbase, and climatic information.

***31. What happens when I select "Saw at Optimum Time"?***

- The selection of this option affects the way the analysis is performed. When "Saw at Optimum Time" is selected, HIPERPAV assumes that as soon as the concrete is strong enough to sawcut, the joints are formed, and HIPERPAV performs the analysis based on the transverse joint spacing entered.

- If "user-defined sawing age" is entered, HIPERPAV simulates the stress development for a semi-infinite slab until the time the joints are cut. After that time, the stress development is simulated as a function of the transverse joint spacing entered.

***32. Is the skip sawing option a common construction operation?***

- Although skip sawing is not a recommended practice, this option is allowed in the software to help the user possibly avoid undesirable situations where this may be a "last resort" option.

***33. What should I enter under "Sawing age of skipped joints"?***

- This corresponds to the number of hours AFTER PLACEMENT when the skipped joints will be cut.

***34. Can I use HIPERPAV to determine at what strength I should saw cut?***

- HIPERPAV can theoretically be used to predict the strength when sawcutting could be performed. However, saw cutting time is a function of numerous factors such as aggregate angularity, and other mix specific properties. The desire to use HIPERPAV for this purpose should be supplemented by other means to verify the strength in the field (maturity, for example). For more information on this topic, you can contact the HIPERPAV Support Team (www.hiperpav.com).

***35. How can I determine the optimum window of time for joint sawing?***

- The latest time to sawcut can be determined by looking at the stress development setting sawing age to 72 hours. The time when the stress exceeds the strength for this scenario would correspond to the latest sawcutting time. However, this option must be used with caution, since a great liability is involved. It should also be stressed that there are numerous factors that would impact the sawcut time that HIPERPAV does not consider. HIPERPAV is only a planning tool, and should not be considered a replacement for an experienced sawcut operator.

## ❖ Questions on CRCP Module

***36. Is the final cracking reported that which occurs at the lowest temperature date?***

- Yes, whether user-defined or determined from the weather database, the CRCP results are reported for the lowest temperature within one year of construction. Other reporting dates include 1-day, 2-days, 3-days, and for the critical analysis period (immediately after wheel loading is applied).

***37. Does the CRCP model consider the depth the steel?***

- No, the model currently employed in the software is one-dimensional. Newer models that consider the depth of the steel are currently being validated, and may be considered as an improvement to a future HIPERPAV version.

***38. How is the number of steel layers considered – top and bottom mats?***

- The number of steel mats is used to determine the effect on the calculated percent steel only. As new models are available that consider the effects on shrinkage and other behaviors as a function of the steel depth and number of bar mats, they may be included in HIPERPAV.

***39. How do I know whether my CRCP design will have a good performance?***

- The crack spacing, crack width, steel stress, and bond development length have to be evaluated in terms of the predefined design thresholds. To increase the probability of good performance, the design and construction procedures should strive at achieving cracking characteristics that are within recommended thresholds.

***40. Does the software take into account the timing of longitudinal joint cuts in CRCP?***

- No, the model assumes longitudinal joints are cut at optimum time.

***41. Does the software model long-term performance of CRCP?***

- No, long-term CRCP prediction is not included in this version of HIPERPAV, but may be included in the future.

***42. Is "early age" different for JPCP and CRCP?***

- "Early age" in HIPERPAV includes the first 72 hours after construction for both pavement types. However, in the case of CRCP, the cracking behavior continues to change until approximately one year after construction. After one year, cracking generally remains constant. Therefore, HIPERPAV predicts the cracking behavior of CRCP during the early-age and also during the early-life (up to one year). Cracking during the early-life is predicted to ensure that the cracking characteristics have stabilized and provide a good indication of the cracking characteristics that CRCP will have during the service life.

## ❖ Questions on the JPCP Long-Term Module

***43. Can I improve the performance by doing things differently in the early age?***

- Yes, the intended use of the long-term module is to compare the impact of design and construction practices on performance. However, it is assumed that the design has already been determined with other tools, such as the AASHTO Pavement Design guidelines. The long-term module in HIPERPAV has been designed with the intent of comparing the effects that early-age factors can have on long-term performance. Early-age strategies can be optimized by comparing the performance in the long-term. To accomplish this, HIPERPAV considers the effect that early-age conditions have on joint opening, load transfer efficiency, and built-in curling. The temperature at set will largely govern the joint opening and the built-in curling characteristics. These, in turn, affect long-term performance. In short, the long-term module in HIPERPAV can be used to reinforce the early-age decisions from a different perspective. The result is better assurance of good paving practices.

***44. How is the hourly and seasonal traffic distribution considered in HIPERPAV?***

- HIPERPAV has a hard-coded traffic distribution typical for most interstate highways. The flexibility to go to different distributions is there, but not available to the user at this time, in order to keep the software simple.

***45. Does HIPERPAV consider the drainability of the base?***

- Subbase is explicitly defined in terms of stiffness and subbase restraint. Indirectly, these factors can be defined for subbases of varying drainability. A more robust characterization of drainage conditions was not considered in this version, in order to keep the software simple.

***46. Is the effect of axle spacings of trucks versus joint spacing considered?***

- The HIPERPAV prediction of pavement response to traffic loading is rather simple compared to the more sophisticated models that are currently being used or considered for use in design procedures. A significant benefit to this approach is the improved user-friendliness of the software.

## ❖ Questions on HIPERMOIST

***47. Is the predicted evaporation rate in HIPERPAV the same as the actual evaporation from the concrete?***

- No, the evaporation analysis computes the free evaporation rate of a standing body (pan) of water. This evaporation rate is a function of the temperature of the air, wind speed, relative humidity, and the temperature of the concrete. The free evaporation rate is useful as it has been found to relate to the potential evaporation rate that can occur in the concrete.

***48. Is the effect of curing methods considered in the evaporation analysis?***

- The curing method used will affect the temperature of the concrete and in turn the computed evaporation rate. However, no reduction in evaporation rate is currently considered as a function of the moisture barrier that one curing method can have versus another.

## ❖ Questions on the Analysis

***49. Why is the program limited to 72 hours of analysis?***

- It has been found from experience that most of the potential problems associated with early-age behavior occur within the first two or three days after placement.

***50. Why doesn't the stress drop when it shows that it cracks?***

- The software in its current form does not actually model the crack development. Instead, it provides a warning for the potential of cracking on the pavement structure. Due to the associated variability of materials and construction procedures, HIPERPAV indicates the chances of excessive stresses in the pavement. It does not necessarily indicate that a failure will occur, just that one scenario is more likely than another.

***51. Can HIPERPAV determine what the pattern of cracking would be for any given concrete age at saw cut?***

- The current version of HIPERPAV predicts the potential for early-age cracking – it does not predict the optimum patterns or timing of saw cutting operations.

***52. Is the strength value predicted by the program actually reached after the time of simulation, or does it vary with conditions?***

- It varies according to the field conditions based on the inputs selected by the user.

***53. Why did the predicted strength not change when I increased my Cement Content?***

- HIPERPAV adjusts the strength gain curve based on the 28-day design strength provided by the user. If the mix design inputs are changed, the 28-day design strength determined from lab tests for the new mix has to be modified by the user as well.

***54. Why don't the program results change significantly with different curing compound dosage rates (single, double, triple)?***

- A small change is considered by HIPERPAV based on the heat loss estimated for single, double, or triple compounds. However, at the present time there is little information available on the effect of moisture loss as a function of curing compound application. HIPERPAV can be easily modified to account for such effects as soon as validated research results are available.

## ❖ Questions on Modeling

***55. How does HIPERPAV consider the effect that air temperatures have on the development of strength?***

- HIPERPAV uses a maturity model (Arrhenius Method) to take into account the deviations in strength development from specimens cured at normal curing lab temperatures.

***56. What reference is taken for the temperature differential considered in the model for computation of stresses?***

- Temperature at final set is considered as the reference temperature since it is at set time when the concrete changes from a plastic to a hardened state and stresses start to develop. However, adjustments are made to account for stress relaxation (creep).

***57. At what point geometrically is the strength predicted by the program?***

- The strength predicted is the average strength through the slab thickness.

***58. Is bleed rate accounted for in HIPERPAV?***

- Not in the current version, but a more robust moisture model is being developed and may be added in a later version.

***59. Before the joint sawing, what is the slab length considered by HIPERPAV in the analysis?***

- Before joint sawing, HIPERPAV considers an infinite slab length to simulate the restraint conditions. If time at saw cutting is entered as zero, HIPERPAV will simulate the development of stresses for a slab with the length entered in the design inputs. In this form, it is assumed that joint sawing is performed at a time before excessive stresses develop (optimum time). On the other extreme, if it is desired to know what is the latest that joint sawing can be performed, the sawing time can be entered as 72 hours, and the moment at which stresses exceed the strength will indicate the latest time for joint sawing. Please refer to the responses to Questions 34 and 35 for more information on joint sawing.

***60. What is the maximum thickness that can be modeled?***

- Since most of the models in HIPERPAV are of a mechanistic nature and the core of the program is a 2-D finite element model, the maximum thickness that can be modeled depends mainly on the limitations of the model. Currently, HIPERPAV has been validated for thicknesses of up to 12 inches and it is believed it would provide good results for thicker pavements although further validation may be needed if significantly thicker pavements are to be modeled.

***61. Is timing of the longitudinal joint considered?***

- Not directly, but the program can be “tricked” to consider the impact of sawcut timing of the longitudinal joint. The transverse joint spacing input can be set to the lane width in this case and vice-versa.

***62. Can HIPERPAV show the temperature predictions of the pavement with age?***

- This is calculated behind the scenes, but is not presented in order to keep the results simple.

## ❖ Questions on Software Interface

***63. Is it possible to input mixed U.S. and Metric units?***

- Yes, the software gives the flexibility to use any combination of both units systems.

***64. Is there online help?***

- An online help system will be developed in the near future. Further guidance for the user can be provided via the User’s Manual and Final Report.

***65. How can I compare strategies?***

- Strategies can be compared by switching between the different strategies on the strategy list.

***66. Does the software have capabilities to model PCC on old PCC (Bonded Concrete Overlays)?***

- There is another related program available for this type of analysis: HIPERBOND. Information on this program can be obtained by contacting the HIPERPAV Support Team (www.hiperpav.com).

## ❖ Questions on Availability

***67. When will HIPERPAV be available?***

- HIPERPAV Version 2.5 is now available on the HIPERPAV website at www.hiperpav.com. The FHWA HIPERPAV II Version 3.0 will be available for distribution some time in the summer or fall of 2003.

## ❖ General Questions

***68. Why should I trust this software? It seems like a "black box"?***

- HIPERPAV has been through an extensive validation of all its models during numerous field visits. Located throughout the United States, these sites included instrumentation of real pavements to monitor the early-age pavement behavior in terms of strength and stress development. During this validation effort, the software proved to provide reliable results for a range of design, environmental, and construction conditions. In addition, numerous experts including academics and practitioners have reviewed the software for its validity.

***69. Can HIPERPAV predict cracking of my bridge decks?***

- Some modification would be required for this purpose, but the core of HIPERPAV can be used in many other concrete applications including bridge decks. For more information on the status of any ongoing work in this area, contact the HIPERPAV Support Team (www.hiperpav.com).

***70. Is aggregate shape or size considered?***

- Currently none of the models in HIPERPAV require the shape or size of the aggregates as an input. However, this may be considered in future versions as newer models have been identified.

***71. How is reliability considered?***

- The stress and strength internally computed by the HIPERPAV system are <u>mean</u> values. Based on these mean values, HIPERPAV uses a probabilistic approach to calculate a critical stress and critical strength as a function of the variability associated with the materials and construction procedures for a typical concrete placement, as well as the reliability or level of risk selected. As the selected reliability level increases, the critical stresses will be higher, and the critical strength will be lower.

***72. Why is reliability an input for the user?***

- A large reliability (closer to 100%) has higher associated construction costs due to the additional precautions that must be taken to minimize early-age damage. Therefore, reliability is an input for the user to give the option of the level of risk the user is willing to take based on the importance of the project and regional policies. Generally, the higher the risk, the higher the reliability the user should assign.

***73. How is reliability considered for the long-term module?***

- The approach to reliability in the long-term module is very similar to the approach used by the current AASHTO pavement design guidelines that adjust traffic as a function of the variability of materials and construction practices.

***74. A lot of times, we simply won't know what is "out there" – are there default inputs in the software?***

- Yes, default inputs based on "typical" conditions nationwide are included in the software. However, it has been recognized that customized versions of the software may be necessary to include local materials designations, types of testing, and construction methods. A number of states have recently initiated efforts to localize HIPERPAV. More information on these studies can be found by contacting the HIPERPAV Support Team (www.hiperpav.com).

***75. Are the validation limits beyond the bounds of best practice?***

- Yes, in some cases the software is allowed to run for out-of-bound inputs to see what the impact of bad practice can be. Interpretation of the results from these analyses should be made with extreme caution.

***76. Where can I learn more about the models used in HIPERPAV?***

- A final report that includes the development of HIPERPAV II will be available shortly. This report includes information on models selected, validation efforts, and design and construction guidelines. For more information on the availability of the report, contact the HIPERPAV Support Team (www.hiperpav.com).

***77. Does this software consider fracture properties of the aggregate?***

- Not directly, but a fracture-mechanics based version of the software has been explored, and has been found to be feasible. This would allow for better characterization of the concrete mixture, as well as additives such as fiber micro-reinforcement.

***78. What is the difference between "projects" and "strategies"?***

- A "project" refers to the overall set of conditions such as location of the section in study, section characteristics, etc. Every HIPERPAV file contains one single project. Within that project a number of "strategies" with different design, materials, climate, and construction conditions can be evaluated. When a new project is open, default values appear automatically for every input. These default values can be changed and saved with custom values.

Appendix D

Case Studies Documents

Case Study 1: Scheduling Saw Cutting

Case Study 2: Cold Front

Case Study 3: Post Mortem Investigation

Case Study 4: Aggregate Selection

**Case Study Topic:** ***How late can the sawing operations be scheduled? Can initial sawing be performed at every other joint without causing thermal cracks to occur?***

## BACKGROUND

When sawcutting the joints in a concrete pavement, two critical factors are considered:

1) earliest saw cutting time, and
2) latest saw cutting time.

If joints are cut too early, the strength gained by the concrete may be not enough to support the saw cutting equipment, and structural damage to the pavement may occur. In addition, saw cutting operations may cause raveling along the joint which may progress into significant spalling damage. If joints are not cut before the magnitude of tensile stress exceeds the concrete strength, uncontrolled random cracking may occur in the pavement. Both, slab spalling and random cracking distresses are an undesirable situation that affect the performance of the pavement and significantly reduce its service life.

In this case study, the latest time for joint sawing is analyzed with HIPERPAV. Also, the possibility of temporarily skipping designated joint cuts to minimize the risk of cracking for a large paving placement is analyzed and the risks are evaluated.

For this case study, a 10" JPCP is scheduled for construction alone I-94 on April 20th. A section of pavement to be constructed at 10am is being evaluated.

## ANALYSIS STRATEGY

The saw cutting time before significant stresses develop should be selected carefully making sure that no significant risks arise from delay of the sawing operations. It is thus critical to monitor climatic conditions for abrupt changes that may change the stress condition in the pavement.

Due to the expensive risks that late saw cutting implies, a high reliability is recommended when performing this type of analysis. A 95% reliability is selected for this case.

The recommendations for latest sawing time for each scenario are presented based on the HIPERPAV analysis.

By doubling the transverse joint spacing in the design input section of HIPERPAV the risks of saw cutting at every other joint (skip sawing) are evaluated for every scenario.

## SOLUTION

The results of the analysis for the three climatic scenarios are presented in Tables 1, 2 and 3.

*Table 1: Analysis for Scenario #1*

| Saw cutting age | Critical Strength (psi) | Critical Stress (psi) | Critical Strength/ Stress | Time at critical $f_t / \sigma$ |
|---|---|---|---|---|
| 9 h | 184 | 167 | 1.10 | Max at 18 hrs |
| 12 h | 184 | 167 | 1.10 | Max at 18 hrs |
| 15 h | 140 | 130 | 1.08 | Max at 14 hrs |
| 18 h | 173 | 236 | 0.73 | Max at 17 hrs |

Table 1 shows the results of the analysis in terms of the critical strength to stress ratio. A strength to stress ratio lower than one indicates that excessive stresses occur. In this case the results suggest performing the sawing operations before 12 hours after placement.

The analysis for skip sawing was performed for the above scenario with joint sawing at 12 hours after placement and considering twice the design joint spacing. The results indicate that the stress equals the concrete strength at 18 hours. This situation represents high risks of thermal cracking. Therefore, skip sawing is not a feasible solution for this case.

*Table 2: Analysis for Scenario #2*

| Saw cutting age | Strength | Stress | Max. Strength/Stress | Time at maximum stresses |
|---|---|---|---|---|
| 9 | 181 | 148 | 1.22 | Max at 18 hrs |
| 12 | 181 | 148 | 1.22 | Max at 18 hrs |
| 15 | 140 | 127 | 1.10 | Max at 14 hrs |
| 18 | 170 | 215 | 0.79 | Max at 15 hrs |

From Table 2, the results of the analysis for the second scenario suggest to perform the joint sawing operations before 18 hours. By sawing every other joint before 12 hours after placement, a maximum strength to stress ratio of 1.12 was obtained. For this case, skip sawing is a viable alternative. Therefore, the skipped joints could be sawed at a later time without representing a risk to the structure.

Again, it should be emphasized that weather conditions would have to be closely monitored to avoid problems.

For scenario #3, a lower concrete mix temperature and subbase temperature are expected. It is observed that the sawcutting of the pavement can be postponed up to 36 hours without considerable risks to the structure. Skip sawing can also be accomplished with no significant risk.

*Table 3: Analysis for Scenario #3*

| Saw cutting age | Strength | Stress | Max. Strength/Stress | Time at maximum stresses |
|---|---|---|---|---|
| 9 | 218 | 88 | 2.48 | Max at 25 hrs. |
| 12 | 218 | 88 | 2.48 | Max at 25 hrs |
| 18 | 156 | 112 | 1.36 | Max at 17 hrs. |
| 24 | 166 | 128 | 1.30 | Max at 18 hrs. |
| 30 | 166 | 128 | 1.30 | Max at 18 hrs. |
| 36 | 267 | 246 | 1.09 | Max at 36 hrs. |
| 40 | 277 | 316 | 0.88 | Max at 40 hrs. |

In summary, the results from this case study demonstrate that for the first scenario, with a high temperature drop, joint sawing should be performed before 12 hrs. Saw cutting every other joint for this case is not recommended.

For the second scenario, with a moderate temperature drop, the concrete has to be sawed before 18 hrs although for this case, temporarily skip sawing is possible.

For low temperature drops (mild climates), late sawcutting and skip sawing joints are both possible given the low ambient temperature drop expected.

***Case Study Topic:*** ***How late can the sawing operations be scheduled? Can initial sawing be performed every third joint without causing thermal cracks to occur?***

## BACKGROUND

If pavement joints are cut too early, the strength gained by the concrete may be not enough to support the saw cutting equipment, and structural damage to the pavement may occur. In addition, saw cutting operations may cause raveling along the joint which may progress into significant spalling damage. Both, slab spalling and random cracking distresses are an undesirable situation that affect the performance of the pavement and significantly reduce its service life. If joints are not cut before the magnitude of tensile stress exceeds the concrete strength, uncontrolled random cracking may occur in the pavement

**In this case study, the latest time for joint sawing is analyzed with HIPERPAV. Also, the possibility of skipping designated joint cuts to minimize the risk of cracking for a large paving placement is analyzed and the risks are evaluated.**

For this case study, a 10" JPCP is scheduled for construction along I-94 on April 20th. A section of pavement to be constructed at 10am is being evaluated.

The estimated mix and subbase temperatures for the April placement are 60° and 50°F respectively. Additionally, the mix design uses a Class F fly ash (CaO < 7%).

Consider HIPERPAV default values for the other inputs.

## ANALYSIS STRATEGY

1. How can the latest time for joint sawing be evaluated with HIPERPAV?

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2. How can the risks of joint sawing at every other joint be evaluated?

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3. How would you investigate paying a premium to saw at night or to schedule sawing with normal rates the next day??

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## CALCULATIONS AND RESULTS

*Table 1: Analysis for Scenario #1*

| Saw cutting age | Critical Strength | Critical Stress | Critical Strength /Stress | Time of occurrence |
|---|---|---|---|---|
| None | | | | |
| | | | | |
| | | | | |

*Is skip sawing possible for this scenario? (Assume skipped joints are cut 36 hours after construction)*

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*A similar project is being constructed with a smooth HMA subbase. Is skip sawing possible for this scenario?*

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| **Case Study Topic:** | ***How late can the sawing operations be scheduled? Can initial sawing be performed every third joint without causing thermal cracks to occur?*** |
|---|---|

1. Open the file “Scheduling Sawcutting Case Study.hp3wi” or input in HIPERPAV the information described in this case study, including:

   PROJECT INFO

   - Geography Screen
     - *Select a section along I-94 near Madison.*

   STRATEGIES

   Rename “New Strategy” to “No Sawing” and change the following inputs:

   - Strategy Information Screen:
     - *Due to the expensive risks that late sawing implies, a high reliability is recommended when performing this type of analysis. Enter 95% reliability*
   - PCC Mix Screen:
     - *In the “Fly Ash Class” dropdown menu, select “Class F (CaO <=7%)”*
   - Construction Screen:
     - *Change Mix and Subbase Temperature to 60°F and 50°F respectively.*
     - *Select “No Sawing” option.*
   - Environment Screen:
     - *Uncheck “Prompt to update hourly data” to automatically update weather data.*
     - *Enter Construction Date and Time: April 20th at 10am.*

   Assume the HIPERPAV default values for all other parameters.
2. Run the analysis and determine, if applicable, the time after placement when the stresses exceeded the strength for these conditions.
3. Create a copy of the current strategy and select a sawcutting age before excessive stresses occur.
   - Construction Screen:
     - *Select user-defined sawing age.*
4. Perform an analysis for sawcutting age selected and evaluate if this sawcutting age is acceptable in terms of stress development. If not, select an earlier sawing age.
5. Create a copy of the previous strategy. Evaluate the risk of sawcutting every other joint (skip sawing):
   - Construction Screen:
     - *Select “Skip Sawing Every”: 2nd joint.*
     - *Change “Sawing Age of Skipped Joints” to 36 hours.*
6. Create a copy of the current strategy and evaluate skip sawing during a July construction.
   - Construction Screen:
     - *Change Mix and Subbase Temperature to 80°F and 78°F respectively.*
     - *Change the User-Defined Sawing Age to 9 hours*

- Environment Screen
    - *Enter Construction Date and Time: July 20 at 10am.*

7. Evaluate if skip sawing is possible for this strategy.

**Case Study Topic:** ***What changes could be made to minimize risk of high thermal stresses when a cold front is expected to pass by soon after concrete placement?***

## BACKGROUND

Drastic temperature drops during the first days after concrete placement may significantly increase the risk of cracking of a pavement structure.

When significant changes in temperature are expected during the construction of concrete pavements, it is important to assess the risk of damage to the pavement as well as measures that would keep the stresses in the concrete at an acceptable level.

For the present scenario, a section of a concrete pavement construction project has been recently placed and a cold front is forecasted to occur that evening. As a result of the cold front, the minimum air temperature is expected to decrease to 30º F.

The pavement was placed from 6 am in the morning to 6 pm in the afternoon with a maximum air temperature of 85º F and minimum of 70º F under clear sky conditions. The initial mix temperature started at 65ºF in the morning and reached a maximum of 75º F. The subbase temperature increased from 65º F up to 80º F.

The average wind speed for that site is expected to be in the order of 7 mph when the cold front passes by. The curing method being used is a single coat of white curing compound.

It is necessary to assess the impact that the cold front will have and what measures can be used to minimize risks of cracking.

## ANALYSIS STRATEGY

For this case, the pavement design, mix design, environmental, and construction information are collected to provide HIPERPAV with the necessary inputs for this analysis.

For situations when a cold front is expected soon after pavement placement, several measures can be taken to minimize the risk of cracking. Common solutions include improved curing techniques and rescheduling the joint sawing operations.

The use of effective curing methods prevents undesirable temperature losses in the pavement and provides a more uniform curing temperature.

On the other hand, joint sawing of the pavement may have to be performed with anticipation to avoid development of excessive stresses due to the temperature differential expected during the cold front.

*Figure 1. Pavement protected with polyethylene sheets.*

## SOLUTION

HIPEPRAV was used to evaluate the pavement behavior for the critical conditions predicted at that site. For this analysis, the pavement was divided in 6 subsections in terms of placement time and HIPERPAV runs were made for each subsection. The climatic conditions, mix temperature, and estimated subbase temperature at the time of placement for each subsection were used in the analysis. The results are presented in Table 1 in terms of the critical strength to stress ratio. A critical strength to stress ratio lower than one indicates excessive stresses in the slab.

*Table 1. Results from HIPERPAV Analysis*

| Placement Time | Subbase Temp. | Mix Temp. | Strength/Stress Ratio |
|---|---|---|---|
| 6:00-8:00 | 65 | 65 | **0.93 at 24h** |
| 8:00-10:00 | 67 | 68 | **0.98 at 22h** |
| 10:00-12:00 | 70 | 71 | **1.12 at 20h** |
| 12:00-14:00 | 72 | 75 | **1.35 at 18h** |
| 14:00-16:00 | 74 | 78 | **1.47 at 16h** |
| 16:00-18:00 | 75 | 80 | **1.67 at 14h** |

Using a single coat membrane as curing method, excessive stresses occur in the pavement sections placed from 6:00 am to 10:00 am.

During the morning placement (from 6:00am to 10:00am) the maximum heat of hydration appears to coincide with the maximum air temperature. This situation increases the risk of cracking since a higher temperature differential is developed.

Even though the mix temperatures are larger for the sections placed in the afternoon, the maximum concrete slab temperature and tensile stress are less. This counter intuitive condition occurs because the maximum heat of hydration has a greater offset from the maximum air temperature, thus a large hydration heat does not build up. Thus, for these conditions, the risk of cracking is reduced.

The results for the evaluation of different curing methods are presented in Table 2 in terms of the critical strength to stress ratio observed throughout the 72 hrs of analysis. Table 2 shows that polyethylene sheeting and/or cotton mats would provide the best alternative to avoid risks of cracking in the pavement for the sections placed in the morning. Either of those alternatives should be considered as an option for at least the sections placed in the morning with the most critical conditions.

An analysis for latest joint sawing time was also performed for the case with polyethylene sheeting. The joint sawing analysis was performed by evaluating the stresses with an age at sawcutting of 72 hrs. After this, the age at sawcutting was changed to a time just before excessive stresses are observed to develop in the previous analysis.

The latest age for joint sawing with a safe strength to stress ratio is presented in parenthesis in Table 2 for polyethylene sheeting. Obviously, the sections placed in the afternoon require an earlier joint sawing since for those sections the time of placement is closer to the time the cold front occurs.

*Table 2. HIPERPAV Analysis for Different Curing Methods (Critical Strength-Stress Ratio)*

| Placement Time | Polyethylene Sheeting * | Cotton Mats | P.S. + Cotton M. |
|---|---|---|---|
| 6:00-8:00 | 1.02 (22 h) | 1.39 | 1.41 |
| 8:00-10:00 | 1.10 (20 h) | 1.56 | 1.59 |
| 10:00-12:00 | 1.27 (18 h) | 1.96 | 1.96 |
| 12:00-14:00 | 1.61 (16 h) | 3.13 | 3.13 |
| 14:00-16:00 | 1.79 (15 h) | 2.70 | 2.63 |
| 16:00-18:00 | 2.00 (12 h) | 2.33 | 2.27 |

* Latest sawcutting time appears in parenthesis.

Performing a similar analysis for the sections placed in the afternoon, using curing compound only, a comparable latest age at sawcutting to the one determined for polyethylene sheeting is obtained.

This case study demonstrates the importance of monitoring the weather conditions during concrete placement. It also shows how potential problems can be predicted, and thereby, mitigated by performing a simple analysis of the pavement behavior with HIPERPAV when critical weather conditions are expected before or during concrete pavement construction.

***Case Study Topic:*** ***What changes could be made to minimize the risk of cracking when a cold front is expected to pass by soon after concrete placement?***

## BACKGROUND

Drastic temperature drops during the first days after concrete placement may significantly increase the risk of cracking of a pavement structure.

When significant changes in temperature are expected during the construction of concrete pavements, it is important to assess the risk of damage to the pavement as well as mitigating measures that would keep the stresses in the concrete at an acceptable level.

For the scenario described, a cold front is forecasted to occur the night after paving (approximately 9 p.m.). As a result of the cold front, the minimum air temperature is expected to decrease to 30º F.

The pavement was placed on September 15th between 6 am in the morning and 6 pm in the afternoon.

**It is necessary to assess the impact that the cold front will have and what measures can be used to minimize risks of cracking.**

## ANALYSIS STRATEGY

1. What is the expected behavior of the pavement when the cold front passes by?

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2. What precautions should the contractor take to avoid damage to the pavement during the cold front condition?

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3. How could HIPERPAV help in determining the high thermal stress potential and the measures to take that would prevent damage from occurring?

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## CALCULATIONS AND RESULTS

From records:

| Placement Time | Subbase temperature | Mix temperature |
|---|---|---|
| 6:00-8:00 | 65 | 65 |
| 10:00 – 12:00 | 70 | 71 |
| 16:00 – 18:00 | 75 | 80 |

*Table 1. HIPERPAV Analysis for Different Curing Methods (Critical Strength/Stress Ratio)*

| Placement Time | Curing Compound | Cotton Mats |
|---|---|---|
| 6:00-8:00 | | |
| 8:00-10:00 | | |
| 10:00-12:00 | | |
| 12:00-14:00 | | |
| 14:00-16:00 | | |
| 16:00-18:00 | | |

| | |
|---|---|
| ***Case Study Topic:*** | ***What changes could be made to minimize the risk of cracking when a cold front is expected to pass by soon after concrete placement?*** |

8. Open the file "Case Study Cold Front.hp3wi" or input in HIPERPAV the information described in this case study, including:

   PROJECT INFO
   - Geography Screen
     - *Select a location near Green Bay.*

   STRATEGIES:
   Rename "New Strategy" to "Cold Front 07am" and change the following inputs:

   - Construction Screen:
     - *Change Mix and Subbase Temperature to 65°F and 65°F respectively.*

   - Environment Screen
     - *Uncheck "prompt to update hourly data" so that weather data is automatically updated.*
     - *Enter Construction Date and Time: September 15$^{th}$ at 7:00 a.m.*
     - *Under Temperature Inputs, select the Cold Front Feature, uncheck Autoscale, and drag the point at 9 p.m. with the mouse down to 30°F (14 hours after placement).*

   Assume the HIPERPAV default values for all other inputs that are not described in the case study.

9. Create a copy of the first strategy for construction times at 11am and 5pm and rename them to "Cold Front 11am", and "Cold Front 5pm" respectively.
10. For every placement strategy, enter the following:
    - Construction Screen:
      - *Change Mix Temperature to 71°F and subbase temperature to 70°F for 11am placement.*
      - *Change Mix Temperature to 74°F and subbase temperature to 74°F for 5pm placement.*
    - Environment Screen
      - *Enter Construction Time: 11am and 5pm respectively*
      - *Under Temperature Inputs, select the Cold Front Feature, uncheck Autoscale and drag the point at 9pm with the mouse down to 30°F (10 hours after construction for the 11am placement and 4 hours after for the 5pm placement).*
11. For every analysis determine the critical strength to stress ratio.
12. Evaluate the use of polyethylene sheeting and burlap for the 11 am placement by changing the "Curing Method" under "Construction Inputs". Create a copy of the 11 am placement for each curing method.
13. Determine what curing method could prevent excessive stresses in the pavement.
14. Draw your conclusions.

*Case Study Topic:* ***A concrete pavement recently constructed is experiencing mid-panel random cracking, what might be the causes of this problem?***

## BACKGROUND

Cracks developed in concrete pavements due to thermal stresses commonly appear from a few hours to a few days after construction. In some cases, they may not be apparent for 5 or 10 years, but they may rapidly progress into a distress that may significantly affect the long-term performance of the pavement.

Thermal cracking is often due to high temperature differentials, excessive subbase friction, aggregates with high thermal expansion/contraction characteristics, late sawing of contraction joints or a combination of the above.

In this case study a forensics analysis is required for a 10" JCP pavement recently constructed. Mid-panel cracking was observed to occur during the first placement on top of a rough Open Graded Hot Mix Asphalt (OG-HMA) subbase. In a second placement, to reduce the cracking potential, white curing compound was applied on top of the subbase to serve as a bond breaker. However, cracks were also observed on the second placement.

Information and measurements collected during a field inspection visit are presented below:

- The spec calls for a concrete grade A-FA mix design (default HIPERPAV proportioning).
- The air temperature based on climatic data collected from the region presents a high of 90°F and a low of 60°F.
- The slab was covered soon after placement with a white curing compound. The initial PCC mix temperature recorded at placement was 82ºF.
- Sawing operations occurred 12 hrs after placement.

## ANALYSIS STRATEGY

The use of stabilized bases can often lead to extremely high friction resistance at the slab-subbase interface with minimum slab movement before sliding. This situation generates excessive stresses in the slab, as may be the case for the present scenario.

Friction for any subbase type can be easily characterized with a standardized push-off test. The setup for the push-off test is presented in Figure 1.

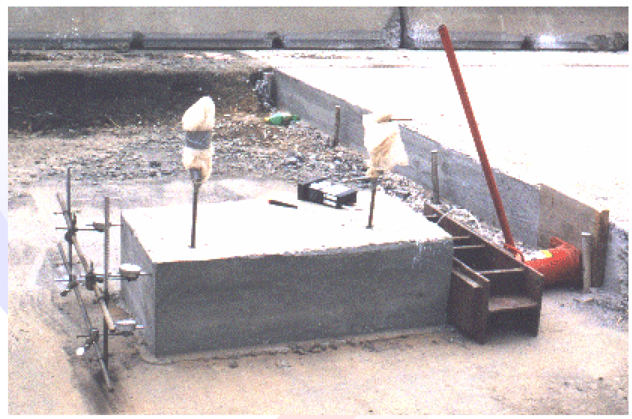

*Figure 1. Setup for push-off test.*

The results obtained with the push-off tests are the characteristic friction force for that subbase and the displacement/friction relationship as depicted in Figure 2. The level of friction is proportional to the slab displacement until the maximum friction force occurs and the slab slides.

A push-off test was performed on both sections. The information obtained with the push-off test procedure yields a maximum friction force per unit area of 16.0 psi and movement at sliding of 0.0015 inches for the first section. The second section where curing compound was used as bond breaker yields a friction of 15.0 psi and movement of 0.0015 inches.

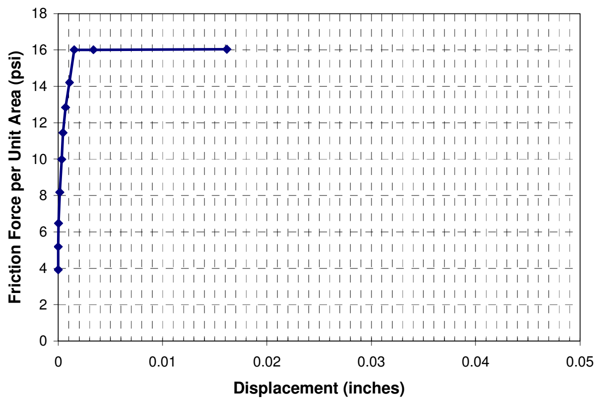


*Figure 2. Typical Friction Curve for rough HMA base*

## SOLUTION

The results of the analysis performed with HIPERPAV and the information collected in the field indicate a high risk of excessive thermal stresses that explains the random cracking observed. According to these results, the strength would be exceeded by the stresses generated in the slab 18 hrs after placement, at 90% reliability for both cases.

Possible causes of cracking for this project may be due to the high friction at the slab/subbase interface, a relatively high concrete temperature differential, the use of aggregates with high Coefficient of Thermal Expansion, and/or late joint sawing.

Several runs were performed with HIPERPAV for the conditions depicted above. Using aggregates with lower coefficient of thermal expansion could contribute to reduce the thermal stresses in the concrete. Placement time was also investigated, and although night placement could reduce the thermal stresses, construction costs might increase significantly. Changes in sawing time were also analyzed with no significant reduction in the stresses observed. Finally it was found that by reducing the subbase friction the potential of high thermal stresses was minimized and yielded the most cost effective solution.

When a subbase with high frictional characteristics exists for a specific project, a bond breaker may be required to minimize friction. The effectiveness of different bond breakers to reduce subbase friction can also be evaluated objectively by performing various push-off tests.

The effect of reducing the subbase friction can be evaluated with HIPERPAV, by comparing the magnitude of the stresses that develop.

For this scenario, several bond breakers on top of the OG-HMA subbase were tested. Table 1 presents the friction characteristics determined from push-off tests and the results obtained with HIPERPAV for each option in terms of the critical strength-stress ratio.

*Table 1. Push-off Test Results*

| Condition | Friction (psi) | Movement at sliding (in) | Critical Strength to Stress Ratio |
|---|---|---|---|
| **Untreated OG-HMAC** | 16.0 | 0.0015 | 0.96 |
| **Curing Compound** | 15.0 | 0.0015 | 0.97 |
| **Slurry seal** | 12.0 | 0.08 | 1.40 |
| **Polyethylene Sheeting** | 1.0 | 0.09 | 1.42 |
| **1/16" Sand** | 6.0 | 0.05 | 1.39 |
| **Petromat** | 6.0 | 0.03 | 1.37 |

Strength to stress ratio smaller than one indicates excessive stresses. It is observed in Table 1 that with the exception of the curing compound option tried initially; any of the other alternative bond breakers would significantly reduce the friction for the subbase, and thus, minimize the slab cracking potential.

It must be noted that the friction characteristics for the bond breaker materials vary depending on the subbase where they are applied. The values presented here apply only to the OG-HMA subbase where they were tested.

***Case Study Topic:*** ***A concrete pavement recently constructed is experiencing mid-panel random cracking, what might be the causes of this problem?***

## BACKGROUND

Cracks developed in concrete pavements due to thermal stresses commonly appear from few hours to few days after construction. In some cases, they may not be apparent for 5 or 10 years, but rapidly progress into a detrimental situation.

In general, this type of distress is often due to large air temperature drops, excessive subbase friction, late sawing of contraction joints, use of aggregates with high thermal expansion/contraction characteristics, or a combination of the above.

## PROBLEM STATEMENT

For this case study, a forensics analysis is required for a recently constructed 10" JCP. **Mid-panel cracking was observed during the first placement on top of a rough Open Graded Hot Mix Asphalt (OG-HMA) subbase.** In a second section, to reduce the cracking potential, white curing compound was applied on top of the subbase to serve as a bond breaker. However, cracks were also observed on this section.

Information and measurements collected from a field inspection are as follows:

While at the site, push-off tests were performed on both sections. Also several bond breakers on top of that subbase were tested with the following results:

| | Friction (psi) | Movement (in) |
|---|---|---|
| OG-HMA Subbase | 16.0 | 0.0015 |
| OG-HMA Subbase + curing compound | 15.0 | 0.0015 |
| Polyethylene Sheeting | 1.0 | 0.09 |
| 1/16" Sand | 6.0 | 0.05 |
| Slurry seal | 12.0 | 0.08 |

- The spec calls for a concrete grade A-FA mix design (default HIPERPAV proportioning).
- The air temperature based on climatic data collected from the region presents a high of 90°F and low of 60°F.
- The slab was cured soon after placement with white curing compound. The initial PCC mix temperature recorded for that section was 82ºF.
- Sawing operations occurred 12 hrs after placement.

## ANALYSIS STRATEGY

1. How could the primary factor that lead to the pavement distress be determined?

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2. From your experience and review of the data what do you think caused the cracking?, temperature?, base type?, late sawing?

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## SOLUTION

3. Use HIPERPAV to determine what changes could be made to minimize the risk of high thermal stresses in subsequent placements

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| *Case Study Topic:* | ***A concrete pavement recently constructed is experiencing mid-panel random cracking, what might be the causes of this problem?*** |
|---|---|

15. Open the file "Case Study Post Mortem.hp3wi" or input in HIPERPAV the information described in this case study, including:

    PROJECT INFO:
    - Geography Screen
        - *Select Fond du Lac as your location.*

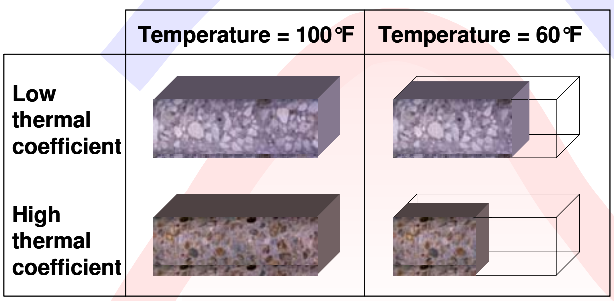
    STRATEGIES
    Rename "New Strategy" to "Base Case" and change the following inputs:
    - Slab Support Screen
        - *Select "Asphaltic Base (Rough)" as your material type.*
        - *Select User-Defined Linear under the "Axial Restraint" area, and enter critical restraint stress and movement at sliding for OG-HMA subbase from push-off test results shown in Case Study Worksheet.*
    - Construction Screen:
        - *Change Mix and Subbase Temperature to 82° and 80°F, respectively.*
        - *Select "User-defined sawing age" and enter 12 hours.*
    - Environment Screen:
        - *Uncheck "Prompt to update hourly data" so that weather data is automatically updated, and enter Construction Date and Time: July 18$^{th}$ at Noon.*

    Assume the HIPERPAV default values for all other inputs that are not described in the case study.
16. Perform an analysis with HIPERPAV for the "Base Case" strategy.
17. Create a copy of the first strategy and rename it to "Earlier sawing". Perform an analysis changing the sawing time, i.e. to 5 hrs in the "Construction Screen" to determine if this could have minimized the risk of cracking.
18. For each of the bond breakers tested, create a copy of the base case strategy and rename them accordingly. For each strategy change:
    - Slab Support Screen:
        - *Enter critical restraint stress and movement at sliding from push-off test*
        - *Assume 5°F lower subbase temperature for subbase with curing compound.*
19. Perform an analysis for each strategy. You can hover the mouse over the stress-strength curves to determine the critical strength to stress ratio for each hour of analysis.
20. Determine if any of the friction conditions would be acceptable and compare them with the original conditions.
21. Draw your conclusions.

***Case Study Topic:*** ***How would a change in aggregate type affect the probability of cracking under a specific set of climatic conditions?***

## BACKGROUND

The aggregate property that has the most significant effect on early-age (and long term) pavement performance is its coefficient of thermal expansion (CTE). The aggregate contributes between 60-80% of the concrete by volume and, therefore, the concrete's CTE is predominantly affected by the CTE of the aggregate. The CTE provides an indication of how the volume of material will expand or contract when exposed to a change in temperature. The following figure provides an indication of the relative volume changes that concretes with different CTE's will experience while being exposed to a temperature drop.




The CTE is especially important for pavements placed in the summer season when temperature extremes are high, and when the peak ambient temperature may coincide with the peak heat of hydration (as in morning placements). Under such conditions, concrete pavements with a high CTE tend to have an increased probability of early-age cracking compared to a pavement constructed from coarse aggregate with a lower thermal coefficient.

The following table provides an indication of typical CTE values for selected aggregates.

| Aggregate Type | CTE Range (με/°F) |
|---|---|
| Sandstone | 4.4 - 7.2 |
| Siliceous Gravel | 3.9 - 6.7 |
| Granite / Gneiss | 3.3 - 5.6 |
| Basalt | 2.8 - 5.0 |
| Limestone / Dolomite | 2.2 - 4.4 |

The following scenario was selected for this case study. A contractor is experiencing an aggregate shortage. He can only get enough aggregate to complete the project by using aggregates from two different pits. The project will take about one year to complete. What would be the best time to use the aggregates form each pit? The aggregates from the two sources have the following properties:

- → Pit A, CTE = 4 microstrain/°F
- → Pit B, CTE = 8 microstrain/°F

A 9 inch thick jointed concrete pavement is to be constructed in an area where the summer air temperatures will vary between 65 and 95°F, and winter air temperatures between 45 and 75°F. Although unlikely, assume for the purpose of this case study that none of the other concrete mix properties or strengths are affected by changing the aggregate type. The HIPERPAV default values may be assumed for all other inputs that are not affected by the change in air temperature or change in aggregate type.

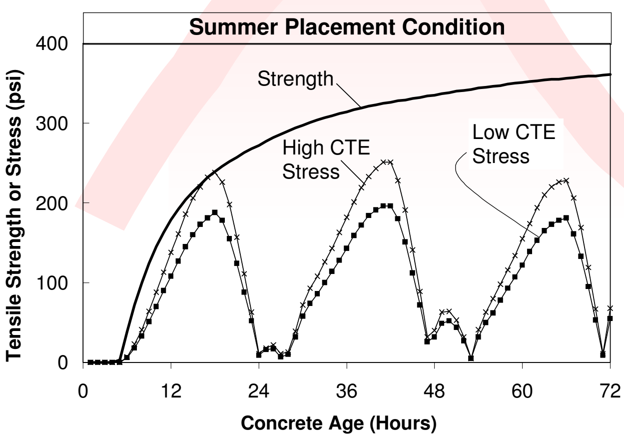
## ANALYSIS STRATEGY

HIPERPAV can, with ease, be used to determine what impact a change in aggregate type will have on the probability that early-age cracking could occur. For each of the aggregate types, HIPERPAV analyses can be done under summer and winter conditions. The results of these analyses can then be compared to determine which aggregate type is best suited for each season. The concrete mix temperature and the subbase temperature are expected to change from summer to winter conditions.

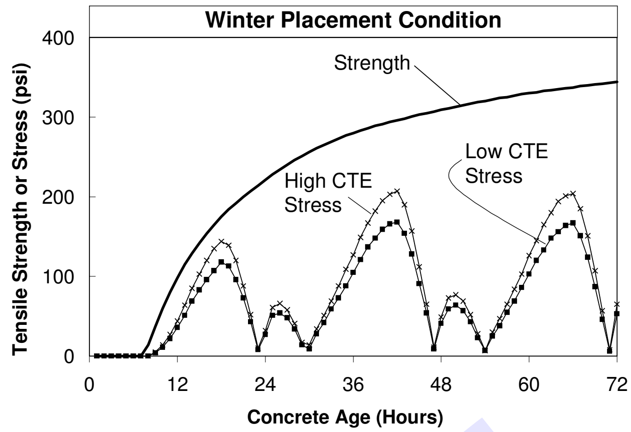
It is expected that use of the lower CTE aggregate will reduce the probability of early-age cracking under most conditions.

## SOLUTION

HIPERPAV analyses were performed for each of the two aggregate pits; first under summer placement conditions. A mix temperature of 85ºF and a subbase temperature of 80°F were assumed. The results of this analysis can be seen in the following figure. The impact of a change in aggregate type can clearly be seen. Under the conditions analyzed the concrete with a high CTE aggregate (Pit B) is close to cracking, while the concrete with a low CTE aggregate (Pit A) still has some reserve strength.




The analyses performed above were now repeated, but for the winter placement conditions. A mix temperature of 65ºF and a subbase temperature of 55°F were assumed. The results of this analysis can be seen in the following figure. Winter placement conditions seem to be more favorable than summer conditions, because cracking is not expected to occur at a reliability of 90%. The stresses that develop in the pavement with a high CTE aggregate (Pit B) are higher than those expected to develop in the pavement constructed with a low CTE aggregate (Pit A).




From the results of these HIPERPAV analyses, it may be concluded that the probability of early-age cracking under high temperature conditions (summer) can be minimized by using low CTE aggregates (Pit A). Aggregates with a high CTE (Pit B) could be used during winter months with minimal risk.

The analysis performed in this section could be repeated for the conditions expected to occur in each month to obtain a better understanding of when to switch to the other pit. Under conditions where the daily temperature differential is the highest (cold front), the use of aggregates with a low CTE can be beneficial. In some parts of the country, autumn is often the season where large fluctuations in air temperatures occur. The use of aggregates from Pit A may be preferred during these periods.

The section paved with a low CTE aggregate should provide better long term performance, as lower tensile stresses due to thermal effects should develop. Therefore, if more aggregates of Pit A are available at no extra cost, they should be used all year round to improve the overall pavement performance.

## WORKSHEET

**Case Study Topic:** ***How would a change in aggregate type affect the probability of cracking under a specific set of climatic conditions?***

### BACKGROUND

Concrete pavements with a high CTE tend to have an increased probability of early-age cracking as compared to a pavement constructed from coarse aggregate with a lower thermal coefficient. The aggregate contributes between 60-80% of the concrete by volume and, therefore, the concrete's CTE is predominantly affected by the CTE of the aggregate. The CTE provides an indication of how the volume of material will expand or contract when exposed to a change in temperature. The CTE is especially important for pavements placed in the summer season when temperature extremes are high.

### PROBLEM STATEMENT

A contractor is experiencing an aggregate shortage. He can only get enough aggregate to complete the project by using aggregates from two different pits. The project will take about one year to complete. **What would be the best time of the year to use the aggregates from each pit?** The aggregates from the two sources have the following properties:

→ **Pit A**, CTE = 4 microstrain/°F

→ **Pit B**, CTE = 8 microstrain/°F

Assume the following scenario for this case study:

- 9 inch JCP is to be analyzed based on a 90% reliability
- Cement Type I, Holcim: Clarksville (GU)
- Summer air temperatures: 65 to 95°F
- Winter air temperatures: 45 to 75°F

Although unlikely, assume for the purpose of this case study that none of the other concrete mix properties or strengths are affected by changing the aggregate type. Assume the HIPERPAV default values for all other inputs that are not affected by the change in air temperature or change in aggregate type.

### INTUITIVE BEHAVIOR & ANALYSIS PLAN

1. Which aggregate type should reduce the probability of cracking?

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2. How would you use HIPERPAV to determine what time of year is best suited to use the aggregates from Pit A and B?

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### CALCULATIONS & RESULTS

| ***Summer Placement Condition*** | | | |
|---|---|---|---|
| ***Pit*** | *Subbase Temp.* | *Fresh Mix Temp.* | *Critical Strength-to-Stress ratio* |
| A | | | |
| B | | | |

| ***Winter Placement Condition*** | | | |
|---|---|---|---|
| ***Pit*** | *Subbase Temp.* | *Fresh Mix Temp.* | *Critical Strength-to-Stress ratio* |
| A | | | |
| B | | | |

3. Which aggregate should be used in the autumn, where the air temperature could change by as much as 50°F when a cold front passes through?

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22. Open the file "Aggregate Selection Case Study.hp3wi" or input in HIPERPAV the information described in this case study, including:

    PROJECT INFO:

    - Geography Screen:
        - *Select a section along the intersection of I-94 and I-90 between Madison and Eau Claire as your location.*

    STRATEGIES:

    Rename "New Strategy" to "June CTE low" and change the following inputs:

    - Geometry Screen:
        - *Change pavement thickness to 9 inches.*
    - Cement Screen:
        - *Select "User-Defined Oxides" and click on the "Library" button. Under the Type I cement type, select "Holcim: Clarksville (GU)".*
    - PCC Properties Screen:
        - *Select "User Defined PCC CTE" and change to 4 microstrains/°F.*
    - Construction Screen:
        - *Change Mix and Subbase Temperature to 85°F and 80°F respectively.*
    - Environment Screen:
        - *Uncheck "Prompt to update hourly data" to automatically update weather data.*
        - *Enter Construction Date and Time: June 30 at 12 pm.*

    Assume the HIPERPAV default values for all other parameters.

23. Create a copy of the current strategy, rename to "June CTE high", and change the "User-Defined PCC CTE" to 8 microstrains/°F.

24. Create a copy of each strategy and consider paving in October with the following inputs (rename accordingly):

    - Construction Screen:
        - *Change Mix and Subbase Temperature to 65°F and 55°F respectively.*
    - Environment Screen:
        - *Enter Construction Date and Time: October 10 at noon.*

25. Perform an analysis for each strategy and determine the stress to strength ratio.

26. Draw your conclusions.

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