PERFORMANCE BASED SPECIFICATIONS
FINAL REPORT

Sponsored by the Project Development Division
of the Iowa Department of Transportation
and the Iowa Highway Research Board
Iowa DOT Project TR-403
CTRE Management Project 97-4

JUNE 1998

CTRE

Center for Transportation Research and Education

IOWA STATE UNIVERSITY

Iowa Department of Transportation

CTRE's mission is to develop and implement innovative methods, materials, and technologies for improving transportation efficiency, safety, and reliability, while enhancing the educational experience of students in transportation-related fields.

Performance Based Specifications
Final Report

Principal Investigator
James K. Cable
Associate Professor of Civil and Construction Engineering
Iowa State University

Graduate Research Assistant
Lisa L. McDaniel
Iowa State University

Sponsored by the Project Development Division
of the Iowa Department of Transportation
and the Iowa Highway Research Board
Iowa DOT Project TR-403

Preparation of this report was financed in part
through funds provided by the Iowa Department of Transportation
through its research management agreement with the
Center for Transportation Research and Education.
CTRE Management Project 97-4

Center for Transportation Research and Education
Iowa State University
Iowa State University Research Park
2625 North Loop Drive, Suite 2100
Ames, IA 50010-8615
Telephone: 515-294-8103
Fax: 515-294-0467
http://www.ctre.iastate.edu

June 1998

TABLE OF CONTENTS

LIST OF TABLES

ACKNOWLEDGEMENTS

The researchers acknowledge the contribution of the Iowa Highway Research Board in sponsoring this research project, TR-403. The researchers thank Mark Bortle, Iowa Department of Transportation and the members of his advisory committee for their guidance in the development of the survey documents and information for this report. They have done much to help direct continued research in this area.

ABSTRACT

The goal in highway construction and operation has shifted from method based specifications to specifications relating desired performance attributes to materials, mix designs, and construction methods. Shifting from method specifications to performance based specifications can work as an incentive or disincentive for the contractor to improve performance or extend pavement life. This literature search was directed at a review of existing Portland Cement Concrete (PCC) performance specification development, and the criterion that can effectively measure pavement performance. The criterion identified in the literature include concrete strength, slab thickness, air content, initial smoothness, water-cement ratio, unit weight, and slump. A description of each criterion, along with the advantages, disadvantages, and test methods for each are identified.

Also included are the results from a survey that was sent out to various state, federal, and trade agencies. The responses indicated that 53% currently use or are developing a performance based specification program. Of the 47% of agencies that do not use a performance based specification program, over 34% indicated that they would consider a similar program. The most commonly measured characteristics include thickness, strength, smoothness, and air content.

Lastly, recommendations and conclusions are made regarding other factors that affect pavement performance and a proposed second phase of the research is suggested. The research team suggests that a regional expert task group be formed to identify performance levels and criterion. The results of that effort will guide the research team in the development of new or revised specifications.

PERFORMANCE BASED SPECIFICATIONS

INTRODUCTION

Recently, emphasis has been placed on developing performance-based specifications where the contractor's payment is adjusted in relation to any loss in pavement life or performance that may result from contractor nonconformance [2]. The goal in highway construction and operation has shifted from method specifications to specifications relating desired performance attributes to materials, mix designs and construction methods. Shifting from method specifications to performance based specifications can work as an incentive or disincentive for the contractor to improve performance or extend pavement life. This literature search is directed at a review of existing Portland Cement Concrete (PCC) performance specification development.

RELATED RESEARCH

The concept of performance-based specifications (PRS) has been a topic of numerous research projects. Following are overviews of research done previously on PRS by the National Cooperative Highway Research Program (NCHRP), the Federal Highway Association (FHWA), and the private consulting firm, ERES Inc.

NCHRP Project 10-26A – Framework for Development of Performance-Related Specifications for Hot-Mix Asphaltic Concrete

This project assisted in the development of a conceptual framework for performance related specifications that was used as a guide for the work that was performed as a part of the SHRP Asphalt Program and other research programs conducted by the FHWA and NCHRP. The objectives of this research project included:

1. Develop a general conceptual framework for statistically based PRSs that can be applied in general to highway materials and their associated construction process

2. Demonstrate the validity of the conceptual framework [2].

The results reached from this research concluded that a specification for hot-mix asphaltic concrete is a "realistic and implementable goal." However, in order to achieve this goal, two types of pavement performance prediction models need to be developed. The pavement performance prediction models that are needed include those that relate materials and construction (M&C) variables to fundamental mixture response variables and models that relate either fundamental mixture response variables or fundamental pavement response variables to field performance [2]. Suggestions are provided that explain how these models can be developed and implemented in order to develop performance related specifications for hot-mix asphaltic concrete. In addition, recommendations are made regarding areas where additional research is needed.

FHWA-RD-89-211 – Development of Performance-Related Specifications for Portland Cement Concrete Pavement Construction

The main goal of this project was to demonstrate a performance-related specification system for portland cement concrete construction. This project, conducted by the FHWA, had four objectives. These objectives included:

1. To identify relationships, between measures of material and construction quality and pavement performance, that are necessary for the development of performance-related rigid pavement specifications

2. To develop a laboratory/field testing program designed to quantify the necessary relationships

3. To conduct laboratory/field testing to quantify all necessary relationships between one materials and construction specification variable and rigid pavement performance

4. To demonstrate the development of a performance-related specification (including incentive/disincentive provisions) for the one selected materials and construction specification variable [11].

After determining a general framework for specification development, the quality characteristics that were to be used as performance indicators were decided. The quality characteristics chosen were PCC strength, slab thickness, and initial serviceability. Next, primary and secondary relationships for predicting the performance and pavement stresses and distresses of PCC were developed. Performance-related specifications were then developed using statistical analysis and computer algorithms. Finally, a description of a program designed from a performance-related specification demonstration for performance-related M&C specifications of concrete pavement construction was given.

Recommendations from this study indicated the need for additional work on:

1. Laboratory experiments for the development of better so-called secondary prediction relationships

2. Field studies for the development/verification of better primary performance prediction relationship

3. Analysis to improve the fundamental mechanics (i.e., cost components, acceptance and payment plans, operating characteristics, etc.) of future PRS systems [11].

ERES Consultants Inc. – Development of Prototype Performance-Related Specification for Concrete Pavements

ERES Consultants Inc. conducted research that resulted in a prototype performance-related specification for concrete pavements. The basis for this prototype requires that a pavement lot be divided into consistent sublots for the measurement of quality characteristics, which are then used to estimate future performance and life-cycle cost [5]. Concrete strength, slab thickness, air content, and initial smoothness were the quality characteristics that were selected to be measured. At the time of construction these quality characteristics are measured on the in situ pavement. The results of the tests used to determine quality characteristics are then used to predict transverse cracking, longitudinal cracking, joint spalling, and many other distress indicators in the pavement. The contractor's pay is increased or decreased depending on the amount of rehabilitation that the pavement is estimated to need over its serviceability life cycle.

The results and conclusions from this research summarize an approach to developing a prototype for performance related specifications. In addition, consequences of implementing a PRS are provided along with areas requiring more research.

Each of these organizations, along with a few others, have contributed valuable information which has provided a foundation for further research on performance based specifications.

Previous research has demonstrated that one of the first steps to developing a performance related specification is to determine the criterion that measures the performance of concrete and how they are related to the design, construction, and maintenance of pavements by highway agencies and the construction industry. However, in order to determine the criterion best used to measure pavement performance an understanding of the various distresses that occur in pavements and the factors influencing them is required. During this literature review, information was gathered that described various distresses and causes that attributed to their formation. Following is a table that was generated using the accumulated information. The table indicates different distress types and factors influencing them.

When determining the criterion which best measure pavement performance, Table 1 should be referenced. Picking factors that influence pavement distresses as selected performance criterion is critical when trying to minimize or eliminate future pavement distresses.

Iowa currently uses flexural strength, pavement thickness, and longitudinal profile as the characteristics to measure concrete quality. Research at the national level has determined that the measurements of strength, thickness, longitudinal profile, and air voids adequately predict pavement performance.

TABLE 1 Distress Type and Influencing Factors

DISTRESS TYPE	FACTORS INFLUENCING DISTRESS
Transverse Cracking	Slab Thickness, Shrinkage, Moisture, Age, Strength, Temp & Moisture Volume Change, Subbase Type & Uniformity, Joint Development Timing
Longitudinal Cracking	Slab Thickness, Shrinkage, Age, Strength, Subbase Type & Uniformity, Joint Development Timing
Joint Spalling	Slab Thickness, % Air, Strength, Temp & Moisture Volume Change, Alkali-Aggregate Reaction, Dowel Alignment
Aggregate Popouts	Moisture, Aggregate Type, Aggregate Soundness, Alkali-Aggregate Reaction, Deleterious Content
Diagonal Cracking	Slab Thickness, Shrinkage, Moisture, Age, Strength, Temp & Moisture Volume Change, Joint Design, Joint Development Timing
Shrinkage Cracking	W/C Ratio, Cement Content & Type, Shrinkage, Moisture
Corner Spalling	Slab Thickness, % Air, Strength, Temp & Moisture Volume Change, Alkali-Aggregate Reaction, Subbase, Construction
Faulting	Slab Thickness, Age, Strength, Temp & Moisture Volume Change, Load Transfer, Subbase
Scaling	% Air, W/C Ratio, Cement Content & Type, Moisture, Aggregate Type, Aggregate Size, Aggregate Soundness, Alkali-Aggregate Reaction, Overwork, Excess Water
Durability "D" Cracking	Moisture, Age, Strength, Temp & Moisture Volume Change, Aggregate Type, Aggregate Size, Aggregate Soundness
Pumping	Slab Thickness, Load Transfer, Subbase
Punchouts	Slab Thickness, Distribution of Air, Strength, Transverse Crack Spacing
Blowups	Slab Thickness, Moisture, Age, Strength, Temp & Moisture Volume Change, Alkali-Aggregate Reaction, Expansive Aggregate, Dowel Alignment

Pavement performance is highly dependent upon construction techniques and materials used in the pavement construction. As changes are made in these areas, the quality and methods used to evaluate concrete also changes. These changes will require a new system to evaluate the durability and performance concrete. Currently, concrete strength, slab thickness, air content, and initial roughness are used to predict the durability and performance of concrete. The following paragraphs describe these quality characteristics in further detail along with the tests and advantages and disadvantages of each. In addition, two other characteristics will be presented that can be used to determine pavement performance.

CONCRETE STRENGTH

Concrete strength may be expressed as a compressive, flexural, tensile, torsional, or shear strength. The design process for concrete pavements is usually concerned with the flexural strength. Generally though, compressive strength is the property that is measured. The definition of compressive strength is the measured maximum resistance of a concrete or mortar specimen to axial loading [12]. Compressive strength is used to develop empirical relationships between the other strength types. The relationship between the compressive strength and flexural, tensile, torsional, or shear strength varies with concrete batch mixes and the environment.

Test Methods

The most commonly used methods to determine strength include:

- ASTM C 31 – *Making and Curing Concrete Test Specimens in the Field*
- ASTM C 192 – *Making and Curing Concrete Specimens*
- ASTM C 39 – *Test for Compressive Strength of Cylindrical Concrete Specimens*

Other test methods include:

- ASTM C 42 – *Method of Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*
- ASTM C 78 – *Test Method for Flexural Strength of Concrete (Using Simple Beam with Third Point Loading)*
- ASTM C 293 – *Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)*
- ASTM C 873 – *Test Method for Compressive Strength of Concrete Cylinders Cast in Place in Cylindrical Molds*

Advantages

There are many reasons why strength is the most frequently measured quality characteristic of concrete. These reasons include the ease with which the tests are repeated, the low variability of the test results, and the relatively low-cost of the tests.

Disadvantages

Although strength is the most commonly measured quality characteristic, its results are easily influenced by a variety of factors. These include age, quality of curing, type and grading of aggregates, quality and type of cement, batch proportions, temperature of placement, and admixtures. In addition, because laboratory analysis of the concrete cylinders is required, the pavement may already be hardened and cured before the results are obtained. This eliminates the possibility of making any corrections in the field.

SLAB THICKNESS

Slab thickness is important to the construction of concrete pavements because of its contribution to the structural adequacy of the pavement. The slab thickness determines whether the pavement will be capable of supporting the projected traffic over the lifetime of the pavement, without failing. In addition, sufficient slab thickness is needed to reduce fatigue cracking (Table 1) and increase design reliability.

Test Methods

Tests used to measure slab thickness are:

- ASTM C174 – *Standard Test Method for Measuring Length of Drilled Concrete Cores*
- AASSTO T148 – *Standard Method of Measuring Length of Drilled Concrete Cores*

Advantages

Slab thickness is a commonly used criteria to measure pavement quality because of the ease of collecting data. The test methods are also easily repeated and have a low variability of results.

Disadvantages

The methods used to measure slab thickness are destructive tests, which are taken after the pavement has cured and hardened. This makes changes in the construction techniques impossible. Another disadvantage associated with measuring slab thickness includes the variability found associated with base type.

AIR CONTENT

A well-dispersed air system in concrete can enhance the amount of resistance to distress in areas that are exposed to freezing and thawing and deicing chemicals. The amount of air voids contained in concrete provides for the space needed for the expansion of freezing water and can thereby reduce or eliminate the internal stress that leads to cracking of the pavement. Air content specifications range from 4 to 7 percent. Air content levels greater then 7 percent can result in a sufficient reduction in the strength of concrete, especially in rich mixes. This directly relates air content to the durability of concrete pavements.

Test Methods

The most commonly used tests for determining the air content of concrete are:

- ASTM C231 – *Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method*
- ASTM C173 – *Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method*

Other tests include:

- ASTM C138 – *Standard Test Method for Unit Weight, Yield and Air Content of Concrete*
- ASSHTO T199 – *Standard Method of Test for Air Content of Freshly Mixed Concrete by the Chance Indicator*

However, research is being conducted to develop more efficient methods for determining air content. Concepts using an air void analyzer, a fiber optic air meter and a mini air meter are among the methods being studied. In addition, procedures are being developed that will determine the air content in hardened concrete.

Advantages

Measurement of the air void system in a pavement is one of the most commonly used performance criteria for a number of reasons. These reasons include the ease with which the test methods are repeated, the low-cost of the tests, and low variability of results.

Disadvantages

Air tests don't make a distinction between larger air pockets and very fine bubbles, which improve frost resistance. The air content of plastic concrete may be quite different than that of in situ pavements.

As with all testing procedures performed by skilled operators, the results can vary. However, the methods describe can also produce accurate and reliable results when the operator performs the test with little variation. Frequent testing is necessary for maintaining air content at specific levels.

INITIAL SMOOTHNESS

All pavements are built to ensure maximum ride comfort to the user. Therefore, ride comfort has been directly related to the smoothness of a pavement. Pavement smoothness is described by the magnitude of profile irregularities and their distribution over the measurement interval [14]. A study performed by the NCHRP in 1992 identified 22 states responding to the survey and 91 percent used smoothness as a criterion to check pavement quality. A separate study also conducted in 1992 indicated that out of 25 states surveyed, 21 indicated that there would probably be an increase in ride quality specifications for new pavements.

Test Methods

The first methods used to measure pavement smoothness were subjective serviceability methods. Examples of these methods include the Present Serviceability Index (PSI) and the Individual Present Serviceability Rating (PSR). However, it is impractical and expensive to do serviceability ratings on long sections of pavement, so considerable effort has been made to correlate subjective serviceability methods to objective mechanical methods.

The most widely used mechanical device to measure pavement smoothness is the profilograph. Two main types of profilographs are the California and Rainhart. Another common device is the road test profilometer. Examples of this device include the road test profilometer and TRRL Profilometer. Other mechanical devices include the pavement profiler and a battery-powered robotic model.

Advantages

An important advantage to using the profilograph is the repeatability of results when different operators are used, or the direction of travel is changed. In addition, tests using the profilograph can be conducted four to six hours after concrete pavements have been placed. The ability of the profilograph to quickly measure large sections of pavements, up to 15,500 feet per hour, is another advantage to using this device to measure pavement profile.

Disadvantages

One significant disadvantage to using a profilograph is the time needed to perform one complete test of the road width. The tests taken using a profilograph only measure the pavement profile of one wheelpath at a time. Other drawbacks to using any type of mechanical pavement profiler include high initial cost, complexity of operating the devices, and slow operating speed. Computer software has been developed that does most of the calculations thereby reducing the consuming profilograph trace time, another important disadvantage to using a pavement profiler.

WATER-CEMENT RATIO

The water-cement ratio (w/c) of concrete is defined as the weight of water divided by the weight of cement. Research has shown that the w/c of concrete is an important quality characteristic when it comes to defining strength and durability. When cement and water are mixed, microscopic crystals form that link cement grains together. This process assists in the development of strength and other mechanical properties. The microscopic crystals also begin to fill in the voids between the cement grains making the paste more dense and less permeable to water, deicing salts, sulfates and gases. Therefore, it is important to keep the w/c ratio as low as possible within the limits of having a workable mixture. As the w/c ratio goes down, the strength of the concrete increases, the permeability decreases, and the possibility that the durability of the concrete pavement increases.

Test Methods

Two test methods are available to measure the cement and water content in fresh concrete.

- ASTM C1078 – *Test Methods for Determining Cement Content of Freshly Mixed Concrete*
- ASTM C1079 – *Test Methods for Determining Water Content of Freshly Mixed Concrete*

The results of these tests can be used to assure that the desired cement and water contents are obtained. In addition, the potential strength and durability can be estimated before the concrete hardens. Using these ASTM methods in combination with the Willis-

Hime test or Rapid Analysis Machine, the w/c ratio can be determined. A Water/Cement Gauge has also been used measure the w/c.

Advantages

Using w/c ratio as performance criteria can be extremely advantageous to technicians in the field. Water-cement ratio is measured using plastic concrete, which can assist technicians in detecting concrete that is out of specification, and then adjustments in the field can be made. However, the characteristics of plastic concrete and hardened concrete can be extremely different.

Disadvantages

Although using w/c as performance criteria can be advantageous in making corrections before the concrete has hardened and cured, there are some disadvantages that should be mentioned. The test methods used to measure w/c don't account for admixtures added to the batch and exclude the air matrix.

UNIT WEIGHT

Unit weight is controlled by the amount of aggregate, relative density, air content, and water and cement contents. The unit weight of fresh concrete is determined by estimating the volume of air present on the basis of the weight/volume relationship. Specifications of the unit weight of concrete used for pavements range from 140 to 150 pounds per cubic foot (pcf).

Test Methods

The most widely used method to determine unit weight is ASTM C138 – *Test for Unit Weight, Yield and Air Content (Gravimetric) of Concrete*. Using this test method will also give indications of the air content, provided the specific gravities of other ingredients are known. Another test procedure that has been developed to determine unit weight in both fresh and hardened concrete involves the use of nuclear methods. This test procedure is described in ASTM C1040 – *Test Methods for Density of Unhardened and Hardened Concrete in Place by Nuclear Methods.*

Advantages

The test methods used to measure unit weight can also be an approximate indicator of the air content and density of concrete. Performed on plastic concrete technicians can make adjustments in the field if the concrete is out of specification.

Disadvantages

Disadvantages include periodic calibration of the container. The calculation of unit weight is based on assumptions of relative quantities and specific gravity or relative density of the constituent materials. Making an incorrect or bad assumption can lead to an incorrect calculation of unit weight. The density of aggregate, air content, and the cement and water content can cause variations in unit weight.

SLUMP

The slump of fresh concrete is the difference between the height of a specimen in a bottomless conical metal mold and its height after the mold is removed. A high slump would indicate a higher mixing water content, which would result in a lower expected strength. A low slump would mean a lower mixing water content with a higher expected strength. The properties measured by slump include uniformity, consistency, and cohesion of fresh concrete. Slump is a prime indicator of the workability of concrete.

Test Methods

The methods used to determine slump are outlined in ASTM C94 – *Specification for Ready-Mixed Concrete* and ASTM C143 – *Test for Slump of Portland Cement Concrete*. Currently, no research is being conducted to develop an improved method to test slump that measures the uniformity, consistency, and cohesion of fresh concrete in the field as accurately as ASTM C94 and ASTM C143.

Advantages

Using the preceding methods to measure slump is advantageous due to the low cost, simplicity, and repeatability of the test. In addition, the slump test provides information on the workability and uniformity of concrete, showing the within batch and between batch variations.

Disadvantages

However, objections have been raised regarding the importance of the results from the slump test. These objections are based upon the fact that the slump measurement is easily influence by admixtures, aggregate gradation, delivery time, and temperature. Slump test accurately measures consistencies ranging from "medium plastic" to "highly plastic" **only**.

Arguments have been raised regarding the sensitivity of the slump test to changes caused by the differences in operators or operations. However, it has been proven that a qualified technician can reproduce accurate slump measurements if he/she keeps the testing procedure constant, thereby eliminating variations. For example, if he/she keeps the rate at which the cone is lifted constant.

STATE SURVEY RESULTS

In addition to conducting a literature review of the characteristics that best describe PCC performance, a survey was developed and sent to various public/private trade organizations and federal and state agencies. A copy of the survey and a summary of the results can be found in Appendix A.

Of the 50 state highway agencies contacted, 32 responded. Out of the 32 responses, 53% are currently using or developing a performance based specification program. Of the 47% of agencies that do not currently use a performance based specification program, 34 % are considering a similar program. The 13% of agencies that aren't considering the use of a performance based specifications either didn't respond to the question or felt that they do not construct enough concrete to justify such a program. Results of the survey indicate that state agencies have selected thickness, compressive strength, smoothness, and air content as the most common PCC characteristics measured in their performance based specification programs. These characteristics agree with the results of the literature review conducted. In addition, when asked what measures best define PCC pavement performance, the most common responses from the agencies were strength, air content, thickness, and smoothness (rideability).

Methods of qualitatively measuring PCC performance are based on statistics and/or upper/lower limits. Other bases of qualitative measurement include empirical methods, incentive methods, standard pay factors, and historical averages.

RECOMMENDATIONS AND CONCLUSIONS

The amount of literature relating to the development of performance based PCC specifications is limited. The primary effort has come from NCHRP, FHWA, and ERES consultants. That work has centered on the performance factors of concrete strength, air content, depth, and initial smoothness. Development of a statistically based specification for these factors is underway. Iowa's experience with the development of specifications and construction guides indicate any one of the four factors may induce other detrimental effects on performance.

Before performance criterion can be selected, an understanding of the types of pavement distresses and their causes needs to be realized. Different pavement distresses and the factors which influence them are provided in Table 1. Referring to Table 1, the current quality characteristics selected that can best control pavement performance include concrete strength, slab thickness, air content, initial smoothness, water-cement ratio, unit weight, and slump. Each criterion is briefly described with the test methods and advantages and disadvantages of each. In addition, all the performance criteria selected are identified as a factor that affects at least one type of pavement distress listed in Table 1. Measuring selected performance criteria can aid in the prediction of pavement distresses and the maintenance costs needed to repair the distresses. Predicting maintenance costs needed over the life of the pavement can determine the amount of payment adjustment required at the time of construction.

In addition to the identification and description of pavement distresses and quality characteristics that can be beneficial in predicting pavement performance, a survey was developed and sent to different public/private trade organizations and state and federal agencies. A copy of the survey and a summary of the results can be found in appendix A. The results of this survey helped to reveal what various state agencies are currently doing in the area of performance based specifications. In addition, the survey revealed what these agencies felt was important to the performance of PCC pavements.

It should be noted that the measurement of pavement performance should not be limited to the criteria and test methods described in this paper. Other factors that affect the performance of concrete and have been suggested as potential criteria include: joint spacing, depth of sawing, time of sawing, dowel bar placement and alignment, tie bar placement, workability, impact of additives in batch mix, air distribution, and durability. In addition, the environment and construction techniques used have been shown to have a notable impact on the performance of pavements. It has been suggested that only construction techniques should be used to control the quality of concrete. However, that leaves all the responsibility with the contractor. If the quality of concrete is to improve both the highway agencies and the contractors must work together.

The question still remains. What factors measured at the construction site will provide an adequate measure of future performance? The research team suggests that in Phase II a regional expert task group be formed to identify performance levels and criterion. The results of that effort will guide the research team in the development of new or revised specifications.

REFERENCES

1. Aarre, Tine. "Influence of Measurement Technique on the Air-Void Structure of Hardened Concrete." ACI Materials Journal V. 92, No. 6, November-December 1995: 599-604.

2. Anderson, D., Luhr, D. and Antle, C., "Framework for Development of Performance-Related Specifications for Hot-Mix Asphaltic Concrete." Agency report, NCHRP Project10-26A, NCHRP Washington D.C. (1990).

3. Ansari, Farhad. "Rapid In-Place Air Content Determination in Fresh Concrete." Concrete International V. 13, No. 1, January 1991: 39-43.

4. Basham, Kim. "Testing Fresh Concrete in the Field." Concrete Construction V. 38, No. 8, August 1993: 550-56.

5. Darter, M., Hoerner, T., Smith, K., Okamoto, P., and Kopac, P. "Development of Prototype Performance-Related Specification for Concrete Pavements." *Transportation Research Record* 1544, Transportation Research Board, Washington D.C. (1996) pp.81-90.

6. Darter, M., Abdelrahman, P., Okamota, P., and Smith, K., "Performance-Related Specifications for Concrete Pavements: Vol. 1-Development of a Prototype Performance -Related Specification." *Report No.* FHWA-RD-93-042, Federal Highway Administration, Washington D.C. (1993).

7. Foo, H.C., and G. Akhras. "Prototype Knowledge-Base System For Corrective Maintenance of Pavements." Journal of Transportation Engineering V. 121, No. 6, November-December 1995: 517-23.

8. Hover, Ken and Tullie Stokes. "Making 'Cents' Out of the Water-Cement Ratio." Concrete International V. 17, No. 5, May 1995: 52-54.

9. Hover, Ken. "Measuring Air in Fresh and Hardened Concrete." Concrete Construction V. 38, No. 4,April 1993: 275-78.

10. Hover, Ken. "Specifying Air-Entrained Concrete." Concrete Construction V. 38, No. 5, May 1993: 361-67.

11. Irick, P.E., S.B. Seeds, M.G. Myers, and E.D. Moody, "Development of Performance-Related Specifications for Portland Cement concrete Pavement Construction." *Report No.* FHWA-RD-89-211, Federal Highway Administration, Washington D.C. (1990).

12. Kosmatka, Steven H., and William C. Panarese. Design and Control of Concrete Mixtures. Skokie: Portland Cement Association, 1988.

13. Khayat, Kamal H., K.W. Nasser and Weston T. Hester. "Alternative Method to Measure Air Content in Fresh Concrete." ACI Materials Journal, V. 87, No. 4, July-August 1990: 355-62.

14. Koski, John A. "Measuring Pavement Profile." Concrete Construction V. 39, No. 5, May 1994: 416-422.

15. Malisch, Ward. "Fast Field Tests for Concrete." Concrete Construction V. 41, No. 7, July 1996: 552-560.

16. Mittelacher, Martin. "Re-Evaluating the Slump Test." Concrete International V. 14, No.10, October 1992: 53-56.

17. Parcells, William H., Jr., and Mustaque Hossain. "Kansas Experience with Smoothness Specifications for Concrete Pavements." *Transportation Research Record* 1435, National Research Council, Washington D.C., October 1994.

18. Popovics, Sandor. "The Slump Test Is Useless-Or Is It?" Concrete International V. 16, No. 9, September 1994: 30-33.

19. Shilstone, James M. "Performance Specifications for Concrete Pavements." Concrete International V. 13, No. 12, December 1991: 28-34

APPENDIX A

1. Performance Based Specification Survey (TR-403)
2. Summary of Survey Results

Performance Based Specification Survey (TR-403)

1. Does your organization currently use a performance-based specification program? If so, what concrete characteristics are measured? ____________________

   ____

   For each characteristic measured what are: (use additional sheets if necessary)
   - Units of measure ____________________
   - Test methods ____________________

     ____

     ____
   - Test equipment ____________________

     ____

     ____
   - How are results applied to the construction contract? ____________________

     ____

     ____
   - Acceptable limits and/or target values ____________________

     ____

2. If your organization does use a performance-based specification program, please answer the following:

   a. The specification(s) is: 1.) Statistically Based ______
      2.) Upper/Lower Limits (range) ______
      3.) Other (define) ____________________

   b. What do you feel that your organization has benefited from using a performance-based specification program? ____________________

      ____

   c. What are the reactions or responses from contractors? ____________________

      ____

      ____

   d. Please provide a copy of the specifications used.

3. If your organization doesn't use a performance-based specification program, please answer the following:

   a. Why doesn't your organization use a performance-base specification program?

      ____

      ____

   b. Would you consider using a performance-based specification program in the future? Yes _____ No _____

   c. What quality control measures does your organization use during PCC pavement construction? (Please provide an example or copy of specification/guidelines used

      ____

      ____

4. Regardless, of whether or not your organization uses a performance-based specification program, please answer the following:

   a. What defines good PCC pavement performance in your jurisdiction and what measures are used to predict it at the time of construction?__________________

5. Person responsible for completing this questionnaire:
   Name: Title:
   Phone: Fax:
   E-mail:
   Address:

6. Return by March 10, 1998 to:

Dr. James Cable
378 Town Engineering Building
Ames, Iowa
50011
Phone: (515) 294-2862
Fax: 515-294-8216

Summary of Survey Results

State	Uses PBS Program		Measured Characteristics	Specifications are:			Considering a PBS Program	
	Yes	No		Stat. Based	U/L Limits[1]	Other	Yes	No
Alabama DOT		X						
Arkansas DOT	X		Pavement Smoothness		X		X	
California DOT								
Colorado FHWA		X					X	
Connecticut DOT		X					X	
Delaware DOT								
Florida DOT		X					X	
Georgia DOT		X					X	
Idaho DOT								
Illinois DOT		X					X	
Indiana DOT	Developing						X	
Kansas DOT	X		Thickness, comp. strength, smoothness		X			
Louisiana DOT	X		Thickness, comp. strength, smoothness	X				
Maryland DOT		X						X
Michigan DOT	X		Comp. strength, temp., slump, air content	X	X			
Minnesota DOT	X		W/C, ride		X			
Mississippi DOT		X						
Missouri DOT		X					X	
Nebraska DOT		X					X	
New Hampshire DOT	X		Strength, air content, permeability, W/C	X				
New Mexico DOT	Developing		Comp. strength, air content, unit weight, temp.	X	X			
New York State DOT	X		Pavement Smoothness			Empirical		
North Carolina DOT	X		Flex. strength, air content, unit weight, temp.	X	X			
Ohio DOT	X		Pavement Smoothness		X			
Oklahoma DOT		X					X	
Pennsylvania DOT	X		Pavement smoothness, thickness, comp. strength, air content	X	X	Incentives		
South Carolina DOT								
South Dakota DOT	X(Asphalt)			X	X			
Utah DOT	X		Comp. Strength, thickness, smoothness			Std. Pay Factors		
Virginia DOT	X		Rideability					
Wisconsin DOT	Developing		Comp. strength, thickness, smoothness, air content					
Wyoming DOT	X		Pavement smoothness, thickness	X	X	Historical Avg.	X	

[1]U/L Limits = Upper/ Lower Limits

State	Measures that best define good PCC Pavement Performance:									
	Design Mix	Mix Material	Strength[2]	Air Content	Thickness	Rideability	Durability	W/C	Slump	Other
Alabama DOT	X	X	C, F	X	X	X			X	
Arkansas DOT			C			X				
California DOT										
Colorado FHWA								X		
Connecticut DOT										
Delaware DOT										
Florida DOT			X		X	X				
Georgia DOT			X	X	X	X	X		X	Uniformity
Idaho DOT										
Illinois DOT					X	X				Aggregate
Indiana DOT			X	X	X	X				
Kansas DOT										
Louisiana DOT						X				Constructability, life cycle performance.
Maryland DOT										AASHTO T119, T152, T199
Michigan DOT			X				X			Materials and workmanship.
Minnesota DOT	X			X		X				Aggregate quality, panel length, and load transfer.
Mississippi DOT						X	X			
Missouri DOT		X		X		X			X	
Nebraska DOT	X	X				X				Good performance, absence of cracking.
New Hampshire DOT										
New Mexico DOT			X	X	X	X	X			
New York State DOT	X			X	X	X	X		X	Good joint construction and load transfer.
North Carolina DOT					X	X				Consistent concrete properties.
Ohio DOT			X	X	X	X				
Oklahoma DOT			X			X	X			
Pennsylvania DOT			C					X	X	Cement factor.
South Carolina DOT			F		X	X				
South Dakota DOT										Good performance.
Utah DOT										
Virginia DOT										
Wisconsin DOT		X					X			
Wyoming DOT			F				X			Skid resistance, minimal surface defects.

[2]C = Compressive Strength, F = Flexural Strength