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SHRP CONCRETE AND STRUCTURES RESEARCH: CONTRACTS, REPORTS AND PRODUCTS

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Canadian Strategic Highway
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INTRODUCTION

The Strategic Highway Research Program (SHRP) was initiated to make significant advances in traditional highway engineering and technology through the concentration of new research funds in six technical areas. Of the $150 million (U.S. funds) during the life of the program from 1987-93, $12 million was allocated for research on the use of cement and concrete in highway pavements and structures, and $10 million for research on the protection and rehabilitation of concrete bridges. Prior to the contracting phase, the six technical areas were consolidated into four subject areas, one of which was concrete and structures. A more complete description of the planning, management and execution of SHRP is given in reference 1.

In the course of the concrete and structures research in SHRP (excluding the SHRP-IDEA program), seventeen contracts were awarded, 60 reports were published, and 41 different products identified. The purpose of this paper is to provide a brief summary of the contracting activities, reports and products which resulted from the research.

SCOPE

The scope of the concrete research was defined by the need to address the problems of deterioration of concrete in highway infrastructure components. While both pavements and structures were included, most of the research focused on pavements.

The structures research in SHRP was limited to the protection and rehabilitation of existing, reinforced concrete bridge components.

CONTRACTS

The contracts awarded in the concrete and structures area form a convenient frame of reference for tabulating the reports and products, because each contract covered a specific subject area. A summary of the subject areas is given in Table 1. The actual titles of the contracts, and the names of the contractors, are given in Table 2.

The research plan envisaged that the structures research would be implemented through four contracts (2). Contracts C-101, C-103 and C-104 were executed in accordance with the plan.

The contracting activity for Contract C-102 was complex and eventually involved the execution of seven contracts. After an unsuccessful attempt to award the research as a single contract, it was advertised as two contracts, for electrochemical removal (C-102A) and for cathodic protection (C-102B). The work on inhibitor injection (C-102C) grew out of an unsuccessful bid for Contract C-102A. Contract C-102B was not continued beyond the end of the second year funding because of the lack of progress and inability of the contractor to prepare a workplan which would satisfy the objectives of the project. This action resulted

in the writing of a new request for proposals which anticipated that the work remaining would be completed as a single contract, except for completing one of the tasks of Contract C102-B as a separate contract (C-102E). Because of the successful proposer's position in the cathodic protection industry, the tasks were split into three separate contracts (C-102D, F and G) to avoid any possibility of conflict of interest.

The research plan for the concrete research called for four major projects. After some slight reorganization of the tasks, most of the work was included in Contracts C-201 to C-205.

Contract C-204 was cancelled as a result of unsatisfactory performance of the contractor. This resulted in the writing of the terms of reference for a new contract (C-206) which salvaged as much work as possible from Contract C-204, included development of an expert system envisaged in the research plans, and provided a capstone contract for the concrete research program.

THE SHRP IDEA PROGRAM

In addition to executing the research plans, SHRP developed the IDEA (Ideas Deserving Exploratory Analysis) program to enhance creativity and innovation in the research. As the acronym implies, the program was designed to support feasibility studies to determine the viability of innovative projects. Two percent of SHRP's annual funds were allocated to the program (3). SHRP-IDEA began in 1987 and awarded contracts, which were typically in the $60,000 to $100,000 range and of 12 month duration, in response to proposals which were limited only by the scope of the original research plans. Later in the program, a provision was made for the field validation of innovative products, including those not originally developed under the IDEA program.

The IDEA contracts relating to concrete and structures are listed in Table 3.

REPORTS

The reports from the SHRP contracts were issued in two series "Published" and "Unpublished", which caused some confusion. Reports in the "Published" series were identified as being of interest to practitioners, and received a thorough review and editing. Concrete reports were numbered SHRP-C-XXX, where XXX represents three digits of which the first digit was a three. "Unpublished" reports generally consisted of interim reports, or final reports judged to be primarily of interest to researchers, rather than practitioners. The reports were numbered SHRP-C-XXX where the first X was the digit 6, or SHRP-C/AAA-YY-XXX, where AAA is an alphabetic code (UFR for unpublished final report or UWP for unpublished working paper), YY is the year of publication and XXX three digits. Reports produced under structures and IDEA contracts include the identifier S or ID respectively, in place of C before the numeric or alphabetic code. This numbering system was adopted after some reports had been printed, with the result that

inconsistencies exist. A list of the published and unpublished reports, together with an abstract of each report, is given in Table 4.

PRODUCTS

SHRP was conceived as a results-oriented research program which would yield products and processes to improve the performance and safety of highways. Reports were not considered to be "products", which were defined to be equipment, processes, test methods, specifications or manuals. The products were described in the SHRP Product Catalog (4). The products from the contracts listed in Tables 2 and 3 are given in Table 5, which also provides a cross-reference to the major report in which the product is described.

REFERENCES

1. Manning D.G., "Structures Research in SHRP and C-SHRP", Proceedings, International Road Federation Conference and Exposition, Calgary, Alberta, July 1994, Transportation Association of Canada, Ottawa, Ontario, Vol 9 (1994) pp A3-A25

2. "Strategic Highway Research Program Research Plans", Transportation Research Board, Washington DC (1986).

3. "Innovations Deserving Exploratory Analysis (IDEA) Program, 1989-1991", Strategic Highway Research Program, Washington D.C. (May 1989) 18 pp.

4. "SHRP Product Catalog", Strategic Highway Research Program (1992) 62 pp.

TABLE 1: SUBJECT AREAS OF THE SHRP CONCRETE AND STRUCTURES CONTRACTS

Contract	Subject
C-101	Inspection and Assessment of Concrete Bridges
C-102	Electrochemical Methods for Protection and Rehabilitation
C-103	Physical and Chemical Methods for Protection and Rehabilitation
C-104	Decision Model for the Protection and Rehabilitation of Concrete Bridges
C-201	Concrete Microstructure
C-202	Alkali-Silica Reactivity of Concrete
C-203	Freeze-Thaw Resistance of Concrete
C-204	Non-Destructive Testing of Concrete
C-205	High Performance Concrete
C-206	Optimization of Highway Concrete Technology

TABLE 2: SHRP CONCRETE AND STRUCTURES CONTRACTS

Contract	Title	Contractor
C-101	Assessment of Physical Condition of Concrete Bridge Components	Penn State Univ.
C-102A	Electrochemical Chloride Removal and Protection of Concrete Bridge Components	Eltech Research Corp.
C-102B	Cathodic Protection of Concrete Bridge Components	Battelle Columbus Labs.
C-102C	Injection of Synergistic Corrosion Inhibitors	SRI International
C-102D	Manual, Model Specifications and Cost Information on Cathodic Protection of Reinforced Concrete Bridge Elements	Eltech Research Corp.
C-102E	Anode Freeze-Thaw Resistance	CTL Inc.
C-102F	Field Activities and Data Collection, Existing Installations	Corrpro Companies Inc.
C-102G	Field Activities and Data Collection, New Installations	Kenneth C. Clear Inc.
C-103	Concrete Bridge Protection and Rehabilitation	Virginia P.I. and S.U.
C-104	Methodology for the Protection and Rehabilitation of Existing Reinforced Concrete Structures	Wilbur Smith Assoc.
C-201	Concrete Microstructure	Penn State Univ.
C-202	Eliminating or Minimizing Alkali-Silica Reactivity	CTL Inc.
C-203	Resistance of Concrete to Freezing and Thawing	Washington State Univ.
C-204	Non-destructive Testing for QC/Condition Analysis of Concrete	Trow Inc.
C-205	Mechanical Behavior of High Performance Concretes	North Carolina State Univ.
C-206	Optimization of Highway Concrete Technology	CTL Inc.

TABLE 3: SHRP IDEA CONTRACTS RELATING TO CONCRETE AND STRUCTURES

Contract	Title	Contractor
ID 001	Evaluation of Stratlingite-Hydrogarnet Glass Cement as a Quick Setting Patching Material	Corning Glass Inc.
ID 002	Evaluation of the Use of Laser Ultrasonics for the Rapid, Noncontact Inspection of Concrete and Asphalt	Harwell Laboratory
ID 005	An Electrochemical Method for Detecting Ongoing Corrosion of Steel in a Concrete Structure with CP Applied	Cortest Columbus
ID 007	Quantitative and Rapid Measurement of the Air-Void System in Fresh Concrete	Univ. of Michigan
ID 008	Evaluation of Electrochemical Impedance Techniques for Detecting Corrosion on Rebar in Reinforced Concrete	SRI International
ID 010	Identification of Chemical Agents for the Control of Alkali-Aggregate Reaction in Concrete	Cornell Univ.
ID 011	In Situ Determination of Air Voids in Fresh Concrete	New Jersey Inst. of Technology
ID 012	Carbon Fiber Reinforced Concrete	State Univ. of New York
ID 014	Feasibility Studies on Nondestructive Incorporation of a Conducting Polymer Anode Bed into a Bridge Deck Concrete	SRI International
ID 016	Smart Structural Technology for Nondestructive Evaluation of Concrete	Westinghouse Electric Corp.
ID 019	Electro-Acoustic Technology as a Means to Modify the Properties of Concrete - A Feasibility Study	Battelle Memorial Inst.
ID 023	Development of Metallic Coatings for Corrosion Protection of Steel Rebars	SRI International
ID 024	Low-Cost Sprayed Zinc Galvanic Anode for Control of Corrosion of Reinforcing Steel in Marine Bridge Substructures	Univ. of South Florida

TABLE 4: SHRP CONCRETE AND STRUCTURES REPORTS

Contract	Report Title and Abstract	Report No.
C 101	**Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Vol. 1: State of the Art of Existing Methods** Reviews existing methods to detect damage caused by corrosion of steel in concrete, poor quality or deteriorated concrete, and damage to prestressed or post-tensioned tendons embedded in concrete. Discusses each method and includes experiences reported in literature sources and in interviews with state and provincial department of transportation inspection and maintenance personnel. 70 pages.	SHRP-S-323
	Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Vol. 2: Method for Measuring the Corrosion Rate of Reinforcing Steel Examines parameters that affect corrosion rate measurements and ranks the most important parameters. Laboratory and field studies were performed using three commercially developed corrosion rate devices. 105 pages.	SHRP-S-324
	Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Vol. 3: Method for Evaluating the Condition of Asphalt-Covered Decks Investigates the use of short pulse, ground-penetrating radar to nondestructively identify delaminations at the top and bottom reinforcement levels of asphalt-covered concrete bridge decks. Results help to estimate service life, to program rehabilitation and maintenance activities, and to estimate quantities for rehabilitation contracts. 84 pages.	SHRP-S-325
	Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Vol. 4: Deck Membrane Effectiveness and a Method for Evaluating Membrane Integrity Investigates membrane performance and effectiveness to develop a nondestructive test to evaluate in-place membranes. An ultrasonic pulse velocity method was developed. Conclusions indicate that properly installed and maintained preformed membrane systems reduce chloride intrusion. 143 pages.	SHRP-S-326
	Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Vol. 5: Methods for Evaluating the Effectiveness of Penetrating Sealers Two methods, an electrical resistance and a water absorption method were used to evaluate penetrating sealers for portland cement concrete bridge structures. A survey of highway agencies in the United States and Canada describes the organizations' experience with various penetrating sealants. 59 pages.	SHRP-S-327

Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Vol 6: Method for Field Determination of Total Chloride Content SHRP-S-328

Evaluates four procedures to measure the chloride content of reinforced concrete in the field. The methods were used on samples from bridges located in different environments. Includes a detailed test procedure. 155 pages.

Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Vol. 7: Method for Field Measurement of Concrete Permeability SHRP-S-329

Evaluates a prototype surface air flow (SAF) device for the estimation of concrete surface permeability. A portable field device was constructed that obtains readings at one per minute, allowing a large amount of information to be developed at close intervals across a given concrete member. 87 pages.

Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Vol. 8: Procedure Manual SHRP-S-330

Describes a procedure to assess the condition of concrete bridge components. Integrates the 13 applicable, current test methods and procedures with methods presented in the previous seven volumes. Emphasis is on deterioration associated with chloride-induced corrosion of reinforcing steel, but all aspects of durability relative to concrete bridge components are addressed. Designed to be tailored to the needs of a highway agency. 124 pages.

C 102A

Evaluation of Norcure Process for Electrochemical Chloride Removal from Steel-Reinforced Concrete Bridge Components SHRP-C-620

This report is an analysis of the rate and total amount of chloride removed, the corrosive state of the steel before and after the process, the effects on the concrete, and other aspects of the installations. Comparisons are made to slabs used in other SHRP research on electrochemical chloride removal and protection of concrete bridge components. 31 pages.

Electrochemical Chloride Removal and Protection of Concrete Bridge Components: Laboratory Studies SHRP-S-657

The feasibility of electrochemical removal and concurrent protection as a rehabilitation option for concrete bridge structures was investigated. Chloride removal process procedures were developed, and the effects of the process on structure concrete integrity and reinforcing steel were studied. This report discusses the laboratory evaluations of this process. 201 pages.

Electrochemical Chloride Removal and Protection of Concrete Bridge Components: Field Trials SHRP-S-669

This report discusses the results of field validation trials, based on laboratory procedures for electrochemical chloride removal, completed on a bridge deck, column substructures, and a bridge abutment within North America. 149 pages.

Chloride Removal Implementation Guide SHRP-S-347

This report describes equipment and procedures for the electrochemical removal of chloride from reinforced concrete structures. Also provided is the basic information needed to implement the chloride removal process on field structures. Pretreatment and post-treatment procedures are also discussed. 45 pages.

C 102B	**Cathodic Protection of Reinforced Concrete Bridge Components** This report describes a two-year investigation of cathodic protection (CP) systems installed on interstate highway bridges in North America. The performance of 287 systems was reviewed through analysis of questionnaire responses and select field investigations. 79 pages.	SHRP-C/UWP -92-618
C 102C	**Electrochemical Chloride Removal and Protection of Concrete Bridge Components (Injection of Synergistic Corrosion Inhibitors)** A report on synergistic inhibitors for protecting concrete bridge components. Corrosion inhibitors were electrically injected into concrete matrices using an in situ technique. It was demonstrated that inhibitors developed under this project provide 78-85% corrosion protection for rebars; advantages: novelty, nondestructive nature, temporary installation. 53 pages.	SHRP-S-310
C 102D-G	**Cathodic Protection of Reinforced Concrete Bridge Elements: A State-of-the-Art Report** This report describes the evolution of cathodic protection of reinforced concrete bridges and its current state-of-the-art. It discusses: how cathodic protection works; the effectiveness of the techniques and an extensive history of cathodic protection of reinforced concrete is included covering all aspects of completed projects. Design and construction details are available for various types of anode systems. The ancillary equipment such as power supplies and monitoring equipment are reviewed. Research and development needs address essential research work required to further the development and use of cathodic protection of reinforced concrete structures. 89 pages.	SHRP-S-337
	Cathodic Protection of Concrete Bridges: A Manual of Practice This manual provides explanation, guidance, and direction concerning cathodic protection of concrete bridge elements to the highway engineer. The manual is divided into three sections: Design, Construction, and Operation and Maintenance. Provides standard specifications for cathodic protection systems for both decks and substructures. Specifications are modeled after those currently being developed under AASHTO, Associated General Contractors (AGC) and American Road and Transportation Builders' Association (ARTBA) Task Force 29 and provide a basis for other sections of the manual. Contributes useful reference for engineers who design and prepare specifications or who oversee turnkey operations. 293 pages	SHRP-S-372
	Control Criteria and Materials Performance Studies for Cathodic Protection of Reinforced Concrete This report demonstrates through mathematical models the feasibility of improved and simplified control criteria for cathodic protection of concrete structures. The models were developed to establish concentration profiles which develop as a result of cathodic protection current, and to study current distribution which results from geometric factors. 260 pages.	SHRP-S-670
	New Cathodic Protection Installations This report presents survey information collected for 36 cathodic protection systems in North America in 1991 and 1992. Eight structures using different cathodic protection systems in different environments were selected from detailed monitoring. 120 pages.	SHRP-S-671

Technical Alert: Criteria for the Cathodic Protection of Reinforced Concrete Bridge Elements SHRP-S-359
This technical alert presents the results and recommendations of research to investigate improved and simplified control criteria for cathodic protection. 14 pages.

C 103 **Techniques for Concrete Removal and Bar Cleaning on Bridge Rehabilitation Projects** SHRP-S-336
This report addresses the partial removal of concrete from decks and other parts of bridge structures. Three technologies are identified and studied in detail: pneumatic breakers, milling and hydrodemolition; analysis addresses work characteristics, production, cost and quality of product. 121 pages.

Concrete Bridge Protection and Rehabilitation: Chemical and Physical Techniques - Rapid Concrete Bridge Deck Protection, Repair and Rehabilitation SHRP-S-344
This report presents the rapid methods used on state highway agencies for the protection, repair and rehabilitation of bridge decks. The report is based on a review of the literature; the responses to questionnaires sent to state Departments of Transportation, Canadian provinces, selected turnpike and thruway authorities, technology transfer centers, and material suppliers; and the evaluation of 50 bridge decks located in seven states. Polymer overlays, sealers, high-early-strength hydraulic cement concrete overlays, and patches are compared for their performance characteristics and service life. 110 pages.

Concrete Bridge Protection, Repair, and Rehabilitation Relative to Reinforcement Corrosion: A Methods Application Manual SHRP-S-360
The manual is intended to be a practical guide for protecting, repairing and rehabilitating concrete bridges in a cost-effective manner. Methods are presented to estimate service life and remaining service of concrete components. Economic models are presented so that the most cost-effective methods may be selected. 268 pages.

Concrete Bridge Protection and Rehabilitation: Chemical and Physical Techniques - Field Validation SHRP-S-658
This report covers the field application and short-term corrosion performance of six trial installations of two inhibitor-modified concrete systems. The installations were applied to both deck and substructure components in a range of environments. Both pre- and post-treatment corrosion assessments were performed to estimate the corrosion performance of inhibitor modified concrete systems, including visual inspections, delamination surveys, cover depth surveys, chloride contamination levels, corrosion potential measurements, and corrosion current measurements. Though long-term data will be needed in order to make any firm conclusions, preliminary data appears promising for some application techniques. 67 pages.

Concrete Bridge Protection and Rehabilitation: Chemical and Physical Techniques - Price and Cost Information SHRP-S-664
This report provides an essential component in the process of determining life-cycle costs for ranking alternative techniques for concrete bridge protection and rehabilitation. Data from state highway agencies and toll road agencies in all major geographic regions were utilized. Where some new techniques did not have historical data, costs were estimated using classical engineering procedures. 270 pages.

Concrete Bridge Protection and Rehabilitation: Chemical and Physical Techniques - Feasibility Studies of New Rehabilitation Techniques — SHRP-S-665

This report examines chemical methods for corrosion protection of reinforcing steel in concrete bridges. A broad spectrum of chemicals were evaluated including corrosion inhibitors, chloride scavengers, and polyaphrons. 169 pages.

Concrete Bridge Protection and Rehabilitation: Chemical and Physical Techniques - Corrosion Inhibitors and Polymers — SHRP-S-666

This report discusses the improvement of existing non-electrochemical methods for protecting and rehabilitating chloride-contaminated concrete with and without concrete removal and the development of new methods. Polymer-impregnated concrete was compared to LMC overlay. LSDC overlay, polymer-impregnated concrete with an LMC overlay, and polymer-impregnated concrete with LSDC overlay. Five corrosion inhibitors were evaluated and service lives were estimated for the two most effective treatments. Asphalt Portland Concrete Composite (APCCC) was designed and evaluated. In addition, APCCC was compared with hot-mix asphalts and portland cement concrete for strength properties, resistance to freeze-thaw and resistance to chloride intrusion. 248 pages.

Concrete Bridge Protection and Rehabilitation: Chemical and Physical Techniques - Service Life Estimates — SHRP-S-668

This report presents definitions of end of service life of reinforced concrete bridge components exposed to chloride-laden environments; categorizes corrosive environments; and defines end of functional life of untreated bridge decks and substructures. Data from 52 bridge decks distributed in different environmental conditions were collected including chloride contents, cover depths, potentials, corrosion current density estimates, and damaged area measurements. Models were developed to estimate and compare service life of untreated and rehabilitated bridge decks with models based on historical data and time-to-rehabilitate models.

C 104 **A Literature Review of Time-Deterioration Prediction Techniques** — SHRP-C/UFR-92-613

This report reviews existing deterioration models used to predict corrosion-related deterioration on reinforced concrete bridges. Most models are based on the performance of all bridges in a system. In addition, the model information was developed using condition ratings provided by technician-inspectors performing visual surveys in accordance with the National Bridge Inspection Standards (NBIS). Discussion of the models illuminates equation definitions, research parameters, and life-cycle cost analyses. Included in the report is an annotated bibliography. 136 pages.

Life-Cycle Cost Analysis for Protection and Rehabilitation of Concrete Bridges Relative to Reinforcement Corrosion SHRP-S-377

This report consists of three parts. Part One discusses the development of a systematic methodology to determine the most cost-effective treatment, and its timing, for specific concrete bridge components that are deteriorating or are subject to deterioration. Part Two presents the methodology in the form of a handbook for highway agencies. The handbook includes nomograms, tables and other aids to facilitate the selection of the most cost-effective strategy. The methodology has also been incorporated into a microcomputer program. Part Three of this report documents the microcomputer program's user's manual, explaining the system's features, options, and displays. 289 pages.

C 201

A Guide to Evaluating Thermal Effects in Concrete Pavements SHRP-C-321

Describes use of tables developed to help determine problems that result from early thermal effects in concrete. Parameters like concrete temperature, air temperature, cement type and content affect the thermal behavior of concrete. The tables help predict whether pavement temperature will become too high; whether temperature differences between the concrete slab or base and the air will result in early thermal cracking. 104 pages.

A Guide to Determining the Optimal Gradation of Concrete Aggregates SHRP-C-334

This guide provides a means to determine the optimal gradation of fine and coarse aggregates for use in the concrete mix using a set of tables. The tables are based on a computer model for the theoretical packing of spherical particles which takes into account their size and specific gravity. Use of these tables in conjunction with the American Concrete Institute's ACI Standard Practice 211.1 should help produce a more workable mix and a better consolidated hardened concrete with decreased permeability and improved durability. 200 pages.

Concrete Microstructure: Recommended Revisions to Test Methods SHRP-C-339

This report analyzes and evaluates the results of research methods performed by SHRP for possible modifications to existing standard methods and specifications from the American Society of Testing and Materials (ASTM), the American Concrete Institute (ACI), the American Association of State Highway and Transportation Officials (AASHTO), and the Pennsylvania Department of Transportation. The evaluation criteria are described. Both specific and general recommendations are made. Implications of results of packing for aggregate grading on ASTM C33 are discussed. An extensive appendix contains trilinear packing diagrams. 107 pages.

Concrete Microstructure SHRP-C-340

Durability of concrete in highway systems is a problem of national concern. In order to better understand the mechanisms which intrinsically control durability in highway concrete it is necessary to define and understand those factors which impact concrete microstructure which is a consequence of both its formulation and the processes taking place during mixing, placing and curing. This report documents an investigation of those variables which control cement hydration and consequent microstructural development. 179 pages.

Concrete Components Packing Handbook SHRP-C-624

Data are based upon a computer model of dry-packed, monosized particles adapted from the theories developed by Aims and Toufar (1967). The model has been demonstrated to adequately describe similar dry packing of powders with varying size distributions in terms of the Rosin-Rammler D'coefficient. The model has been successfully applied to the system cement/fine aggregate/coarse aggregate and has modeled CCA, PCA and PADOT recommended concrete formulations. The results theoretically support the location of recommended concrete formulations in a region of ternary particle mixing which possesses the maximum dry packing density. 161 pages.

Maturity Model and Curing Technology SHRP-C-625

This report proposes a new method for determining concrete maturity based on kinetic models of cement hydration employing short-term measurements of heat generated during hydration using isothermal calorimetry. The method uses Computer Interactive Maturity System (CMIS) software. The interrelationship of heat generation, maturity and strength development can be used to predict thermal conditions and strength gain in concrete during curing. The results are presented in table form. 86 pages.

Development of Transient Permeability Theory and Apparatus for Measurement of Cementitious Materials SHRP-C-627

A permeability apparatus was designed and constructed that would allow a rapid and accurate measurement of water transport in concrete. The apparatus consists of a design which can isolate two pressurized, large volume reservoirs on both sides of the test specimen where the test specimen was acting as a permeable membrane between the two. Very rapid measurements are possible with this apparatus for specimens possessing permeabilities on the order of microdarcy to nanodarcy. However, in order to measure permeabilities below a nanodarcy the problems of establishing pressure equilibration throughout the test specimens becomes increasingly more difficult. 30 pages.

Concrete Microstructure Porosity and Permeability SHRP-C-628

A model has been developed that lays the foundation for relating porosity to permeability. This is based on knowledge gained from previous work as well as experimental and theoretical input from the present program. A linear combination of lognormal distribution may be used to define the pore structure. This report contains five papers relevant to this topic. 86 pages.

Cement Paste Aggregate Interface Microstructure SHRP-C-629

This report describes research into the nature of the interfacial region in concrete. The interfacial region considered more porous than the paste itself, could act both as a localized "weakness" where fractures are initiated, and as an avenue of attack for aggressive chemical agents. Computer simulations demonstrate that it is the efficiency by which particles pack against the aggregate during mixing which influences the nature and strength of the interfacial region which develops over time. 76 pages.

Concrete Microscopy — SHRP-C-662

Concrete microstructure can be evaluated using both thin and polished sections. Methods described in this report were developed as a supplement to ASTM 856 procedures. The use of an epoxy resin containing a fluorescent dye tended to enhance the ability to view porosity and mechanical features such as interface porosity and cracking. Relationships of formulation and microstructure for a series of 19 concrete samples are presented. A less skilled operator can use the epoxy impregnation technique for developmental and forensic purposes, to more easily observe effects of making and formulation on homogeneity, and the relationship of cracking and secondary hydration products in deteriorated concrete, respectively. 106 pages.

C 202

Alkali Aggregate Reactions in Concrete: An Annotated Bibliography 1939-1991 — SHRP-C/UWP -92-601

This annotated bibliography contains nearly 1300 citations from before 1940 to 1991. It includes numerous contributions from international literature in languages other than English, especially Japanese, French, Chinese, and German. 470 pages.

Handbook for the Identification of Alkali-Silica Reactivity in Highway Structures — SHRP-C-315

Provides guidance for the field identification of alkali-silica reactivity (ASR) in portland cement concrete structures such as highways and bridges. ASR development is assessed on two bases: the occurrence and disposition of cracking and displacement of concrete, and the presence of reaction products from ASR. Color photographs. 49 pages.

Alkali-Silica Reactivity: An Overview of Research — SHRP-C-342

This two-part report summarizes current knowledge of how alkali-silica reactivity affects concrete; and areas targeted for further research. 105 pages.

Eliminating or Minimizing Alkali-Silica Reactivity — SHRP-C-343

This report describes various studies of alkali-silica reactivity (ASR) as it affects highway structures. Procedures to evaluate material for safe use in concrete; means to mitigate ASR and its adverse effects in existing concrete; and various tests to detect ASR are discussed. 266 pages.

C 203

Freeze-Thaw Resistance on Concrete - An Annotated Bibliography — SHRP-C/UFR -92-617

This bibliography contains over 550 citations considered relevant to the phenomenon of freezing and thawing of concrete. Detailed abstracts of studies on the mechanism of frost action as well as case histories and laboratory investigations are provided. Work from fields of Ceramics, Geology, Physics, and Soil Physics was selected for insight in the roles of moisture movement and ice crystal growth in frost heave and cracking of porous solids. Entries are alphabetical by author or agency. There are author and subject indexes. 227 pages.

Resistance of Concrete to Freezing and Thawing SHRP-C-391

This study, aimed at improving the freeze-thaw resistance of concrete, consists of three parts. Part I evaluates parameters affecting the freeze-thaw durability of concrete. A modification of the existing standard method for determining the durability factor of concrete specimens is proposed, and a new procedure for fundamental transverse frequency has been developed. Part II focuses on developing better methods for identifying nondurable aggregates. This research developed a new, rapid test based on the hydraulic fracture of aggregares. Part III describes field experiments to evaluate the freeze-thaw resistance of a number of specified concrete mixes and the use of sealants to mitigate D-cracking. Preliminary field performance results are presented. 201 pages.

C 205

High Performance Concretes: An Annotated Bibliography 1974-1989 SHRP-C-307

Over 800 references from the past 15 years are presented. 403 pages.

High Performance Concretes: A State-of-the-Art Report SHRP-C-317

Summarizes results of a literature review on the mechanical properties of concrete, with particular reference to the highway application of high performance concrete (HPC). Discusses the selection of materials and the manufacture of high performance concrete; the behavior of plastic and hardened concrete; the behavior of fiber-reinforced concrete; and the applications of high performance concrete. 250 pages.

Mechanical Behavior of High Performance Concretes, Volume 1: Summary Report SHRP-C-361

This report describes a literature search and review, the development of mixture proportions of three categories of high performance concrete, the laboratory studies and field trials of the concretes, and the laboratory studies of high early strength fiber-reinforced concrete. It points out the need to remove certain limitations in some of the current specifications that prevent the use of high performance concrete, and concludes with a list of future research needs. Included are two technical guides for the production and use of high performance concrete, and two proposed specifications for test methods. 98 pages.

Mechanical Behavior of High Performance Concretes, Volume 2: Production of High Performance Concrete SHRP-C-362

This report details the laboratory development work on producing high performance concrete for highway applications. Twenty-one different mixture proportions were selected from 360 trial batches for in-depth study and evaluation of the mechanical behavior of the concrete. The objective was to explore the feasibility of developing appropriate mixture proportions for three different categories of high performance concrete with only locally available, conventional constituent materials and normal production and curing procedures. 92 pages.

Mechanical Behavior of High Performance Concretes, Volume 3: Very Early Strength Concrete SHRP-C-363

This report describes the laboratory investigation, field trials and tests to obtain information on the mechanical behavior of VES concrete. Tests for the hardened concrete include compression tests for strength and modulus of elasticity; tension tests for tensile strength, flexural strength, and tensile strain capacity; freezing-thawing tests for durability factor; shrinkage tests; rapid chloride permeability tests; tests for AC impedance; and tests for concrete-to-concrete bond. 116 pages.

Mechanical Behavior of High Performance Concretes, Volume 4: High Early Strength Concrete SHRP-C-364

This report documents laboratory investigations of the mechanical behavior and field trials of high performance concrete for highway applications. Tests of hardened concrete included compression tests for strength and modulus of elasticity, tension tests for tensile strength and flexural modulus, freezing-thawing tests for durability factor, rapid chloride permeability tests, and various tests for durability factor, rapid chloride permeability tests, and various tests on concrete bonding. Field experiments conducted in New York, North Carolina, Arkansas, Illinois, and Nebraska represent a variety of environmental and exposure conditions. 179 pages.

Mechanical Behavior of High Performance Concretes, Volume 5: Very High Strength Concrete SHRP-C-365

This report documents laboratory investigations of the mechanical behavior of high performance concrete for highway applications. Hardened concrete tests included compression tests for strength and modulus of elasticity, tension tests for tensile strength and flexural modulus, freezing-thawing tests for durability factor, shrinkage tests, creep tests, rapid chloride permeability tests, tests for AC impedance, and tests for bond between concrete and steel reinforcement. 101 pages.

Mechanical Behavior of High Performance Concretes, Volume 6: High Early Strength Fiber Reinforced Concrete SHRP-C-366

A database and a summary of a comprehensive experimental investigation of the fresh state and mechanical properties of high early strength fiber reinforced concrete is provided. Fresh properties tested included air content, workability (by the inverted slump test), temperature, and plastic unit weight. Tests on the mechanical properties included compressive strength, elastic modulus, flexural strength, splitting tensile strength, and fatigue life. Sixteen different combinations of parameters were investigated; the variables were the volume fraction of fibers (1 & 2%), the type of fiber (steel, polypropylene), the fiber length or aspect ratio, and the addition of latex or silica fume to the mix. It identifies optimal mixes that satisfied the minimum compressive strength criterion, and showed excellent values of modulus of rupture, toughness indices in bending, and fatigue life in the cracked state. 297 pages.

NCSU Concrete Materials Database SHRP-C/UWP -91-501

This program was designed to collect and organize research data on the mechnical properties of high performance concrete. Based on the relational model and developed using commercial software, it contains a menu system and other user interfaces that guide users with little database knowledge to extract desired data for data analysis. The NCSU database is the first attempt to demonstrate the feasibility of establishing a general database that encompasses all aspects of concrete properties. See also User Manual: NCSU Concrete Materials Database program, SHRP-C-UWP-91-502. 39 pages.

User Manual: NCSU Concrete Materials Database Program — SHRP-C/UWP-91-502

This companion document to NCSU Concrete Materials Database, SHRP-C/UWP-91-501, contains instructions on how to log onto the database, query the database for information, and input data. A reference section provides information on hardware and software requirements, as well as further information on querying and adding information to the database. 71 pages.

C 206

Expert/Knowledge-Based Systems for Cement and Concrete: State-of the-Art Report — SHRP-C/UWP-91-527

This report surveys the expert/knowledge-based systems applications and development methods related to concrete pavements and structures. The initial step in the development of expert systems. The report addresses the following subjects: 1) the potential for the application of expert systems for concrete mixture design and diagnostics, repair and rehabilitation; 2) a description of interference procedures that are best suited for representing the concrete pavement and structure knowledge domain; and 3) recent expert/knowledge-based systems activities. 31 pages.

Synthesis of Current and Projected Concrete Highway Technology — SHRP-C-345

This report summarizes results from an extensive literature review in the fields of concrete materials, construction practices, and applications in highway construction technology. In addition, the report covers current and projected developments in materials systems including cements, aggregates, admixtures, fibers, and sealers. Other topics include mix proportioning, batching and transport, placement, finishing, and curing; applications focused on repair and reconstruction, full-depth repairs, slab replacement, partial depth repairs, overlays, and recycling; and new tests and quality assurance methods. The appendix includes a history of concrete pavement construction in Europe. 286 pages.

Optimization of Highway Concrete Technology — SHRP-C-373

This report summarizes state-of-the-art technology, evaluates test methods for in-place concrete density, and offers guidelines to avoid thermal effects in concrete pavement slab placements and packing-based aggregate proportioning of concrete mixtures. The report also contains descriptions of field evaluations of a variety of concrete pavement repairs and bridge deck overlays, and descriptions of the methodology and content of HWYCON expert system and audiovisual implementation packages for highway personnel dealing with materials testing and pavement and bridge rehabilitation. 275 pages.

Field Manual for Maturity and Pullout Testing on Highway Structures — SHRP-C-376

This report provides guidance on the use of maturity testing and pullout testing on highway construction projects. It describes background on the use of these procedures together with advice on the selection, and the correct and safe use of testing equipment. Site testing and correlation with standard cured cylinders are described. Guidance on the use of ACI and ASTM documents, and a list of recommended publications is given. 78 pages.

	Users Guide to the Highway Concrete (HWYCON) Expert System HWYCON is designed to assist state highway departments in three areas: 1) diagnosing distresses in highway pavements and structures; 2)selecting materials for construction and reconstruction: and 3) obtaining recommendations on materials and procedures for repair and rehabilitation methods. This document is intended to provide a reference for users of the system who need information about the knowledge base, installation, and operation of HWYCON.	SHRP-C-406
ID 001	**Evaluation of Stratlingite-Hydrogarnet Glass Cement as a Quick Setting Patching Material** This report evaluates S-HG cements, a new type of high alumina cements developed by Corning Glass Works, for use in highway and bridge-deck patching applications. Five blends of S-HG cement are tested and two promising blends identified. Data from these preliminary tests suggest that S-HG cements can be developed into an excellent high early strength highway patching material. 44 pages.	SHRP-ID/UFR-92-607
ID 002	**Evaluation of the Use of Laser Ultrasonics for the Rapid, Noncontact Inspection of Concrete and Asphalt** This report documents the investigation of the use of a laser system for the detection of voids, delaminations, and defects in asphalt and mesh reinforced concrete structures. The goals of the research were to discover whether laser systems could: generate and receive ultrasound in concrete and asphalt; verify that such a system obtains the same information as conventional ultrasonic tests; see if the laser system could obtain more information than conventional tests; and consider how laser ultrasonics would be used in the field.	SHRP-ID/UFR-92-604
ID 005	**An Electrochemical Method for Detecting Ongoing Corrosion of Steel In a Concrete Structure with CP Applied** This report examines the feasibility of using AC impedance spectroscopy (ACIS) as a monitoring tool for detecting corrosion on cathodically protected reinforced steel in concrete. Both relatively small concrete blocks with a single reinforcing steel specimen, and large concrete slabs containing two mats or reinforcing steel were constructed for the purpose of evaluating the ACIS technique. Although the feasibility of the technique was demonstrated for the concrete blocks containing a single reinforcing steel specimens, difficulties in interpretation of the data were created by the large macro-cell couples that were present in the large-scale slab tests. 47 pages.	SHRP-ID/UFR-91-512
ID 007	**Quantitative and Rapid Measurement of the Air-Void System in Fresh Concrete** This report evaluates a new method for determining air void characteristics in fresh concrete. The method uses a laser counting device to evaluate the number and distribution of air voids. The measurements are made on a core extracted from a sample of fresh concrete frozen with liquid nitrogen. 29 pages.	SHRP-ID/UFR-91-519

ID 008	**Evaluation of Electrochemical Impedance Techniques for Detecting Corrosion on Rebar in Reinforced Concrete, Volume I: Summary Report** This report examines the applicability of ultralow frequency ac impedance spectroscopy (ULFACIS) for characterizing corrosion of rebar in concrete. The study demonstrates that ULFACIS can be used to locate and characterize corrosion nondestructively in reinforced concrete structures. A primary objective of the study was to establish whether ULFACIS could be used to determine the polarization resistance, and hence the corrosion rate, of the steel rebar. 82 pages.	SHRP-ID/UFR-91-524
ID 010	**Identification of Chemical Agents for the Control of Alkali-Aggregate Reaction in Concrete** This report identifies a number of chemical compounds for their effectiveness in inhibiting alkali-silica reaction in concrete, either as admixtures in the concrete mix or as penetrating agents to stop further progress of the reaction in already-affected or damaged concrete. Two compounds, zinc sulfate and aluminum sulfate, were found to be effective admixtures for fresh concrete. Zinc sulfate also appeared to significantly reduce the subsequent expansion of mortar bars, and could be a suitable penetrating agent for arresting alkali-silica reaction in hardened concrete. 60 pages.	SHRP-ID/UFR-92-609
ID 011	**Fiber-Optic Air Meter** This report discusses a three-phase program to evaluate both acrylate-filled and diamond-tipped fiber optic air meter probes as well as to gather and evaluate test results comparing fiber optic measurements of entrained air in concrete mix to gravimetric and volumetric measuring methods. 64 pages	SHRP-C-677
ID 012	**Carbon Fiber Reinforced Concrete** This report concludes that the use of short-pitch-based carbon fibers (0.05% of weight of cement, 0.189 vol.% concrete), together with a dispersant, chemical agents and silica fume in concrete with fine and coarse aggregates resulted in a flexural strength increase of 85%, and a flexural toughness increase of 205%, a compressive strength increase of 22%, and a material price increase of 39%. The minimum carbon fiber content was 0.1 vol. %. The drying shrinkage was decreased by up to 90%. The electrical resistivity was decreased by up to 83%. 80 pages.	SHRP-ID/UFR-92-605
ID 014	**Feasibility Studies on Nondestructive Incorporation of a Conducting Polymer Anode Bed into a Bridge Deck Concrete** This feasibility study on the nondestructive incorporation of a conducting polymer anode bed into bridge deck concrete proves that incorporating polymers into concrete by both chemical and electrochemical approaches is feasible. However, it appears that the lateral growth of conducting polymers to form an anode bed requires carefully controlled electrochemical oxidation of the monomer in the concrete matrix. 21 pages.	SHRP-ID/UFR-91-517
ID 016	**Smart Structural Technology for Nondestructive Evaluation of Concrete** This report identifies two specific applications for use of tagged particles in construction materials for long-term condition assessment and quality control. These particles were tested in asphalt and portland cement concrete mixes. 43 pages.	SHRP-ID/UFR-92-608

ID 019	**Electro-Acoustic Technology as a Means to Modify the Properties of Concrete - A Feasibility Study** This study investigates the feasibility of applying Battelle's Electro-Acoustic Technology (BEAT) in the impregnation of organic monomer(s) and in the electro-osmotic removal of chloride ions to stop or retard corrosion in reinforced concrete structures. Results show that using BEAT in the impregnation technique will cause the monomer to polymerize in situ, and will cost less than conventional polymer impregnation methods. Although the use of BEAT did accelerate the movement of chloride ion in concrete, research shows that water content is a significant determinant of electrical conductivity. 90 pages.	SHRP-ID/UFR-91-526
ID 023	**Development of Metallic Coatings for Corrosion Protection of Steel Rebars** This report demonstrates the feasibility of applying a silicon-based diffusion coating on steel rebars, wires and fibers in fluidized beds of Si particles. In comparison to fusion-bonded epoxy coatings, or galvanized bars, the silicon coated samples indicate a higher corrosion resistance in aggressive chloride environments. In addition, the less expensive silicon-coated samples resist scratching. 44 pages.	SHRP-I-622
ID 024	**Sprayed Zinc Galvanic Anodes for Concrete Marine Bridge Substructures** This report describes a low-cost method for galvanic cathodic protection by exposing the reinforcing steel, then arc-spraying zinc on to the steel and surrounding concrete to create a 0.5mm thick galvanic anode. Field tests in the Florida Keys showed that the anodes retained physical integrity over at least four and one-half years. Laboratory tests indicated that concrete resistivity does not represent a main limiting factor in the performance of such anodes, and that periodic water contact is necessary for long-term anode performance. 85 pages.	SHRP-S-405

TABLE 5: SHRP PRODUCTS FROM CONCRETE AND STRUCTURES CONTRACTS

Contract No.	Product No.	Product	Report
C-101	2001	Corrosion Rate Test Method	SHRP-S-324
	2015	Radar Investigation of Asphalt-Covered Decks	SHRP-S-325
	2016	Nondestructive Membrane Integrity Test	SHRP-S-326
	2029A	Electrical Resistance Test for Sealers	SHRP-S-327
	2029B	Water Absorption Test for Sealers	SHRP-S-327
	2030	Field Test for Chloride Ion Content	SHRP-S-328
	2031	Field Test for Concrete Permeability	SHRP-S-329
	2032	Concrete Bridge Component Evaluation Manual	SHRP-S-330
C-102	2033	Chloride Removal Manual	SHRP-S-347
	2034	Cathodic Protection Manual	SHRP-S-372
	2040	Null Probe Criterion for Cathodic Protection	SHRP-S-359
C-103	2003	Concrete Removal Manual	SHRP-S-336
	2035	Manual on Rapid Repair of Bridge Decks	SHRP-S-344
	2036	Guide for Concrete Bridge Repair	SHRP-S-360
C-104	2037	Manual for Selecting Method of Bridge Repair	SHRP-S-377
	2038	Computer Program for Selecting Method of Bridge Deck Repair (CORRODE)	SHRP-S-377
C-201	2005	Concrete Mix Design Handbook	SHRP-C-334
	2006	Guide to Thermal Effects in Concrete	SHRP-C-331
	2007	Laboratory Test For Concrete Permeability	SHRP-C-627
	2008	Fluorescent Microscopy Manual	SHRP-C-662
C-202	2009	Test Method for Screening Reactive Aggregates	SHRP-C-343
	2010	Manual for ASR Detection	SHRP-C-315

	2011	Mitigating ASR in Existing Structures	SHRP-C-343
	2013	Chemical Test for ASR Detection	SHRP-C-315
	2017	ASR-Safe Concrete Mix Designs	SHRP-C-343
C-203	2002	Aggregate Durability Test Method	SHRP-C-391
	2004	Mitigating D-Cracking in Existing Concrete	SHRP-C-391
	2018	Modified Freeze-Thaw Test	SHRP-C-391
	2019	Soundness Test for Concrete	SHRP-C-391
	2020	Air Entrainment Specifications	SHRP-C-391
	2021	Aggregate Specifications	SHRP-C-391
C-205	2014	Specifications for High Performance Concrete	SHRP-C-361
	2023	Flexural Strength Test	SHRP-C-364
	2024	Compressive Strength Test	SHRP-C-364
	2025	Interfacial Bond Test	SHRP-C-364
	2026	AC Impedance Test for Concrete Permeability	SHRP-C-363
C-206	2012	Flaw Detection by the Impact-Echo Method	SHRP-C-373
	2022	Field Measurement of Concrete Strength and Maturity	SHRP-C-376
	2027	Test for Water Content of Fresh Concrete	SHRP-C-373
	2028	Test for Consolidation of Concrete	SHRP-C-373
	2039	HWYCON - Concrete Expert System	SHRP-C-406
ID005	4003	Corrosion Rate Test Equipment	SHRP-ID/UFR-91-512
ID011	4001	Fiber Optic Air Meter	SHRP-S-677
ID024	4009	Arc-sprayed Zinc Coatings for Marine Structures	SHRP-S-405