PROJECT SUMMARY REPORT 3925-S

EVALUATION OF THE PERFORMANCE OF TEXAS PAVEMENTS MADE WITH DIFFERENT COARSE AGGREGATES: PROJECT SUMMARY REPORT

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BUREAU OF ENGINEERING RESEARCH
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16. Abstract

This report summarizes 23 years of work undertaken in Texas to understand the reasons for significant performance differences found in pavements placed around the state. To a significant degree, pavement performance can be predicted based on the concrete material properties, on the environmental conditions prevailing when the pavement was placed, and on the pavement type.

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by

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IMPLEMENTATION STATEMENT

This report summarizes the findings obtained from 12 years of study on the effects of coarse aggregate on pavement performance. The implications of this project have a wide range of application to design practice in Texas. Specific implementation recommendations are presented in Chapter 2 (starting on page 9) of this project summary report.

DISCLAIMERS

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Research performed in cooperation with the Texas Department of Transportation.

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CHAPTER 1. INTRODUCTION

This report summarizes 23 years of work undertaken in Texas to understand the reasons for significant performance differences found in pavements placed around the state. To a significant degree, pavement performance can be predicted based on the concrete material properties, on the environmental conditions prevailing when the pavement was placed, and on the pavement type.

1.1 BACKGROUND

Continuously reinforced concrete (CRC) pavements are characterized by the presence of longitudinal reinforcing steel placed continuously throughout their length. Technically speaking, CRC pavements have no intentionally placed transverse joints other than construction joints in the pavement. However, the continuity of the concrete in the pavement is interrupted by a great number of transverse cracks caused by volumetric changes in the concrete that occur in response to shrinkage and temperature changes. When a transverse crack occurs, the stress distributions in concrete and the reinforcing rebar change greatly from point to point in the pavement. Experience has indicated that pavement performance is significantly linked to the resulting transverse crack pattern (or postcracking) behavior of CRC pavement. For example, short crack spacings coupled with pavement locations where poor support conditions exist have shown a strong correlation with a high frequency of punchout distress. On the other hand, long crack spacings can lead to large crack openings that may result in crack spalling, steel rupture, and poor load transfer efficiency. Once load transfer has diminished to a certain extent, punchout distress or faulting may be evident particularly where loss of support exists under the pavement.

In the 1986/1993 *AASHTO Guide for Design of Pavement Structures*, a procedure was set forth that considers crack spacing, crack width, and steel stress at a crack in the design of CRC pavement. The design percentage of longitudinal steel is selected in such a way that the results from the analysis satisfy the desired range in crack spacing, allowable steel stress, and crack width. This analysis is a function of such predetermined parameters as concrete tensile strength, thermal coefficients of steel and concrete, rebar diameter, concrete tensile stress generated by wheel load, concrete shrinkage, and design temperature drop based on predictive formulas. This design method suggests providing an appropriate percentage of steel reinforcement to distribute transverse cracks, so that instead of a few wide cracks there are numerous small-width cracks.

During construction, it is expected that the final crack spacing will fall into the desirable range as a result of the above-mentioned design parameters. Unfortunately, it is difficult to eliminate “Y” cracks and other defects (such as closely spaced transverse cracks) by adjusting only the amount of longitudinal steel. Such difficulty is primarily a result of the variability of material properties, construction factors, and environmental conditions that are to some extent outside of the contractor’s control. Moreover, the early-aged cracking behavior of CRC pavements is affected not only by the previously noted design parameters, but also by the vertical location of the longitudinal and transverse steel reinforcement, coarse aggregate type, and ambient temperature condition at the time of paving. This has been a concern for some time, and efforts were undertaken to develop a greater knowledge base of these factors and their influence on CRC performance during construction. A primary focus of the test sections constructed in these projects was on investigating the influence of the above factors (under field conditions) on crack development in CRC pavement, and on developing construction guidelines that consider these factors in providing and advancing new concepts in the technology of CRC pavement construction. The sections that follow will describe these efforts, along with some of the experiments conducted to better understand and improve CRC pavement performance.

1.2 HISTORICAL DEVELOPMENT

Beginning in 1974, the Texas State Department of Highways and Public Transportation (now the Texas Department of Transportation, or TxDOT) initiated research that investigated ways to improve the performance of concrete pavements. The first step in the process was to survey every mile of portland cement concrete (PCC) pavement in the state for rehabilitation prioritization (Figure 1.1). When performance differences were noted in the sections, TxDOT decided to continue periodically surveying the continuously reinforced concrete pavement (CRCP) sections and to establish a database. The objectives of the database were to provide performance data for developing design methods and construction specifications, for monitoring maintenance effects, and for comparing pavement types.

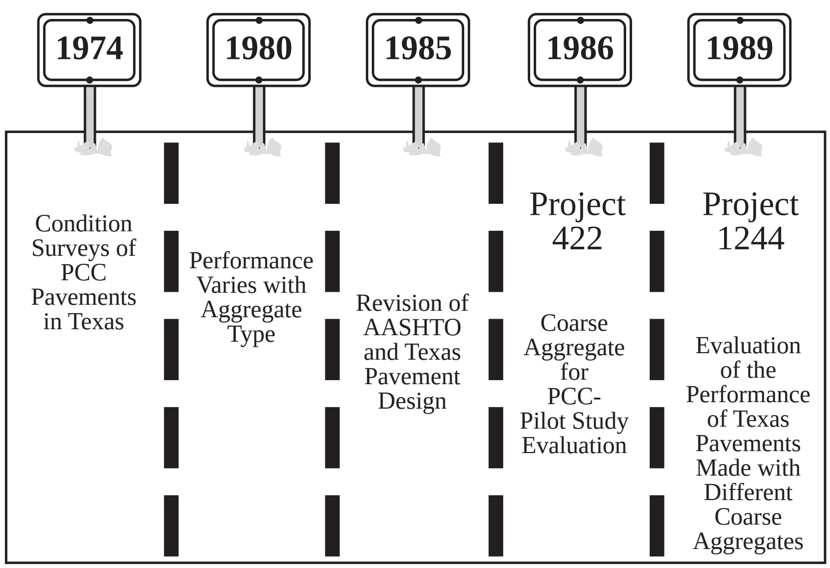

Figure 1.1 Historical development of the coarse aggregate evaluation project

Using the database, researchers were able to look at the data to find performance differences in similar pavements. When performance differences were found, the Center for Transportation Research (CTR) at The University of Texas at Austin began to investigate what caused the differences, with the goal of achieving improved pavement performance.

One of the primary original findings of the pavement surveys was that the concrete coarse aggregate type was a significant factor in pavement performance. This finding was so important that when the AASHTO and Texas pavement designs were modified in 1985, they reflected the differences in performance that were found.

Figure 1.2 shows the difference in performance between pavements constructed with siliceous river gravel (SRG) and limestone (LS) aggregates. The curves in the figure were fit to the 20-year performance histories in the Rigid Pavement Database and, thus, represent the average rate of failure development for limestone and river gravel pavements with and without swelling subgrades. Again using the Rigid Pavement Database, Figure 1.2 was prepared, showing the significant difference between LS and SRG in terms of crack spacings — LS pavements tending to stabilize at a crack spacing of around 1.83 m versus a much lower spacing of 0.61–0.91 m for SRG pavements. The closer crack spacing for the SRG pavements greatly increases the probability of a longitudinal crack intersecting two transverse cracks, ultimately resulting in a greater number of failures per 1.61 km.

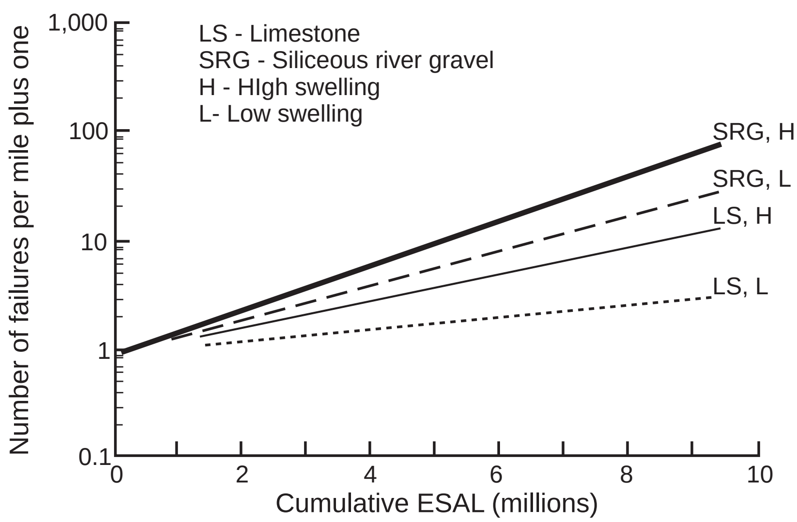

Figure 1.2 Development of failures in SRG and LS pavements

After finding the differences in pavement performance based on aggregate type, it was important to understand the material properties causing the differences, and to then evaluate ways to improve concrete pavement performance through a controlled study. With this purpose in mind, TxDOT commissioned a series of coarse aggregate studies — Project

422 and, subsequently, Project 1244 — that looked at the differences in pavement performance considering coarse aggregate type and other factors.

1.3 COARSE AGGREGATE STUDIES OVERVIEW

As these studies began, the primary objective was to evaluate concrete with different coarse aggregates using both laboratory and field methods. The laboratory work began first, with the results of the laboratory work leading to guidelines for the design of the field test sections. Eight different sets of test sections were placed in the Houston, Texas, area to study ways to improve concrete performance. In each project, a number of pavement conditions were varied to better understand their effects on pavement performance. Monitoring the performance of these test sections over the years has led to improved design and construction procedures. (For detailed descriptions of these test sections, see Research Report 3925-1.)

1.3.1 Summary of Findings from Projects 422 and 1244

Research Studies 422 and 1244 produced some very important findings and led to some new hypotheses regarding concrete performance with different coarse aggregate types. The major finding from the variables directly considered was that a large part of the performance differences in concrete pavements could be directly attributed to the coarse aggregate used in the concrete. The steel percentages, which ranged from low to high value, i.e., a difference of approximately 0.2%, used on these test sections did not have a significant effect on the performance of the pavement. This could be attributed to the fact that all the steel percentages were acceptable values for the Houston area. Indirectly, it was also found that high placement temperatures, e.g., ambient temperatures above 32.2°C, could lead to a very erratic crack pattern and, consequently, poor performance. These conditions led to PCC temperatures in the 60°C-to-65.55°C range and to rapid decreases in temperature during the first 24 hours when the concrete is relatively weak. This difference is the single most important factor controlling early-aged crack development and the primary cause of the difference in performance in pavements made with either aggregate. It was found that the high temperature conditions overwhelm all other variables considered. And while no steel combinations can offset this phenomenon, in the past when the cause of the problem was not fully understood, the longitudinal steel percentages were unfortunately arbitrarily increased over the years. Thus, original steel percentages that were providing acceptable design conditions were increased to offset problems caused by other phenomena. It should also be pointed out that although early-aged concrete strength is relatively low, the bond strength of concrete with limestone aggregate is significantly greater than that of concrete with SRG coarse aggregate.

Failure models for siliceous river gravel and limestone aggregates were also developed; since portland cement concrete fails primarily in tension, the effects of tension on concrete were the focus of the failure model development.

A variety of techniques were developed for improving pavement performance. These techniques included night placement, sawcutting of the fresh concrete to control crack development, use of aggregate blends and various curing techniques, and the use of methods to improve base materials. The projects showed that night placement gave better results than day placement. By using sawcutting, the cracks in the pavement became much straighter, thus reducing the randomness that can sometimes lead to punchouts. Curing techniques, such as polyethylene sheeting and double-membrane curing, were used to reduce the pavement evaporation rate, which, in turn, helped to control future spalling and reduced the number of cracks that occur very early in the pavement life.

The projects also were undertaken to produce computer programs for concrete pavement design. The CHEM2 computer program was developed to provide the designer with a preliminary estimate of the fundamental concrete properties from simple chemical tests of the coarse aggregate. CHEM2 uses the chemical constituents of the coarse aggregate, which can be obtained relatively cheaply through oxide residue testing, to predict its mineral composition. Based on the aggregate's mineral composition, the program predicts the fundamental concrete properties, such as the coefficient of thermal expansion.

These studies have provided continuing development of a mechanistic-empirical program, dubbed CRCP-8, that has been calibrated and validated using empirical data obtained from the Rigid Pavement Database. The first version of the program dates back to 1974, with subsequent modifications undertaken to incorporate the latest research. The data from these projects were used to further calibrate the crack width and the performance curves. In this program, the concrete properties (e.g., tensile strength) and aggregate properties (e.g., coefficient of thermal expansion) must be input. The expected air temperatures, steel percentage, and loading conditions must also be provided. From that information, crack spacing distributions and a mean crack spacing are computed, as well as the mean crack width and maximum steel stress. In addition, a cumulative failure development as a function of time is computed. The program provides a performance prediction for a specific design and is especially valuable in comparing and evaluating several different pavement designs and construction conditions. It is also useful in diagnostic studies.

Another computer program developed from these projects was a design aid, CRCPAV, that can be used to find CRCP steel percentages based on the highway geometric properties, other material properties and acceptable levels of crack width, steel stress, aggregate properties, and crack spacing. Since CRCP-8 is a predictive program for a specific design, numerous program solutions were investigated for use in developing a regression model. This model then permitted development of the CRCPAV program, which allows the desired performance to be input and then solves for the design parameters, i.e., a design program. Once the properties are given as input into the program, a graph produced by the program shows the optimal steel range.

Another important development from Research Study 422 was the CRCP89 Steel Standard. Although it was used for only 1 month, CRCP89 set a precedent for a new type of steel design standard, one that varies the steel in the section based on the coarse aggregate type. The purpose of the standard is to develop similar crack patterns in concrete made from either siliceous river gravel or limestone aggregate. Other findings of the projects dealt with testing such concrete properties as strength. A large number of specimens were compared using tensile, flexural, and compression testing. The results showed that flexural and tensile strengths have a reasonable correlation across all aggregate types. However, poor correlations were found between tensile and compressive strengths, unless the aggregate type was taken into account. It should be noted that SRG mixtures require less steel than limestone concrete because SRG aggregates have a lower bond strength and a greater coefficient of thermal expansion than mixtures with limestone aggregates.

Since compression test results do not have a reliable correlation to the tensile strength of the concrete when comparing concrete made from different aggregates, care should be taken when evaluating results from compression tests. If results from compression testing are compared directly, erroneous conclusions could be made about a specimen's resistance to cracking. Therefore, tension testing was used in these test sections to avoid this problem and, more importantly, because concrete fails in tension. A special test procedure was also developed to measure aggregate bond strength.

Recommendations that can be used to improve pavement performance were provided based on the results obtained from Research Studies 422 and 1244. Night placement and the use of blended aggregates have been recommended, insofar as they seem to overcome some of the differences in siliceous river gravel and limestone performance. Given the numerous key hypotheses developed from these two projects, more research was needed to validate the previous findings.

1.3.2 Research Study 7-3925

For Project 7-3925, pavement sections were designed and constructed in Hempstead, Texas, with the primary objective being the validation of hypotheses generated from previous experiments and to determine feasible sawcutting requirements for SRG CRC pavements. Figure 1.3 shows the locations of the test sites. Some specific objectives were to perform early-age and later-life condition surveys of the test sections, to monitor performance based on coarse aggregate type, to refine thermal coefficient (α_c) testing and crack control techniques for SRG CRC pavement, to develop a spalling model, and to support the quality control/quality assurance (QC/QA) specification development. The purpose behind each of these objectives is discussed in the following paragraphs.

Coarse aggregate type relative to bond strength, shrinkage, and coefficient of thermal expansion was identified from the beginning of the study as a very important factor in predicting pavement performance; indeed, these are the strongest factors in determining a pavement's performance, given that the coarse aggregate forms such a large percentage of the concrete's volume and, consequently, are the dominant factors relative to aggregate type selection and specification.

Since these factors are so important for concrete exposed to large environmental stresses at both early and late ages (as are pavements), testing has focused on developing equipment that can measure the coefficient of thermal expansion and the bond strength of the coarse aggregate in simple and direct procedures using a water bath for the coefficient of thermal expansion and split tensile test specimen for the aggregate bond strength. Pavement designs could easily be changed to account for differences in aggregate properties using tests.

Another major objective of this project was to develop and identify the spalling mechanism for future use in a spalling model. Spalling occurs in concrete mixtures having relatively high shrinkage stresses and low aggregate bond strengths. A spalling model would be useful in identifying such combinations, since spalling is one of the significant distresses that CRC pavements experience. If such information can be developed to decrease spalling in concrete pavements, the life-cycle cost of CRC pavements could be significantly reduced.

The final objective of Research Study 7-3925 was to support QC/QA specification development. All findings from this project are being shared directly with the QC/QA specification development team, so that improvements in concrete pavement performance can be made as quickly as possible.

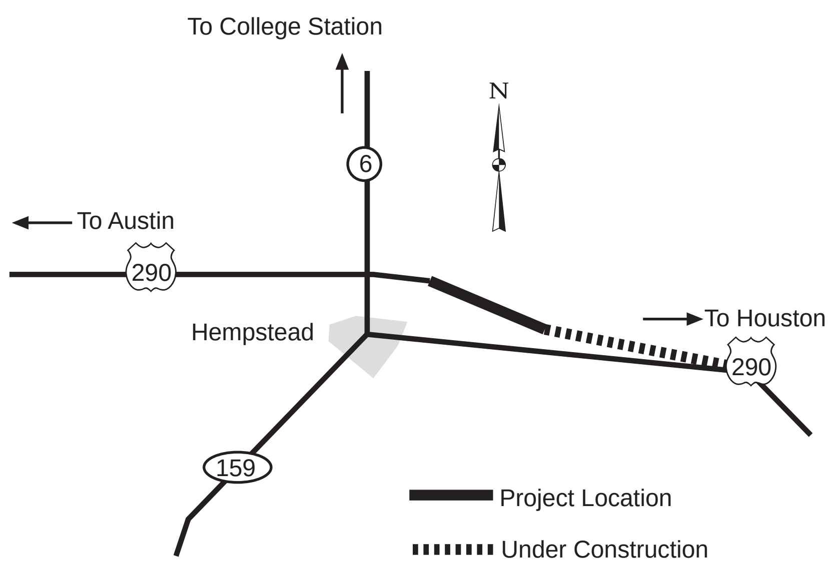

Figure 1.3 Test sections in Hempstead, Texas

With these objectives in mind, the final series of test sections was placed in Hempstead, Texas, near Houston. These sections are part of the new US 290 Hempstead bypass. The layout developed for Hempstead called for 22 test sections, with each about

365.76 m long. As reported in Research Report 3925-1, the effects of time of placement (i.e., night or day), longitudinal saw cuts, and varying the steel percentages were investigated.

1.4 REPORT OBJECTIVE

The objective of this report is to summarize all the recommendations developed from this and previous projects. Combining all the available data in this way summarizes the methods and concepts identified as important for improving the performance of concrete pavements, especially that of CRCP. These recommendations are presented in the next chapter.

CHAPTER 2. CONCLUSIONS AND RECOMMENDATIONS

2.1 INTRODUCTION

The observations and recommendations developed as a part of the PCC pavement coarse aggregate studies conducted by CTR, TTI, and TxDOT's development program for a QC/QA specification for PCC pavements provide an excellent starting point for an improvement program. Using this information, a plan is organized for developing a high-performance concrete pavement (HPCP) in Texas that encompasses design, construction, specifications, and testing. The objective of this program is to eliminate or minimize the instances in which PCC pavement failures cause CRC pavement sections to fall far short of their predicted life. Thus, the program will result in PCC pavement that serves for 25 to 40 years on high-volume facilities with minimum maintenance.

For the work plan, an improvement program is presented in five basic areas as follows:

(1) Improving pavement performance

(2) Guidelines for selecting PCC coarse aggregate

(3) Developing concrete pavement placement guidelines

(4) Improving and refining CRCP design models

(5) General PCC pavement developments

In the following sections, conclusions and recommendations are presented for a continuous improvement program in each of these areas. These are followed by a series of action items that may be achieved over the next 5 years. The intent is to achieve a series of *progressive* steps that will lead to an evolution of an HPCP; such evolutionary change is preferred over a single massive change that would undoubtedly be subject to controversy and, consequently, have a low probability of being accepted.

2.2 IMPROVING PAVEMENT PERFORMANCE

1. The field data from the eight projects manifest that the most important variables affecting PCC pavement performance are aggregate type, placement season, placement above ambient temperature of 32.2°C (90°F), and surface moisture evaporation. Thus, these factors should be reflected in the design and construction of PCC pavement as follows:

   a) Aggregate type and placement season are design variables and may be taken into consideration in the design process. The effect of aggregate type on performance is primarily due to the PCC thermal concrete coefficient, and, owing to the aggregate volume, it is primarily controlled by the coarse aggregate thermal coefficient.

Specific Recommendations:

(1) Design standards should be developed for various regions of the state, for various aggregate types, and for the construction seasons of summer and other than summer.

(2) A testing manual should include a test method for thermal coefficient of concrete and aggregates for reference in the specifications. Also include/develop a test for a 12-hour aggregate bond strength.

b) The factors of placing above ambient temperatures of 32.2°C (90°F) and surface moisture evaporation are basically construction/specification items. For placements above 32.2°C, special precautions should be taken to minimize the excess buildup of the heat of hydration of the concrete. The evaporation should be monitored and managed to maintain stress levels to acceptable levels, and with critical situations of excessive evaporation special steps should be taken to minimize moisture loss (e.g., the process of applying curing compound should be expedited, special curing techniques utilized, and a monomolecular film used).

Specific Recommendations:

(1) The specifications should encompass hot weather concreting, i.e., ambient temperatures >32.2°C with controls on the concrete temperature, curing effectiveness, and techniques during construction for reducing the temperature (e.g., adding ice, cooling stockpiles, wet cotton mats, etc.).

(2) The effectiveness of all curing membranes and specifically monomolecular film in maintaining acceptable stress levels should be evaluated by testing in the lab and the field.

(3) If the monomolecular film performs satisfactorily, then its use should be incorporated into the specifications.

(4) Testing techniques should be added to the manual for measuring concrete temperature and for acceptance of the monomolecular film.

(5) The use of a weather station for measuring the water evaporation from the surface should be included in the specifications with limits and corrective techniques for various levels of evaporation.

(6) Testing techniques for measuring evaporation should be included in the test manual.

c) The vertical loss of strength from top to bottom owing to excessive moisture leaving the slab and the delamination (spalling) may be controlled by preventing excessive moisture from being lost from the slab as a result of evaporation. This must be handled through various techniques during the placement and curing of the concrete.

(1) A technique for cutting a core into segments (two to three levels) and testing them should be developed and included in the testing manual.

(2) The Rigid Pavement Database and previous QC/QA test sections should be used to develop a correlation between vertical distribution of strength and spalling.

(3) Small test slabs should be instrumented for maturity using moisture and temperature gauges, and cored for testing. The small slabs should include various effective curing thickness and moisture losses, curing types, etc. The information should be used to develop a relationship between the strength loss moisture-based maturity and the parameters investigated.

2. At the present time, the acceptance testing of PCC is based on flexural testing of specimens made at the side of the road, cured in water at a constant temperature, and aged to 7 days. Since concrete fails in tension, splitting tensile strength testing should be used for acceptance testing. Furthermore, the QC/QA development work and basic strength mechanics have demonstrated the viability of the splitting tensile test.

   a) The use of splitting tensile testing for the official TxDOT tool for the planning, design, and construction of PCC pavements should evolve over time.

   Specific Recommendations:

   (1) A testing program on cores and cylinders from small slabs should be used to investigate the relation between in situ cores and cylinders cured with simulated field conditions, etc.
   (2) The testing program in Item 1 should also reflect the effect of reinforcement.
   (3) An acceptable strength level for use in design and acceptance testing should be established using previous QC/QA experience and the evaluation of in-service pavements selected from TxDOT's Rigid Pavement Database.
   (4) The test method should be included in the testing manual.

3. Several techniques of marginal value relative to Items 1 and 2 should be investigated further.

   a) The crack initiators and skewed placement of the transverse steel were the least effective in controlling the pavement performance under hot weather placement conditions.

Specific Recommendations:

(1) Consider techniques for developing design standards for hot weather conditions.

b) The blending of aggregates of high thermal coefficient and high bond strength showed promise with success on Project 7 (Cypress).

Specific Recommendations:

(1) Consider additional projects to further evaluate hot weather conditions.

c) The longitudinal steel percentage and the bar diameter had only a small effect on the projects where it was considered. This finding probably indicates that the range used was small (0.19%), and that we have more than an adequate amount of steel in the present designs.

2.3 GUIDELINES FOR SELECTING PCC COARSE AGGREGATE

1. Utilization of coarse aggregates in concrete paving should be made in light of specific engineering properties that affect pavement performance and crack development. The width of transverse cracks and the degree of load transfer govern CRCP performance. The aggregate bond strength, the method of construction (curing practice and degree of crack control), and the weather conditions during paving influence the initial crack pattern. The final crack pattern is largely influenced by the coefficient of thermal expansion (CTE) of the concrete and by the steel design, which also influence transverse crack opening.
2. It is important to recognize the utilization of coarse aggregate involves the selection of curing methodology, the degree of cracking control, and steel design. In light of these conditions, it is clear that the characterization of coarse aggregate CTE and bond strength dictate certain construction and curing practices. Aggregate CTE serves as an indicator of the CTE of concrete, while the concrete fracture toughness serves as an indicator of the aggregate bond strength.

Specific Recommendations:

(1) Develop the design approach for CRCP systems to maintain a sufficient balance between stress buildup and strength gain with time to achieve a specific crack pattern for a given steel design and aggregate type. The development of stress should account for curing, crack control, and shrinkage effects, while strength development will need to accurately account for moisture and bond effects in addition to the other factors currently taken into account.

(2) Complement Item 1 above with a CTE model for concrete based on the CTE of the aggregate and other relevant properties. Further develop the test procedure for both the aggregate CTE and bond strength so that a laboratory procedure can be adopted by TxDOT to determine these important properties.

2.4 CONCRETE PAVEMENT PLACEMENT GUIDELINES

The ambient temperature and evaporation were two important parameters affecting the performance of the pavement. The following are conclusions and implementation recommendations pertaining to both items:

1. The revisions of the construction process and the specifications should encompass several areas.

   a) The ambient and the concrete temperature should be continuously monitored, since summer placement generally involves conditions that are more problematic, and especially since ambient air temperatures above 32.2°C are critical. Steps should be taken during the critical placement to ensure that the heat of hydration does not become excessive; such steps include using ice, cooling the aggregate stockpiles, and restricting placement during the heat of the day.

   Specific Recommendations:

   (1) Further research is needed to develop an improved mathematical model correlating the relation between heat of hydration and concrete set temperature relative to the ambient temperatures, cement chemistry, wind speeds, concrete temperature at placement, subbase condition, curing type, and effectiveness. The Hyperpave Model developed by the FHWA can be used as a starting point.
   (2) The model developed from Item 1 should be used to develop construction guidelines and specification requirements, (i.e., ice, time of placement, etc.).
   (3) The model should be incorporated in the CRCP computer model as part of Section D.

   b) Low thermal coefficient and high bond strength concrete mixtures are suitable for all placement times and seasons; suitable placing conditions for high coefficient and low bond strength concrete mixtures must be established by appropriate computer simulation and analysis, but may be appropriate only for summer placement unless special precautions are taken.

Specific Recommendations:

(1) The existing CRCP-8 program should be used to develop specific initial criteria for ambient temperatures when using high thermal coefficient aggregates.

(2) When the improved version of CRCP is developed in Section D that encompasses the heat of hydration model developed in Section C.1.a.(3), a recomputation of Item 1 should be developed.

2. The evaporation of surface moisture during concrete placement conditions should be continuously monitored as follows:

   a) Excessive evaporation rates (i.e., greater than 0.976 $kg/m^2/hr$) correspond to low curing effectiveness and may lead to detrimental conditions of strength loss vertically from the top to the bottom of the slab, delamination, and, consequently, spalling.

   Specific Recommendations:

   (1) The strength loss model developed in Section A.2.b.(3) should be used to determine the acceptable/unacceptable evaporation rate and quantity to minimize the vertical strength loss.

   (2) The information obtained from Item 1 should be used for developing criteria to eliminate or minimize delamination spalling. These criteria should be incorporated into the revised CRCP model developed in Section D.

   b) During excessive evaporation periods, several operational techniques should be considered for inclusion in the specifications or in a manual on PCC pavement placement.

   Specific Recommendations:

   (1) Cease concrete placement or place during the day when conditions are more favorable.

   (2) Place a molecular material immediately after the PCC surface strike-off operations that prevents evaporation and does not interfere with the finishing operations.

   (3) Apply two separate coats of curing compound as soon after the finishing operation as possible and consider appropriate levels of curing effectiveness to control the balance between stress development and strength gain with time.

2.5 IMPROVING AND REFINING CRCP DESIGN MODELS

1. The CRCP-8 program, a mechanistic-empirical design procedure, was calibrated and validated in previous studies using the data obtained from the various experimental projects considered.

   a) The application of the program to the test section data demonstrated that crack spacing distribution and crack width can be predicted very reliably with the CRCP-8 model. The field studies also revealed that the predicted crack spacing distribution should be studied by the design engineer and used as criteria in lieu of the average crack spacing. Furthermore, crack spacings below 0.9144 m have a significant effect on reducing the pavement life.

      Specific Recommendations:

      (1) The crack spacing distributions and the pavement performance data from the RPDP may be used to establish acceptable limits as the crack spacing distribution.

      (2) The maximum allowable crack width based on water infiltration, joint stiffness, and spalling developed in previous TxDOT and NCHRP studies should be further studied using laboratory test slabs. The data may be used to reference the present criteria.

      (3) Full-scale field slabs should be tested using the MLS to further refine Item 2.

      (4) Include the effects of crack control in Items 1, 2, and 3 above to determine the range of the balance between strength gain and stress development suitable for selected aggregate types and concrete mixtures to achieve the best crack pattern.

   b) Since the steel stress was not measured as part of recent projects, the steel stress algorithm in the CRCP-8 program could not be validated; nonetheless, the predicted results for the various projects appeared to be logical and in line.

      Specific Recommendations:

      (1) Several future projects should incorporate strain gauges on the steel to measure the steel stress variation with time.

      (2) The projects selected for Item 1 should encompass both grade 60 and 70 steels.

      (3) The measured and predicted steel stresses from projects included in Items 1 and 2 should be compared. The models should be updated periodically.

c) The CRCP-8 computer program provides an excellent design or diagnostic tool that may be used for site-specific studies.

Specific Recommendations:

(1) As new projects are added to the Rigid Pavement Database, their actual performance should be compared with the predicted performance, thus providing a continuous calibration and validation program. The validation should be more precise with time, since the evolutionary specifications will result in properties required in the model to be collected during the construction operation.

(2) If Item 1 identifies areas where the computer model needs to be improved, steps should be taken to develop submodels that will improve the model precision.

d) In lieu of developing a pavement standard that is general and very conservative for the entire state, the program may be used to develop designs for a specific project, as previously discussed in Section A.1. a). (1).

2. The CRCP-8 program has evolved over time. Based on the results presented herein, the following enhancements and additional developments are recommended:

a) The improved finite element model for predicting stresses resulting from wheel load developed in Project 0-1758 should be inserted into the program to permit a more accurate calculation of stresses for the thicker pavements.

Specific Recommendations:

(1) Since pavement thickness and subbase type are variables in the Rigid Pavement Database, the predicted and actual performances should be calibrated.

(2) New projects added to the Rigid Pavement Database should be used for validation.

b) As a part of this study, the spalling mechanism has been characterized and modeled; the program should thus be revised to cover the spalling.

Specific Recommendations:

(1) The spalling model should be added to the CRCP program.

(2) Sensitivity studies using the spalling should be conducted to verify the program logic.

(3) The Rigid Pavement Database should be used to compare predicted and measured performance for calibration purposes.

2.6 GENERAL PCC PAVEMENT DEVELOPMENTS

The following are a number of conclusions and recommendations relative to the general area of PCC pavement development:

1. For the Rigid Pavement Database that has been maintained since 1974, a number of factors should be added to the database and developed using it, given that these studies have shown their importance. Those requiring minimal effort should be added immediately and those requiring more effort should be added over time.
   a) Within the next year, the following items could be added to the Rigid Pavement Database as a part of an existing project:
      (1) The evaporation rate (relative to curing effectiveness) at the time of the PCC placement for the test section should be added.
      (2) As part of the survey, the spall depth should be recorded, since the results from this study indicate that the depth of the spall is related to the evaporation rate and is tied to the amount of water leaving the pavement during the curing period.
      (3) The test sections on Projects 1–8 reported herein should be included in the Rigid Pavement Database, since significant information is available on the initial stages of the pavement and for a number of years thereafter. Thus, after a period of time, these sites could be revisited to ascertain the effect of the parameters on punchout formation and spalling.
   b) The following items will require more effort and could be added in subsequent years to the Rigid Pavement Database project:
      (1) At the present time the crack spacing distribution is recorded for only the first 60.96 m of a test section; based on its importance, we recommend it be kept for the entire 304.8 m.
      (2) The vertical distribution of the tensile strength has been identified as an important factor affecting concrete pavement performance, especially in the spalling area. Thus it is recommended that the tensile strength distribution vertically be determined for a subsection of the Rigid Pavement Database in order to determine what is an acceptable range.
   c) The results of this study indicate that several areas of criteria need to be developed for use in the design and construction of PCC:
      (1) The Rigid Pavement Database should be used to identify the acceptable level of cracking less than 0.9144 m (3 ft). Since the information is currently in the database (along with performance information), the criteria may be developed by analyzing the data.

(2) Once the vertical strength distribution is ascertained from the additions to the database as described in Item 1, then an acceptable level of difference between top and bottom may be established by examining the pavement's performance at various levels.

2. Performance-based specifications for PCC pavement should be developed using these studies, insofar as significant information has been derived and may be used to improve the overall level of rigid pavement performance in Texas. The specification should be developed incrementally by adding only those concepts that have been verified.

   a) Factors that should be included as special provisions to the PCC pavement specification on an immediate basis are as follows:

      (1) Control should be placed on the pavement for concrete placement with ambient air temperature greater than 32.2°C to ensure this concrete does not develop excessive hydration temperatures.

      (2) The evaporation rate on every project should be monitored in real time and for use by the contractor to adjust the curing conditions of placed pavements to ensure that a desirable set of conditions are realized.

      (3) The thermal coefficient of the portland cement concrete and, specifically, the coarse aggregate should be included in the specification so that various design levels (and in some instances crack control) may be established by the designer for various conditions experienced in the field.

   b) Concepts that should be added at later stages include the following:

      (1) The CRCP-8 program should be used along with the present technique to develop the pavement factor adjustment, since it can add the RI for cracks, the measured crack spacing distribution, and the vertical strength distribution.

      (2) The desire is to develop an NDT for measuring in situ strength. This project has demonstrated that, in addition to a temperature history, the moisture in the pavement is a very important factor affecting the strength of portland cement concrete. Of course, the importance of concrete density is well known. Therefore, to ensure that proper concrete conditions are achieved so as to provide acceptable portland cement concrete pavement in place, an equation with tensile strength as a function of temperature, moisture, and density should be developed. At the present time, only temperature is used in a maturity equation; but in order to ensure that the in situ strength is adequate, the moisture and density should be considered. The technology for achieving these factors is now presently available.