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Mechanical Behavior of High Performance Concretes, Volume 1

Summary Report

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Preface

The Strategic Highway Research Program (SHRP) is a 5-year, nationally coordinated research effort initiated in 1987 at a cost of $150 million. This highly focused and mission oriented program originated from a thorough and probing study* to address the serious problems of deterioration of the nation's highway and bridge infrastructure. The study documented the need for a concerted research effort to produce major innovations for increasing the productivity and safety of the nation's highway system. Further, it recommended that the research effort be focused on six critical areas in which the nation spends most of the $50 billion used for roads annually and thus technical innovations could lead to substantial payoffs. The six critical research areas were as follows:

- Asphalt Characteristics
- Long-Term Pavement Performance
- Maintenance Cost-Effectiveness
- Concrete Bridge Component Protection
- Cement and Concrete
- Snow and Ice Control

When SHRP was initiated, the two research areas of Concrete Bridge Component Protection and Cement and Concrete were combined under a single program directorate of Concrete and Structures. Likewise, the two research areas of Maintenance Cost-Effectiveness and Snow and Ice Control were also combined under another program directorate of Highway Operations.

* *America's Highways: Accelerating the Search for Innovation.* 1984. Special Report 202, Transportation Research Board, National Research Council, Washington, D. C.

Abstract

This report presents a summary of each phase of a 4-year research program sponsored by the Strategic Highway Research Program under contract C-205. For each phase of the research, the objective, scope, results, and conclusions are summarized.

The report covers the 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. An assessment is made of how the research met its objectives and what the limitations of the research are. Finally, the report 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.

To provide guidance to engineers, concrete producers, and contractors, two technical guides on the production and use of high performance concrete, as well as two proposed specifications for test methods, are included in the appendixes.

Executive Summary

This report presents a summary of each phase of a 4-year research program. The primary objective of the research was to develop needed information on the mechanical behavior of high performance concrete (HPC) with significantly improved criteria for highway applications. For this purpose, HPC was defined as concrete with rapid early strength development and greatly enhanced durability against freezing and thawing. Three categories of HPC were investigated: very early strength (VES) concrete, high early strength (HES) concrete, and very high strength (VHS) concrete.

HPC has many useful applications and potential benefits to the highway industry:

- Better performance and service life of highway facilities.
- Less maintenance, because of enhanced concrete durability.
- Lower life-cycle cost.
- Less construction time, as in emergency repairs and fast-track constructions.
- Higher productivity and better quality of precast and prestressed products.
- Less consumption of materials and more conservation of resources.
- More efficient designs of long-span bridges with higher strength, longer span, and reduced dead load.
- Less thickness of pavements and bridge deck overlays.
- Faster construction schedule from early removal of formwork.
- Less surface cracking with fiber reinforcement.
- More impact resistance, achieved by using fibers in applications such as concrete median barriers or piles exposed to moving marine traffic.

For the research to be practical and useful to highway engineers, it was decided at the outset that the concrete should be produced *with only locally available, conventional constituent materials and normal production and curing procedures.*

Furthermore, the investigation was to include four different types of coarse aggregates from a wide geographical area so that the research results would be applicable to different regions rather than being valid for only a local area. Accordingly, it can be said that *the research plan was designed for breadth rather than depth.*

An extensive literature search and review up to 1989 revealed that an adequate working time is critical for VES concrete in view of its rapid chemical reaction. More information is needed on

all aspects of the short-term and long-term mechanical properties of VES concrete, including modulus of elasticity, strength and strain capacities, creep, shrinkage, and fatigue, as well as frost durability.

For HES concrete, ensuring adequate workability and an adequate entrained air-void system at the time of placement is a critical problem. Balancing set time, rate of strength gain, and workability requires extra care in selecting raw materials and production methods. Although much is already known about the mechanical properties of concrete with a strength range comparable to that of HES concrete, most existing data are based on tests conducted at 28 days. Since HES concrete achieves its expected strength in only 24 hours, there is a need to confirm the mechanical properties of HES concrete with the existing data.

For VHS concrete, most existing data are based on tests conducted at older ages, such as 56 or 90 days; thus, more information on its mechanical properties at 28 days is needed. In addition, there is a dearth of data on durability, fatigue, and brittleness of VHS concrete.

For fiber reinforced concrete, more information is needed on long-term effects. In pavement applications, steel fibers have been used almost exclusively. Virtually no research has been conducted on the use of other fibers or mixed fibers, such as a combination of steel and polypropylene fibers, which may enhance both strength and ductility of concrete.

Finally, for all types of HPC, more information is needed on how vibration and curing affect the mechanical properties of the concrete.

Research results summarized in this report demonstrated that *it was feasible to produce the HPC for highway applications with conventional materials and normal techniques*. In addition, the concrete mixtures with about 5% entrained air had greatly enhanced frost durability. The study showed that mixtures that used washed rounded gravel as the coarse aggregate lacked resistance against freezing and thawing.

In general, the different types of HPC behaved very much like conventional concrete *of comparable strength,* except that the HPCs developed their strength characteristics much more rapidly than the conventional concrete. Test results indicated that the various mechanical properties, such as the modulus of elasticity, the splitting tensile strength, and the flexural tensile strength (or modulus of rupture), of the HPCs could all be predicted by the relationships published by the American Concrete Institute (ACI 1993a, 1993b) at *the appropriate strength levels*. The same was true for concrete-to-concrete bond and concrete-to-steel bond.

Shrinkage of the HPCs was found to be considerably less than that of conventional concrete. This should be expected because of the very low W/C used for HPC. In fact, VES (B) concrete with marine marl and rounded gravel exhibited an expansion of approximately 140 microstrains rather than shrinkage for the entire test period of 90 days. The expansion is attributed to the lack of evaporable water in the concrete because of its very low W/C (0.17 and 0.22).

The observed creep strains of the different groups of VHS concrete ranged from only 20% to 50% of that of conventional concrete, also because of low W/C and higher compressive strength. The creep strains were especially low for concretes with a 28-day strength in excess of 10,000 psi (69 MPa). Since marine marl is a softer aggregate, the specific creep of the concrete with marine marl was much higher than that with either crushed granite or washed rounded gravel.

Tests for chloride ion permeability by both the rapid chloride permeability test and AC impedance test showed close correlations between the two. However, the results for both VES and HES concretes indicated relatively high chloride permeability values in comparision with *high-quality* conventional concrete. It was observed that the results were greatly affected by the very short curing time and the large amounts of ions introduced into the concretes from the admixtures used in the two concretes.

Studies of high early strength fiber reinforced concrete (HESFRC) indicated that the greatest benefit of introducing fibers (both steel and polypropylene) into the HES concrete was the vast improvement in the toughness of the concrete in bending. Two percent by volume of 30/50* hooked steel fibers (or an equal combination of 30/50 and 50/50) was found to be the optimal amount. The addition of steel fibers significantly improved compressive strength, modulus of rupture, splitting tensile strength, toughness indices, ductility (or strain capacity), and fatigue strength of the HES concrete. There was no beneficial effect, however, from the use of polypropylene fibers to improve compressive strength and elastic modulus.

In evaluating the results of this extensive research program, it should be kept in mind that the desire to examine many mechanical properties of HPCs with a wide variety of constituent materials led to a research plan that was *very broad in scope at the expense of sufficient depth.* There were many uncontrolled parameters involved in the experiments, such as the variations of cement characteristics and other constituent materials, ambient conditions during specimen preparation, curing temperatures, and different concrete batches from which specimens of the same test series were prepared.

Besides the uncontrolled parameters, there were several nonstandard test procedures used in the experiments. For example, laboratory mixing procedures were modified to simulate more closely typical concrete dry-batch plant operations. Laboratory curing conditions were also modified using an insulation box to simulate the field curing conditions. Furthermore, 4 x 8-in (100 x 200-mm) cylinders rather than the standard 6 x 12-in (150 x 300-mm) cylinders were used for most of the laboratory and field tests, since the smaller cylinders required less material to make and could be tested with lower capacity testing machines. In addition, smaller cylinders were much closer to the size of concrete cores taken in the field.
It should be emphasized that in spite of the many variations discussed above, the experimental program reported herein was conducted consistently with many replications and field trials. So

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* In this notation for fiber designation, the first number represents the fiber length in millimeters and the second represents the fiber diameter in millimeters multiplied by 100.

the data obtained in this program are still valid, even though the database is not large enough to have a meaningful statistical analysis to estimate its degree of variability.

Current specifications for highway materials and construction have been formulated primarily from the knowledge of conventional materials. Some requirements may not be applicable to HPCs and thus would serve as barriers to acceptance of such concretes for highway applications.

Review of a number of specifications revealed that while no such barriers could be identified in the major national codes and specifications of AASHTO, ASTM, and ACI, several barriers were found in the specifications of state highway agencies. For example, the North Carolina Department of Transportation *Standard Specifications for Roads and Structures* (January 1, 1990) contains a provision that states that the cement content for prestressed concrete shall not exceed 752 lbs (340 kg) and that the slump of the concrete shall be no more than 3.5 in. (88 mm). These limitations are barriers to the acceptance of HPCs, since HPCs generally require higher cement contents and often produce greater slumps because of greater amounts of paste and the use of high-range water reducer.

Similarly, the Michigan Department of Transportation *Standard Specifications for Construction* (1990) considers the slump test as a standard for all concrete materials. However, the "inverted cone test" is recommended for fiber reinforced concrete by ACI Committee 544 on Fiber Reinforced Concrete. In addition, the specifications require that all concrete shall be designed to contain 6.5±1.5% entrained air. For HESFRC, the air content is generally at a lower amount, ranging from 3% to 6%, because some of the entrained air in the concrete tends to be lost during mixing with fibers.

These examples illustrate that to encourage use of HPC, state highway agencies should update certain specifications to accommodate the latest information on and knowledge of concrete technology.

The experience and knowledge gained from this 4-year study helps to identify future research needs so as to enhance further understanding of the nature and behavior of HPCs and to encourage wider acceptance of the materials for highway applications.

To provide guidance to engineers, concrete producers, and contractors, two technical guides on the production and use of HPC, as well as two proposed specifications for test methods, are included in the appendixes.

1

Introduction

SHRP's research on the mechanical behavior of high performance concretes (HPCs) had three general objectives:

1. To obtain information needed to fill gaps in the present knowledge.
2. To develop new, significantly improved engineering criteria for the mechanical properties and behavior of HPCs.
3. To provide recommendations and guidelines for using HPCs in highway applications according to the intended use, required properties, environment, and service.

Both plain and fiber-reinforced concretes were included in the study. The research findings are presented in a series of six project reports:

Volume 1 *Summary Report*

Volume 2 *Production of High Performance Concrete*

Volume 3 *Very Early Strength (VES) Concrete*

Volume 4 *High Early Strength (HES) Concrete*

Volume 5 *Very High Strength (VHS) Concrete*

Volume 6 *High Early Strength Fiber-Reinforced Concrete (HESFRC)*

This volume is the first of these reports. The readers will notice a certain uniformity in format and similarity in many general statements in these reports. This feature is adopted intentionally so that each volume of the reports can be read independently without the need of cross-reference to other reports in the series.

1.1 Definition of High Performance Concrete

In general terms, HPC may be defined as any concrete that provides enhanced performance characteristics for a given application. For example, concretes that provide substantially improved durability under severe service conditions, extraordinary properties at earlier ages, or substantially enhanced mechanical properties are potential HPCs. These concretes may contain materials such as fly ash, ground granulated slags, silica fume, fibers, chemical admixtures, and other materials, individually or in various combinations.

Engineers are making increasing use of HPC for a variety of highway applications, including new construction, repairs, and rehabilitation. Higher-strength concrete will provide more structural design options. Improved early age properties of concrete will facilitate construction and rehabilitation tasks and improve quality. Higher durability will increase the service life, which may reduce life-cycle cost.

For the purpose of this research program, HPC is defined in terms of certain *target* strength and durability criteria as specified in Table 1.1.

Table 1.1 Criteria for high performance concrete

Category of HPC	Minimum Compressive Strength	Maximum Water/ Cement Ratio	Minimum Frost Durability Factor
Very early strength (VES)			
Option A (with Type III cement)	2,000 psi (14 MPa) in 6 hours	0.40	80%
Option B (with PBC-XT cement)	2,500 psi (17.5 MPa) in 4 hours	0.29	80%
High early strength (HES) (with Type III cement)	5,000 psi (35 MPa) in 24 hours	0.35	80%
Very high strength (VHS) (with Type I cement)	10,000 psi (70 MPa) in 28 days	0.35	80%

In the above definition, the target minimum strength should be achieved in the specified time after water is added to the concrete mixture. The compressive strength is determined from 4 x 8-in. (100 x 200-mm) cylinders tested with neoprene caps. The water/cement ratio (W/C) is based on all cementitious materials. The minimum durability factor should be achieved after 300 cycles of freezing and thawing according to ASTM C 666 (AASHTO T 161), procedure A.

These working definitions of HPC were adopted after several important factors in the construction and design of highway pavements and structures were considered. The rationale for the selection of the various limits is discussed in detail with respect to the time constraint, the strength requirement, the W/C limit, and the frost durability requirement. The discussion can be found in volume 2 of this report series, *Production of High Performance Concrete.*

1.2 Organization of Report

This report presents an overview of the tasks and activities performed during this research program. The first task was to conduct an extensive search of published literature on mechanical properties of concrete with particular reference to HPC for highway applications. Based on the results of this literature search, a critical review of literature was conducted to identify the gaps in the present knowledge. This task is described in chapter 2. Chapter 3 covers production of HPC. Laboratory studies of VES, HES, and VHS concretes are discussed in chapters 4, 5, and 6, respectively. Also summarized in chapter 5 is the experience of field trials with HES and VES concretes. Laboratory study of fiber reinforced HES concrete is covered in chapter 7. Finally, a summary and conclusions are presented in chapter 8, and several useful documents are assembled in appendixes that include (1) a guide to field production and use of HPC, (2) a guide to use of Pyrament PBC-XT cement, (3) a proposed specification for the AC impedance test, and (4) a proposed specification for a concrete-to-concrete bond test.

2

Annotated Bibliography and State-of-the-Art Report

2.1 Objective and Scope

The first objective of this research program was to obtain information that fills gaps in the present knowledge and to synthesize this information in a form that is directly useful to highway engineers. To accomplish this objective, an extensive on-line electronic literature search was conducted to identify the gaps in the existing knowledge of mechanical properties of concrete with particular reference to HPC for highway applications.

The search covered a period of 15 years (1974-89). The principal sources for the search were TRIS (Transportation Research Information Service) and COMPENDEX (Engineering Index). These two electronic files contain extensive collections of literature, both domestic and international. In addition, several other bibliographic sources were also searched manually. Among them were 12 issues of *Concrete Abstracts* published in 1987-89, *Nordic Concrete Research* (nos. 1-7), and other publications such as the *Magazine of Concrete Research*, *Nordisk Betong*, and *Transactions of the Japan Concrete Institute*. The computer software Biblio-Link was used to transform the bibliographic information obtained from TRIS and COMPENDEX into a consistent format so that the software Pro-Cite could be used to sort and manage the bibliographic database.

2.2 Results and Conclusions

The literature search produced an initial list of more than 9,000 annotated references containing almost 4,200 citations on plain concrete, 3,800 on concrete pavement, and 1,300 on fiber reinforced concrete. The list was reduced in size through several stages of screening and reviews based on the following criteria:

1. The amount and applicability of the data as they relate to the mechanical properties and behavior of HPC.

2. The relative importance of the data for the prediction of concrete behavior.

3. The sensitivity of a behavior prediction as affected by variations in the material property considered.

4. The potential impact of obtaining specific research information on the ultimate cost-effectiveness of concrete.

5. The validity and practicality of the interrelationships considered or anticipated.

The final selection resulted in a reference document in the form of an annotated bibliography (Leming et al. 1990) containing 830 citations: 626 on plain concrete and 204 on fiber reinforced concrete. The bibliography is divided into two sections — one for plain concrete and the other for fiber reinforced concrete. An author index and a subject index are located at the end of each section for convenient reference.

In addition, a computerized database structure was developed so that available research data on HPC can be assembled in electronic form as a valuable source of research information. This database structure has been described elsewhere (Chi 1990a, 1990b; Zia et al. 1990).

From the annotated bibliography, about 150 references were selected for critical review. The results of the review are summarized in a state-of-the-art report (Zia et al. 1991). Included in the report are discussions regarding selection of raw materials and manufacture of HPC, behavior of hardened concrete, behavior of fiber reinforced concrete, and applications of HPC. Major conclusions are as follows.

It is crucial that criteria for the selection of raw materials for producing HPC be carefully established. In general, there are more varieties of materials available for VHS concrete, but only limited choices of cementitious materials and admixtures for VES and HES concretes.

The use of admixtures should be carefully controlled. For VES concrete, special cements (such as Pyrament blended cement) are usually required, and no admixtures should be used. For HES concrete, conventional pozzolans will provide no strength advantage. In addition, there are usually limitations on the type and quantity of the chemical admixtures used. For VHS concrete, many different kinds of admixtures may be used advantageously if set times are not critical and longer hydration periods are possible. Entrained air of appropriate amount and distribution is usually needed to ensure frost durability. The effects of other admixtures on frost durability of concrete with low W/C have not been fully established.

Because of rapid chemical reaction, adequate working time is critical for VES concrete. More information is needed on all aspects of its short-term and long-term mechanical properties. These include modulus of elasticity, strength and strain capacities, creep, shrinkage, and fatigue.

For HES concrete, ensuring adequate workability and an adequate entrained air-void system at the time of placement is a critical consideration. Balancing set time, rate of strength gain, and workability requirements will require extra care in raw materials selection and methods of production.

Much is already known about the various mechanical properties of concrete with strength ranges comparable to that of HES concrete. However, most of the existing data are based on tests at 28 days. Since HES concrete achieves its expected strength in only 24 hours, there is a need to confirm the mechanical properties of HES concrete with the existing data.

For VHS concrete, most of the existing data are based on tests conducted at older ages, such as 56 or 90 days; thus, more information on its mechanical properties at 28 days is needed. In addition, there is a dearth of data on durability, fatigue, and brittleness of VHS concrete.

For HPC, there is insufficient information on how vibration and curing affect the subsequent mechanical properties of the concrete.

Although there is ample information on the mechanical properties of fiber reinforced concrete under short-time loading, except thermal expansion and Poisson's ratio after cracking, more research is needed for different aspects of long-term effects.

In pavement applications, steel fibers have been used almost exclusively. Use of other types of fibers is practically nonexistent. Mixed fibers, such as a combination of steel and polypropylene fibers, may enhance both strength and ductility of concrete. Virtually no research has been conducted in this area.

There is little evidence that HPC is used in current pavement applications. However, for such applications, one can anticipate significant potential benefit. The use of VES and HES concretes will permit rapid repair and construction of pavements so that the interruption of traffic can be substantially minimized, while at the same time providing adequate long-term performance at a reasonable cost.

Most rigid pavement design methods rely heavily on empirically developed relationships, and the data on which these empirical methods were based do not include any of the HPCs. Therefore, research data on durability, shrinkage, thermal properties, fatigue, and long-term strength gain of HPC are critically needed. Field trials will also be required to establish its performance record.

3

Production of High Performance Concrete

3.1 Objective and Scope

Volume 2 of this report series documents the laboratory developmental work to produce HPC for highway applications. The objective was to explore the feasibility of developing appropriate mixture proportions of HPC *with only locally available, conventional constituent materials and normal production and curing procedures*.

For the research results to be applicable to different regions, the study included four types of coarse aggregates and three kinds of sand, as summarized in Table 3.1. The materials were chosen as being representative of a wide geographical area. The characteristics of all constituent materials used for the concrete mixtures were described in detail in terms of physical, chemical, and mineral properties.

The normal laboratory mixing and batching procedures, ASTM C 192 (AASHTO T 126), were modified slightly to represent more closely typical concrete dry-batch plant operations.

Curing procedures were developed to simulate more closely the conditions in the field and were considerably different from the normal laboratory curing procedure described in ASTM C 192 (AASHTO T 126). For VES concrete, whether using Type III portland cement or PBC-XT cement, insulation was used to achieve rapid strength gain in the first few hours. For HES and VHS concretes, early strength gain was not as critical; thus it was not necessary to use insulation.

3.2 Results and Conclusions

A total of 360 trial batches were produced. Their mixture proportions and the plastic and strength properties can be found in appendixes A and B of volume 2 of this report series. Each trial batch was evaluated successively against four basic characteristics: good workability, adequate air content, sufficient design strength, and acceptable durability. If a trial batch failed

Table 3.1 Types of coarse and fine aggregates

Type	Symbol	Source
Marine marl	MM	Castle Hayne, North Carolina
Crushed granite	CG	Garner, North Carolina
Dense crushed limestone	DL	West Fork, Arkansas
Washed rounded gravel	RG	Memphis, Tennessee
Sand		Lillington, North Carolina
Sand		Memphis, Tennessee
Sand		Van Buren, Arkansas

to develop any of the four characteristics, it was excluded from further consideration. By such a screening procedure, 21 different mixture proportions were selected from the trial batches for in-depth evaluation. Each mixture was reproduced several times in the laboratory for studies of its mechanical behaviors in both plastic and hardened states. Certain VES and HES mixtures and the batching, mixing, and accelerated curing methods developed in the laboratory were confirmed in large-scale productions for five field trials which are discussed in detail in volume 4 of this report series, *High Early Strength (HES) Concrete*.

From the experience of laboratory experiments and field trials, it is concluded that the three categories of HPC considered in this investigation can be successfully produced in the field. VES and HES mixtures are more sensitive to time and temperature than most conventional mixtures because of the rapid hydration; therefore, slump and air content of the VES and HES mixtures should be monitored more closely than conventional concretes.

Before producing the HPC in the field, it is important to take the following steps:

1. Using the mixture proportions developed in this investigation as a guide, conduct trials in the laboratory, before field placement, with the specific raw materials to be used. This allows refinement of the batch weights before further adjustments needed in the field and reduces confusion during initial practice placements.

2. Before concrete placement, conduct preconstruction meetings with all key personnel involved, including construction managers, batch plant operators, and finishing crew supervisors.

3. Include at least one practice placement of the concrete, and expect a significant learning experience. Generally, full day should be allowed for the practice placement.

4. Pay attention to truck load size and batching sequence. Be especially sensitive to truck condition and mixing efficiency. Keep the load to no more than two-thirds of

the maximum rated mixing capacity of the truck. In some cases, it may be advisable to reduce the truck load to no more than half the rated mixing capacity.

5. Allow 10 minutes for mixing time, beginning with the addition of cement to water in the truck. No tempering of the mixture should be allowed. Keep hauling time to no more than 20 minutes. Consider hot-weather and cold-weather concrete practices under extreme temperatures.

6. Discharge the concrete quickly at job site. If the concrete is to be insulated, minimize the time before the insulation is placed. Sawing the pavement joints should be scheduled for no later than 8 hours after concrete placement or immediately after removal of insulation.

4

Very Early Strength Concrete

4.1 Objective and Scope

Laboratory studies on the mechanical behavior of VES concrete are presented in volume 3 of this report series. The objective of the investigation was to develop and analyze basic data on the mechanical properties of the concrete. Seven different types of tests were conducted:

Compression test	ASTM C 39 (AASHTO T 22)
Flexural and split tension tests	ASTM C 78, C 496 (AASHTO T 97, T 198)
Shrinkage test	ASTM C 157 (AASHTO T 160)
Freezing-thawing test	ASTM C 666 (AASHTO T 161)
Rapid chloride permeability test	ASTM C 1202 (AASHTO T 277)
AC impedance test	New
Concrete-to-concrete bond test	New

The initial research plan called for laboratory experiments as well as field studies, which would have involved field installations in three states — North Carolina, Arkansas, and Illinois — during the summer of 1990. Later, New York and Nebraska expressed interest and were included in the program.

Planning and negotiations with the various state highway departments and the selection of appropriate sites for field installations consumed more time than expected. It was not until the summer of 1991 that the first two field installations were constructed in New York and North Carolina. In the fall of 1991, two more field installations were placed in Illinois and Arkansas. By July 1992, the fifth field installation was constructed in Nebraska.

Unfortunately, the development of the VES mixture proportions and the corresponding laboratory experiments were delayed because of modifications of the strength criterion for the VES concrete. It was therefore not possible for the five field installations to include the VES mixtures investigated in the laboratory.

However, in the earlier laboratory studies of the HES concrete mixture, it was found that when the concrete was insulated, its strength development characteristics were quite similar to those of the VES concrete. Therefore, two comparable test pavement patches were constructed at each field installation. One patch was insulated to mimic the VES mixture, and one was not insulated, as is standard for the HES concrete. In North Carolina, an early version of the VES mixture was used. A full account of the field experience and the results of subsequent studies is given in volume 4 of this report series.

4.2 Results and Conclusions

Using conventional materials and equipment, but with more care than needed for conventional concrete, two options of VES concrete can be produced. VES (A) will achieve a minimum compressive strength of 2,000 psi (14 MPa) in 6 hours and VES (B) will achieve a minimum compressive strength of 2,500 psi (17.3 MPa) in 4 hours. Such concretes can be produced with a variety of aggregates, including crushed granite, marine marl, dense crushed limestone, and washed rounded gravel. Insulation must be used to trap the heat of hydration to accelerate the early strength development of the VES concretes.

Because of a larger amount of Type III cement or Pyrament XT cement used in the VES concrete mixtures along with a low W/C, the strength development of these concretes is much more rapid in the first 3 days than predicted by the current ACI recommendation (1993a) for conventional concrete.

Since the VES concretes are kept moist for only the first 6 or 4 hours, to be followed by air curing in the laboratory, the strength development of the small laboratory samples is very rapid during the first 3 days, and the subsequent rate of strength gain is greatly reduced. The same is true for the modulus of elasticity.

Since the design strength of both options of the VES concrete is within the range of conventional concrete, the mechanical behavior of the VES concrete, such as the modulus of elasticity and the compressive and tensile strain capacities, is similar to that of conventional concrete. The modulus of elasticity, the flexural modulus, and the splitting tensile strength can all be predicted reasonably well by the ACI Code equations (1993b). At the early design ages (6 or 4 hours), the compressive strain capacity ranges from approximately 1,000 to 2,000 microstrains, and the tensile strain capacity varies from 100 to 180 microstrains. These strain values increase somewhat as the concrete ages.

The stress-strain relationship of the VES concretes is more nonlinear at 6 or 4 hours than at later ages, and the modulus of elasticity is lower for the concrete with softer aggregate, such as marine marl.

For VES (B) concrete made with Pyrament XT cement, its flexural modulus was observed to decrease after the first 7 days because of the drying of the test specimen due to possible self desiccation resulting from the very low W/C of the concrete.

Even with a very low W/C, the VES concretes should have enough air entrainment to enhance their frost resistance, because the concretes are under moist curing for only a few hours. The test results indicate that if the VES concrete contains at least 5% entrained air, it will meet the stringent requirement of a durability factor of 80% (as compared with 60% for conventional concrete) after 300 cycles of freezing and thawing according to ASTM C 666 (AASHTO T 161), procedure A.

The VES concretes produced with washed rounded gravel from Memphis, Tennessee, failed the freeze-thaw test according to ASTM C 666 (AASHTO T 161), procedure A, because the aggregate had an absorption of about 5% and pore sizes of about 0.10 μm (as observed in scanning electron micrographs), the worst possible condition for freeze-thaw deterioration.

Shrinkage of the VES (A) concrete follows the general trend of conventional concrete. The average shrinkage strains of the concretes at 90 days range from 59 to 321 microstrains, depending on the type of coarse aggregate used. These values represent 10% to 55% of the ultimate shrinkage strain recommended by ACI Committee 209 (1993a) for conventional concrete. On the other hand, the 90-day shrinkage strain of the VES (B) concrete with crushed granite was only 52 microstrains, and the VES (B) concrete with marine marl or rounded gravel exhibited an expansion of approximately 140 microstrains rather than shrinkage for the entire period of 90 days. The expansion is attributed to the lack of evaporable water in the concrete because of its very low W/C (0.17 and 0.22).

The normal procedure of the rapid chloride permeability test (RCPT) is to measure the total electrical charge in coulombs flowing through a vacuum-saturated concrete specimen in 6 hours. This measurement is regarded as an indication of chloride ion permeability of the concrete. The VES concrete may exhibit high chloride permeability by the RCPT, since many additional ions introduced in the concrete by the various admixtures will cause the concrete to be more electrically conductive, and the concrete thus appears to be more permeable than it really is.

The initial current in amperes flowing through the concrete specimen in the RCPT correlates closely ($r^2 = 0.922$) with the total charge measured in 6 hours. Therefore, the initial current, which is an indirect measure of the concrete conductance, can be used as an alternative measurement for the RCPT and thus shorten the total testing time by 6 hours.

The AC impedance test measures the total resistance of a concrete specimen in ohms. This test is simpler and faster than the RCPT and has the potential to be used as a substitute for the RCPT. The best approach to correlate between the two test methods is to express the inverse impedance (reciprocal of impedance) as a linear function of the initial current measured in the RCPT.

Concrete-to-concrete bond strength can be determined by a direct shear test. The VES (A) concrete with crushed granite developed a nominal bond strength at 6 hours ranging from 120 psi

(0.83 MPa) to 150 psi (1.03 MPa) with the normal North Carolina Department of Transportation (NCDOT) pavement concrete. The VES (B) concrete with crushed granite developed a 4-hour nominal bond strength of 225 psi (1.55 MPa) with the same NCDOT pavement concrete. These values are much lower than the corresponding value of 330 psi (2.28 MPa) obtained from the control test using the NCDOT concrete. However, the control test was performed at the age of 7 days. Since the compressive strength of the VES concretes increases rapidly in the first 3 days, it is expected that its concrete-to-concrete bond strength will also increase substantially as the concrete ages.

5

High Early Strength Concrete

5.1 Objective and Scope

An extensive program of laboratory studies and the experience of five field experiments on the performance of HES concrete are presented in volume 4 of this report series. The objective was to develop and analyze basic data on the mechanical properties of HES concrete. The laboratory studies included eight types of tests:

Compression test	ASTM C 39 (AASHTO T 22)
Flexural and split tension tests	ASTM C 78, C 496 (AASHTO T 97, T 198)
Shrinkage test	ASTM C 157 (AASHTO T 160)
Freezing-thawing test	ASTM C 666 (AASHTO T 161)
Rapid chloride permeability test	ASTM C 1202 (AASHTO T 277)
AC impedance test	New
Concrete-to-concrete bond test	New
Concrete-to-steel bond test	New

The field experiments were conducted in five states: New York, North Carolina, Arkansas, Illinois, and Nebraska, as summarized in Table 5.1. The five test sites represent a wide variety of environmental and exposure conditions.

5.2 Results and Conclusions

Using conventional materials and equipment, but with more care than needed for the conventional concrete, it is possible to produce in the laboratory, as well as in the field, HES concrete that will achieve a minimum compressive strength of 5,000 psi (35 MPa) in 24 hours. Such concrete was produced with four types of aggregates: crushed granite, marine marl, dense crushed limestone, and washed rounded gravel.

Table 5.1 Summary of field installations

Location	Number and Size of Test Sections	HES Concrete Mixture	Date of Construction
New York	Length 3 @ 20 ft Width 12 ft Depth 9 in.	Insulated*	June 25, 1991
North Carolina	Length 12 @ 15 ft Width 14 ft Depth 9 in.	Noninsulated Insulated*	July 26, 1991
Illinois	Length 6 @ 15 ft Width 12 ft Depth 10 in.	Noninsulated Insulated*	October 24, 1991
Arkansas	Length 6 @ 15 ft Width 12 ft Depth 10 in.	Noninsulated Insulated*	November 6, 1991
Nebraska	Length 6 @ 16 ft Width 11 ft Depth 8 in.	Noninsulated Insulated*	July 15, 1992

* Insulated HES concrete mixture simulates VES concrete mixture.

By using insulation to trap the heat of hydration, the strength development of the HES concrete can be accelerated to achieve a VES concrete with a strength of 2,000 psi (14 MPa) or more in 6 hours.

Because of a larger amount of Type III cement used in the HES concrete mixture along with a fast-acting accelerator and a relatively low W/C, the strength development of the concrete is much more rapid in the first 15 days than predicted by the current ACI recommendation (1993a) based on conventional concrete.

Since the HES concrete in this study was kept moist only for the first 24 hours, to be followed by air curing in the laboratory, the strength development of the small laboratory samples was very rapid during the first day, and the subsequent rate of strength growth was greatly reduced. The same was true for the modulus of elasticity.

Since the design strength (5,000 psi, or 35 MPa) of HES concrete is within the range of conventional concrete, the mechanical behavior of the HES concrete, such as the modulus of elasticity and the compressive and tensile strain capacities, is similar to that of conventional concrete. The modulus of elasticity, the flexural modulus, and the splitting tensile strength can

all be predicted quite well by the ACI Code equations (1993b). The compressive strain capacity ranges fram 1,500 to 2,000 microstrains and the tensile strain capacity varies from 150 to 250 microstrains.

Shrinkage of the HES concrete follows the general trend of conventional concrete. The average shrinkage strains of the HES concretes at 90 days range from 210 to 481 microstrains, depending on the type of coarse aggregate used. These values represent 30% to 70% of the ultimate shrinkage strain recommended by ACI Committee 209 (1993a) for conventional concrete.

Even though its W/C is low, the HES concrete should have enough air entrainment to enhance its freezing-thawing resistance. The results of this investigation indicate that the HES concrete will meet the stringent requirement of a durability factor of 80% (as compared with 60% for conventional concrete) after 300 cycles of freezing and thawing, according to ASTM C 666 (AASHTO T 161), procedure A, if the concrete contains at least 5% entrained air.

The normal procedure of the RCPT is to measure the total electrical charge in coulombs flowing through a vacuum saturated concrete specimen in 6 hours. This measurement is regarded as an indication of chloride ion permeability of the concrete. The HES concrete may exhibit high chloride permeability by the RCPT, since many additional ions introduced into the concrete by the various admixtures will cause the concrete to be more electrically conductive, and the concrete thus appears to be more permeable than it really is.

The AC impedance test measures the total resistance of a concrete specimen in ohms. This test is simpler and faster than the RCPT and has the potential to be used as a substitute for the RCPT. The best approach to correlate between the two test methods is to express the inverse impedance (reciprocal of impedance) as a linear function of the initial current measured in the RCPT.

Concrete-to-concrete bond strength can be determined by a direct shear test. The HES concrete with crushed granite developed a nominal bond strength of 275 psi (1.90 MPa) with the normal NCDOT pavement concrete. The HES concrete with marine marl developed a nominal bond strength of 350 psi (2.41 MPa) with the same NCDOT pavement concrete. These values are comparable to the corresponding value of 330 psi (2.28 MPa) obtained from the control test using the NCDOT concrete. Based on a "beam"-type concrete-to-steel bond test, the HES concrete also developed sufficient bond strength with steel to satisfy the ACI Committee 318 requirement on development length (1993b).

The experience gained from the five field experiments indicates that the slump and the air content of the HES concrete are much harder to control in the field than in the laboratory. This is not unlike the case of conventional concrete.

The temperature history of the control cylinders cured in an insulated curing box in the field generally corresponded very well with the temperature history of the pavement. At the various ages of the concrete, the strengths of the cores taken from the experimental pavements generally correlated well with the strengths of the control cylinders.

The results of the RCPT performed on the cores taken from the experimental pavement in North Carolina confirmed the results obtained from the specimens prepared in the laboratory.

To produce HES concrete in the field, thorough mixing of the concrete is critical. Batch size should be limited to no more than one-half to two-thirds of the rated capacity of the ready-mix concrete truck. To optimize the performance of any field installation, preconstruction meetings should be held with contractors and concrete suppliers, including batch plant operators and appropriate highway agency personnel. Laboratory and field trial batches should be produced in sufficient number to confirm the mixture proportions, batching sequence, and workability of the concrete.

6

Very High Strength Concrete

6.1 Objective and Scope

Volume 5 of this report series presents laboratory studies on the performance of VHS concrete. The objective was to develop and analyze basic data on the mechanical properties of the concrete, with particular reference to highway applications. The laboratory experiments included eight types of tests:

Compression test	ASTM C 39 (AASHTO T 22)
Flexural and split tension tests	ASTM C 78, C 496 (AASHTO T 97, T 198)
Freezing-thawing test	ASTM C 666 (AASHTO T 161)
Shrinkage test	ASTM C 157 (AASHTO T 160)
Creep test	ASTM C 512
Rapid chloride permeability test	ASTM C 1202 (AASHTO T 277)
AC impedance test	New
Concrete-to-steel bond test	New

6.2 Results and Conclusions

Using conventional materials and equipment, but with more care than needed for the conventional concrete, VHS concrete, with either fly ash or silica fume as the mineral admixture, can be produced, which will achieve a minimum compressive strength of 10,000 psi (70 MPa) in 28 days. Such concretes can be produced with either crushed granite or dense crushed limestone as the coarse aggregate. However, with such weaker aggregates as marine marl and washed rounded gravel, the compressive strength would be slightly lower for comparable mixture proportions.

Since early strength gain is not critical for VHS concrete, insulation is not necessary for curing under normal conditions. Because of a larger amount of Type I cement plus fly ash or silica fume used in the VHS concrete mixtures, along with a relatively low W/C, the strength

development of the concretes is much more rapid in the first 7 days than predicted by the current ACI recommendation (1993a) for conventional concrete. The subsequent rate of strength growth is greatly reduced and is comparable to that predicted by the ACI method. The modulus of elasticity increases with time like the compressive strength. The same is true for the flexural modulus.

Since the design strength of VHS concrete is not much higher than the upper ranges for conventional concrete, the mechanical behavior of the VHS concrete, such as the modulus of elasticity and the compressive and tensile strain capacities, is similar to that of conventional concrete. The modulus of elasticity, the flexural modulus, and the splitting tensile strength can still be predicted reasonably well by the ACI Code equations (1993b). As VHS concrete ages, its stress-strain relationship becomes more linear.

The concrete with either silica fume or fly ash showed comparable stiffness as measured by the modulus of elasticity. The modulus of elasticity is lower, however, for the concrete with softer aggregate, such as marine marl. The observed compressive strain capacity ranged from 1,000 to 2,500 microstrains. The compressive strain capacity of the concrete with fly ash averaged 20% greater than that of the concrete with silica fume. As for the observed tensile strain capacity, it varied between 120 to 180 microstrains. The tensile strain capacity of the concrete with fly ash averaged 17% less than that of the concrete with silica fume.

Even with a very low W/C, the VHS concrete should have enough entrained air to enhance its freezing-thawing resistance. The results of this investigation indicate that VHS concrete will meet the stringent requirement of a durability factor of 80% (as compared with 60% for conventional concrete) after 300 cycles of freezing and thawing according to the ASTM C 666 (AASHTO T 161), procedure A, if the concrete contains at least 5% entrained air.

The VHS concretes produced with washed rounded gravel from Memphis, Tennessee, failed the freeze-thaw test according to ASTM C 666 (AASHTO T 161), procedure A, because of the deterioration of the aggregate, even though the concrete contained 8% entrained air. The aggregate had an absorption of about 5% and pore size of about 0.10 µm (as observed in scanning electron micrographs), the worst possible condition for freeze-thaw deterioration.

Shrinkage of the VHS concrete follows the general trend of conventional concrete. The average shrinkage strain of the VHS concrete with fly ash and crushed granite was 521 microstrains at 90 days, about 70% of the ultimate shrinkage strain recommended by ACI Committee 209 for conventional concrete (1993a). On the other hand, the average 90-day shrinkage strains of the VHS concrete with silica fume varied from -72 microstrains for concrete with washed rounded gravel to 361 microstrains for concrete with crushed granite, which indicates that the concrete with silica fume has even less shrinkage potential than the concrete with fly ash.

The observed creep strains of the different groups of VHS concrete ranged from 20% to 50% of that of conventional concrete, due to low W/C and higher compressive strength. The creep strains were especially low for concretes with a 28-day strength in excess of 10,000 psi (69 MPa). The specific creep of the concrete with marine marl was much higher than that of the

concrete with either crushed granite or washed rounded gravel, since marine marl is a softer aggregate.

With very low W/C, and using silica fume or fly ash as mineral additive, the VHS concrete after being moist cured for 14 days exhibited farely low chloride permeability as measured by RCPT.

The initial current in amperes flowing through the concrete specimen in a RCPT correlates closely ($r^2 = 0.922$) with the total charge measured in 6 hours. Therefore the initial current, an indirect measure of the concrete conductance, can be used as an alternative measurement for the RCPT and thus shorten the total testing time by 6 hours.

The AC impedance test measures the total resistance of a concrete specimen in ohms. This test method is simpler and faster than the RCPT and has the potential to be used as a substitute for the RCPT. The best approach to correlate between the two test methods is to express the inverse impedance (reciprocal of impedance) as a linear function of the initial current measured in the RCPT.

A "beam"-type concrete-to-steel bond test showed that by using the ACI Committee 318 requirement for development length (1993b), VHS concrete developed enough bond strength that the steel reinforcement yielded before any significant bond slip occurred.

7

High Early Strength Fiber Reinforced Concrete

7.1 Objective and Scope

An experimental study of HESFRC is detailed in volume 6 of this report series. The main objectives were (1) to establish a consistent and comprehensive database on HESFRC, (2) to document and synthesize information on the properties of the fresh mixture and the mechanical properties of the hardened composite, and (3) to develop recommendations for use of HESFRC by engineers.

Similar to HES concrete, HESFRC is defined as achieving a minimum target compressive strength of 5,000 psi (35 MPa) in 24 hours. Since the minimum strength criterion could be satisfied by the control specimens without fibers, and since in current applications of fiber reinforced concrete for pavements, only low fiber contents (0.10% to 1% by volume of concrete) are used, it was decided to explore and document a higher range of fiber content (1% and 2% by volume of concrete). The main intent was to achieve, in addition to the minimum specified target compressive strength, a post-cracking strength in bending (i.e., a modulus of rupture) higher than the cracking strength so as to minimize crack widths and ensure sufficient resistance to repeated loads after cracking. This led to a load-deflection response with a post-cracking resistance above the cracking load level, at deflections up to 5 times the deflection at cracking. It implied a minimum ductility behavior in bending otherwise not present in the control specimens without fibers.

Several properties of HESFRC were investigated including the air content; inverted slump; temperature; unit weight of the fresh mixture; and the compressive, bending, tensile, and fatigue properties of the hardened composite. Particular attention was given to record not only key properties such as compressive strength, elastic modulus, and modulus of rupture, but also the entire stress-strain response in compression and load-deflection curve in bending so as to provide additional information on strain capacity and complete data for future reference. Also, values of toughness indices at different deflections were calculated from the load-deflection curves.

Sixteen combinations of parameters were investigated for each type of test. Moreover, for the bending tests only, one additional mixture containing 0.15% by volume of polypropylene fibers was also tested to simulate current low-fiber-content mixtures used in some applications such as slabs on grade.

The main parameters included (1) four matrix mixtures (one control without fibers, one with fibers but without additive, one with fibers and silica fume, and one with fibers and latex; see Table 7.1); (2) two different volume fractions of fibers (1% and 2%); (3) two fiber materials (see Table 7.2); (4) two steel fiber lengths corresponding to aspect ratios of 60 and 100, respectively; and (5) hybrid mixtures containing either an equal amount of steel and polypropylene fibers or equal amounts of steel fibers of different lengths. The compressive properties were measured at ages 1, 3, 7, and 28 days, and the bending properties at ages 1, 7, and 28 days. Information from the compression tests comprised the compressive strength, the elastic modulus, and the strain capacity. Also the effect of specimen size (4 x 8-in. [100 x 200-mm] cylinders versus 6 x12-in. [150 x 300-mm] cylinders) was documented. Information from the bending tests included the modulus of rupture and the toughness indices according to ASTM C 1018 standards.

Table 7.1 Mixture proportions of series A, B, C, and control

Mix ID	Ad. Type	C	W	Total W/C	S	CA	Mel.	AEA	DCI	Ad.
Control	---	1	0.2	0.3	1.4	1.8	3.5	0.5	9.2	---
A	---	1	0.2	0.3	1.4	1.8	3.5	0.5	9.2	---
B	Latex	1	0.1	0.3	1.4	1.8	3.5	0.3	9.2	0.2
C	SF	1	0.2	0.3	1.4	1.8	3.5	0.3	9.2	0.1

Note: Ad. = additive (latex or silica fume), C = cement, W = water, S = sand, CA = coarse aggregates, Mel. = melment based accelerator, AEA = Air-entraining agent, DCI = calcium nitrite, SF = silica fume.

7.2 Results and Conclusions

Overall, the addition of 2% by volume of 30/50 hooked steel fibers (or 2% of an equal combination of 30/50 and 50/50) gave optimal composite properties in the plastic and hardened states. The addition of fibers caused significant increases in the compressive strength, modulus of rupture, splitting tensile strength, toughness indices, ductility (or strain capacity), and fatigue limit when compared with all other HESFRC mixtures, as well as with the control mixture without fibers. In comparison with the control mixture, average increases of 30% in compressive strength, 270% in modulus of rupture, 250% in splitting tensile strength, and predicted endurance limit in bending of 65% of ultimate while in the cracked state were observed. Moreover, values of toughness indices I_5 and I_{10}, as high as 30 and 60 imply energy absorption capacities at least 30 to 60 times that of the control mixture without fibers.

Table 7.2 Properties of fibers used

Fiber Name	Fiber Material	Length (mm)	Diameter (mm)	Aspect Ratio (length/diameter)	Density (pcf)**	Specific Gravity
30/50	Steel	30	0.5	60	490	7.85
50/50	Steel	50	0.5	100	490	7.85
PP	Polypropylene	12.7	0.095*	133.6	56.80	0.91
PP	Polypropylene	19	0.095*	200	56.80	0.91

*Monofilament **1 pcf (pound per cubic foot) = 16 kg/m^3

Next in performance were the mixtures containing 1% by volume of 50/50 or 30/50+50/50 hooked steel fibers; both mixtures performed similarly in terms of compressive strength, elastic modulus, modulus of rupture, and splitting tensile strength. In comparison with the control mixture without fibers, these mixtures led to little change in compressive strength, but, on average, increased the modulus of rupture and splitting tensile strength by 200% and 173%, respectively. Here toughness indices I_5 and I_{10} as high as 9 and 23, respectively, were observed.

In general, the property affected most by the addition of fibers, be they steel or polypropylene fibers, is the toughness index in bending. Toughness indices I_5 and I_{10} generally exceeded 5 and 10, respectively, when 1% fibers by volume was added. Thus, a substantially improved energy absorption capacity (which can be translated into improved performance under impact) seems to be the most evident benefit of adding fibers to HES concretes.

Mixtures containing 1% or 2% by volume of polypropylene fibers showed deterioration in the compressive stress-strain response when compared with the control mixture. The mixture with 2% by volume of polypropylene fibers was more difficult to mix, led to a larger volume of entrapped air, and resulted in poorer properties than the mixture with 1% polypropylene fibers by volume. Therefore, the use of polypropylene fibers only to improve compressive strength and elastic modulus is not recommended. However, as mentioned above, polypropylene fibers did markedly improve the toughness index of the composite.

Although latex improved the workability of HESFRC mixes and their 28-day compressive strength, its use is not desirable for the sole purpose of improving early age properties. However, it should be observed that latex is generally used to improve the bond between new and old concrete in repair applications and is known to improve durability. These very important properties were not investigated in this study.

The addition of silica fume does not significantly affect the 1-day compression, bending, and tension properties of HESFRC composites. However, properties at later ages were improved, as in the case of plain concrete.

Hybrid mixtures with steel and polypropylene fibers did not fare as well as all-steel-fiber mixes with same total fiber content by volume in terms of improvements in strength and toughness.

The compressive strength of HESFRC mixtures obtained from 6 x 12-in. (150 x 300-mm) cylinders was, on average, 3.9% lower than that obtained from 4 x 8-in. (100 x 200-mm) cylinders.

Given the properties observed in this investigation, it can be inferred that HESFRC containing fibers (particularly hooked steel fibers) in 1% to 2% by volume can be used for several highway-related applications. They include (1) repair projects for which early strength and toughness (energy absorption and impact properties) are needed, such as for potholes, bridge decks, overlays, pavement joints, piers, median barriers, facilities subjected to impact by marine traffic, and runways, and (2) applications in new structures, particularly bridge decks, pavements, bridge piers, piles, reusable median barriers, taxiways, and runways. These are applications that require the specific advantages of HESFRC (compared with HES concrete without fibers), such as increased resistance to cracking, increased toughness (i.e., energy absorption capacity against dynamic and impact loadings and resistance to damage), increased ductility, smaller crack widths (thus reducing penetration of chlorides), and increased fatigue strength. Moreover, HESFRC can be used in conventional reinforced and prestressed concrete structures. In such cases, its use is expected to lead to substantially improved structural ductility, better hysteretic response under cyclic load reversals, better bonding of the reinforcing bars, improved resistance of the concrete cover against spalling, improved shear resistance, savings in stirrups, and overall improved energy absorption capacity of the structure.

8

Summary and Conclusions

8.1 Research Goals

The primary objective of this research program was to develop needed information on the mechanical behavior of HPC with significantly improved criteria for highway applications. For this purpose, HPC was defined as the concrete with rapid early strength development and greatly enhanced durability against freezing and thawing. Three categories of high performance concrete were investigated: VES concrete, HES concrete, and VHS concrete.

HPC has many useful applications and potential benefits to the highway industry:

- Better performance and service life of highway facilities.
- Less maintenance, because of enhanced concrete durability.
- Lower life-cycle cost.
- Less construction time, as in emergency repairs and fast-track constructions.
- Higher productivity and better quality of precast and prestressed products.
- Less consumption of materials and more conservation of resources.
- More efficient designs of long-span bridges with higher strength, longer span, and reduced dead load.
- Less thickness of pavements and bridge deck overlays.
- Faster construction schedule from early removal of formwork.
- Less surface cracking with fiber reinforcement.
- More impact resistance, achieved by using fibers in applications such as concrete median barriers or piles exposed to moving marine traffic.

For the research to be practical and useful to highway engineers, it was decided at the outset that the concrete should be produced *with only locally available, conventional constituent materials and normal production and curing procedures*.

Furthermore, the investigation was to include four different types of coarse aggregates from a wide geographical area so that the research results would be applicable to different regions rather

than being valid for only a local area. Accordingly, it can be said that *the research plan was designed for breadth rather than depth.*

8.2 Existing Knowledge Gaps

An extensive literature search and review up to 1989 revealed that an adequate working time is critical for VES concrete in view of its rapid chemical reaction. More information is needed on all aspects of the short-term and long-term mechanical properties of VES concrete, including modulus of elasticity, strength and strain capacities, creep, shrinkage, and fatigue, as well as frost durability.

For HES concrete, ensuring adequate workability and an adequate entrained air-void system at the time of placement is a critical problem. Balancing set time, rate of strength gain, and workability requirements requires extra care in selecting raw materials and producing methods. Although much is already known about the mechanical properties of concrete with a strength range comparable to that of HES concrete, most existing data are based on tests conducted at 28 days. Since HES concrete achieves its expected strength in only 24 hours, there is a need to confirm the mechanical properties of HES concrete with the existing data.

For VHS concrete, most existing data are based on tests conducted at older ages, such as 56 or 90 days; thus, more information on its mechanical properties at 28 days is needed. In addition, there is a dearth of data on durability, fatigue, and brittleness of VHS concrete.

For fiber reinforced concrete, more information is needed on long-term effects. Furthermore, in pavement applications, steel fibers have been used almost exclusively. Use of other types of fibers is practically nonexistent. Mixed fibers, such as a combination of steel and polypropylene fibers, may enhance both strength and ductility of concrete. Virtually no research has been conducted in this area.

Finally, for all types of HPC, there is insufficient information on how vibration and curing affect the mechanical properties of the concrete.

8.3 Research Accomplishments

Research results summarized in this report, which have been replicated many times in laboratory studies and confirmed by field trials, demonstrated that *it was entirely feasible to produce HPC for highway applications with conventional materials and normal techniques,* provided that care is exercised in the selection of materials and that certain steps are taken to ensure quality production. As shown in Table 8.1, of the 21 HPC mixtures studied in detail, 7 failed to reach the target strength levels within the time limit. Six of the 7 mixtures contained either of the two weaker aggregates (i.e., marine marl or rounded gravel).

Table 8.1 Comparison of target strength and actual strength of high performance concrete

Type of HPC	Target Strength	Actual Strength of HPC with Different Types of Aggregates CG	MM	RG	DL
VES (A)	2,000 psi in 6 hours	2,090 psi	2,000 psi	2,360 psi	3,090 psi
VES (B)	2,500 psi in 4 hours	2,510 psi	2,270 psi	3,060 psi	2,890 psi
HES	5,000 psi in 24 hours	5,410 psi	5,610 psi	5,690 psi	5,300 psi
HES (Latex)	5,000 psi in 24 hours	NA	4,225 psi	NA	NA
VHS (fly ash)	10,000 psi in 28 days	12,200 psi	7,620 psi	8,970 psi	9,833 psi
VHS (silica fume)	10,000 psi in 28 days	11,780 psi	8,460 psi	9,120 psi	10,010 psi

Note: CG = crushed granite, MM = marine marl, RG = washed rounded gravel, DL = dense crushed limestone, NA = not applicable, 1 psi = 6.89 kPa.

Furthermore, all the mixtures containing roughly 5% well-entrained air were found to have greatly enhanced frost durability, with a durability factor of at least 80% (in contrast to 60% for conventional concrete) as measured by ASTM C 666 (AASHTO T 161), procedure A. The only exceptions were the mixtures using washed rounded gravel as coarse aggregate, because the aggregate lacked resistance against freezing and thawing.

In general, the different types of HPC behaved very much like the conventional concrete *of comparable strength,* except that the HPCs developed their strength characteristics much more rapidly than the conventional concretes. Test results indicated that the various mechanical properties, such as the modulus of elasticity, the splitting tensile strength, and the flexural tensile strength (or modulus of rupture), of the HPCs could all be predicted by the existing relationships recommended by ACI (1993a, 1993b, 1993c) at *the appropriate strength levels* (see Figures 8.1 through 8.4). The same was true for concrete-to-concrete bond and concrete-to-steel bond.

On the other hand, shrinkage of the HPCs was found to be considerably less than that of the conventional concrete. This should be expected because of the very low W/C used for HPC. In fact, VES (B) concrete with marine marl and rounded gravel exhibited an expansion of approximately 140 microstrains rather than shrinkage for the entire test period of 90 days. The

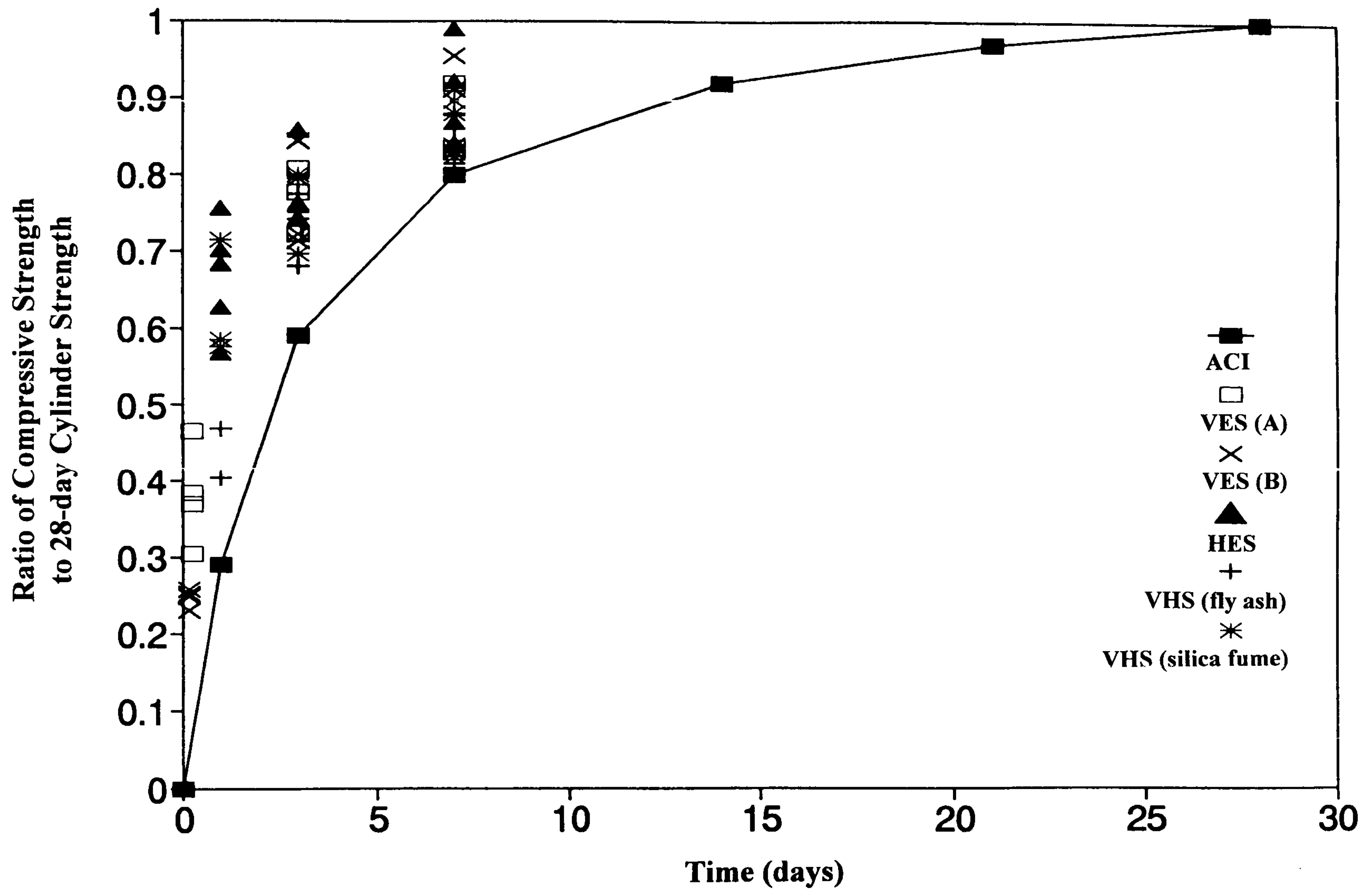

Figure 8.1 Variation of compressive strength with time

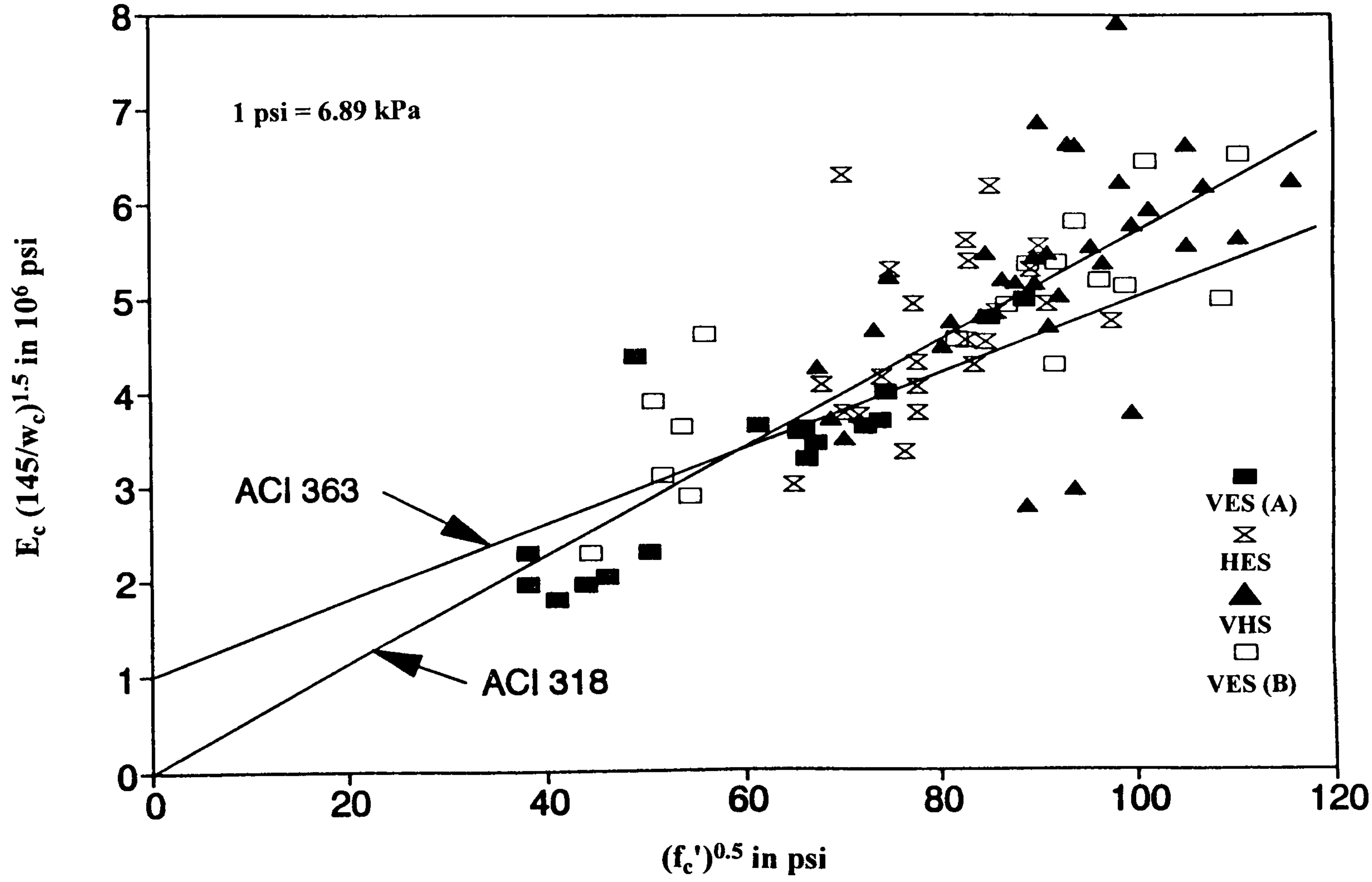

Figure 8.2 Variation of modulus of elasticity E_c with square root of compressive strength f_c' (E_c is normalized by unit weight w_c in lbs per cubic foot)

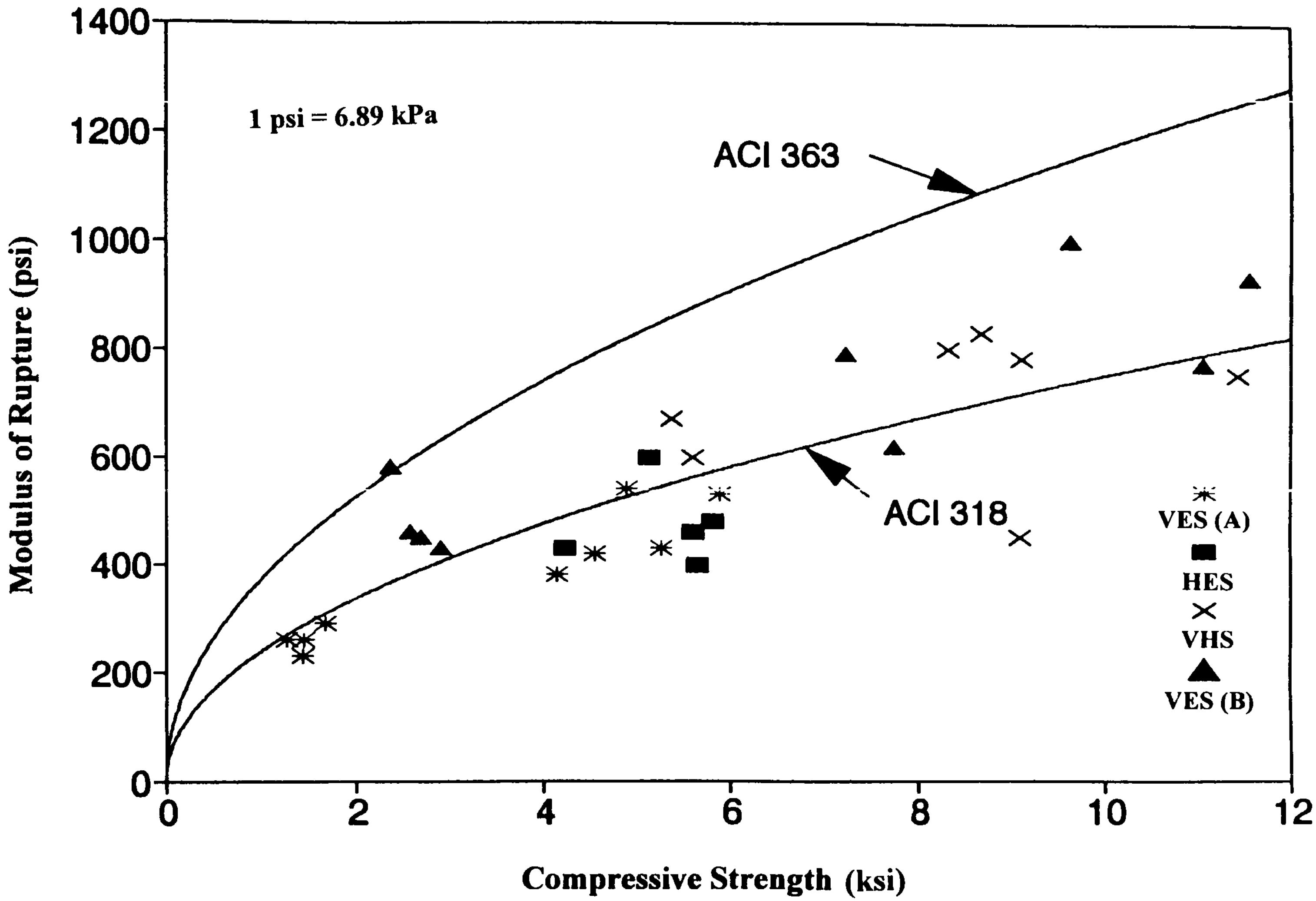

Figure 8.3 Modulus of rupture versus compressive strength

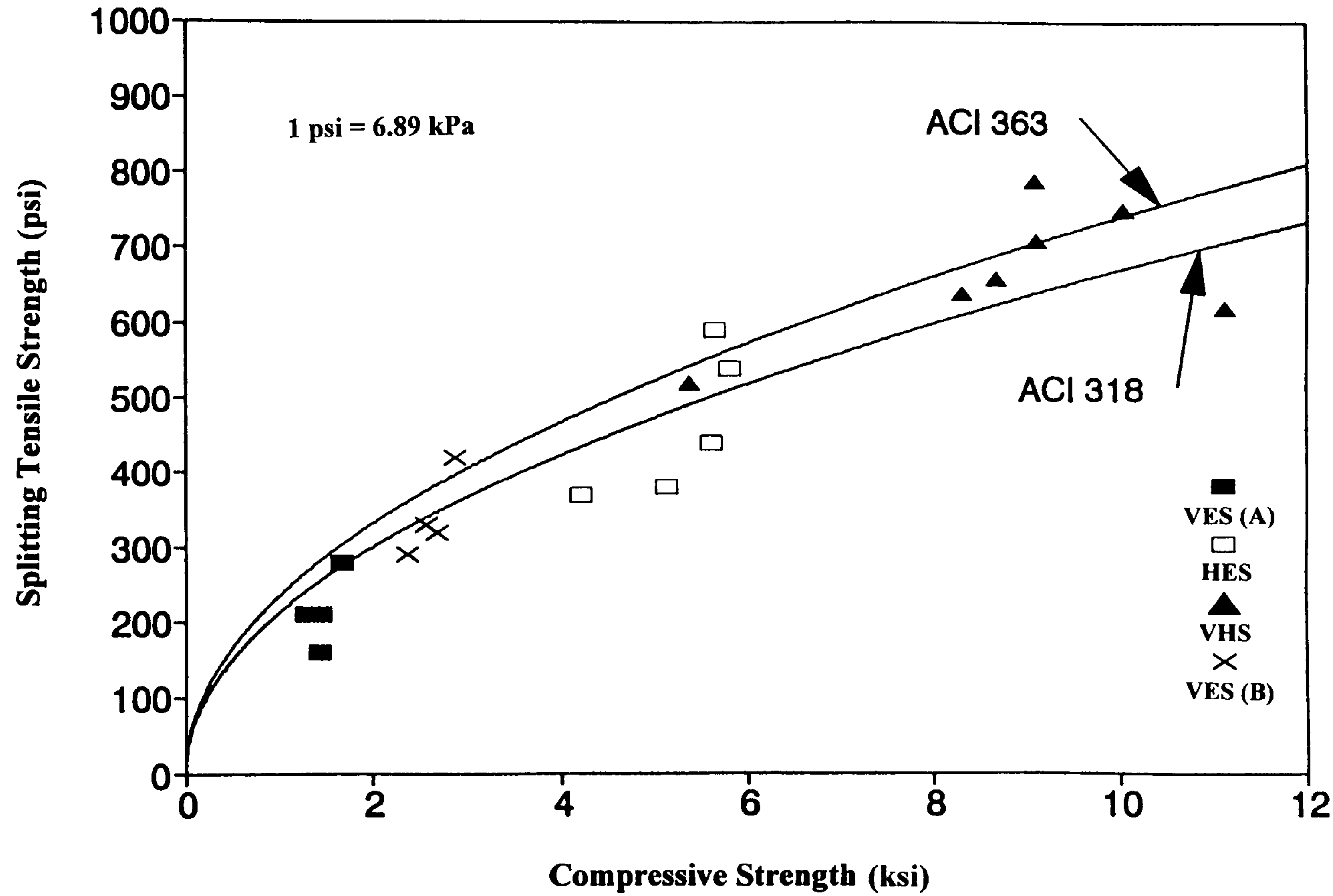

Figure 8.4 Splitting tensile strength versus compressive strength

expansion is attributed to the lack of evaporable water in the concrete because of its very low W/C (0.17 and 0.22).

The observed creep strains of the different groups of VHS concrete ranged from only 20% to 50% of that of the conventional concrete, also because of low W/C and higher compressive strength. The creep strains were especially low for concretes with a 28-day strength in excess of 10,000 psi (69 MPa). Since marine marl is a softer aggregate, the specific creep of the concrete with marine marl was much higher than that with either crushed granite or washed rounded gravel.

Tests for chloride ion permeability by both the RCPT and the AC impedance test showed good correlations ($r^2 = 0.840$) between the two. However, the results for both VES and HES concretes indicated relatively high chloride permeability values in comparison with *high-quality* conventional concrete. It was observed that the results were greatly affected by the very short curing time and the large amounts of ions introduced into the concretes from the admixtures used in the two concretes.

Studies of HESFRC indicated that the greatest benefit of introducing fibers (both steel and polypropylene) into the HES concrete was the vast improvement in the toughness of the concrete in bending. Two percent by volume of 30/50 hooked steel fibers (or 2% of an equal combination of 30/50 and 50/50) was found to be the optimal amount. The addition of steel fibers significantly improved compressive strength, modulus of rupture, splitting tensile strength, toughness indices, ductility (or strain capacity), and fatigue strength of the HES concrete. There was no beneficial effect, however, from the use of polypropylene fibers to improve compressive strength and elastic modulus.

8.4 Limitations of Research Results

In evaluating the results of this extensive research program, it should be kept in mind that the desire to examine a great many mechanical properties of HPCs with a wide variety of constituent materials led to a research plan that was *very broad in scope* at the expense of sufficient depth. For practical reasons, there were many uncontrolled parameters involved in the experiments, such as the variations of cement characteristics and other constituent materials, ambient conditions during specimen preparation, curing temperatures, and the variation of different concrete batches from which specimens of same test series were prepared.

Although a definite effort was made to obtain all constituent materials for the various concrete mixtures (at a given test site) from the same sources of supply, no control was exercised to obtain a very large supply of basic materials for the entire test program, because overly controlled laboratory tests would not be a valid representation of the actual conditions encountered in the field installations. The materials used for field installations depended on what were available to the local concrete producers. For the same reason, no controls were exercised for the ambient conditions and the curing temperatures. Concrete batch variations were necessary because of the

limitation of laboratory mixing capacity. In addition, with rapid strength development of VES and HES concretes, only limited amounts of time were available for testing small numbers of specimens before the specimens changed their strength characteristics.

Besides the uncontrolled parameters, there were several nonstandard test procedures used in the experiments. For example, laboratory mixing procedures were modified to simulate more closely typical dry-batch plant operations. Laboratory curing conditions were also modified using an insulation box to simulate the field curing conditions. Furthermore, 4 x 8-in. (100 x 200-mm) cylinders rather than the standard 6 x 12-in. (150 x 300-mm) cylinders were used for most laboratory and field tests, since the smaller cylinders required less material to make and could be tested with lower-capacity testing machines. In addition, smaller cylinders were much closer to the size of concrete cores taken in the field. Since VES and HES concretes had to be tested shortly after they were cast, it was not feasible to cap the cylinders with sulfur compound. Therefore the cylinders were tested with steel caps enclosing a neoprene pad as permitted by AASHTO T 22. The specimens for the flexure test were also modified by placing a No. 2 steel bar at their neutral axis (which prevented sudden collapse of the specimens) to facilitate the measurement of the tensile strain capacity under the maximum load.

It should be emphasized that in spite of the many variations discussed above, the experimental program reported herein was conducted consistently with many replications and field trials. Therefore the data obtained in this program are still valid, even though the database is not large enough to have a meaningful statistical analysis to estimate its degree of variability.

8.5 Removing Specifications Barriers

Current specifications for highway materials and construction have been formulated primarily from the knowledge of conventional materials. Some requirements may not be applicable to HPCs and thus would serve as barriers to acceptance of such concretes for highway applications.

Review of a number of specifications revealed that while no such barriers could be identified in the major national codes and specifications of AASHTO, ASTM, and ACI, several barriers were found in the specifications of state highway agencies. For example, the North Carolina Department of Transportation *Standard Specifications for Roads and Structures* (January 1, 1990) contains a provision that states that the cement content for prestressed concrete shall not exceed 752 lbs (340 kg), and that the slump of the concrete shall be no more than 3.5 in. (88 mm). These limitations are barriers to the acceptance of HPCs, since HPCs generally require greater cement content and often produces greater slumps because of greater amounts of paste and the use of high-range water reducers.

Similarly, the Michigan Department of Transportation *Standard Specifications for Construction* (1990) considers the slump test as a standard for all concrete materials. However, the "inverted cone test" is recommended for fiber reinforced concrete by ACI Committee 544 on Fiber Reinforced Concrete. In addition, the specifications require that all concrete shall be designed to

contain 6.5±1.5% entrained air. For HESFRC, the air content is generally at a lower amount ranging from 3% to 6%, because mixing with fiber tends to drive out some of the entrained air in the concrete.

The above examples illustrate that to encourage use of HPC, efforts should be organized to encourage all state highway agencies to review their specifications and remove possible barriers to use of HPC.

8.6 Guides and Specifications

From the results and experience of this research program, two technical guides on the production and use of HPC, as well as two proposed specifications for test methods, were developed to provide guidance to engineers, concrete producers, and contractors. These documents are included in the four appendixes of this report.

Appendix A presents a *Guide to Field Production and Use of High Performance Concrete for Highway Applications*, which provides useful recommendations on the selection of materials, production procedures, and appropriate practices for using HPCs in the field. It may be used as a guide reference for materials and construction specifications.

A *Guide to Use of Pyrament PBC-XT Cement* is presented in appendix B. This guide is prepared solely for the convenience of those who may wish to experiment with the material and it is based on the current recommendations of the manufacturer. It is advisable for all prospective users of the material to consult the manufacturer for the latest recommendations.

Appendix C presents *Proposed Specifications for AC Impedance Test of Concrete*. This test method is recommended as a substitute for the method specified by ASTM C 1202 (AASHTO T 277), commonly known as the rapid chloride permeability test (RCPT). The method requires less equipment and takes less time to conduct the test than the RCPT. Therefore, the method is sufficiently portable to be used in field laboratory. However, both the AC impedance test and the RCPT are subject to the same limitation: Test results may be affected by chemical admixtures used in concrete, because the admixtures introduce ions into the concrete that will cause it to be electrically more conductive.

Appendix D contains *Proposed Specifications for Test of Bond between High Performance Concrete and Conventional Concrete*. This test method determines the interfacial bond between two concretes under a direct shearing force. It is recommended as a research tool to be used in the laboratory. The method is not intended for field use, since it is not economically feasible to obtain the specific type of test specimen from an existing concrete pavement with overlay in the field.

8.7 Future Research Needs

Using the experience and knowledge gained from this 4-year study, it is recommended that additional research be pursued so as to enhance further understanding of the nature and behavior of HPCs and to encourage wider acceptance of the materials for highway applications. Some of the research needs of higher priority are discussed here.

1. Efforts should be organized to continue monitoring the five field installations established in this research program. Each site should be visually inspected at least semiannually, and concrete cores taken from the pavement should be tested annually for the next 3 years. The cores and other control cylinders or beams that were prepared at the time of construction should be tested for strength, freezing-thawing resistance, and chloride permeability by RCPT (and AC impedance test if available), as well as by the ponding test for chloride penetration. Records on traffic and weather conditions should also be gathered periodically.

2. Additional studies of the mechanical properties and strength development of VES and HES concretes should be pursued with fewer variables and more controlled parameters so that a large enough database can be obtained to permit a more meaningful statistical analysis to establish the degree of variability of the test results. Important variables that should be included in the studies are variations of cement and mineral admixtures, curing method and length of curing time, amount of air entrainment, amount of mixing time, alternative types of accelerators, and high-range water reducers.

3. Studies should be conducted to assess the effect of using steel caps with neoprene pads instead of the regular sulfur capping compound.

4. Much more research is needed to determine the effects of curing methods and procedures on the short-term and long-term properties of HPCs.

5. Although the present limited research data have demonstrated the enhanced durability of HPCs against freezing and thawing, other aspects of durability of these concretes, such as abrasion resistance, scaling resistance, and potential for alkali silica reactivity, should be investigated.

6. The nature of the microstructures of HPCs should be studied, and the optimal amount of entrained air should be determined.

7. Ponding tests should be conducted along with AC impedance tests and RCPTs for HPCs so that a better correlation can be established between chloride ion permeability and chloride penetration of the concrete.

8. Improved and more realistic methods and procedures for evaluations of frost resistance and chloride permeability of concrete should be developed.

9. Brittleness of HPCs and how it might affect their fatigue resistance should be evaluated.

10. The use of different types of fibers for HPCs, particularly for their applications with VES concrete for rapid repairs of bridge decks and potholes, should be investigated.

References

ACI Committee 209. 1993a. Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures (ACI 209R-92). *ACI Manual of Concrete Practice*, Part 1, 47 pp.

ACI Committee 318. 1993b. Building Code Requirements for Reinforced Concrete (ACI 318-89) and Commentary (ACI 318R-89), (Revised 1992). *ACI Manual of Concrete Practice*, Part 3, 347 pp.

ACI Committee 363. 1993c. State-of-the-Art Report on High-Strength Concrete (ACI 363R-92). *ACI Manual of Concrete Practice,* Part 1, 55 pp.

America's Highways: Accelerating the Search for Innovation. 1984. Special Report 202, Transportation Research Board, National Research Council, Washington, D.C.

Chi, W. K. 1990a. *NCSU Concrete Materials Database.* SHRP-C/WP-90-002, Strategic Highway Research Program, National Research Council, Washington, D.C.

Chi, W. K. 1990b. *User Manual: NCSU Concrete Materials Database.* SHRP-C/WP-90-003, Strategic Highway Research Program, National Research Council, Washington, D.C.

Leming, M. L.; Ahmad, S. H.; Zia, P.; Schemmel, J. J.; Elliott, R. P.; and Naaman, A. E. 1990. *High Performance Concretes: An Annotated Bibliography 1974-1989.* SHRP-C307, Strategic Highway Research Program, National Research Council, Washington, D.C.

Zia, P.; Leming, M. L.; and Ahmad, S. H. 1990. Research on High Performance Concrete. *Proceedings* of Conference on the United States Strategic Highway Research Program. The Institution of Civil Engineers, London, October 29-31, pp. 63-75.

Zia, P.; Leming, M. L.; and Ahmad, S. H. 1991. *High Performance Concrete: A State-of-the-Art Report.* SHRP-C317, Strategic Highway Research Program, National Research Council, Washington, D.C.

Appendix A

Guide to Field Production and Use of High Performance Concrete for Highway Applications

Appendix A

Guide to Field Production and Use of High Performance Concrete for Highway Applications

A.1 Introduction

This guide is developed to assist engineers, concrete producers, and contractors in making use of high performance concrete (HPC) for highway applications. It is based on the results of laboratory experiments and field experiences obtained during a 4-year study under the Strategic Highway Research Program (SHRP) contract C-205, "Mechanical Behavior of High Performance Concretes (HPC)."

This guide discusses the selection of materials and concrete proportions and offers guidance in the production and placement of HPC with particular reference to any changes from normal procedures required of the concrete supplier, the contractor, and the project engineer. For more specific details, the reader should refer to other volumes of this report series.

A.2 Definitions

HPC is defined as concrete with enhanced durability and rapid early strength development characteristics. It should have a low water/cement ratio (W/C) in order to limit permeability and should have a durability factor of at least 80% when tested in accordance with ASTM C 666 (AASHTO T 161), procedure A. Three categories of HPC are defined according to certain target strength criteria as shown in Table A.1.

Table A.1 Criteria for high performance concretes

Categrory of HPC	Minimum Compressive Strength	Maximum Water/ Cement Ratio	Minimum Frost Durability Factor
Very early strength (VES)			
Option A (with Type III cement)	2,000 psi (14 MPa) in 6 hours	0.40	80%
Option B (with PBC-XT cement)	2,500 psi (17.5 MPa) in 4 hours	0.29	80%
High early strength (HES) (with Type III cement)	5,000 psi (35 MPa) in 24 hours	0.35	80%
Very high strength (VHS) (with Type I cement)	10,000 psi (70 MPa) in 28 days	0.35	80%

In the above definition, the target minimum strength should be achieved in the specified time after water is added to the concrete mixture. The compressive strength is determined from 4 x 8-in. (100 x 200-mm) cylinders tested with neoprene caps, as described in AASHTO T 22. W/C is based on all cementitious materials.

A.3 Background

The primary application of VES concret is expected to be in full-depth or partial-depth highway pavement patches. The primary application of HES concrete is expected to be in fast-track bridge deck construction or rehabilitation. These concretes would have an ultimate strength far in excess of that needed for structural capacity. The primary application of VHS concrete is anticipated to be in bridge superstructure or substructure members.

Different mixtures were formulated for these categories, but the mixtures were also selected to meet simultaneously as many of the strength-time criteria as possible, thereby providing the engineer with a choice of mixture depending on the specific criteria for a given project. For example, mixtures developed primarily for the VHS applications will frequently provide rapid early strength performance similar to HES mixtures. However, the VHS mixtures contain a mineral admixture and do not contain a corrosion-inhibiting admixture. If one is concerned about alkali silica reactivity and the corrosion potential is low, the selection of a VHS-type mixture would be appropriate if HES-type early strength performance were needed.

In the research and development work pursued under SHRP C-205, HPC criteria, materials, proportions, and production controls were selected using practical goals that meet the needs of the practicing engineer and using materials and methods that are routinely available or could be obtained with minimum effort. Laboratory mixing, curing, and testing procedures were developed or modified as necessary to avoid unrealistic performance. Practicality was much more important than simply creating some arbitrary but impressive strength level in the laboratory that could not be reliably duplicated in the field and had little applicability to the needs or concerns of the practicing engineer.

Simplicity of material constituents was another important criterion in the selection of mix proportions, both for economy and for flexibility. In general, the minimum amount of material was used, consistent with achieving the desired performance level.

Emphasis in the research was placed on obtaining data where none or very little existed for HPC intended for specific transportation-related applications. Conventional fast-track paving mixtures were not considered, since a reasonable amount of data already exists on these mixtures and since the mixtures would rarely meet all the proposed performance criteria.

Field installations were conducted in New York, North Carolina, Illinois, Arkansas, and Nebraska to confirm the ability to produce and place HPC and to attain required strength levels at given time intervals under realistic field conditions, using different sources of raw materials. There were also several intermediate and parallel objectives:

1. To confirm procedures developed in the laboratory and verify the ability to reproduce the concrete under field conditions,
2. To verify the laboratory results for strength-time data,
3. To identify potential problems not encountered in the laboratory — in particular, any major difficulties in full-scale production,
4. To obtain some idea of performance under actual exposure conditions (both traffic and environmental loads), at least up to one year.

A.4 Selection of Materials

A.4.1 Aggregate

Aggregates should be of the best available quality — a hard, durable, nonpolishing coarse aggregate and a clean, well-graded fine aggregate. In previous field trials, locally available aggregate meeting AASHTO M 6 and M 43, with no special limitations, and, in a few cases, with limited performance characteristics, was found to give acceptable results.

Both silicious and carbonate coarse aggregates, which included both a limestone and a silicious aggregate with low absorption and high strength, plus a relatively porous, high-absorption, moderate-strength carbonate marl, were successfully used. In the laboratory, both crushed and

rounded silicious aggregates were investigated. One type of silicious aggregate with moderate absorption was found to be nondurable in rapid freeze-thaw testing.

A natural, silicious sand was used in all laboratory and field mixtures. The mixtures all contained a large quantity of cementitious material. Since excessive fines will tend to make the mixtures overly sticky, a high-fineness-modulus sand should be used, if available.

The nominal maximum size of coarse aggregate (NMSA) used in pavements is frequently 1½ in. (40 mm), except where D cracking is a problem. However, to make the mixes more universally applicable, both regionally and with respect to application, #57 NMSA with virtually all the material passing the 1-in. (25-mm) sieve was used both in the laboratory and in the field. The use of a smaller or larger aggregate should pose no particular problem, but results must be confirmed in trial batches.

The quantity of coarse aggregate used should be similar to that recommended by ACI 211.* As with NMSA, the quantity used in pavements is typically higher than that used in other concrete members. Using a smaller quantity of coarse aggregate will increase the amount of fine aggregate, which will typically be somewhat beneficial in reducing stickiness of the concrete mixture.

A.4.2 Cement

Type I portland cement is used for the VHS mixtures. For the VES (A) and HES mixtures, Type III portland cement is used. The VES (B) mixtures are based on Pyrament blended cement. This is a specialty cement that must be handled somewhat differently from portland cement. It requires a much lower W/C and is not used with any chemical admixtures, including air-entraining agents. Additional information concerning Pyrament PBC-XT cement is given in appendix B.

The use of a high-quality cement will enhance results but is subject to local availability. Conventional-quality cements should provide acceptable results. Specific performance characteristics should be determined with trial batches.

A.4.3 Chemical Admixtures

In the SHRP C-205 investigations, a 30% solution of calcium nitrite was added to all the VES (A) and HES mixtures. The calcium nitrite solution is known to enhance performance of the concrete under conditions that encourage corrosion of reinforcing steel. However, it is also a fast-acting set accelerator. It was therefore selected as a nonchloride accelerator that would also improve long-term durability of such reinforced structures as bridge decks. It was not added to VHS mixtures, since early strength development is not required of such mixtures.

* ACI Committee 211. 1993. Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91). *ACI Manual of Concrete Practice*, Part 1, 38 pp.

Several implications in using calcium nitrite solution should be noted. First, since it is an accelerator, it could not be added at the time of batching with the mixtures. (An alternative product containing a retarding admixture to help control slump loss was found to retard early strength development in laboratory testing and could not be used as a substitute.) Second, the solution contains a substantial amount of water, and it was necessary to withhold that water during initial batching.

Because of the low W/C of all the portland-cement-based HPC mixtures, the use of a high-range water reducer (HRWR) or superplasticizer, is necessary for adequate workability. Two generic types of HRWR are commonly available: those based on naphthalene and those based on melamine. Naphthalene-based HRWRs typically have a higher water-reducing capacity but a greater tendency to retard set than the melamine-based HRWRs. High dosages of either type of HRWR will cause retardation of the concrete and low early strengths, although strengths at 1 day will typically be comparable to other mixtures. Dosages must therefore be carefully selected, and maximum permissible quantities established.

To prevent excessive stickiness, promote better workability, reduce slump loss, and still provide an acceptable platform for generation of a stable air-void system, a minimum initial water content is required. This, combined with the low W/C, plus the water held back for calcium nitrite solution to be added in the mixtures, means that the cement content has to be fairly high, even though an HRWR is used, particularly since the dosage of HRWR must be limited somewhat. However, the high cement content helps the early strength development of the VES (A) and HES mixtures.

The only other chemical admixture used in HPC mixtures is an air-entraining agent (AEA). Because of the high fines content of the mixtures, a relatively high quantity of AEA is required. Exact quantities of all admixtures used must be determined by trial batches. AEA should not be used with the VES (B) mixtures.

A.4.4 Mineral Admixtures

Pozzolanic materials have long been known to enhance durability in certain exposure conditions and have frequently enhanced strength characteristics of very high strength mixtures. Fly ash and silica fume were therefore included in the VHS mixtures. Ground granulated iron blast-furnace slag (GGBFS) was not investigated for several reasons. GGBFS is more limited regionally than fly ash, and the results using GGBFS are frequently intermediate between fly ash and silica fume in terms of strength development. Effects on durability are similar to those with fly ash, although the quantity of GGBFS needed is typically much higher.*

Since slag and fly ash typically do not contribute substantially to strengths at 1 day or less, there is no apparent advantage for VES and HES mixtures to include these materials. Silica

* ACI Committee 226. 1993. Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete (ACI 226.1R-87). *ACI Manual of Concrete Practice*, Part 1, 16 pp.

fume, on the other hand, is reactive at early ages. therefore, consideration was given to its use in HES mixes. The decision not to use silica fume in the HES mixtures was based primarily on the desire to keep the mixtures as simple and economical as possible. The silica fume used in the VHS mixtures did provide HES-type strength performance at 1 day. Silica fume was used in a slurry form, which was found to be relatively easy to store, handle, and mix.

A.5 Mixture Proportioning

Conventional proportioning techniques should be used to develop or adjust proposed mixture proportions. Typical mixture proportions developed from the SHRP C-205 study are given in Tables A.2 through A.6. The quantity of water shown in the mixture proportions was based on an angular, micaceous sand and a subangular sand. With clean, rounded sands, water demand may be significantly lower.

A.6 Trial Batches

Any change in raw materials will require adjustments in the proportions used or in the results attained. Laboratory trial batches and field trial batch adjustments should always be conducted. The mixes listed in Tables A.2 through A.6 should serve as the basis for further developments to attain other similar characteristics or to provide incremental improvements.

A modification of standard laboratory mix procedures was necessary to ensure that mixture performance could be reasonably duplicated in the field (see Trial Batch Procedure at end of this appendix). Since the use of HRWRs and high cement contents can lead to fairly rapid slump loss, an extended period of mixing or agitating was employed for VES and HES mixtures. Additionally, the batching sequence was modified slightly to more closely simulate typical concrete dry-batch plant operations. A rotating-drum mixer was used for all laboratory batches. Modification of the batching sequence and use of extended mixing for VES and HES mixtures in the laboratory produced results that were duplicated reasonably well in subsequent field trials (see volumes 3 and 4 of this report series).

Extended mixing times were also employed for a few VHS mixtures, but the VHS mixtures were not difficult to control. Slump loss can be controlled by using retarding admixtures. Since early strength was not a critical requirement, the use of a retarding admixture was not detrimental to performance; therefore, the use of longer mixing periods for VHS mixtures was not required.

As noted above, because of the high water content of the calcium nitrite solution and because the solution could not be added until just before concrete placement, adding an HRWR initially was a practical necessity. Although modern HRWRs may have improved performance, earlier

Table A.2 Mixture proportions of VES (A) concrete with four types of aggregate

Aggregate Type Source of Sand	CG Lillington	MM Lillington	RG Memphis	DL Van Buren
Cement (Type III), pcy	870	870	870	870
Coarse aggregate, pcy	1,720	1,570	1,650	1,680
Sand, pcy	820	800	760	920
HRWR (melamine-based), oz/cwt	5.0	5.0	10	4.0
Calcium nitrite (DCI), gcy	6.0	6.0	6.0	6.0
AEA, oz/cwt	3.0	2.5	4.0	2.5
Water, pcy	350	350	350	340
W/C	0.40	0.40	0.40	0.39
Slump after addition of HRWR, in.	5	7	6	5.75
Air, %	6.5	6.4	7.5	4.40
Strength at 6 hours (insulated), psi	2,090	2,000	2,360	3,090
Concrete temperature at placement, ^{o}F	71	75	79	78

Note: CG = crushed granite, MM = marine marl, RG = washed rounded gravel, DL = dense crushed limestone, HRWR = high-range water reducer, AEA = air-entraining agent, W/C = water/cement ratio; 1 pcy (pound per cubic yard) = 0.593 kg/m^3, 1 oz/cwt (ounce per hundredweight) = 0.625 g/kg, 1 gcy (gallon per cubic yard) = 4.95 L/m^3, 1 in. = 25.4 mm, 1 psi (pound per square inch) = 6.89 kPa, $^{o}C = (^{o}F - 32) \times 5/9$.

Table A.3 Mixture proportions of VES (B) concrete with four types of aggregate

Aggregate Type Source of Sand	CG Lillington	MM Lillington	RG Memphis	DL Van Buren
Cement (Pyrament), pcy	850	850	850	855
Coarse aggregate, pcy	1,510	1,500	1,510	1,680
Sand, pcy	1,440	1,460	1,400	1,560
HRWR (melamine-based), oz/cwt	0	0	0	0
Calcium nitrite (DCI), gcy	0	0	0	0
AEA, oz/cwt	0	0	0	0
Water, pcy	195	145	183	200
W/C	0.23	0.17	0.22	0.23
Slump, in.	6.5	4	3.5	7.0
Air, %	6.0	7.0	3.7	7.6
Strength at 4 hours (Insulated), psi	2,510	2,270	3,060	2,890
Concrete temperature at placement, ^{o}F	72	72	75	77

Note: CG = crushed granite, MM = marine marl, RG = washed rounded gravel, DL = dense crushed limestone, HRWR = high-range water reducer, AEA = air-entraining agent, W/C = water/cement ratio; 1 pcy (pound per cubic yard) = 0.593 kg/m^3, 1 oz/cwt (ounce per hundredweight) = 0.625 g/kg, 1 gcy (gallon per cubic yard) = 4.95 L/m^3, 1 in. = 25.4 mm, 1 psi (pound per square inch) = 6.89 kPa, $^{o}C = (^{o}F - 32) \times 5/9$.

Table A.4 Mixture proportions of HES concrete with four types of aggregate

Aggregate Type Source of Sand	CG Lillington	MM Lillington	RG Memphis	DL Van Buren
Cement (Type III), pcy	870	870	870	870
Coarse aggregate, pcy	1,720	1,570	1,650	1,680
Sand, pcy	960	980	900	1,030
HRWR (naphthalene-based), oz/cwt	26	26	26	16
Calcium nitrite (DCI), gcy	4.0	4.0	4.0	4.0
AEA, oz/cwt	9	1.0	1.0	4.0
Water, pcy	280	280	300	300
W/C	0.32	0.32	0.34	0.34
Slump after addition of HRWR, in.	1.0	6.75	7.0	3.5
Air, %	5.3	5.6	6.6	5.4
Strength at 1 day, psi	5,410	5,610	5,690	5,300
Concrete temperature at placement, ^{O}F	80	73	84	78

Note: CG = crushed granite, MM = marine marl, RG = washed rounded gravel, DL = dense crushed limestone, HRWR = high-range water reducer, AEA = air-entraining agent, W/C = water/cement ratio; 1 pcy (pound per cubic yard) = 0.593 kg/m^3, 1 oz/cwt (ounce per hundredweight) = 0.625 g/kg, 1 gcy (gallon per cubic yard) = 4.95 L/m^3, 1 in. = 25.4 mm, 1 psi (pound per square inch) = 6.89 kPa, $^oC = (^oF - 32) \times 5/9$.

Table A.5 Mixture proportions of VHS concrete with fly ash with four types of aggregate

Aggregate Type Source of Sand Type of Fly Ash	CG Lillington F	MM Lillington F	RG Memphis F	DL Van Buren C
Cement (Type I), pcy	830	830	830	830
Fly ash, pcy	200	200	200	200
Coarse aggregate, pcy	1,720	1,570	1,650	1,680
Sand, pcy	937	900	860	1,020
HRWR (naphthalene-based), oz/cwt	26	20	20	18
Retarder, oz/cwt	3.0	3.0	3.0	3.0
AEA, oz/cwt	3.5	1.3	1.2	2.5
Water, pcy	240	240	240	240
W/(C+FA)	0.23	0.23	0.23	0.23
Slump after addition of HRWR, in.	3.5	10	7.0	2.75
Air, %	5.5	8.0	2.0	4.5
Strength at 28 days, psi	12,200	7,620	8,970	10,260
Concrete temperature at placement, ^{o}F	80	72	69	70

Note: CG = crushed granite, MM = marine marl, RG = washed rounded gravel, DL = dense crushed limestone, HRWR = high-range water reducer, AEA = air-entraining agent, W/(C+FA) = ratio of water to cement plus fly ash by weight; 1 pcy (pound per cubic yard) = 0.593 kg/m^3, 1 oz/cwt (ounce per hundredweight) = 0.625 g/kg, 1 gcy (gallon per cubic yard) = 4.95 L/m^3, 1 in. = 25.4 mm, 1 psi (pound per square inch) = 6.89 kPa, ^{o}C = (^{o}F - 32) x 5/9.

Table A.6 Mixture proportions of VHS concrete with silica fumewith four types of aggregate

Aggregate Type Source of Sand	CG Lillington	MM Lillington	RG Memphis	DL Van Buren
Cement (Type I), pcy	760	760	760	770
Silica fume, pcy	35	35	35	35
Coarse aggregate, pcy	1,720	1,570	1,650	1,680
Sand, pcy	1,206	1,140	1,150	1,250
HRWR (naphthalene-based), oz/cwt	14	12	14	17
Retarder, oz/cwt	2.0	2.0	3.0	3.0
AEA, oz/cwt	0.9	0.6	0.9	1.5
Water, pcy	230	240	240	230
W/(C+SF)	0.29	0.30	0.30	0.29
Slump after addition of HRWR, in.	2.75	4.25	3.0	3.75
Air, %	5.0	5.6	7.3	5.5
Strength at 28 days, psi	11,780	8,460	9,120	10,100
Concrete temperature at placement, ^{o}F	80	77	80	72

Notes: CG = crushed granite, MM = marine marl, RG = washed rounded gravel, DL = dense crushed limestone, HRWR = high-range water reducer, AEA = air-entraining agent, W/(C+SF) = ratio of water to cement plus silica fume by weight; 1 pcy (pound per cubic yard) = 0.593 kg/m^3, 1 oz/cwt (ounce per hundredweight) = 0.625 g/kg, 1 gcy (gallon per cubic yard) = 4.95 L/m^3, 1 in. = 25.4 mm, 1 psi (pound per square inch) = 6.89 kPa, $^{o}C = (^{o}F - 32) \times 5/9$.

research by Smutzer and Zander* for the Indiana Department of Transportation indicated that delayed additions of HRWR can cause some reduction in frost durability. Therefore, addition of HRWR was not permitted after it was added initially to a mixture. The addition of the calcium nitrite solution increased the slump because of the high dosage used, although slump loss was very rapid thereafter.

The air content was more difficult to control than normal because of the extended mixing, the delayed addition of the calcium nitrite solution, and the relatively rapid slump loss of these mixes. The addition of the calcium nitrite solution resulted in a significant increase in slump, with some increase in the air content in most cases. However, the response was very sensitive to the slump of the batch just before addition of the calcium nitrite solution. The use of a higher initial water content was helpful in reducing these problems to some degree.

Raw materials and water temperature may need to be adjusted such that the temperature of the HES and VES (A) mixtures at time of placement is around 80°F (27°C).

Stated briefly, laboratory mixing procedures consisted of charging the mixer with the initial mixing water, AEA, and most of the aggregate. The mixer was then started. After a few minutes the cement, remaining aggregate, and HRWR were added (with the drum stopped for safety). Mixing was then resumed for an additional time appropriate for the delivery of the concrete. At that time, the nonchloride set accelerator was added, and the concrete was mixed for an additional 5 minutes and then discharged for testing and specimen fabrication. A total of 30 minutes elapsed from the time water and cement were first mixed until testing and specimen fabrication were begun for the VES (A) and HES mixtures. Mixing for the VES (B) concrete was similar, except that no AEA or HRWR was used.

Specimen fabrication should be completed as quickly as possible because the concrete stiffens rapidly. Cylinders should be fitted with tight-fitting lids, beams may be covered with plastic, but early protection against evaporation must be provided.

If the concrete is to be insulated in the field, specimens should also be insulated. Specimens should be placed in insulated, closed containers immediately after fabrication. Internal temperatures should be monitored. All specimens should be removed from the insulated containers at the designated time, either for testing or for storage.

Storage of HES or VES (A) specimens after the initial curing period may be in plastic bags in a typical laboratory environment. Since these concretes are intended to be in service at early ages, continued moist storage may provide misleading results. Placing them in plastic bags is intended only to slow the moisture loss, not to prevent it.

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* Smutzer, R. K., and Zander, A. R. 1985. A Laboratory Evaluation of the Effects of Retempering Portland Cement Concrete with Water and a High-Range, Water-Reducing Admixture. *Transportation Research Record,* no. 1040, National Research Council, Washington, D.C., pp. 34-39.

A.7 Production, Placement, and Quality Control

HPC mixtures are more sensitive to water content than conventional concrete mixtures. Since HPC mixtures have a high cement content, they are stickier and more difficult to mix, particularly in a dry-batch operation. However, the HPC mixtures respond well to vibration, and, if desired, the VHS mixtures can be pumped easily.

The VES (A) and HES mixtures are more prone to rapid slump loss and require additional handling at the job site because of the addition of calcium nitrite solution. But the VHS mixtures are typically less sensitive to slump loss because, for many sets of raw materials, slump loss may be controlled by appropriate use of water-reducing and/or retarding admixtures without undue concern for early strength development. In addition, since VHS mixtures will typically be placed in forms, a wider range of slumps may be successfully used, although higher slumps are preferred. A substantial amount of information on high strength concrete, including placement and handling techniques, can be found in the report of ACI Committee 363.*

A.7.1 Ready-Mixed Concrete Supplier

Batch plant facilities should be located as close as possible to the point of final concrete placement. Travel times in excess of 20 minutes may cause difficulties because of rapid slump loss with VES (A) and HES mixtures. Because of the low W/C in the mixtures, accurate moisture control of aggregate is critical. Batch plants should have electrical moisture meters in the sand bins. These should be checked at least twice daily by drying samples, with adjustments being made as necessary. The sensitivity of the mixture to variations in water content requires a higher level of supervision to maintain the desired level of quality control at the batch plant. Obviously, truck drums should be reversed before loading to ensure that they are free of extra water.

Because of scale capacity limitations, it may be necessary to weigh out these high-cement-content mixtures in two equal half-batches, treating each as a separate batch. This adjustment and additional testing will typically increase the batching time. Including adjustments of mixtures at plant, 10 minutes of batching time per truck would not be uncommon in field trials. wash down), and remaining HRWR were added. Typically 3 to 5 gallons (10 to 20 liters) of

The batching sequence often needs to be modified slightly from conventional practice. To avoid head pack, it is necessary to add both water and HRWR to the first part of the load, which includes a portion of both the fine and coarse aggregates. The specific batch sequence used for the North Carolina field installation was to first load one-third of the batch water and two-thirds of the HRWR into the truck. Then, with the drum rotating at mix speed, approximately one-third of both fine and coarse aggregates were added. At that point, all the cement was ribbon-fed in with the remaining aggregate. Following that, all the AEA, then the remaining water (less

* ACI Committee 363. 1993. State-of-the-Art Report on High Strength Concrete (ACI 363R-92). *ACI Manual of Concrete Practice*, Part 1, 55 pp.

washdown), and remaining HRWR were added. Typically, 3 to 5 gallons (10 to 20 liters) of batch water, depending on the batch size, was held back for washing down the hopper during plant mixing. After mixing for a minimum of 70 revolutions at the plant, the mix was checked (at least visually) and sent to the job site. Adjustments to this batching sequence may be needed at any given plant.

As noted below, full-sized trial batches should be conducted in the field at least several days before job placement, to provide experience for the crews and supervisors and to adjust proportions and batch sequence, if needed.

During field installations, particularly in dry-batch operations, some trucks may experience difficulty in discharging the last part of the load, or a lack of homogeneity throughout the truck may be noted. In these instances, batch size should be reduced so that the maximum batch size is no more than two-thirds of the mixing capacity of the truck as rated by the Truck Mixer Manufacturers Bureau. In some cases, it may be necessary to have a maximum batch size not exceeding half the rated mixing capacity. This will depend to a large extent on the condition of the truck, including fin buildup and mixing speed. Also, a smaller batch size will help minimize discharge time and reduce placement problems associated with rapid slump loss. Batch size may be increased as conditions warrant.

The addition of the calcium nitrite solution in VES (A) and HES mixtures should be handled or at least supervised by a representative of the ready-mixed concrete supplier who also has the training and the authority to adjust the concrete proportions as needed, in conjunction with the contractor and the project engineer, particularly for dosages of admixtures.

To keep trucks from stacking up at the job site, trucks should be batched as needed. However, extra time is needed to batch and test the concrete before it leaves the plant. The ordering of trucks therefore requires direct radio communications capability with someone at the job site who can coordinate delivery of each truck with the contractor and who also knows the capabilities of the batch plant. This can be the same person supervising the addition of the calcium nitrite solution.

Acceptance testing of concrete must be conducted at the job site for each load of concrete delivered. However, concrete should also be tested at the batch plant for at least the first few loads until target slumps and air contents of the concrete leaving the plant have been attained. At that point, the testing frequency at the batch plant may be reduced. Minor adjustments at the plant, particularly in HRWR dosage, of the first few loads should be expected.

It is not necessary to test every load of concrete at the batch plant; in fact, this should be avoided as much as possible, since the truck will be delayed and potential problems with slump loss on the job site will increase. Testing at the batch plant should minimally consist of estimating the slump of each load, followed by complete testing when there is any doubt about the suitability of the concrete or when any change in the material or concrete characteristics has been noted.

To provide acceptable slumps and air at the job site, target values for slump and air at the plant will be high These values should be determined in the field trial batches conducted before the first actual placements. In previous field trials, slump values of 6 in. and air contents of 8% to 10% at the plant have generally yielded acceptable results on the job for VES (A) and HES mixtures, but these values vary dramatically depending on the materials used and their interactions, the temperature of the concrete, the length of haul, and the mixing efficiency of the truck or plant. Conventional rules of thumb for adjustments may not be accurate.

All checks should be made after a minimum of 70 revolutions at mixing speed for a dry-batch plant. Care should be taken to conduct testing and make adjustments as rapidly as possible, since the "pot life" of VES (A) and HES mixtures is relatively short, particularly after addition of the calcium nitrite solution.

A.7.2 Contractor

Several full-sized trial batches should be conducted in the field before job placement. These batches may be placed in nonstructural working pads or storage slabs. The trial batches are conducted to refine the mixture proportions for the actual raw materials used on a job to allow the concrete supplier, the contractor's crew, and the local highway department staff to get a feel for what to expect from the mixtures and to confirm that desired strength levels may be attained. These trial batches create an opportunity to try different construction techniques and to train both the concrete crew and the inspectors in handling HPC.

On arrival at the job site, with VES (A) and HES mixtures, the truck should proceed to a point where the calcium nitrite solution is added and the concrete receives additional mixing. With smaller batches, 30 revolutions at mixing speed were found to provide adequate mixing. With larger batch sizes, mixing time must be increased. The truck then proceeds to the point of placement and discharges the load. Unloading should be delayed only long enough to ensure adequate remixing on site.

As noted above, batch size should be reduced so that the maximum batch size is no more than two-thirds (sometimes half)the rated mixing capacity of the truck. This may affect job planning and scheduling. The truck should not be allowed to set on site, and crews must be ready for the concrete when it is delivered. In fact, concrete deliveries frequently had longer intervals between them to make sure the loads were not backing up on the job; therefore, longer times between deliveries should be expected. With rapid strength gain of VES (A) and HES mixtures and longer time between deliveries, the potential for a cold joint is increased somewhat. The presence of the HRWR reduces this danger, and the use of whole-number truck loads that conform to required joint spacing will also help when placing slabs. The rate of construction is not typically changed otherwise. Larger batch sizes may be possible with VHS mixtures, particularly with a central mix plant. The optimal batch size should be determined by field trials.

For HES mixtures used in pavements, an adequate surface finish has been obtained in field applications with both a motorized screed and with hand placement only. In both cases, internal vibration was applied by the concrete crew. All mixtures responded well to vibration, even with a low measured slump. With a screed, additional finishing by hand tools and burlap drag before tining the surface was not substantially different from using a traditional high-cement-factor, low-slump mix, as long as finishing was not delayed. Placement should be completed as rapidly as possible, since the concrete will stiffen rapidly and the surface will become difficult to close with hand tools only. However, the surface texture produced by tining is acceptable for highway use. After texturing, the slab should be immediately covered with curing compound.

The use of a slip form paver may cause problems in two areas. Slump is somewhat more difficult to control because of the rapid slump loss of the concrete. The mixtures are also more sensitive to vibration than conventional mixtures and therefore may be prone to sagging out behind the paver. However, slip form pavers should provide acceptable results as long as the slump is consistent and vibration is carefully controlled. Clearly, only very low slump concrete should be considered. Since slip form pavers have not been used to date in field trials, either preliminary trials should be scheduled or use of side forms should be planned. In cooler weather, it may be necessary to provide some insulation to side forms.

The contractor may mist the area immediately above the concrete pavement from time to time when using portland-cement-based HPCs. Since these are nonbleeding mixes, misting is believed to be beneficial.

If the pavement section is to be insulated, spread plastic sheets on the surface once it is tackfree, taking care not to wrinkle the sheet. A sheet of rigid foam building insulation 1 in. (25 mm) thick may then be placed on the slab, and boards, sandbags, or other weights placed on top of the insulation to hold it down. Insulation is removed when the pavement is ready to be opened to traffic, at which time joints are normally sawed. If sawing is conducted before insulation is removed, or if large sections have been placed, move just enough of the insulation aside to operate the saw and replace the insulation until sawing has been completed over the entire length.

Sawing should be completed within 6 to 8 hours after placement if VES (A) or HES mixes are used. Field trials in which sawing was delayed until the following day resulted in either cracking of the slab or cracks running out ahead of the saw blade. Delaying sawing of concrete past 12 hours will frequently result in crack development. With HPC, this tendency may be increased because of volume changes of the concrete at very early ages as it undergoes significant temperature drops.

Direct radio communications with the plant will be necessary to ensure a minimum of delay and yet avoid stacking up trucks. In addition, adjustments to subsequent batches may be necessary during the first few loads or as temperatures change during the placement. This job should be handled by a representative of the ready-mixed concrete supplier, who should also be in charge of adding calcium nitrite at the job, although assistance from the contractor may be necessary in some cases.

For HES and VHS mixtures used in formed, fast-track construction of structural members, temperature control may be critical. If the concrete is not protected, cooler temperatures may inhibit early strength development and slow construction. On the other hand, internal temperatures should be monitored to ensure that durability and strength are not compromised. These mixtures are cement rich and can create a substantial temperature rise in large members. The recommendations of ACI Committee 207* and ACI Committee 363 should be followed.

Rapid temperature changes can create steep thermal gradients within the member that can lead to unacceptable cracking. Formed members, especially those with fast-track mixtures, should be stripped carefully to allow slow cooling. Loosening the forms before removal and leaving forms up for extended periods will enhance both strength and durability, not only for curing but for thermal equilibrium as well. This will decrease form turnaround time.

A.7.3 Project Engineer

The project engineer has many obligations besides ensuring that the concrete is delivered and placed in accordance with specifications. Successful use of HPC will require close coordination between the ready-mixed concrete supplier, the contractor, and the project engineer or project supervisor. Many of the concerns and recommendations listed above will also apply to the project engineer or project supervisor. Some of the more critical points are repeated below along with suggestions for managing concrete placement.

A.7.3.1 Management Hints

Before any field placements, trial batches *must* be conducted in the laboratory.

A thorough briefing of all participants, before any construction, plus adequate field trial batches to confirm mix proportions and to give the participants a chance to practice handling the concrete was found to be essential. The use of at least three full-size trial batches is strongly recommended. The learning curve for producing, placing, and testing HPC is relatively short, but it is always present. All parties will benefit from this exercise.

Even more than usual, strict control of aggregate moisture is required because of the increased sensitivity of HPC to water content. Batch plants should have electrical moisture meters in the sand bins and the meters should be checked at least twice daily by drying samples. The sensitivity of the mixture to variations in water content may create more difficulty in maintaining the desired level of consistency at the batch plant than is usually found.

VES (A) and HES mixtures in particular will have a tendency to lose slump and air rapidly, approximately 20 to 30 minutes after batching, depending on temperatures, raw material characteristics, and mixing operations. Therefore, batch plant facilities should be located as

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* ACI Committee 207. 1993. Mass Concrete (ACI 207.1R-87). *ACI Manual of Concrete Practice*, Part 1, 44 pp.

close as possible to the point of final placement. Travel times in excess of 20 minutes may cause difficulties that result from rapid slump loss.

The VES (A) and HES concretes have not been prone to shrinkage cracking in field trials as pavements, probably because they are gaining strength faster than they are shrinking. Timing for sawed joints, however, can be critical. Concrete pavement should be sawed as early as practicable to avoid cracking the concrete, because it may undergo dramatic thermal shrinkage at very early ages. Cracks may form in long pavements if they are sawed after the temperature in the pavement has peaked (typically 6 to 8 hours), and shortening of the pavement, as it cools, is restrained by the subgrade. These pavements may be more prone to cracks running ahead of the sawed joint if sawing is appreciably delayed.

Since calcium nitrite is a fast-acting set accelerator, it must be added at the job site. This will require facilities at the job site for measuring and adding the material. Both the use of scaffolding when adding the calcium nitrite solution by hand and the use of a trailer-mounted tank with a volumetric pump have proven useful. Additionally, time for on-site mixing must be built into the schedule. The use of extended-set calcium nitrite compounds, to allow batch plant addition, has not been helpful because retardation causes low concrete strengths at early age.

To minimize any delays in placing concrete, trucks should be batched only as needed. However, extra time is required to batch and to test the concrete at the plant. Ordering concrete therefore requires dedicated radio communications with a representative of the ready-mixed concrete supplier at the job site who can coordinate delivery of concrete with the contractor and who knows the capabilities of the batch plant and is familiar with concrete performance and proportioning. The addition of the HRWR should be supervised by this person.

The ready-mixed concrete representative should have the training and the authority to adjust the concrete proportions as needed, in consultation with the contractor and the project engineer, particularly for dosages of admixtures.

Adjustments to subsequent batches may be necessary during the first few loads or as conditions change during the placement. As with all jobs, it is important to have already established the job site coordinating team of the contractor, the representative of the ready-mixed concrete supplier, and the project engineer before any placement. Because the concrete's sensitivity to time, and since changes will almost certainly be required from time to time with HPC, it is especially critical that the mechanism for making and executing timely decisions be in place from the beginning. Again, an excellent place to develop this relationship is during field trial batches.

A.7.3.2 Plastic Properties: Values and Testing

Slump and air content should be determined at the same rate as any critical placement. Air content may be determined by the pressure method.

Slumps and air contents will typically be more variable with VES (A) and HES mixtures than with conventional concrete, because of the increased time sensitivity, the average higher temperatures at placement, and the presence of HRWR and nonchloride accelerators.

Variability, along with generally higher values of slump and air, will typically increase as construction rates increase and as the time the trucks are held at the plant for testing and adjustment is reduced. The effects of time on slump loss, with a consequent loss in air content, when using a HRWR are consistent with prior reports.

Target values for air content should be 5% to 9% for #67 or #57 aggregate. Target values for slumps should be determined by consultation with the contractor regarding placement technique. It is important to remember that these concretes respond well to vibration even when at a low slump. Higher slumps should not necessarily be considered to indicate greater water contents. For HES and VHS mixtures used in precast and cast-in-situ constructions, higher slumps will improve placement quality as long as segregation is avoided.

It is difficult to accurately control water contents at a concrete batch plant, and in general, additional precautions must be exercised to avoid the unintentional addition of water to a batch. However, with HPC, the use of slump as a means of quality control may be very limited. Low slump of HPC in field trials was linked to either low air content or longer times between batching and placement. Batch plant control of water content and air content on the job site will probably provide adequate preventive precautions in terms of W/C. Liquidated damages should consider, however, the effect of low strengths not only on delays in opening the pavement or bridge deck to traffic, but also on possible reductions in durability due to increased permeability.

With VHS concretes, relatively high slumps are common, even after 30 minutes.

A.7.3.3 Strength Testing

It is recommended that routine quality control be based on cylinder tests rather than beam tests for the HPC mixtures. HPC in structural members will rarely, if ever, require beam tests, and handling and testing beams at very early ages is more troublesome than normal.

Preparation is considerably more time consuming for beam tests than for cylinder tests. Testing at precisely the correct time to determine whether strength is high enough to open the road or bridge deck to traffic means that the beams must be demolded, marked, and placed in the testing apparatus while still in a relatively "green" condition.

Strength gain is very rapid during that time. Although the concrete may have adequate strength to support traffic at, say, 6 hours, it may still be too "green" to be handled without inducing microcracking as early as, for example, 4½ to 5 hours. In addition, when testing insulated concrete, premature loss of insulation will reduce measured strength values. Furthermore, early cooling of the outside of the beams may induce tensile stresses that further reduce the measured

strength. Similarly, since the beams will not be saturated, drying of the outside may also induce tensile stresses, reducing the measured strength.

If designs are based on flexural strength, these correlations should be developed only under closely controlled laboratory conditions for early strength testing. For later ages, conventional techniques are adequate, modified as noted below.

Cylinders of 4 x 8 in. (100 x 200 mm) may be fabricated for each concrete placement using plastic molds with tightly fitting lids. The cylinders should then be tested at the appropriate early age (4 or 6 hours, or 1 day), plus 7 and 28 days. If the concrete is to be insulated, the cylinders should be insulated in the same manner.

Cylinders to be insulated may be placed in specially constructed containers. Each container may be made by gluing together eight layers of 1-in. (25-mm) rigid foam insulation board and boring nine holes just large enough to accommodate 4 x 8-in. (100 x 200-mm) cylinders (in their molds). The overall size of the container should be such that when fully loaded, the container can be lifted by two individuals. Two layers of insulation board with plywood backings should be used on the top and bottom of the container. At least 4 in. (100 mm) of insulation should be provided from an outside edge of the container to any cylinder. Plastic shipping straps may be used to secure the insulation container during transport. The containers may be stacked two high when full. All insulated cylinders should be removed from the containers at the same time the insulation is removed from the concrete castings in the field, regardless of testing age. "Slaved" or "match-cured" cylinders, for which the internal temperature of a cylinder is monitored and controlled to match the internal temperature of a cast member, may also be used, although the cost of equipment for a large number of cylinders may be excessive and prohibitive.

Cylinders conditioned as described here should give reasonable estimates of in-place strength, at least at later ages. According to both the cylinder and core data, HPC continues to gain strength with time, under typical field exposure conditions without continuous moist curing.

For testing of VHS concrete, the recommendations of ACI Committee 363 should be followed.

A.7.3.4 Temperature

The initial temperature of the concrete, as delivered and placed, is very important for VES (A) and HES mixtures. Initial temperatures for these mixtures should be around 80°F (27°C). Higher temperatures are normally discouraged because of difficulty in placing and finishing, however, these mixtures stiffen rapidly anyway, and the higher temperatures are beneficial in early strength development. In addition, the applications for VES and HES concretes typically involve relatively thin sections, and heat of hydration is not a major problem. With structural members, normal guidelines for handling high strength concrete, with possible implications for mass concrete thermal effects, should be followed.

Thermocouples may be placed in the pavement to monitor curing temperatures and temperature gradients. Type T, copper-constantan thermocouples were used in the field trials. They were placed along the longitudinal centerline of the lane, 6 feet (1.8 m) from the edge, and were placed at either mid-depth of the pavement or at mid-depth plus top and bottom quarter points, depending on desired information. Temperatures were taken with a hand-held digital thermometer. It is strongly recommended that these thermocouples be epoxy coated to provide protection against damage during installation, to improve long-term durability, if needed, and to prevent potential chemical reactions between the calcium nitrite in the concrete and the metal in the thermocouples.

Final set and the beginning of strength gain are marked approximately by a large and steady increase in slab temperature. In the Williamston, North Carolina, experimental pavement section, insulated concrete strengths of about 2 000 psi (14 MPa) at 6 hours were found to coincide approximately with 135°F (57°C). Monitoring the temperature will also provide an indication of any retardation of the mixture, since the start of temperature rise will be delayed in a retarded mixture. Cylinders should not be transported until the temperature rise has begun, which typically occurs about 4 to 5 hours after batching in a warm environment. As noted above, the guidelines of ACI Committee 363 and ACI Committee 207 provide additional information concerning temperature control of concrete members.

A.8 High Early Strength Fiber Reinforced Concrete (HESFRC)

A.8.1 Field Mixing Procedure

Just like the mixing of HES concrete, field mixing of HESFRC requires very careful planning and execution. Care is required because adding fibers to a mix that typically has a very low W/C leads to a noticeable reduction in workability. Trial mixes are recommended, since local conditions and materials vary. It should be kept in mind that mixing HESFRC becomes even more difficult as the volume fraction of fibers in the mix or the length of the fibers used increases. In any case, fiber volume fractions of less than 2% and fiber aspect ratios (i.e., length over diameter) of less than 100 are strongly recommended.

The initial step in field mixing HESFRC is to dry mix the sand and coarse aggregates thoroughly for a minute or two in a standard field mixer (drum mixer). Clean crushed limestone aggregate of 0.5-in. maximum size is recommended. Next, the cement (Type III) is added and mixed with the sand and coarse aggregates for another minute or two. The mixer can be moved a few times back and forth about its axis to improve mixing.

The second step involves adding about half the water and half the superplasticizer allocated for the mix, while moving the mixer back and forth about its axis. The general rule that tap (drinkable) water should be used for concrete applies here as well. Furthermore, the water temperature should be kept below 70°F (21°C).

The third step is the addition of the AEA and the silica fume or latex, if any. If silica fume is prescribed, it should first be mixed with some of the remaining water, then added to the mix immediately after the addition of the AEA. Latex, on the other hand, can be added without the need to premix it with water, since the latex already comes in liquid emulsion. It is noted that latex increases the workability of HESFRC mixes but reduces their high early strength.

The fourth step involves the addition of the corrosion inhibitor, DCI. The corrosion inhibitor is added at the end of the mixing process because it tends to reduce the workability of HESFRC mixes.

Finally, the required amount of fibers is slowly added to the mix simultaneously with the remaining portion of superplasticizer. Loose steel or polypropylene fibers are added to the mix via a sieve to ensure random fiber distribution. Some commercially available fibers are collated together by a water-soluble glue and can be dumped into the mixer directly. Once all the ingredients are added, the mixer is allowed to rotate for 2 to 3 additional minutes to ensure good fiber distribution before casting.

In general, the use of cold or cooled materials (sand, aggregate, cement, water) should improve the workability of the mix

A.8.2 Preparation of Sample Cylinders

HESFRC must be sampled at time of placement. The samples must be taken at locations where a specified strength is required. Using 6 x 12-in. (150 x 300-mm) cylinders in field testing is recommended unless there are limitations to the capacity of the testing machine. Should 4 x 8-in. (100 x 200-mm) cylinders be used, their expected strength will be, on average, about 4% greater than that of the 6 x 12-in. (150 x 300-mm) cylinders. This should be accounted for in the design. Until testing, cylinders should be kept at the location where they are cast. Should cylinders be moved, relocation should not take place less than 2 hours after casting.

A.8.3 Placing and Finishing

Although the current experience with HESFRC has been limited to laboratory work, the behavior of HESFRC in its plastic state is not different from that of conventional fiber reinforced concrete. Therefore, for field placement and finishing of HESFRC, the recommendations of ACI Committee 544* should be followed.

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* ACI Committee 544. 1993. Guide for Specifying, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete. *ACI Materials Journal*, vol. 90, no. 1, January-February, pp. 94-101.

Trial Batch Procedure

Make sure that the size of the batch is such that mixing efficiency is not impaired. The HPC mixtures are very sticky and require greater than usual mixing energy.

1. Butter the mixer as appropriate.

2. Charge the mixer with approximately

   a. Half of the coarse aggregate.
   b. Half of the fine aggregate.
   c. Two-thirds of the water, with all of the AEA.
   d. Two-thirds of the HRWR.

   Mix for 1 minute, stop the mixer (for safety), and add

   a. All the cement.
   b. The remaining aggregate, water, and HRWR.

   (This is intended to approximate the type of ribbon-feed batching procedure encountered in a dry-batch ready-mix operation.)

   Begin mixing, record as time zero, mix for 5 minutes.

3. Change the mixing speed to simulate an agitate, or slow-roll, motion. If this is not possible, simply continue mixing. Cover the mixer opening to prevent evaporation.

   (The purpose of this period is to simulate the truck travel time, which would be done at agitate speed [approximately 4 revolutions per minute for a concrete truck]. It is critical that mixing action continue during this time. Continue mixing for 20 minutes.)

4. Add the calcium nitrite solution, and mix for 5 minutes at full speed. Discharge the concrete for tests, specimens, etc.

Total time from when the cement and water are first mixed (time zero) until discharge is 5 (initial mixing) + 20 (agitate) + 5 (mixing the calcium nitrite solution), for a total of 30 minutes. Field results indicate that this procedure will provide conservative but reasonable results regarding air and slump at time of placement.

Appendix B

Guide to Use of Pyrament PBC-XT Cement

Appendix B

Guide to Use of Pyrament PBC-XT Cement

Research conducted under Strategic Highway Research Program (SHRP) Contract C-205 included laboratory studies of very early strength (VES) concrete made with Pyrament PBC-XT cement. The manufacturer's guidelines given below are included solely for the convenience of those who may wish to experiment with this proprietary product. The inclusion of these guidelines does not provide or imply an endorsement of the material by SHRP and its sponsors or by the authors of this report.

Pyrament PBC-XT cement is a proprietary product manufactured by Lone Star Industries. It may be classified as an alkali-activated system composed of about 60% portland cement that meets ASTM C 150 specifications for Type III and 35% fly ash that meets ASTM C 618 class C specifications for use as a mineral admixture in portland cement concrete. The remaining 5% is essentially a proprietary functional addition consisting of high-range water reducers, citric acid, and potassium carbonate. No chloride compounds are used. The cement is manufactured under U.S. patent 4,842,649.

Concrete mixture proportioning using Pyrament PBC-XT cement can generally follow the recommendations of ACI 211*, *except for the water-cement ratio, since the cement is extraordinarily sensitive to water.* The following guidelines are based on the current (1993) recommendations of the manufacturer. These do's and don'ts should be followed as closely as possible to achieve satisfactory results. It is advisable for future users of the material to consult the manufacturer for the latest recommendations.

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* ACI Committee 211. 1993. Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1 - 91). *ACI Manual of Concrete Practice*, Part 1, 38 pp.

B.1 Mixture Design

A. Select nonreactive coarse aggregates with 0.75-in. (19 mm) top size.

B. Select nonreactive fine aggregates of natural silica. Avoid carbonate sands.

C. Select a coarse-to-fine aggregate ratio from 55/45 to 50/50 by volume.

D. Choose water-cement ratio from *0.25 to 0.29.*

E. Use a minumum cement content of 611 lb/yd^3 (276.5 kg/m^3).

F. Use a specific gravity of 2.90 for Pyrament.

G. Assume an air content of 3.5%.

H. Use *no* admixtures.

B.2 Laboratory Mixing Procedures

A. Determine the quantity of concrete needed by calculating the volumes of test specimens required:

1. 0.2 ft^3 (0.0057 m^3) for each 6 x 12-in. (150 x 300-mm) cylinder
2. 0.06 ft^3 (0.0017 m^3) for each 4 x 8-in. (100 x 200-mm) cylinder

B. Determine *moisture* contents of aggregates and *make proper adjustments* to mixture quantities.

C. Add coarse and fine aggregates, *90%* of calculated water, and cement.

D. Mix for *6* minutes before adjusting for slump.

E. If water is needed, *add it very carefully*. One gallon of added water per cubic yard of concrete (5.0 L/m^3) will increase slump by 1.5 to 2 in. (38 to 50 mm).

F. Mix for an additional *3* minutes before conducting tests.

B.3 Field Charging and Mixing Procedures

A. Thoroughly clean out all mixers, both central and truck, and all conveying equipment.

B. Reverse the mixer drum for 5 to 10 minutes to make sure that *all water* is out of the drum.

C. Use no more than 75% of the mixer capacity when mixing.

D. Charge the mixer with coarse and fine aggregates and with no more than *85%* of calculated amount of water.

E. Cement can be added either at the concrete plant or at the job site. If the job site is more than 30 minutes from the concrete plant (including loading time), cement should be added at the job site. Cement can be obtained in 50-lb (22.6-kg) bags, in supersacks of 3,760 or 1,880 lb (1,700 or 850 kg) or customized, or as bulk from silos.

F. Mix for *6* or *8* minutes (90 revolutions) before adjusting slump.

G. If water is added, mix for an additional *3* minutes (30 revolutions). Remember that one gallon of added water per cubic yard of concrete (5.0 L/m^3) will increase slump by 1.5 to 2 in. (38 to 50 mm).

H. Keep the mixer agitating at all times while not discharging.

B.4 Placing and Finishing Pavement at Job Site

A. Standard conveying methods can be used, but pumping will require more energy than for portland cement concrete. Remember that all conveying equipment should be clean.

B. Deposit the concrete as near as possible to its final position.

C. The concrete should be placed and screeded with vibration. Best results have been obtained with a roller screed.

D. Use several stinger vibrators just in front of screed.

E. Do not get more than 3 to 5 ft (0.92 to 1.53 m) of fresh concrete in front of the screed.

F. Once the concrete is screeded, follow closely behind with a float.

G. A light fog mist of water may be used to help minimize plastic shrinkage. Commercial products are available for this purpose.

H. Immediately texture the pavement surface with a broom, tine, or burlap drag.

I. Cure the pavement immediately behind the texturing operation. Membrane curing compound meeting ASTM C 309 should be used. It is too soon to use water to cure the concrete.

J. Under normal conditions, Pyrament PBC-XT cement concrete will be ready for traffic in 4 to 6 hours.

Appendix C

Proposed Specifications for AC Impedance Test of Concrete

Proposed Method of Test

for

Rapid Determination of the Chloride Permeability of Concrete by AC Impedance

SHRP Product No. 2026

1. SCOPE

1.1 This method covers the determination of the permeability of conventional portland cement and blended portland cement concretes to chloride ions by the AC impedance method. It consists of measuring the impedance, in ohms, across a specimen 95 mm (3.75 in.) diameter by 51 mm (2 in.) long when 0.20 v AC at 1,000 Hz is applied with electrodes on each face. The impedance, in ohms, is related to the total charge passed, in coulombs, which in turn is related to chloride permeability.

2. APPLICABLE DOCUMENTS

2.1 AASHTO Standards:

T 24	Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
T 259	Resistance of Concrete to Chloride Ion Penetration
T 277	Rapid Determination of the Chloride Permeability of Concrete

2.2 ASTM Standards:

C 1202	Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

3. SIGNIFICANCE AND USE

3.1 This method covers the laboratory evaluation of the relative permeability of concrete samples to chloride ions. The test results have shown good correlation with the results of the rapid chloride permeability test (AASHTO T 277) on the same specimens.

3.2 The method is suitable for design purposes, service evaluation, and research and development. The numerical results from this test method must be used with caution, especially in applications such as quality control and acceptance testing.

3.3 This test should not be used on surface-treated concretes until test data become available.

3.4 The method may be used on cores of diameters other than 95 mm (3.75 in.) or specimens of any shape. However, the thickness of 51 mm (2 in.) between the electrodes must be maintained. The values in Table 1 are not valid for other specimen thicknesses, and no relationships have been established to adjust the values in that table for other specimen thicknesses. The values in Table 1 are valid for an electrode contact area of 161 mm^2 (0.25 $in.^2$) only, and no relationships have been established to adjust the values in that table for other electrode contact areas. Data for specimens of other thicknesses or tested with other electrode configurations may be used for relative comparisons of chloride permeabilities among specimens of the same thickness and electrode configuration.

3.5 ASTM C 1202 cautions that the rapid chloride permeability test (RCPT) can produce misleading results when calcium nitrite has been admixed into the concrete. The RCPT has shown higher coulomb values on concrete with calcium nitrite than on identical concrete without calcium nitrite. However, ponding tests on concrete with calcium nitrite have shown it to be as resistant to chloride ion penetration as concrete without calcium nitrite. The high coulomb measurement may be due to additional ions being introduced with the calcium nitrite, making the water in the concrete more electrically conductive and making the concrete *appear* more permeable: This may be a problem any time ions are added from any admixture or other source. Any precautions for RCPT should likewise be applied to the AC impedance test.

3.6 Sample age may have a significant effect on the test results, depending on the type of concrete and the curing procedure. Most concretes, if properly cured, become progressively more resistant to current flow and exhibit greater impedance with time.

3.7 The specimen may heat up to some extent during the RCPT because current is flowing. The AC impedance test procedure avoids this heating problem, since a low voltage is applied for a very short time.

3.8 Kawamura and Torii [3] have applied the RCPT to concrete made with fly ash and slag. They found that 90-day old cut specimens always showed a greater (up to 50%) chloride ion permeability than 90-day old molded specimens. ASTM C 1202 allows the use of either saw-cut or molded specimens, but one type or the other must be used throughout a test program. The same restrictions should be applied to the AC impedance test.

3.9 Resistivity of concrete is almost always measured using alternating current (AC). Resistivity to direct current (DC) may be slightly different, since it has a polarizing effect. However, at 50 Hz there is no significant difference between resistivity to AC and DC. DC resistance is approximately equal to AC impedance [4].

3.10 Monfore [5], at the Portland Cement Association (PCA) Laboratories, has conducted resistivity experiments on concrete, using 4-in. cubes. He explains that DC will cause a slight polarization, effectively reducing the potential. AC is commonly used in the study of electrolytic solutions (such as ions in capillary water in concrete) to avoid the polarization effects. For resistivity experiments, PCA used a bridge circuit, using AC, similar to the Wheatstone bridge, which is used for DC current. The proposed AC impedance test at 1,000 Hz

and 0.2 v avoids any polarization problem and eliminates any capacitance problem with low voltage and high frequency.

3.11 According to Scali, Chin, and Berke [6], "The RCPT follows Ohm's law (V/R x Time = coulombs) and as such is actually a dc (inverse) resistivity measurement. A rapid measurement of either ac or dc resistivity will provide essentially the same information as the 6-hour long coulomb measurement."

3.12 Additional resistivity (from AC impedance) and coulomb (from RCPT) tests were reported by Berke and Roberts [7] in 1989. They stated that the AASHTO T 277 test is primarily a conductivity measurement which happens to give a reasonable estimate of chloride diffusivity. A plot of the inverse resistivity versus coulombs up to the 2,000 level gave a good indication of the straight-line relationship between the two with extremely high r^2 value of 0.97.

3.13 Hope and Ip [8] have also measured the AC impedance of concrete as part of corrosion studies of steel in concrete. Their resistance measurements were made using a bridge energized by a 1-kHz oscillator. External electrodes were clamped to the surface of concrete prisms. They used a conducting medium of potassium chloride agar gel between the electrodes and the concrete. Their conclusions — all as expected — were that resistivity increased with age of the concrete, with decrease in W/C, with decrease in moisture, and with decrease in temperature.

4. APPARATUS, REAGENTS, AND MATERIALS

4.1 Vacuum saturation apparatus (see Figure 1).
4.1.1 Separatory funnel, 500 mL capacity.
4.1.2 Beaker, 1,000 mL.
4.1.3 Vacuum desiccator,* 250 mm inside diameter.
4.1.4 Vacuum pump, capable of maintaining a pressure of less than 1 mm Hg (133 Pa) in desiccator.
4.1.5 Vacuum gage or manometer, accurate to 0.5 mm Hg (66 Pa) over range 0–10 mm Hg (0–1,330 Pa) pressure.

4.2 Specimen sizing equipment.
4.2.1 Movable radial diamond saw.

4.3 Kohlrausch bridge circuit apparatus (see Figures 2 and 3).
4.3.1 Electrode wires with 161 mm^2 (0.25 $in.^2$) contact area.
4.3.2 Conductivity gel.
4.3.3 Rubber gloves.

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* Desiccator must allow two hose connections, through rubber stopper and sleeve or through rubber stopper only. Each connection must be equipped with a stopcock. Be sure the desiccator is a vacuum type as the non-vacuum-type desiccator may implode when subjected to this amount of vacuum, presenting an extremely dangerous situation.

The AC impedance test development was done using a Kohlrausch bridge instrument model 4000 (manufactured by AEMC Instruments, Boston). The Kohlrausch bridge uses 1,000 Hz AC with an accuracy of 1% on the impedance measurement. Eight ranges are available for selection by pushbuttons, but usually the range of 1 to 10 kiloohms was used. The voltage actually placed across the specimen was measured to be about 0.20 v. The power supply is six 1.5 v AA batteries. A good electrical connection between the Kohlrausch bridge terminals and the concrete specimen is ensured by using potassium agar gel. Rubber gloves were used to insulate the fingers from the test specimen.

5. TEST SPECIMENS

5.1 Obtain samples from the structure to be evaluated using a core-drilling rig equipped with a diamond-dressed core bit that has a nominal 102-mm (4-in.) diameter (95-mm [3.75-in.] actual inside diameter). Select and core samples following procedures in AASHTO T 24. Rectangular samples may be obtained by saw cutting. Place the cores or other samples in a plastic bag for transport to the laboratory.

5.2 Using the diamond saw, cut a 51-mm (2-in.) slice from the top of the core or sample, with the cut parallel to the top of the core or sample. This slice will be the test specimen.

6. CONDITIONING

6.1 Vigorously boil tap-water in a large (2-L) container. Remove the container from heat and allow water to cool to ambient temperature.

6.2 Place specimens, separated slightly, in a tilted position in a beaker, then place thebeaker in the desiccator. Seal the desiccator and start the vacuum pump. Pressure should decrease to less than 1 mm Hg (133 Pa) within a few minutes. Maintain the vacuum for 3 hours.

6.3 Fill a 500 mL separatory funnel with deaerated water. With the vacuum pump still running, open the water stopcock and drain enough water into the beaker to cover specimens (do not allow air to enter the desiccator through this stopcock).

6.4 Close the water stopcock and allow the vacuum pump to run for 1 additional hour.

6.5 Close the vacuum line stopcock, then turn off the pump. Turn the vacuum line stopcock to allow air to reenter the desiccator.

6.6 Soak the specimen under water in the beaker for 18 hours. (Note: This is the same vacuum saturation procedure required for the RCPT.)

7. PROCEDURE

7.1 Air-dry specimens briefly, because a wet surface may distort the measurement.

7.2 Connect the two electrode wires to the measurement box described in Note 1at the end of this appendix. The free ends of the two wires should have a flattened solder piece with a 161-mm^2 (0.25-in.^{2}) contact area, as describe in Note 2.

7.3 Wear a rubber glove on the hand that will press the flattened solder pieces onto the concrete.

7.4 Dip the contact ends of the wires into the conductivity gel to obtain a small amount of gel. The gel will ensure good conductivity between the electrodes and the concrete. One type of conductivity gel is made with potassium agar, as described in Note 3.

7.5 Press the contact ends against each flat surface of the test specimen (across the 51-mm [2-in.] dimension). Hold them in place with the thumb and middle finger of one hand. With a little practice, a good connection can be made by feel. Also, the gel "fingerprint" should be kept constant at 161 mm^2 (0.25 in.^{2}) and *consistent* through all of the testing.

7.6 Balance the bridge circuit with the instrument box and record the impedance measurement (ohms).

7.7 Repeat the measurement at 5 randomly selected locations on the specimen end faces (across the 51-mm [2-in.] dimension). Be careful to not allow the gel fingerprints to overlap as this will affect the conductance.

8. CALCULATION AND INTERPRETATION OF RESULTS

8.1 Use Table 1 to evaluate the test results. These values were developed from data on core slices 95-mm (3.75-in.) diameter x 51-mm (2-in.) long taken from laboratory slabs prepared from various types of concrete.

TABLE 1 Chloride Permeability Based on Charge Passed and AC Impedance

Charge Passed {Ref.1] (coulombs)	Chloride Permeability [Ref. 1]	AC Impedance [Ref. 2, 9] (ohms)	RCPT Initial Current [Ref. 2] (amperes)
>4,000	High	<1,900	>0.14
2,000–4,000	Moderate	2,800–1,900	0.086–0.14
1,000–2,000	Low	3,500–2,800	0.058–0.086
100–1,000	Very low	*	*
<100	Negligible	*	*

* No data in these ranges.

8.2 Numerical results from this test method in this table must be used with caution. The qualitative terms in the second column of Table 1 should be used in most cases.

9. REPORT

9.1 The report shall include the following:

9.1.1 Source of core or sample, in terms of the structure and the particular location in the structure from which the core or sample was obtained.

9.1.2 Identification number of core, sample, and specimen.

9.1.3 Location of specimen within core or sample.

9.1.4 Type of concrete, including binder type, water-cement ratio, and other relevant data supplied with cores.

9.1.5 Description of specimen, including presence and location of reinforcing steel, presence and thickness of overlay, and presence and thickness of surface treatment.

9.1.6 Unusual specimen preparation (e.g., removal of surface treatment).

9.1.7 Test results shall be an average of 5 readings, reported as the AC impedance, in ohms.

9.1.8 The chloride permeability equivalent to the AC impedance (from Table 1).

10. PRECISION

No precision criteria will be available until further testing is done.

11. REFERENCES

1. Whiting, D., "Rapid Measurement of the Chloride Permeability of Concrete," Public Roads, Vol. 45, No. 3, December, 1981, pp. 101-112.

2. Hansen, M. R. Durability of High Performance Concrete, Ph.D. Dissertation, North Carolina State University, Raleigh, North Carolina, 1993.

3. Kawamura M. and K. Torii, "Chloride Permeability of Concrete Containing a Flyash and a Blastfurnace Slag," Pore Structure and Permeability of Cementitious Materials, Vol. 137, Materials Research Society, Pittsburgh, Pennsylvania., 1988.

4. Neville, A. M., Properties of Concrete, John Wiley & Sons, New York, 1973, pp. 17, 28, 36, 383-385, 511-517.

5. Monfore, G. E., "The Electrical Resistivity of Concrete," Journal of the PCA Research and Development Laboratories, Vol. 10, No. 2, Portland Cement Association, Chicago, Illinois, May, 1968.

6. Scali, M. J., D. Chin and N. S. Berke, "Effect of Microsilica and Fly Ash upon the Microstructure and Permeability of Concrete," Proceedings of the Ninth International Conference on Cement Microscopy, Duncanville, Texas, 1987, pp. 375-397.

7. Berke, N. S. and L. R. Roberts, "Use of Concrete Admixtures to Provide Long-Term Durability from Steel Corrosion," Superplasticizers and Other Chemical Admixtures in Concrete, SP 119, American Concrete Institute, Detroit, Michigan, 1989, pp. 383-403.

8. Hope, B. B. and A. K. Ip, "Corrosion and Electrical Impedance in Concrete," Cement and Concrete Research, Pergamon Press Ltd., Vol. 15, No. 3, 1985, pp. 525-534.

9. Zia, P., M. L. Leming, S. H. Ahmad, J. J. Schemmel and R. P. Elliott, Mechanical Behavior of High Performance Concretes, Volume 4: High Early Strength (HES) Concrete, Strategic Highway Research Program, National Research Council, Washington, DC, June, 1993. Forthcoming.

12. NOTES

Note 1. The AC impedance test is conducted with a Kohlrausch bridge, which is similar to a Wheatstone bridge, except that AC is used. A Wheatstone/Kohlrausch bridge model 4000 (manufactured by AEMC Instruments, Boston) was used with the specimen placed into one arm of the bridge simply by connecting two wires to the instrument box, as indicated, from the two ends of the test specimen. This instrument box uses 1,000-Hz AC current with a voltage of about 0.20 v placed across the specimen.

Note 2. Virtually any type of electrical wire can be used to connect the concrete specimen into the bridge circuit, because the current is very low. A wire length of about 0.45 m (1.5 ft) is recommended. One end of each wire should have on it a flattened piece of solder about 6 mm (0.25 in.) in diameter. These two ends will be placed across the specimen for measurement.

Note 3. Potassium agar gel is prepared by using 30% potassium chloride in water, combined with 2% agar.

FIGURE 1 **RCPT Vacuum Saturation Setup (the same vacuum saturation procedure used for AC impedance)**

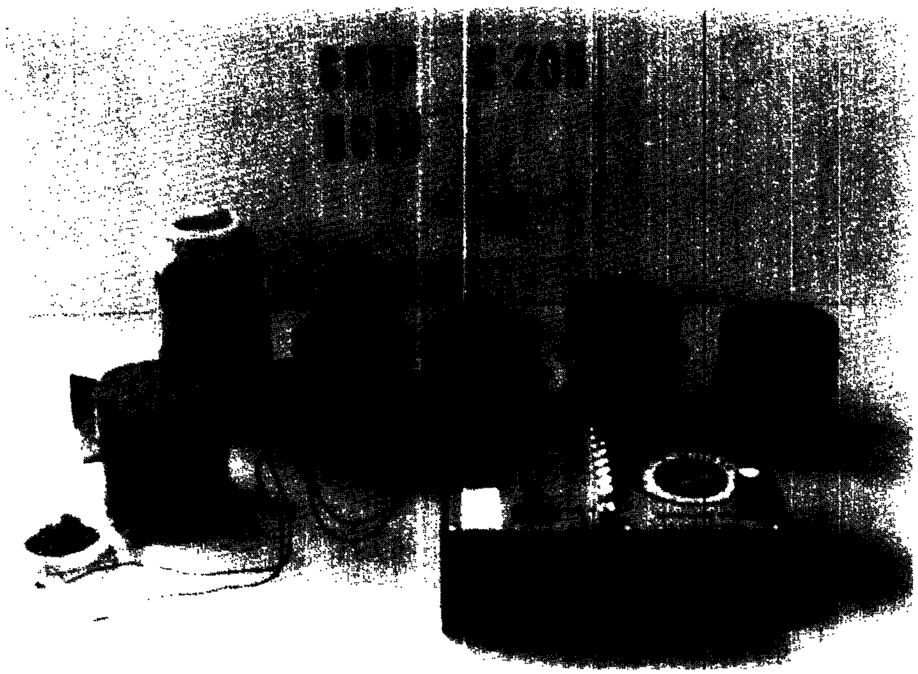

FIGURE 2 **AC Impedance Test Setup**

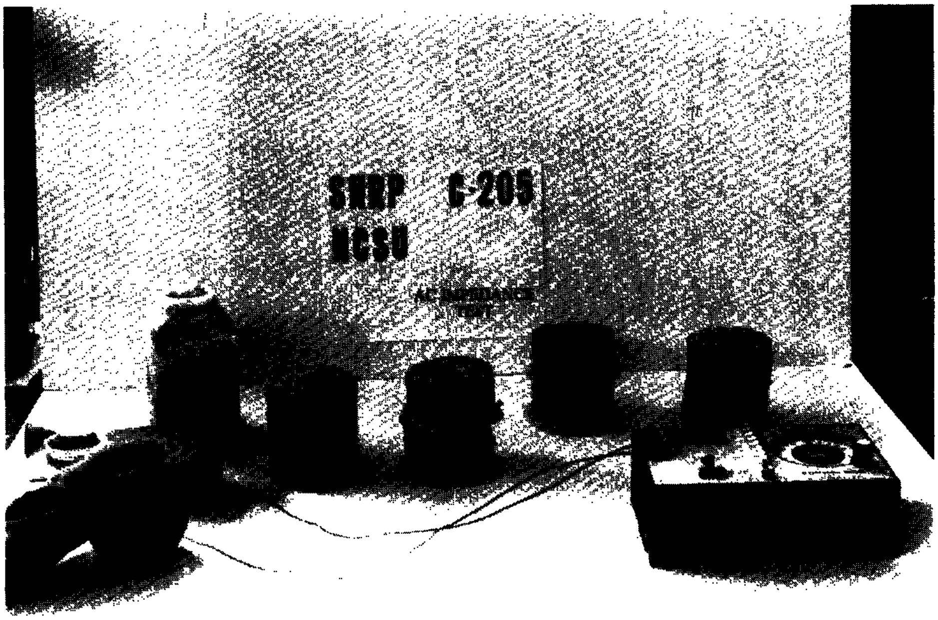

FIGURE 3 AC Impedance Test in Progress

Appendix D

Proposed Specifications for Test of Bond between High Performance Concrete and Conventional Concrete

Proposed Method of Test

for

DETERMINATION OF THE INTERFACIAL BOND STRENGTH OF CONCRETE TO CONCRETE

SHRP Product No. 2025

1. SCOPE

1.1 This method covers the determination of the interfacial bond strength of new concrete to old concrete and the corresponding interfacial deformation.

This method consists of applying a continuous load to the vertical plane of the test specimen along the bonded interface between the new and the old concrete. The load is applied until a shear failure occurs at the bonded interface. The shear strength is calculated by dividing the maximum load attained during the test by the cross-sectional area of the test specimen.

2. APPLICABLE DOCUMENTS

2.1 AASHTO Standards:

- T 24 Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
- T 67 Load Verification of Testing Machines

2.2 ASTM Standards:

- C 39 Compressive Strength of Cylindrical Concrete Specimens
- C 42 Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
- E 4 Practices for Load Verification of Testing Machines
- E 74 Practices for Calibration of Force-measuring Instruments for Verifying the Load Indication of Testing Machines

3. SIGNIFICANCE AND USE

3.1 This method covers the laboratory evaluation of the interfacial bond strength of concrete to concrete and the corresponding interfacial deformation.

3.2 The method is suitable for design purposes, service evaluation, and research and development.

3.3 The specimen is designed to have a direct shear condition at the interface between the two segments of the specimen.

3.4 The method may be used on specimens of sizes different from that described here. However, behavior may be different for specimens of different sizes, and results should be interpreted with caution.

3.5 The method simulates the condition of a concrete overlay on an existing pavement. A specimen of new concrete is cast onto a specimen of old concrete.

3.6 Segment A of the test specimen is the old concrete; segment B is the new concrete.

4. APPARATUS

4.1 Any conventional load application testing machine that has sufficient capacity, sensitivity, and control.

4.1.1 The machine should be capable of load-rate control of 6.68 kN/min (1,500 lb/min).

4.1.2 Care shall be taken, either through a spherically seated loading head or specially designed loading plates, that eccentric load is not applied.

4.2 Specimen sizing equipment.

4.3 Any conventional deformation measuring device having sufficient capacity and sensitivity.

4.3.1 Two linear variable differential transformers (LVDTs) are required: one mounted on the front and the other on the back of the specimen. These will measure the relative slip of the two segments.

4.3.2 LVDTs should have a gage length of about 100 mm (4 in.) and should be attached to angles, which are then glued to the concrete specimen.

4.3.3 The load output and the output from the two LVDTs shall be recorded at 1 to 2 second intervals using an electronic data-acquisition system.

4.4 Safety equipment as required.

4.4.1 Wood blocks should be inserted in the gaps, as shown in Figure 1, to prevent collapse of the specimen at failure.

4.4.2 A chain should be loosely tied to the upper concrete segment to insure that the segment will not fall after the specimen fails.

4.5 Steel plates, as shown in Figure 2, shall be used as loading blocks to distribute the load.

5. TEST SPECIMENS

5.1 The two L-shaped segments shall have dimensions of 375 x 300 x 150 mm (15 x 12 x 6 in.), as shown in Figure 2. Each shall be reinforced with two No. 2 bars and two No. 3 bars, as shown.

5.2 Two companion 100 x 200-mm (4 x 8-in.) cylinders for each segment shall be tested for compressive strength at the time of the bond test.

6. CONDITIONING

6.1 The L-shaped segment used to represent the old concrete (segment A) shall be cast and cured in a moist room for at least 28 days.

6.2 Segment A shall then be air dried and its bonding surface sandblasted with extrafine sand under 0.62 MPa (90 psi) minimum pressure for at least 20 seconds to simulate the field condition for an overlay installation.

6.3 Segment A is then placed on its side with the bonding surface facing up. Before casting segment B, a wet cloth shall be placed on the sandblasted surface for 30 minutes.

6.4 Segment B is then cast against segment A so that the concrete will bond to the 150 x 150-mm (6 x 6-in.) sandblasted contact area.

6.5 After casting, the entire specimen shall be protected from moisture loss by being covered with plastic sheets and cured until the time of testing.

6.6 Companion cylinders shall also be cast when casting segment A and segment B of the test specimens. The curing of these companion cylinders shall be identical to the curing of the segments A and B.

7. PROCEDURE

7.1 The specimen shall be inserted into the testing machine, as shown in Figure 1.
7.2 The data-acquisition equipment is then connected.
7.3 The load may be cycled atup to 0.25 of expected failure load, for seating.
7.4 The load is applied at a rate of 6.68 kN/min (1,500 lb/min), until failure.

8. CALCULATION AND INTERPRETATION OF RESULTS

8.1 The load and deformation shall be plotted as shown in Figure 3.

8.2 The nominal bond stress shall be computed by dividing the maximum debonding load by the nominal bonding area of 225 cm^2 (36 $in.^2$).

9. REPORT

9.1 The report shall include the following:
9.1.1 Specimen ID.
9.1.2 Age of old concrete (segment A) at testing, if known.
9.1.3 Mixture proportions of old concrete, if known.
9.1.4 Characteristics of constituent materials of old concrete, if known.
9.1.5 Compressive strength of old concrete, if determined.
9.1.6 Age of new concrete at testing,
9.1.7 Mixture proportions of new concrete (segment B).
9.1.8 Characteristics of constituent materials of new concrete.
9.1.9 Compressive strength of new concrete at testing.
9.1.10 Load-interfacial deformation curve.

9.1.11 Maximum load at failure.
9.1.12 Maximum interfacial deformation.

10. PRECISION

No precision criteria will be available until further testing is done.

11. REFERENCES

1. Zia, P., M. L. Leming, S. H. Ahmad, J. J. Schemmel and R. P. Elliott, Mechanical Behavior of High Performance Concretes, Volume 4: High Early Strength (HES) Concrete, Strategic Highway Research Program, National Research Council, Washington, DC, June, 1993. Forthcoming.

12. FIGURES

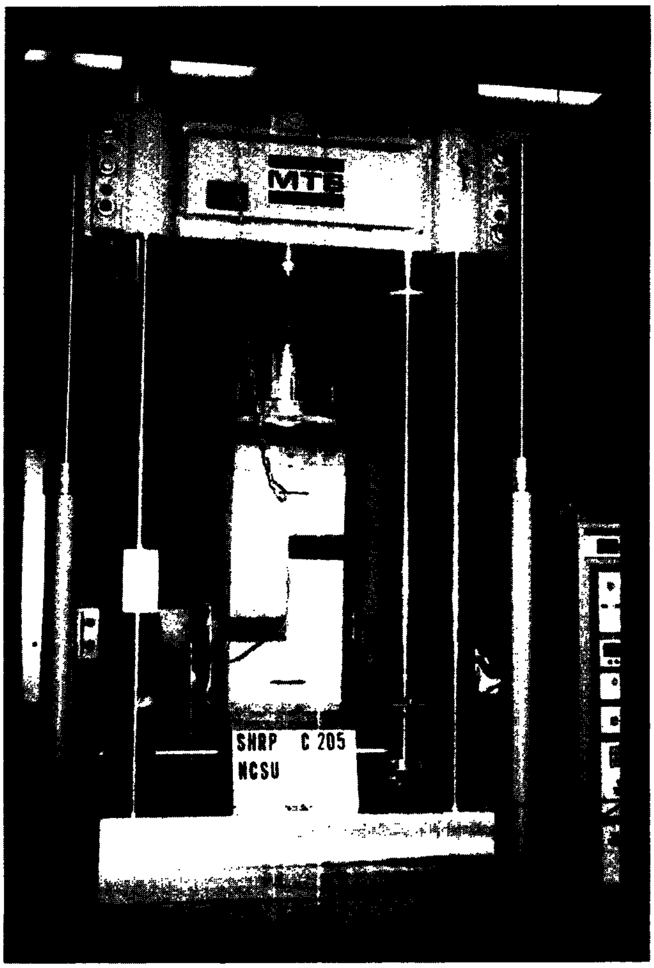

FIGURE 1 A View of the Concrete-to-Concrete Bond Test Setup

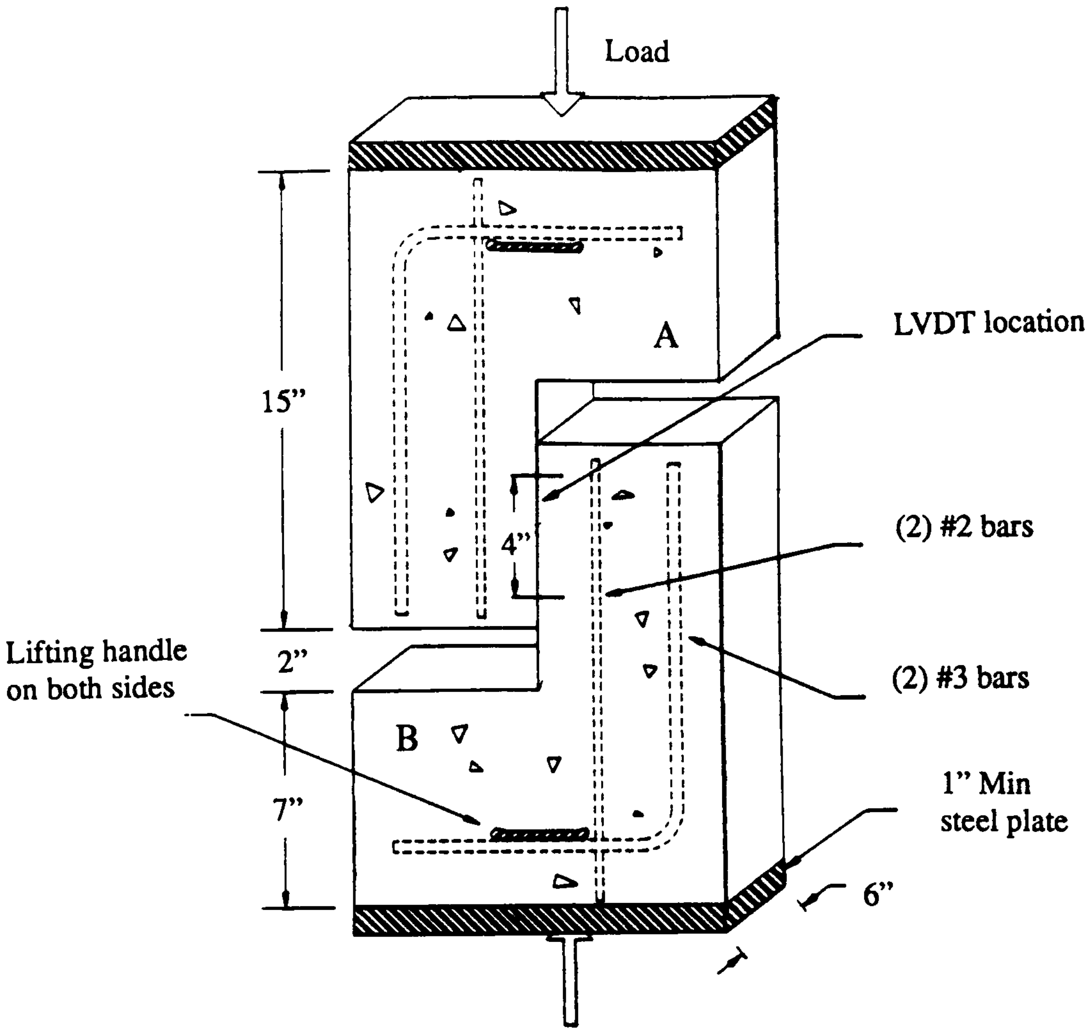

FIGURE 2 Specimen for the Concrete-to-Concrete Bond Test

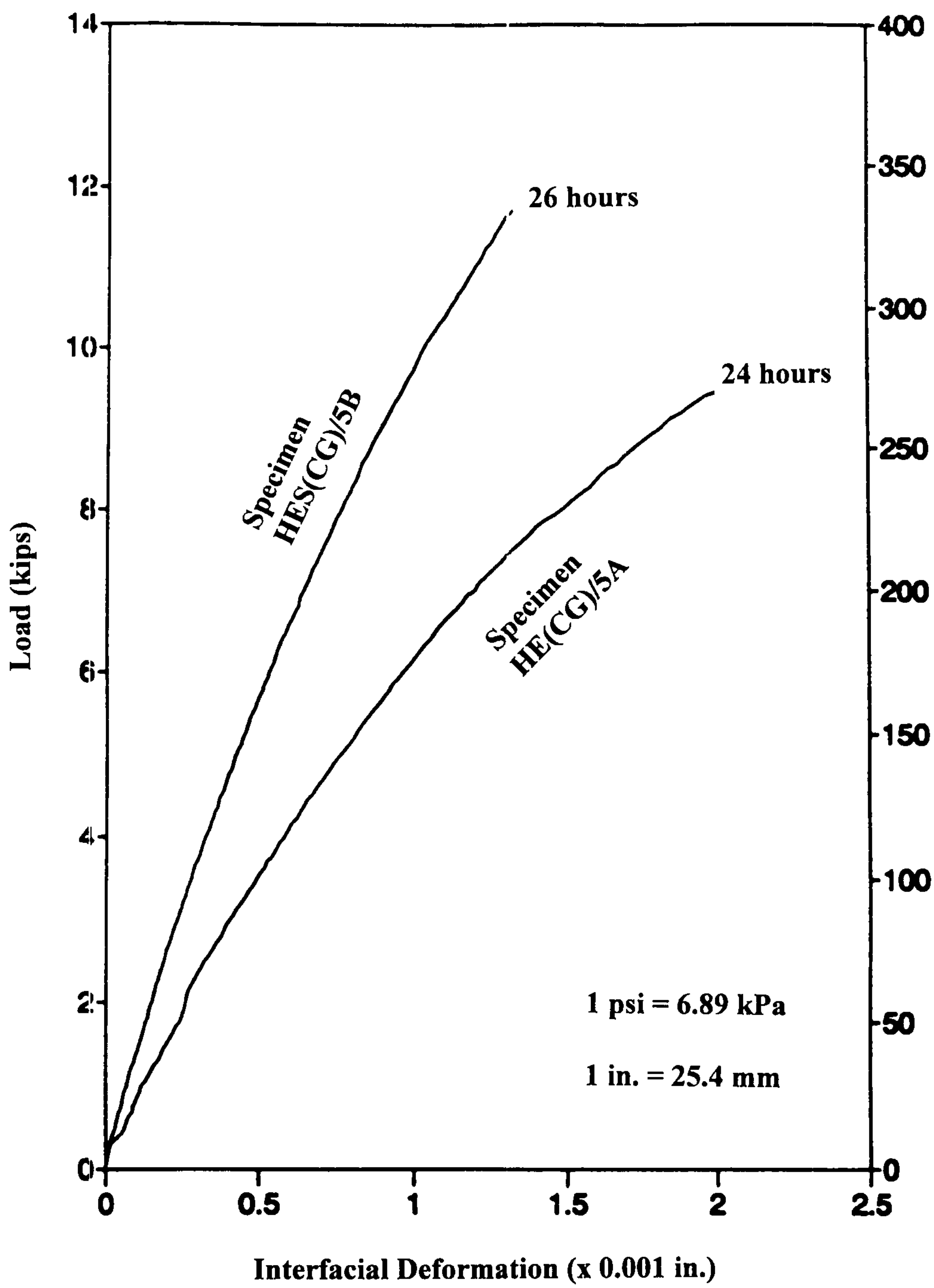

FIGURE 3 **Load versus Interfacial Deformation for Concrete-to-Concrete Bond between HES (CG) Concrete and Control Concrete**

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