





**IDEA PROJECT FINAL REPORT**  
Contract NCHRP-4

IDEA Program  
Transportation Research Board  
National Research Council

July 1995

**EXPLORING THE FEASIBILITY  
OF REPLACING LATEX WITH ASPHALT  
EMULSION FOR USE IN BRIDGE DECK  
OVERLAYS**

Prepared by:  
Chen-Ye David Yang  
Menashi D. Cohen  
Sidney Diamond  
Purdue University

**INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA)  
PROGRAMS  
MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)**

This NCHRP-IDEA investigation was completed as part of the National Cooperative Highway Research Program (NCHRP). The NCHRP-IDEA program is one of the four IDEA programs managed by the Transportation Research Board (TRB) to foster innovations in highway and intermodal surface transportation systems. The other three IDEA program areas are Transit-IDEA, which focuses on products and results for transit practice, in support of the Transit Cooperative Research Program (TCRP), Safety-IDEA, which focuses on motor carrier safety practice, in support of the Federal Motor Carrier Safety Administration and Federal Railroad Administration, and High Speed Rail-IDEA (HSR), which focuses on products and results for high speed rail practice, in support of the Federal Railroad Administration. The four IDEA program areas are integrated to promote the development and testing of nontraditional and innovative concepts, methods, and technologies for surface transportation systems.

For information on the IDEA Program contact IDEA Program, Transportation Research Board, 500 5<sup>th</sup> Street, N.W., Washington, D.C. 20001 (phone: 202/334-1461, fax: 202/334-3471, <http://www.nationalacademies.org/trb/idea>)

The project that is the subject of this contractor-authored report was a part of the Innovations Deserving Exploratory Analysis (IDEA) Programs, which are managed by the Transportation Research Board (TRB) with the approval of the Governing Board of the National Research Council. The members of the oversight committee that monitored the project and reviewed the report were chosen for their special competencies and with regard for appropriate balance. The views expressed in this report are those of the contractor who conducted the investigation documented in this report and do not necessarily reflect those of the Transportation Research Board, the National Research Council, or the sponsors of the IDEA Programs. This document has not been edited by TRB.

The Transportation Research Board of the National Academies, the National Research Council, and the organizations that sponsor the IDEA Programs do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of the investigation.

## **ACKNOWLEDGEMENTS**

This research was sponsored by the National Research Council, National Cooperative Highway Research Program (NCHRP), NCHRP-IDEA Program, contract no. NCHRP-92-ID004. The support and encouragement from Dr. K. Thirumalai, IDEA Program Manager, are greatly appreciated. Thanks are also extended to Cathy Ralston for typing the manuscript.

Jan Olek (Principal Investigator)  
Chen-Ye David Yang (Graduate Student)  
Menashi D. Cohen (Principal Investigator)  
Sidney Diamond (Principal Investigator)



# TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY .....	1
1. INTRODUCTION .....	3
1.1 STATEMENT OF THE PROBLEM .....	3
1.2 OBJECTIVES OF THE INVESTIGATION .....	3
1.3 ORGANIZATION OF REPORT .....	3
2. LITERATURE REVIEW .....	4
2.1 EMULSIFIED ASPHALTS .....	4
2.2 EFFECT OF SUPERPLASTICIZER ON THE PROPERTIES OF CONCRETE .....	5
2.3 POROSITY .....	6
2.4 OTHER MODIFIED CONCRETE SYSTEMS .....	8
2.4.1 Latex-Modified Concrete .....	8
2.4.2 Polymer-Impregnated Concrete .....	9
3. MATERIALS .....	10
3.1 PORTLAND CEMENT .....	10
3.2 ASPHALT EMULSIONS .....	10
3.3 AGGREGATES .....	10
3.4 ADMIXTURES .....	12
4. PRELIMINARY STUDY AND FINDINGS .....	13
4.1 PREPARATION OF MORTARS .....	13
4.2 COMPRESSIVE STRENGTH TEST FOR MORTARS .....	15
4.3 PRELIMINARY EXPERIMENTAL RESULTS .....	16
5. EXPERIMENTAL PROCEDURES .....	17
5.1 PREPARATION OF CONCRETE MIXES .....	17
5.2 CASTING AND CURING OF CONCRETE SPECIMENS .....	19
5.3 TESTING OF HARDENED CONCRETE SPECIMENS .....	21
5.3.1 Modified Point-Count .....	21
5.3.2 Compressive Strength .....	21
5.3.3 Flexural Strength .....	22
5.3.4 Chloride Ion Permeability .....	22
5.3.5 Dynamic Modulus of Elasticity .....	23
5.3.6 Freeze-Thaw Resistance .....	23
5.3.7 Splitting Bond Force .....	24
6. EXPERIMENTAL RESULTS .....	25
6.1 PROPERTIES OF FRESH CONCRETES .....	25
6.1.1 Water:Cement Ratio .....	25

	Page
6.1.2 Properties of Fresh Asphalt Emulsion-Modified Concretes with Superplasticizer .....	25
6.1.3 Properties of Fresh Asphalt Emulsion-Modified Concretes with Superplasticizer and Air Detraining Agent .....	26
6.2 MODIFIED POINT-COUNT .....	27
6.3 STRENGTH .....	27
6.3.1 Compressive Strength of Asphalt Emulsion-Modified Concretes with Superplasticizer .....	27
6.3.2 Compressive Strength of Asphalt Emulsion-Modified Concretes with Superplasticizer and Air Detraining Agent .....	29
6.3.3 Flexural Strength of Asphalt Emulsion-Modified Concretes with Superplasticizer .....	30
6.4 CHLORIDE ION PERMEABILITY .....	32
6.4.1 Chloride Ion Permeability of Asphalt Emulsion Modified-Concretes with Superplasticizer .....	32
6.4.2 Chloride Ion Permeability of Asphalt Emulsion-Modified Concretes with Superplasticizer and Air Detraining Agent .....	34
6.5 DYNAMIC MODULUS OF ELASTICITY .....	35
6.6 FREEZE-THAW RESISTANCE .....	35
6.7 SPLITTING BOND FORCE .....	38
7. SUMMARY AND GENERAL DISCUSSION .....	40
7.1 PROPERTIES OF ASPHALT EMULSION-MODIFIED CONCRETES WITH SUPERPLASTICIZER .....	40
7.1.1 Workability .....	40
7.1.2 Air Content of Hardened Concretes .....	40
7.1.3 Compressive Strength .....	40
7.1.4 Flexural Strength .....	41
7.1.5 Chloride Ion Permeability .....	41
7.1.6 Dynamic Modulus of Elasticity .....	41
7.1.7 Freeze-Thaw Resistance .....	42
7.1.8 Splitting Bond Force .....	42
7.2 PROPERTIES OF ASPHALT EMULSION-MODIFIED CONCRETES WITH SUPERPLASTICIZER AND AIR DETRAINING AGENT .....	42
7.2.1 Effects of Air Detraining Agent on Workability of Asphalt Emulsion-Modified Concretes .....	42
7.2.2 Effects of Air Detraining Agent on Compressive Strength of Asphalt Emulsion-Modified Concretes .....	43
7.2.3 Effects of Air Detraining Agent on Chloride Ion Permeability of Asphalt Emulsion-Modified Concretes .....	43
7.2.4 Summary of Effects of Air Detraining Agent .....	43

	<b>Page</b>
8. FINDINGS, CONCLUSIONS, AND FUTURE RESEARCH NEEDS .....	44
8.1 FINDINGS .....	44
8.2 CONCLUSIONS .....	45
8.3 RECENT DEVELOPMENT AND FUTURE RESEARCH NEEDS .....	46
LIST OF REFERENCES .....	49





## EXECUTIVE SUMMARY

**IDEA Product:** The IDEA Product under development is a new construction material consisting of a mixture of traditional components of plain portland cement concrete (cement, water, and aggregate) and asphalt emulsion. The asphalt emulsion is a dispersion of small droplets of asphalt and emulsifying agent in water. After asphalt emulsion is added to a fresh concrete mixture, the emulsion water separates from the asphalt particles and is utilized during hydration of portland cement. Water-free asphalt globules coalesce to form a membrane-like film throughout the microstructure of concrete. This film reduces the permeability of the concrete by filling up the capillary pores and reducing their interconnectivity. The asphalt emulsion modified concrete shows excellent freezing and thawing resistance, reduced chloride ion permeability, and improved durability. As a result, better long-term performance of highway concrete is expected.

**Concept and Innovation:** The unique feature of this innovation is the utilization of asphalt emulsion for the purpose of modifying the properties of portland cement concrete. In this application, the asphalt emulsion is treated as a polymeric material which essentially impregnates the microstructure of portland cement concrete. The resulting product combines the advantages of portland cement concrete (strength, stiffness) and polymer (ability to partly plug pores and form a membrane-like film, which reduces the ingress of aggressive or corrosive elements). Considerable advances in asphalt emulsion technology have been introduced in recent years, especially the more widespread use of non-ionic emulsifiers and the addition of elastomers, which have greatly increased the potential for successful application of such materials in portland cement concrete modification.

If successfully developed, the proposed IDEA product can offer substantial benefits in the area of durability of concrete structures, especially those which are exposed to severe environmental conditions. Such structures include concrete bridge decks and highway pavements. The repair of deteriorated bridge structures is of major safety and economic concern to state transportation departments and bridge maintenance engineers.

**Investigation:** Plain, unmodified portland cement concrete is a porous material. Under the service conditions the pores existing in the microstructure are penetrated by water or other solution, a process which frequently results in various durability problems including the corrosion of steel, freeze-thaw deterioration, or deterioration due to sulfate or other chemical attacks.

The primary objective of this study was to develop and investigate an asphalt emulsion-modified concrete system with improved mechanical and durability properties for highway and bridge deck applications. Since, to the best of knowledge of this investigating team, there has been no previous work published on asphalt emulsion-modified systems, a preliminary study was conducted on selected asphalt emulsions to determine their compatibility with portland cement system. These investigations were performed on portland cement mortars. Mortars were prepared by selecting constant proportions of portland cement and fine aggregate, and varying the amount of asphalt emulsion from 5% to 40% in 5% increments. These preliminary studies involved the determination of workability of a fresh mortar by means of flow table measurement, as well as an assessment of compressive strength after 3 and 7 days of moist curing.

Based on the results of the preliminary studies a slow setting anionic asphalt emulsion (designated SS-1h) with a harder base asphalt cement was selected for use in further experiments with concrete. Since it was found that at every level of asphalt emulsion addition both the flow and the compressive strength of mortars was reduced, it was decided that each concrete batch containing asphalt emulsion would also contain superplasticizer. The addition of superplasticizer allowed for production of workable concrete with a lower w/c ratio and higher strength.

Following the preliminary studies the main research efforts were concentrated on the following tasks:

(a) Concrete mixtures containing 10 and 20 percent (by the weight of cement) addition of the selected asphalt emulsion, and containing naphthalene sulphonate super plasticizer. Mixtures were made, both with and without air detrainig agent.

(b) Evaluation of mechanical, permeability, and durability properties. Tests were performed to determine the workability, strength, dynamic modulus of elasticity, chloride permeability, porosity and freeze-thaw resistance properties.

In general, untreated (without air detraining agent) asphalt emulsion-modified concretes developed considerably lower strength than conventional portland cement concrete. This is most likely due to high content of entrained air resulting from the use of asphalt emulsion. After the excessive air content was reduced the strength performance of asphalt emulsion-modified concretes improved. Also, the chloride permeability of asphalt emulsion-modified concretes was slightly better than that of conventional portland cement concrete and their freezing and thawing resistance was excellent, although these results surely reflect high air content of the samples.

In summary, the performance of asphalt emulsion-modified concrete demonstrated during the first stage of this project, although adequate, was at best comparable or only marginally better than that of a plain, unmodified concrete. A critical analysis of these findings led to the conclusion that further modifications of both mix proportions and production techniques are needed if significant performance improvement was to be achieved. It was therefore decided to start the second phase of the investigation to explore the influence of different curing regime and addition of mineral admixtures on the properties of asphalt emulsion modified concrete.

In the new series of tests the samples were moist cured only for short initial period of 24 or 48 hours. This brief initial period of moist curing was following by a period of air curing. This modified curing procedure accelerated the evaporation of water from concrete (including the water from asphalt emulsion) and speeded up the development of asphalt "film" throughout the microstructure of the concrete.

For comparison purpose, a second series of companion samples following the same curing regime as used in the first stage of the project (that is moist curing in the fog room) was also tested. These second series test results for moist cured samples are very similar to those obtained during the first part of the project. This indicates that asphalt emulsion modified concrete can be produced in a reproducible fashion, using the standard mixing and batching equipment. A limited number of tests have also been performed on samples containing the addition of both asphalt emulsion and either silica fume or class C fly ash at 10% by weight of cement replacement level.

There were a total of four mixtures prepared for this study. These were as follows: a) conventional portland cement concrete as the first reference, b) asphalt emulsion-modified concrete with 10% of SS-1h asphalt emulsion, naphthalene sulfonate superplasticizer, and an air detraining agent, c) conventional (10% of silica fume by wt. of cement) silica fume concrete with a naphthalene sulfonate superplasticizer as the second reference, d) asphalt emulsion-modified concrete with 10% of SS-1h asphalt emulsion, naphthalene sulfonate superplasticizer, and an air detraining agent.

The results from rapid chloride permeability tests obtained for air-cured samples are superior to those obtained from wet-cured samples. This indicates that exposure of samples modified with asphalt emulsion to the environment which promotes the loss of water by evaporation is beneficial to the properties of the final product. Even at the relatively early age of 28 days the asphalt emulsion-modified samples reached the "low" chloride permeability level (1000 to 2000 coulombs according to AASTO T277) and practically matched the performance of the reference silica fume concrete. The most significant reduction of total charge passed in rapid chloride permeability test was observed in samples containing both silica fume and asphalt emulsion addition. After 56 days of air curing these samples were completely impenetrable (zero coulombs of charge).

*Plans for Implementation:* Although the issue of field application of the proposed technology was discussed with the INDOT the research is still only in an exploratory stage and therefore the results are not ready for an immediate implementation. At this stage the results will be published in a technical literature and presented at technical conferences.

## 1. INTRODUCTION

Concrete and asphalt are the two primary materials used for road pavements in the United States. Out of a total of approximately 4 million miles of roads in United States in 1988, over half of these roads were surfaced with either concrete or asphalt (1). Although concrete and asphalt experts argued for years about which of these two materials is more suitable for road pavements, no definite conclusions have been reached yet. Even though there have been thousands of studies of pavements made out of either concrete or asphalt separately, no significant research has been done on concrete systems modified with asphalt. The study described in this report was undertaken to explore properties of portland cement based concrete system modified with asphalt emulsion in an attempt to assess potential benefits of using such system in pavements and bridge decks applications.

### 1.1 STATEMENT OF THE PROBLEM

One of most important parameters that affect the durability of concrete is its porosity. In general decrease in porosity makes concrete both more impermeable and stronger (2), thus reducing the vulnerability of concrete to deterioration. Porosity of concrete along with its permeability controls the rate of entry of moisture that may contain aggressive chemicals and the movement of water during freezing and thawing (2). When the porosity or permeability of a concrete system is high, its resistance against chemical and physical attack is low. As a result, chemical attack such as corrosion of metal reinforcement and physical attack such as involved ice freezing and thawing or salt scaling can cause severe damage to the concrete structures. Many hours of labor and enormous amount of money have been spent to rehabilitate roads that were damaged by various types of chemical and physical attack. Since resistance against chemical and physical attack is high when the porosity and permeability of a concrete system are low, an effective method to prevent chemical and physical attack is to use concrete systems with low porosity and permeability.

Several new portland cement concrete systems have been developed to improve concrete properties, especially its durability. Modified concrete systems such as latex-modified concrete and polymer concrete all have low permeability and reduced porosity, hence, they all have high resistance against chemical and physical attacks. However, these modified concrete systems are expensive, due to both the substantial cost of the modifying agents and to special processing requirements.

### 1.2 OBJECTIVES OF THE INVESTIGATION

The primary objective of this investigation was to investigate an asphalt emulsion-modified concrete system aimed at providing performances that are comparable to some of the modified concrete systems that have been mentioned earlier, such as latex-modified concrete and polymer concrete systems. Specifically, the effects of the asphalt emulsions on the workability, strength, and dynamic modulus of elasticity of the asphalt emulsion-modified concrete systems were investigated. In addition, some durability related parameters such as chloride ion permeability and resistance to freezing and thawing were also studied. Finally, the porosity of the asphalt emulsion-modified concrete system was also investigated.

### 1.3 ORGANIZATION OF REPORT

This report consists of eight chapters. Chapter 1 is the introductory chapter, and it includes the objectives of this research. A literature review of asphalt emulsions, porosity of concrete, and some of the modified concrete systems that have been developed previously is presented in Chapter 2.

The materials used in the course of this study are described in Chapter 3. Preliminary studies and findings are

presented in Chapter 4. A description of the experimental procedures used in this research is provided in Chapter 5.

The experimental results of concrete testing are presented in Chapter 6. Chapter 7 includes the summary and general discussion of the results obtained from the experiments. Finally, the findings and conclusions from this research are presented in Chapter 8.

Flow charts that summarize the samples prepared and experiments performed in this study are provided in Figures 4.1 and 5.1.

## 2. LITERATURE REVIEW

A literature review on the asphalt emulsions is first presented in this chapter. The effects of superplasticizer on the properties of conventional concrete and the effects of porosity on strength of concrete are then reviewed. Finally, highlights of the literature on latex-modified concrete systems and polymer concrete systems are presented.

### 2.1 EMULSIFIED ASPHALTS

Emulsified asphalts, asphalt cements, and cutback asphalts are the three most common types of asphalts used in flexible pavement construction (1). Emulsified asphalt (or asphalt emulsion) is a dispersion of asphalt cement in water stabilized by an emulsifying agent. A major advantage which emulsified asphalts have over asphalt cements or cutback asphalts is that they can be mixed with aggregates without being heated (3, 4, 5, 9). Thus, significant reductions in energy requirements (6) and air pollution (7) have been reported when using cold mixed emulsified asphalt systems in construction.

Asphalt emulsions are produced by passing hot asphalt cement and water containing the emulsifying agent (such as soap) under pressure through a colloid mill. In the process, extremely small droplets of asphalt cement ranging in diameter from one to five microns become suspended in "soapy" water. A satisfactory emulsion is smooth in appearance and usually brown in color (8).

Asphalt emulsions are typically classified into two types depending on the electrical charge carried by the asphalt droplets. Anionic asphalt emulsions contain electro-negatively charged asphalt droplets; they are covered by standard specification ASTM D 977. Cationic asphalt emulsions are emulsions in which the surfaces of the asphalt droplets carry positive charges; they are covered by standard specification ASTM D 2397. The asphalt droplets bear a negative charge when the emulsifying agent is anionic. If the emulsifying agent is cationic, the asphalt droplets bear a positive charge. Some aggregates, such as limestone, are generally compatible with the negatively charged anionic asphalt emulsions because their surfaces are positively charged. On the other hand, aggregates such as quartz and siliceous gravel are compatible with positively charged cationic asphalt emulsions because their surfaces are negatively charged (1, 3).

Both anionic and cationic asphalt emulsions are further graded according to their setting rates. The setting rates of asphalt emulsions are controlled by the type and amount of the emulsifying agent used in them. According to ASTM D 977 - 91, the anionic asphalt emulsions include rapid setting (RS), medium setting (MS), and slow setting (SS). The grades for anionic asphalt emulsions are: RS-1, RS-2, HFRS-2, MS-1, MS-2, MS-2h, HFMS-1, HFMS-2, HFMS-2h, HFMS-2s, SS-1, and SS-1h. The HF designation refers to a high float residue, the *h* designation means a harder base asphalt cement is used in the emulsions, and the *s* designation means a softer base asphalt cement is used in the emulsions. The cationic asphalt emulsions are specified in ASTM D 2397; they also include rapid setting (CRS), medium setting (CMS), and slow setting (CSS). The grades for cationic asphalt emulsions are: CRS-1, CRS-2, CMS-2, CMS-2h, CSS-1, and CSS-1h. The *h* designation here also refers to a harder base asphalt cement is used in the emulsions.

The selection of a particular type and grade of asphalt emulsion to be used is controlled by type of construction, properties of the mineral aggregate, and environmental conditions during construction. The criteria for selection of asphalt emulsions for various paving and allied uses are given in ASTM D 3628. Generally, rapid setting asphalt emulsions are used for surface treatments and seals. Medium setting asphalt emulsions usually are used for open graded cold asphalt-aggregate mixtures. Slow setting asphalt emulsions are used for tack coat, fog seal,urry seal, and densely graded cold asphalt-aggregate mixtures.

Asphalt emulsions are tested for their composition, consistency, stability in mixing and in storage, and for character of the residue. Standard test methods for asphalt emulsions are given in ASTM D 244 (10). Composition tests include water content, residue by distillation, and residue by evaporation. Consistency of emulsions is measured by the viscosity test. Studies have indicated that salt content of the emulsion has an important effect on viscosity; a higher salt content results in higher viscosity (11, 12, 13). Mixing stability tests include demulsibility, cement mixing, and stone coating. Storage stability tests include sieve, miscibility with water, settlement, and freezing. Tests on asphalt emulsion residues usually include ash content, solubility in trichloroethylene, penetration, ductility, and the float test.

## 2.2 EFFECT OF SUPERPLASTICIZER ON THE PROPERTIES OF CONCRETE

Superplasticizers are increasingly being used in plain concrete mixtures because of the benefits they provide in handling, placing, compaction, and finishing of concrete. Superplasticizers, or high-range water-reducing admixtures (HRWRs), were developed in Japan around 1960 (14, 15). They are linear polymers containing sulfonic acid groups used to disperse the individual particles completely so a relatively fluid concrete at low water contents can be produced.

Chemically, two major polymer types are the basis of most superplasticizers, sulfonated melamine formaldehyde condensates and sulfonated naphthalene formaldehyde condensates (2, 16). A third type of superplasticizers, based on special lignosulfonate polymers, has also been used. Discussions about the manufacture and structure of superplasticizers, as well as their effects on concrete, have been published by Ramachandran and Malhotra (17), Rixom and Mailvaganam (18), and others.

Naphthalene sulfonate (NS) based superplasticizers appear to presently dominate the U.S. construction market and have been used exclusively in this study. They are produced by sulfonating naphthalene with sulfur trioxide, polymerizing the resulting naphthalene sulfonate with formaldehyde, and then neutralizing the sulfonate groups on the polymer chain with sodium hydroxide (18).

According to Meyer (19), NS based superplasticizers exert their action by decreasing the surface tension of water and charging the surface of cement particles equidirectionally to form a lubricating film. Melamine sulfonate (MS) based superplasticizers exert their action by producing a lubricating film at particle surfaces. Finally, lignosulfonate (LS) based superplasticizers exert their action by decreasing the surface tension of water.

The general dosage of superplasticizers used in concrete ranges from 0.5% to as much as 3% by the weight of cement. Higher dosages of superplasticizers are used in concretes with low water:cement ratios or to reduce the high water demand caused by fine mineral additives such as silica fume (20). When a normal dosage of superplasticizer is used, there is a gradual loss in dispersion over time, which manifests itself as slump loss (21, 22). However, such a problem can be moderated by using higher than normal dosages of superplasticizer or by adding several repeated doses at intervals (23).

When superplasticizers are used for the purpose of reducing the amount of water required for a given slump, increases in the strength of concrete are observed. The 28-day compressive strength of superplasticized concrete is significantly higher than the strength of conventional portland cement concrete (24, 25, 27). A compressive strength of 8000 psi can readily be obtained at 28 days (18, 26). Concrete containing superplasticizer can also develop higher flexural strength (17).



At a given water:cement ratio, the durability of superplasticized concrete is generally at least as good as that of conventional portland cement concrete. Studies have shown that the resistance of superplasticized concrete to salt scaling, steel corrosion, and sulfate attack was comparable to conventional portland cement concrete (15, 27, 28, 29, 30). However, the effect of superplasticizers on freeze-thaw resistance is complicated; some laboratory studies reported that superplasticized concrete exhibit poor freeze-thaw resistance (31, 32, 33) yet other laboratory studies have shown that concrete containing superplasticizer exhibit good frost resistance (34, 35, 36). In general, addition of superplasticizer into concrete increases the air-void spacing factor (14), and if the air-void spacing factor is not at an appropriate level, the resistance to freeze-thaw cycles could be poor.

Drying shrinkage of concrete increases when concrete has a high water:cement ratio or a low aggregate:cement ratio. By decreasing the amount of water and cement used in a concrete mixture, drying shrinkage can be reduced. However, a mixture with low water content is difficult to place and compact and addition of superplasticizer eases the placeability of this type of concrete mixture. Hence, superplasticizer reduced the drying shrinkage of concrete when added to a low water:cement ratio concrete mixture (37, 38). Nevertheless, according to Ramachandran and Malhotra (17), superplasticized concrete shrinks more per unit loss of water content. Creep for concrete containing superplasticizer is generally similar to conventional portland cement concrete (29, 39). Finally, there is no significant difference in dynamic modulus of elasticity between superplasticized concrete and conventional portland cement concrete (29).

Superplasticizers offer many advantages and alternatives to the concrete industry. Many aspects of concrete performance can be modified with superplasticizers. However, it should be emphasized that superplasticizers, like all other admixtures used in concrete, are not panaceas for every concrete problem. Before using a superplasticizer, one should have a good understanding of how it interacts with concrete to avoid many unnecessary errors.

### 2.3 POROSITY

During the course of this study, asphalt emulsion was incorporated into concrete system in an attempt to modify the pore structure of concrete. Hence, the effect of porosity on mechanical properties and durability of concrete was reviewed to provide the essential information that could help in explaining some of the findings.

Strength is one of most important mechanical properties of concrete. While many factors influence strength of concrete, porosity has been considered to be having the major impact. The term "porosity" refers to voids filled with air, liquid, or other strengthless materials (40).

If one assumes that the porosity of aggregate particles does not influence the strength of concrete, then the effective porosity of concrete would be solely attributed to the voids in the hardened cement paste plus entrained or entrapped air voids. There are three types of pores in cement paste: gel pores, capillary pores, and macro-porosity (or large air voids). The amount of gel porosity can not be controlled because gel pores are an intrinsic feature of the hydrated cement. The capillary porosity is affected by the water:cement ratio, curing, and the age of paste. Finally, the macro-porosity is the result of incomplete consolidation, entrained air, or both (41). At low cement content, the size of the effect of capillary pores on concrete strength is larger than that of the macro-porosity, but the reverse is true at high cement content (42).

The rule of thumb commonly used to describe the relationship between strength and air void porosity is that for every 1 percent of entrained air, there is a 5 percent reduction in the compressive strength of concrete (43, 44). However, a different and more general approach was proposed to describe the relationship between the compressive strength of concrete and air content (45):

$$f_{rel} = 10^{-0.035v}$$

$$= \frac{1}{1.084^v}$$

$$= \frac{1}{3150^{0.01\nu}}$$

where:  $f_{rel}$  = relative compressive strength of concrete when the air-free strength is the unity

$\nu$  = air content of concrete, percent.

The form of equation above is same as the formula for the relative concrete strength versus water-cement ratio relationship proposed by Abrams (46). In comparison to the 5 percent linear reduction rule, this equation suggests that entrainment of 1, 2, and 8.5 percent of air into a concrete system would reduce its compressive strength by 7.7, 15, and 50 percent respectively. Studies have shown that the equation presented above correlates the relationship between air content and compressive of concrete better than the customary rule of 5 percent linear reduction in compressive strength per percent of increase in air content (47, 48, 49).

According to the experimental results from Kaplan (49) and Gonnerman (50), a change in the air content (macro-porosity) of concrete has relatively less effect on its flexural and tensile strengths than on the compressive strength. Popovics (45) explained such phenomenon was a result of the *slow* crack propagation. Slow crack propagation is much more extensive under uniaxial compression than under uniaxial tension; and the slow crack propagation is promoted by flaws such as pores and voids. Therefore, the role of pores is more pronounced in concrete specimens under compressive than under tension loading. In other words, an increase in porosity weakens the compressive strength of concrete relatively more than its flexural or tensile strengths.

Since the modulus of elasticity of concrete is related to the compressive strength of concrete, thus, factors that affect the strength of concrete should have similar influence on its modulus of elasticity. As stated earlier, an increase in porosity of concrete decreases the compressive strength of concrete, hence, a concrete with high porosity will have low modulus of elasticity (2, 16). The modulus of elasticity of the hardened cement paste is related to the capillary porosity as follows (2):

$$E = E_g(1-P_c)^3$$

where:  $E$  = modulus of elasticity of the hardened cement paste

$E_g$  = modulus of elasticity of the hardened cement paste at zero porosity,  
 $\approx 31 \text{ GPa} \approx 4.5 \times 10^6 \text{ psi}$

$P_c$  = capillary porosity,

$$= \frac{\text{water}}{\text{cement}} - 0.36\alpha$$

$\alpha$  = degree of hydration;  $\alpha$  equals to 1 for fully hydrated cement.

The durability of concrete is strongly dependent on the distribution of porosity, and one of most important properties of concrete related to durability is permeability. Consequently, porosity and pore size distribution controls the permeability of concrete to water and harmful ions such as chlorides and sulphates (51). According to several recent studies about the relationship between permeability and pore size distribution, researchers concluded that the flow of a fluid through concrete is associated with the larger capillary pores rather than total porosity. In addition, pore volume in the region of 0.08 - 0.15  $\mu\text{m}$  is thought to be closely related with permeability (52, 53, 54).

## 2.4 OTHER MODIFIED CONCRETE SYSTEMS

Latex-modified concrete and polymer-impregnated concrete were developed in an attempt to improve concrete properties, especially its durability. This section provides a brief review on latex-modified concrete and polymer-impregnated concrete. This review is intended to gather the necessary information about selected properties of latex-modified concrete and polymer-impregnated concrete so a qualitative comparison can be made between these two modified concrete systems and asphalt emulsion-modified concrete.

### 2.4.1 Latex-Modified Concrete

A latex is an organic polymer system consisting of extremely small, spherical particles of polymer, held in suspension in water by the surface active agents. Most latexes are milky fluids that are generally white in color (55, 56). Out of the eight major types of latexes that are being used with hydraulic cements today, styrene butadiene copolymer latex is used in far greater amounts than any other type (55).

When latex is used in concrete mixes, fresh concrete can be produced with consistency and workability characteristics only slightly different from conventional portland cement concrete. After curing, latex-modified concrete (LMC) consists of hydrated cement and aggregate, all component interconnected by a continuous film of latex. It is the existence of this continuous film which gives latex modified concrete the superior physical properties and good durability (57).

#### *Properties of Fresh Latex-Modified Concrete*

The addition of latex to concrete mixes generally improves the properties of fresh concrete. Those small and spherical polymer particles ( $0.05 \sim 1.0 \mu\text{m}$  in diameter) that make up the latex act much as entrained air bubbles to improve the workability of concrete and reduce the bleeding of paste (58). Furthermore, the addition of latex allows a significant reduction in the water:cement ratio of concrete, and a workable slump of 100 to 150 mm (4 to 6 in.) can be readily achieved at a water:cement ratio of 0.40 or less (2, 59).

It has been determined that LMC responds poorly to extended curing under wet conditions. Popovics (62) found that wet curing LMC produced substantial reductions in compressive strength as compared to air curing. For this reason, in most studies of LMC, the concrete has been air cured at 50% RH instead of being wet cured (58). It is during the air curing period that LMC gains its ultimate properties (60).

#### *Mechanical Properties of Hardened Latex-Modified Concrete*

The addition of the latex, combined with the low water:cement ratio contributed by latex, produce a concrete that has improved flexural, tensile, and bond strength compared to conventional portland cement concrete of similar mix design (60). The presence of latex in concrete results in formation of thread-like "bridges" across the microcracks within the concrete which resist spreading of the cracks. Thus, higher flexural and tensile strengths and greater fracture-toughness are generally achieved in concrete containing latex admixture. In addition, LMC has higher bond strength because its adhesion to various substrates is better (58).

Compressive strength of LMC is typically similar to conventional portland cement concrete (60). Bentur (61) compared LMC with conventional portland cement concrete on an equal void-to-cement ratio basis and found adding latex to a concrete mix dose not change its compressive strength.

Modulus of elasticity of LMC is lower than conventional portland cement concrete because latex, a polymeric material, is less stiff than the cement paste it replaces (63). Study indicates that LMC will yield a modulus of elasticity that is approximately 85% of conventional concrete made of same materials (60).

### *Durability of Hardened Latex-Modified Concrete*

One of most attractive features of LMC for bridge deck applications is its low permeability. Since latex "seals" the cement paste, blocks its pores, and effectively reduces its permeability, the deleterious substances are prevented from seeping into the paste and the durability of concrete significantly improves (58). Generally, the water absorption and permeability of LMC are a function of the latex content; a higher latex content produces a more impermeable concrete. Another important characteristic of LMC in bridge deck applications is its low permeability to chloride ions derived from applied deicing salts. Field tests have indicated that chloride ion content of LMC is significantly lower at equivalent depths below the bridge deck surface than conventional portland cement concrete (58).

At a latex:cement ratio of 5% or more, LMC exhibits better freezing and thawing resistance than conventional portland cement concrete (64). This is because the reduction of porosity as a result of decreased water:cement ratio used, and the blockage of some pores by polymers as well as air entrainment introduced by polymers. A study (65) indicated that the freezing and thawing durability (as judged by ASTM C 666, Procedure A) of LMC has been greatly improved when the dry cure period was extended from 13 days to 27 days, and an adequate air content was incorporated.

### **2.4.2 Polymer-Impregnated Concrete**

Even in well-cured concrete made with low water:cement ratio the cement paste will still have considerable amount of capillary pores. If water present in the capillary pores could be removed and replaced with some solid material, the strength and durability of the concrete would be greatly improved. This is the basis of polymer-impregnated concrete (PIC).

PIC is a precast and cured hydrated cement concrete that has been impregnated with a liquid monomer. The monomer is subsequently polymerized to form the solid polymer in situ within the pores (66). The amount of polymer needed for complete impregnation depends on the porosity of concrete. A more porous concrete will require more polymer. A monomer should have the following properties in order to be successfully used to produce PIC: low viscosity, relatively high boiling point, ease of polymerization, and low toxicity. Methyl methacrylate (MMA) and styrene are examples of some commonly used monomer (2).

#### *Process Procedure for Polymer-Impregnated Concrete*

Once the concrete has been cast and cured, the basic method of producing PIC requires the following sequence of operations: heat and dry the concrete, impregnate the concrete with liquid monomer, and polymerize the monomer (66).

A temperature of 150°C (302°F) is recommended for drying typical structural concrete. The time of drying depends on the drying temperature, water:cement ratio, and thickness of the concrete. Impregnation with monomer is done by soaking the concrete under liquid monomer over a period of time. The monomers used in PIC can be polymerized either by exposing them to gamma radiation such as a cobalt-60 source or by the use of a catalyst and heat. The later procedure is called thermal-catalytic polymerization (2).

#### *Mechanical Properties of Polymer-Impregnated Concrete*

When compared to conventional portland cement concrete, PIC shows great improvement in compressive, tensile, and bond strength (66, 67). Studies indicated that the role of polymer in PIC is twofold: to increase the strength of the hardened cement paste and to improve the bonding between matrix and aggregate (68,69). As a result, the compressive strength of PIC is increased by factor of 4 to 6, and high tensile strength is obtained. The modulus of elasticity of PIC is approximately twice that of conventional concrete (66).

### *Durability of Polymer-Impregnated Concrete*

The great improvements in durability of PIC were achieved because impregnation with polymer fills the capillary pores. As a result, there is a remarkable reduction in the permeability of the concrete and the depth of penetration of aggressive chemicals is reduced. Finally, the freezing and thawing resistance of PIC is also greatly enhanced because most of the freezable water in the concrete evaporates in the process of drying before impregnation (2).

## 3. MATERIALS

This chapter describes the properties of the materials used in this study. Some of the materials properties presented were provided by the manufacturers or suppliers; most were measured by the author. For the later case, the methods used for the measurements are briefly described.

### 3.1 PORTLAND CEMENT

An ASTM Type I portland cement was used throughout this study. It was produced at the Lone Star Industries, Inc., plant at Greencastle, IN. This cement is widely used in the northwestern part of Indiana.

The chemical composition and the physical characteristics of this cement are presented in Table 3.1. All the data reported in Table 3.1 were measured by the cement manufacturer and provided at the time of the shipment.

The composition of this portland cement is in normal range for Type I portland cement. According to Table 3.1, the potential  $C_3S$  content of this cement is approximately 59%, which is somewhat higher than a mean value for Type I portland cement. On the other hand, the potential  $C_2S$  content for this cement is lower than the usual, about 16%. The potential  $C_3A$  content is also higher than some Type I cement and it is around 10%. A relatively high early age reactivity might be expected because of the higher potential  $C_3A$  content.

### 3.2 ASPHALT EMULSIONS

The asphalt emulsion used throughout this study was a slow setting anionic asphalt emulsion with a harder base asphalt cement used in the emulsion and it was designated as SS-1h. The asphalt emulsion used in this study was supplied by Koch Asphalt Company at Wichita, KS.

The physical data of the SS-1h asphalt emulsion was measured by the supplier and provided at the time of the shipment. These data are presented in Table 3.2.

All calculation for the amount of SS-1h asphalt emulsion used in the asphalt emulsion-modified concrete systems were based on the physical data from Table 3.2.

### 3.3 AGGREGATES

The properties of fine and coarse aggregates used in this study were determined by using the following ASTM test methods:

1. ASTM C 136 - 84 for particle size distribution of fine and coarse aggregates;
2. ASTM C 127 - 84 for bulk specific gravity and absorption of coarse aggregate;
3. ASTM C 128 - 84 for bulk specific gravity and absorption of fine aggregate;
4. ASTM C 29 - 78 for dry rodded unit weight of coarse aggregate.

TABLE 3.1 Chemical Composition and Physical Characteristics of Cement Used in This Study

CHEMICAL ANALYSIS, %		PHYSICAL DATA	
SiO <sub>2</sub>	20.82	Normal Consistency, %	25.5
Al <sub>2</sub> O <sub>3</sub>	5.29	Expansion, %	-0.022
Fe <sub>2</sub> O <sub>3</sub>	2.12	Air content of mortar	11.4
CaO	64.87	Setting Time:	
MgO	1.35	Gillmore	
SO <sub>3</sub>	3.04	Initial, Hr:Min	1:30
Na <sub>2</sub> O	0.12	Final, Hr:Min	2:40
K <sub>2</sub> O	0.58	Vicat, Min	100/200
T.A. as Na <sub>2</sub> O	0.50	Fineness:	
Ignition Loss	1.74	#325, % Passing	89.0
Insol. Residue	0.33	Wagner, cm <sup>2</sup> /g	2120
		Blaine, cm <sup>2</sup> /g	3970
Potential Compound Composition, %		Compressive Strength, psi	
C <sub>3</sub> S	58.60	1 Day	2100
C <sub>2</sub> S	15.55	3 Days	3880
C <sub>3</sub> A	10.44	7 Days	4880
C <sub>4</sub> AF	6.43	28 Days	6380
CaSO <sub>4</sub>	5.17		

TABLE 3.2 Physical Characteristics of SS-1h Asphalt Emulsion Used in This Study

Particle Charge	Negative
Specific Gravity @ 60°F	1.0028
Pounds Per Gallon	8.351
Viscosity, Saybolt Furol @ 77°F, sec.	21.2
Residue by Evaporation, %	60.3
Penetration @ 77°F, 100 g, 5 sec., dmm	91



The results of these tests are given in Tables 3.3 and 3.4.

The fine aggregate used in this study was local siliceous pit sand. The selected physical properties and sieve analysis of this sand are provided in Table 3.3.

The coarse aggregate used in this study was clean crushed limestone supplied by Verplank Concrete & Supply Inc., of West Lafayette, IN. This coarse aggregate was determined to be the No. 11 aggregate,  $d_{max} = 12$  mm (1/2 in.) according to Section 903 of Indiana Department of Highways Standard Specifications. The selected physical properties and sieve analysis data for this coarse aggregate are given in Table 3.4.

### 3.4 ADMIXTURES

The superplasticizer used in this study was the Pozzolith 440-N by Master Builders Technology, Inc., and it is a naphthalene sulfonate type of superplasticizer. This superplasticizer meets requirements of ASTM C - 494 for Type

TABLE 3.3 Physical Properties and Gradation of Fine Aggregate

ASTM Sieve Designation	Cumulative Weight Percent	
	Retained	Passing
3/8"	0	100
No. 4	0	100
No. 8	6	94
No. 16	26	74
No. 30	59	41
No. 50	87	13
No. 100	96	4
No. 200	99	1
Pan	100	0

TABLE 3.4 Physical Properties and Gradation of Coarse Aggregate

ASTM Sieve Designation	Cumulative Weight Percent	
	Retained	Passing
1/2"	0	100
3/8"	22	78
No. 4	85	15
No. 8	99	1
Pan	100	0

High range water-reducing admixtures. The normal dosage rate range recommended by manufacturer is 650 to 1625 ml per 100 kg (10 to 25 fl. oz. per 100 lbs) of cementitious materials. However, the dosage rate range used for this study was 1300 to 1955 ml per 100 kg (20 to 30 fl. oz. per 100 lbs) of cement, because these amounts of superplasticizer were found necessary to provide the desirable workability.

It was also found that an air detrainng agent was needed in this study to reduce the excessive amount of air formed in the asphalt emulsion modified-concrete systems during mixing. The material used was purified *n*-butyl phosphate from Fisher Scientific. The quantity of air detrainng agent used was adjusted as necessary to reduce the content of air entrained in the fresh asphalt emulsion modified-concrete mixes to about 6 percent.

#### 4. PRELIMINARY STUDY AND FINDINGS

To the best of the knowledge of this investigation, there was no previous work published on asphalt emulsion-modified concrete systems. Thus, a preliminary study was conducted on selected asphalt emulsion-portland cement mortars to determine their compressive strength. Mortars were prepared by selecting constant proportions of portland cement and fine aggregate and varying the amount of asphalt emulsion from 5% to 40%, with increment of 5% asphalt emulsion in each set of mortars. The compressive strength of these asphalt emulsion-portland cement mortars was then determined.

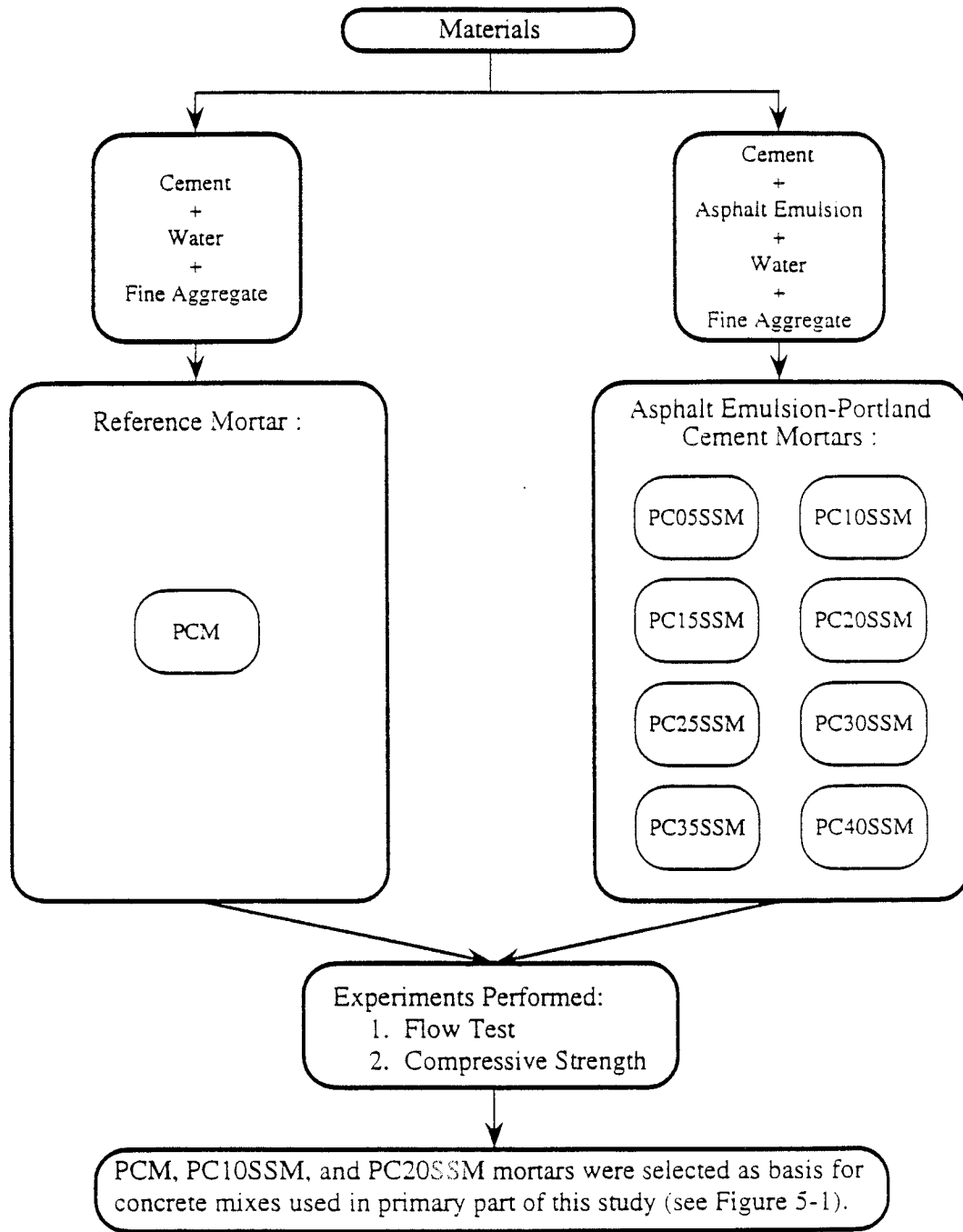
##### 4.1 PREPARATION OF MORTARS

General outline of experiments performed in this portion of the study is summarized in the flow chart shown in Figure 4.1.

Nine mortar mixes were prepared for the preliminary study. These sets are listed below:

1. Plain portland cement mortar (PCM) as the reference;
2. Mortar of portland cement plus 5% of SS-1h asphalt emulsion (PC05SSM);
3. Mortar of portland cement plus 10% of SS-1h asphalt emulsion (PC10SSM);
4. Mortar of portland cement plus 15% of SS-1h asphalt emulsion (PC15SSM);
5. Mortar of portland cement plus 20% of SS-1h asphalt emulsion (PC20SSM);
6. Mortar of portland cement plus 25% of SS-1h asphalt emulsion (PC25SSM);
7. Mortar of portland cement plus 30% of SS-1h asphalt emulsion (PC30SSM);
8. Mortar of portland cement plus 35% of SS-1h asphalt emulsion (PC35SSM);
9. Mortar of portland cement plus 40% of SS-1h asphalt emulsion (PC40SSM).

The percent of asphalt emulsion added to these mixes was based on the weight of the cement. The water:cement ratio for these mortar mixes was 0.48; however, the actual amount of water added to each mix was adjusted according to the amount of SS-1h asphalt emulsion as well as the moisture content of fine aggregate. Since the SS-1h asphalt emulsion used for this study contains 40% water, this amount of water was included in the calculation, and replaced parts of water that should otherwise have been added into these mixes. For example, a mortar mix with 10 lbs of portland cement and 10% SS-1h asphalt emulsion will contain 1 lb of asphalt emulsion, of which 0.4 lb is water. The specific compositions of each of the 9 mixes used for the preliminary study are given in Table 4.1.



**FIGURE 4.1** Flow Chart for the Mortar Specimens Prepared and Experiments Performed during the Preliminary Study

TABLE 4.1 Batch Weight Compositions of Mortar Mixes Used for the Preliminary Study

Mix	Materials (kg)*					
	w:cm	Cement	Asphalt Emulsion	Water from Emulsion	Water Added	Fine Aggregate**
PCM	0.48	0.80	0	0	0.39	2.10
PC05SSM	0.48	0.80	0.04	0.02	0.37	2.10
PC10SSM	0.48	0.80	0.08	0.03	0.35	2.10
PC15SSM	0.48	0.80	0.12	0.05	0.34	2.10
PC20SSM	0.48	0.80	0.16	0.06	0.32	2.10
PC25SSM	0.48	0.80	0.20	0.08	0.30	2.10
PC30SSM	0.48	0.80	0.24	0.10	0.29	2.10
PC35SSM	0.48	0.80	0.28	0.11	0.27	2.10
PC40SSM	0.48	0.80	0.32	0.13	0.26	2.10

\* 1 kg = 2.2 lb

\* The ratio of fine aggregate to cement was kept constant at 2.625. This ratio was selected so the results of this study can be directly compared with the results of the study on properties of latex-modified concrete reported elsewhere (58).

\*\* The correction for moisture content of fine aggregate was not included in Table 4.1. The moisture content of fine aggregate was determined prior to each mixing according to the method listed as Note 2 of ASTM C 566 - 84. When the moisture content of the fine aggregate was found to be above or below its absorption capacity (1.85% for the fine aggregate used in this study), necessary adjustments were made.

All mortar mixes were prepared in the laboratory using a mortar mixer manufactured by Hobart. All mortars were mixed in accordance with the standard procedure of ASTM C 305 - 82. Prior to the start of mixing, a dry paddle and bowl were installed in the mixer. Then all of the mixing water containing previously dissolved asphalt emulsion was placed in the bowl. Then, all of cement was added to the content of the bowl, and mixed for 30 seconds at slow speed ( $140 \pm 5$  rev/min). Next, the entire quantity of sand was slowly added over a 30 second period while

continuing mixing at slow speed. Next, the mixer was stopped and the mixing speed was changed to medium ( $285 \pm 10$  rev/min), and mixing continued for another 30 seconds. Finally, the mixer was stopped and the mortar was left standing for one and half minutes, followed by another minute of mixing at medium speed.

The flow of each mix was measured immediately after completion of mixing in accordance with the procedure listed in Section 10.3 of ASTM C 109 - 87. The flow table used to determine the flows of these mortars satisfied all requirements described in ASTM C 230.

The freshly mixed mortars were placed into 50 x 50 x 50 mm (2 x 2 x 2 in.) steel molds, covered with plastic sheets, and kept in exposed laboratory air for 24 hours. These mortar specimens were then demolded and transferred to the fog room for continuation of curing.

## 4.2 COMPRESSIVE STRENGTH TEST FOR MORTARS

The compressive strength test for mortars was performed according to the standard method of ASTM C 109 - 87. The size of mortar specimens used for the compressive strength test in this study was a 50 x 50 x 50 mm (2 x 2 x 2 in.) cube.

All mortar specimens were tested using a Satec hydraulic universal testing machine (Model M100BTE) with 445 kN (100,000 lbs) capacity. This testing machine was equipped with computerized control and data acquisition system. The loading rate of the testing machine used depended on the age of the mortar specimens. The loading rate was 67 kN/min (15,000 lbs/min) or about 26 MPa/min (3,750 psi/min) for mortar specimens with a test age of 3 days, and 89 kN/min (20,000 lbs/min) or about 34 MPa/min (5,000 psi/min) for specimens with a test age of 7 days. Different loading rates were used at different test ages so that the maximum load can be reached in 20 to 80 seconds from start of loading, as required by ASTM 109 - 87.

### 4.3 PRELIMINARY EXPERIMENTAL RESULTS

The test results for the compressive strength and the measured flow of all mortars are summarized in Table 4.2. The compressive strength testing results are also presented graphically in Figure 4.2.

TABLE 4.2 Compressive Strength of Asphalt Emulsion-Portland Cement Mortars

Mix	Flow (%)	Compressive Strength (MPa)* at:	
		3 days	7 days
PCM	126	28.9	36.0
PC0SSM	110	14.8	20.2
PC10SSM	114	12.7	17.4
PC15SSM	110	12.4	16.4
PC20SSM	104	12.3	16.5
PC25SSM	101	12.2	16.5
PC30SSM	87	12.1	15.6
PC35SSM	83	12.1	15.7
PC40SSM	79	12.0	15.5

\* 1 MPa = 145 psi

#### *Mortar Flow*

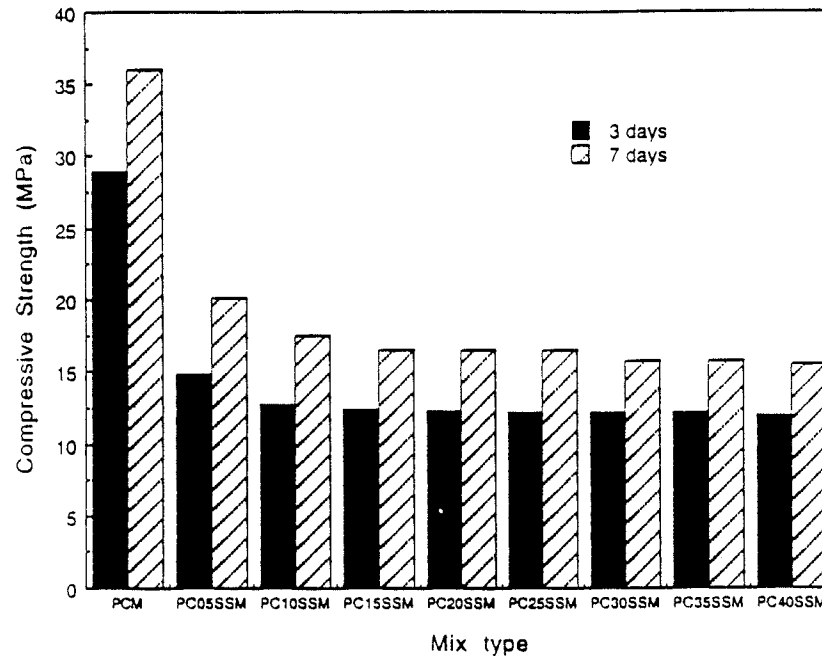
It is apparent from Table 4.2 that the flow of all asphalt emulsion-portland cement mortars was lower than the flow of the plain reference mortar. In addition, as the percent of asphalt emulsion added into the mortar mix increased, the flow of the mortar mix decreased. Therefore, it can be concluded that addition of SS-1h asphalt emulsion reduced the workability of the mortar mixes.

#### *Compressive Strength of the Mortars*

As shown in Table 4.2 and Figure 4.2, the compressive strength of the reference mortar is much higher than that of the asphalt emulsion-portland cement mortars. Even the smallest dose of SS-1h asphalt emulsion used reduced both 3 and 7 days compressive strength of the asphalt emulsion-portland cement mortar substantially. Increasing additions of asphalt emulsion further reduced the compressive strength of the mortar.

#### *Selection of Mix Designs*

Based on the test results presented, two mix designs, 10% and 20% SS-1h asphalt emulsion by the weight of cement, were selected for all future studies, which were conducted using concrete rather than mortar mixes. The preparation of concrete mixes is described in Chapter 5. The mix design of 10% SS-1h asphalt emulsion was selected because



**FIGURE 4.2 Compressive Strength versus Reference Mortar and Asphalt Emulsion-Portland Cement Mortars at 3 and 7 days**

it was thought to provide a sufficient amount of asphalt emulsion to modify a concrete system and its workability. Also, the compressive strength was acceptable as compared to the reference mortar. The mix design containing 20% SS-1h asphalt emulsion was selected for comparison purposes.

## 5. EXPERIMENTAL PROCEDURES

This chapter describes the experimental procedures used in the course of this study. Most of the procedures used were common ASTM standard methods. For such experimental procedures, only the ASTM designation codes are provided. Detailed descriptions are given for those test methods which are not standard or commonly used ASTM procedures, so that the measurement can be accurately repeated.

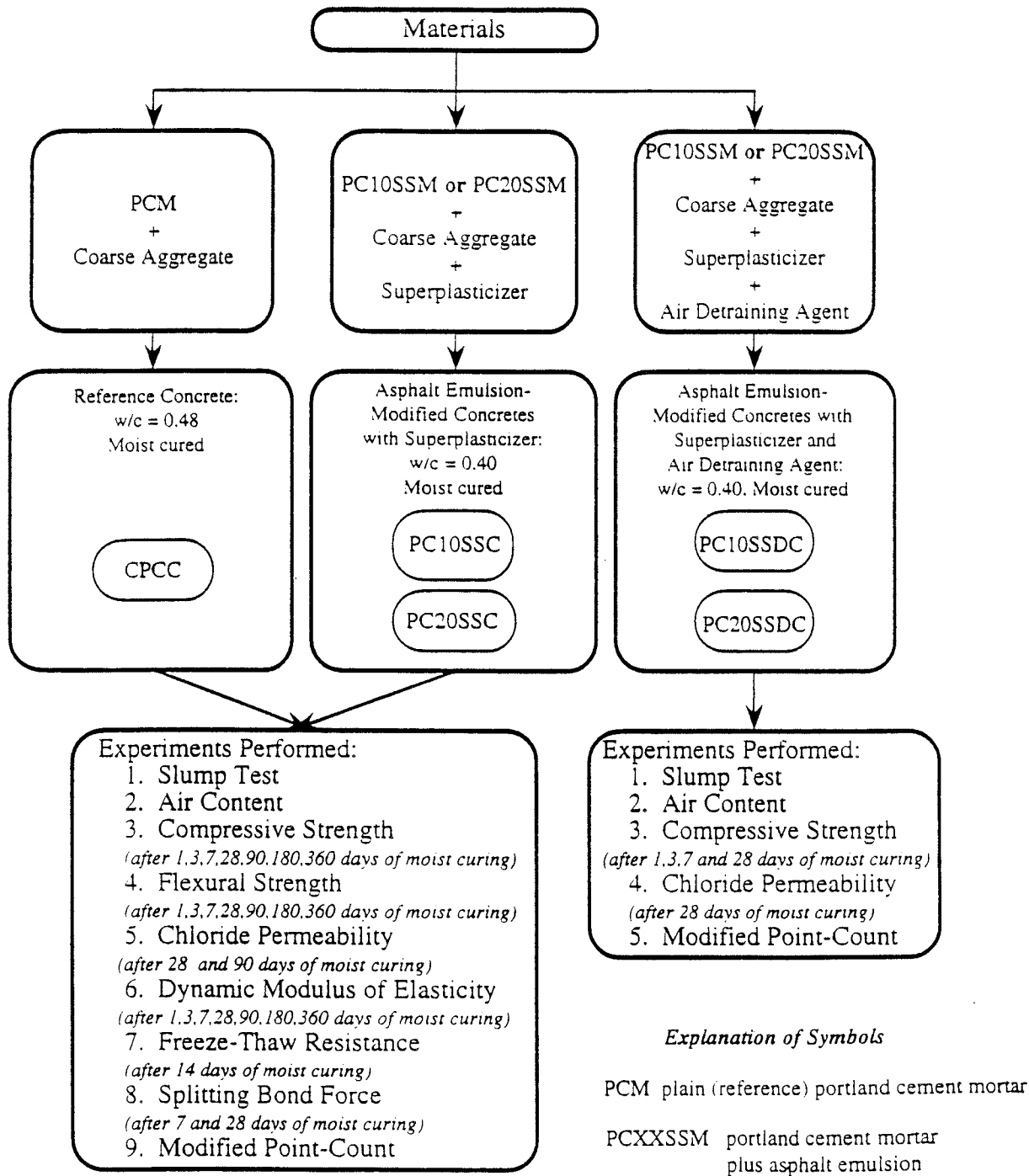
A summary of all the samples used and experiments performed in this study is provided in Figure 5.1.

### 5.1 PREPARATION OF CONCRETE MIXES

There were a total of five concrete mixes prepared for this study. These five mixes are described below:

1. Conventional portland cement concrete (CPCC) as the reference;
2. Asphalt emulsion-modified concrete with 10% of SS-1h asphalt emulsion and a naphthalene sulfonate superplasticizer (PC10SSC);
3. Asphalt emulsion-modified concrete with 20% of SS-1h asphalt emulsion and a naphthalene sulfonate superplasticizer (PC20SSC);





**FIGURE 5.1** Flow Chart for the Concrete Specimens Prepared and Experiments Performed during the Primary Study

4. Asphalt emulsion-modified concrete with 10% of SS-1h asphalt emulsion and a naphthalene sulfonate superplasticizer and an air detraining agent (PC10SSDC);
5. Asphalt emulsion-modified concrete with 20% of SS-1h asphalt emulsion and a naphthalene sulfonate superplasticizer and an air detraining agent (PC20SSDC).

The percent of asphalt emulsion added to the asphalt emulsion-modified concretes was based on the weight of the cement. The water:cement ratio for the reference concrete was 0.48. The water:cement ratio for all asphalt emulsion-modified concretes was reduced to 0.40, so higher compressive strength could be obtained. The amount of portland cement added to all concrete mixes was kept constant. However, the amount of water added to the concrete mixes was adjusted according to the percent of asphalt emulsion used in a concrete, as well as the moisture content of fine and coarse aggregates. Since the SS-1h asphalt emulsion used for this study contained 40% water, an equivalent amount of water was subtracted from the mix water. The actual amount of water added into concrete mix was also affected by the moisture content of fine and coarse aggregates. When the moisture content of fine and coarse aggregates was below their absorption capacities, extra water was added into concrete mix to bring aggregates to the correct moisture level. In cases where moisture content of the aggregates was higher than their absorption capacity, the appropriate amount of water was subtracted. The specific composition of each of the five concrete mixes used in this study is provided in Table 5.1.

All concrete mixes were prepared in the laboratory by using a Lancaster pan type mixer with  $0.1 \text{ m}^3$  (4.0 cu. ft) nominal capacity. The volume of the concrete mixed at a given time was about  $0.03 \text{ m}^3$  (0.40 cu. yd). It should be noted that pan mixing in a controlled laboratory environment probably produces a more uniform mix than mixing under field conditions.

All concrete mixes were mixed in accordance with the standard method listed in ASTM C 192. Before starting rotation of the mixer, coarse aggregate and 1/3 of mixing water were placed in the mixing pan. Then, the mixer was started, and sand, cement, and remaining mixing water were added to the running mixer. The SS-1h asphalt emulsion(if used), superplasticizer (if used), and air detraining agent (if used) were dissolved in the mixing water before it was added into the mixer. After all ingredients were placed in the mixer, the concrete was mixed for 3 minutes followed by a 3-minute rest period, then it was mixed for 2 additional minutes.

The slump of each mix was determined in accordance with ASTM C 143 standard method. The slump of each concrete mix was measured immediately after completion of mixing operation and again 5 minutes after the mixing was completed. Furthermore, the air content of each fresh concrete mix was determined according to the standard pressure method of ASTM C 231.

## 5.2 CASTING AND CURING OF CONCRETE SPECIMENS

After the slump and air content of a fresh concrete mix were measured, the mix was placed into plastic molds in three equal layers and consolidated by rodding each layer 25 times using a 9.5 mm (3/8 in.) diameter steel rod. For compressive strength test of the CPCC, PC10SSC, and PC20SSC mixes, five 75 x 150 mm (3 x 6 in.) test cylinders were cast in plastic molds. For the PC10SSDC and PC20SSDC mixes, three 75 x 150 mm (3 x 6 in.) test cylinders were cast.

For the flexural strength test, three 75 x 75 x 380 mm (3 x 3 x 15 in.) test beams were cast in steel molds. Only the CPCC, PC10SSC, and PC20SSC mixes were cast for flexural strength test. The slump and air content of the mixes were measured first and then the fresh concrete was placed into steel molds in two equal layers and consolidated by rodding each layer 45 times with 9.5 mm (3/8 in.) diameter steel rod.

TABLE 5.1 Batch Weight Compositions of Concrete Mixes Used in This Study

Mix	Materials (kg)*								
	w/cm	Cement	Asphalt Emulsion	Water from Emulsion	Water Added	Fine Aggregate**	Coarse Aggregate***	SP (ml)	Air Detraining Agent
CPCC	0.48	11.92	-	-	5.72	31.24	20.10	-	-
PC10SSC	0.40	11.92	1.19	0.48	4.30	31.24	20.10	155	-
PC20SSC	0.40	11.92	2.38	0.95	3.82	31.24	20.10	233	-
PC10SSDC	0.40	11.92	1.19	0.48	4.30	31.24	20.10	155	0.0119
PC20SSDC	0.40	11.92	2.38	0.95	3.82	31.24	20.10	233	0.0119

\* The basic composition of plain, unmodified concrete used in this study was adopted from the previously completed program on latex emulsion modified concrete (58). Use of the same basic proportions was adopted in order to allow for a more direct comparison of the effect of both asphalt and latex emulsions on various properties of concrete.

\*\* The correction for moisture content of fine aggregate was not included in Table 5.1. The moisture content of fine aggregate was determined prior to each mixing according to the method listed as Note 2 of ASTM C 566-84. When the moisture content of the fine aggregate was found to be above or below its absorption capacity (1.85% for the fine aggregate used in this study), necessary adjustments were made.

\*\*\* The correction of moisture content for coarse aggregate was not included in Table 5.1. The moisture content of coarse aggregate was determined prior to each mixing according to the method listed as Note 2 of ASTM C 555-84. When the moisture content of the coarse aggregate was found to be above or below its absorption capacity (1.28% of the coarse aggregate used in this study), necessary adjustments were made.

1 kg = 2.2 lb

1 ml = 0.061 in<sup>3</sup>

Two 9.5 x 150 mm (3.75 x 6 in.) test cylinders were cast in steel molds for all five mixes for the chloride permeability test. Freshly mixed concrete was placed into these steel molds in three equal layers and each layer was consolidated by rodding 25 times using the 9.5 mm (3/8 in.) diameter steel rod.

For the freeze-thaw resistance test, two 75 x 75 x 380 mm (3 x 3 x 15 in.) test beams were cast in the same way as the flexural strength test beams. This test was only performed on CPCC, PC10SSC, and PC20SSC mixes. The test specimens used for the modified point-count test were prepared in the same way as those cylinders used for the compressive strength test. The modified point-count test was done on all five mixes.

Three 100 x 100 x 100 mm (4 x 4 x 4 in.) test cubes were cast in cubic steel molds for the splitting bond test. This test was only done on CPCC, PC10SSC, and PC20SSC specimens. The reference concrete mix was cast into the bottom half of all cubic steel molds, covered with plastic sheets, and cured in laboratory air for one week. After a week, the top half of each cubic steel mold was filled with either CPCC, PC10SSC, or PC20SSC mix. When casting either the bottom or the top half of the specimens, concrete was placed into the molds in two layers. Each layer was consolidated by rodding 25 times with a 9.5 mm (3/8 in.) diameter steel rod.

After casting, all specimens were covered with plastic sheets and cured in laboratory air for 24 hours. They were then demolded. Finally, all specimens were transferred to a 100% relative humidity fog room and stored there until testing time.

### 5.3 TESTING OF HARDENED CONCRETE SPECIMENS

A description of each type of test performed on hardened concrete is presented in this section.

#### 5.3.1 Air Content

The objective of this test was to determine the air content of all five concrete series used in this study. The "Modified Point-Count Method", described in ASTM C 457, was used during this test.

Before the test specimen could be used for microscopical observation, it was necessary to prepare it by using the technique described below. First, the 75 x 150 mm (3 x 6 in.) test cylinders were sawed in half longitudinally. Then, the sawed surfaces were ground on a lapping-wheel with progressively finer abrasives. Abrasives used were No. 100 silicon carbide power, followed by No. 240 silicon carbide powder, and No. 600 aluminum oxide powder. Then, specimens were ground with No. 800 and then No. 1000 silicon carbide on a flat glass plate. All surfaces of specimens were washed and scrubbed thoroughly with a brush after each grinding operation to remove grit and loose particles of concrete. When a surface viewed in strong light incident at a low angle appeared to be essentially plane, the surface was then considered as satisfactory for microscopical observation.

After the preparations of the test specimen was completed, the point-count test was performed according to the procedure of "Modified Point-Count Method". The magnification of the microscope used for the point-count test was 60x. The dimensions of the examined specimens' surfaces were approximately 70 x 140 mm (2.75 x 5.50 in.).

#### 5.3.2 Compressive Strength

Compressive strength testing was carried out using the 75 x 150 mm (3 x 6 in.) test cylinders, following the standard method of ASTM C 39 - 86. Prior to testing, all test cylinders were capped with a commercial sulfur mortar capping compound according to the general procedure given in ASTM C 617 - 85.

All test specimens used in this study were tested with a Satec hydraulic universal testing machine, Model M100BTE. This testing machine has 4,500 kN (100,000 lbs) capacity and is equipped with computerized control and data acquisition system. All of the compression tests were performed using the loading rate of 67 kN/min (15,000

lbs/min), or approximately 14.5 MPa/min (2120 psi/min).

### 5.3.3 Flexural Strength

Flexural strength testing was done in accordance with the procedure given in ASTM C 78 - 84 (simple beam with third-point loading). All 75 x 75 x 380 mm (3 x 3 x 15 in.) concrete beams were tested using the Satec hydraulic universal testing machine of 530 kN (120,000 lbs) capacity. The loading was applied at a rapid rate to the test specimens, up to approximately 50% of the breaking load. Thereafter, a continuous loading rate of 1 MPa/min (150 psi/min) was applied to the test specimens until failure.

When the fracture of the test specimens initiated in the tension surface was within the middle third of the span length, the modulus of rupture was calculated using the following equation:

$$R = \frac{Pl}{bd^2}$$

where: R = modulus of rupture, MPa (psi)  
 P = maximum applied load indicated by testing machine, N (lbf)  
 l = span length, mm (in.)  
 b = average width of specimen, mm (in.)  
 d = average depth of specimen, mm (in.)

When the fracture of the specimen occurred on the tension surface was outside of the middle third of the span length by not more than 5% of the span length, the modulus of rupture was calculated as follows:

$$R = \frac{3Pa}{bd^2}$$

where: a = average distance between line of fracture and the nearest support measured on the tension surface of the beam, mm (in.)

### 5.3.4 Chloride Ion Permeability

The chloride ion permeability (chloride permeability) of all specimens was measured according to the procedure described in AASHTO Designation T 277 - 83, "Rapid Determination of the Chloride Permeability of Concrete". This method provides a measurement of the relative permeability of concrete samples to chloride ions. It involves monitoring the amount of electrical current passing through a 95 mm (3.75 in.) diameter by 50 mm (2 in.) long core when one end of the core is in contact with a 3.0 percent NaCl solution, while the other end is in contact with a 0.3N NaOH solution, and a potential difference of 60 V DC is maintained across the specimen for 6 hours. The total charge, in coulombs, passed through the specimens at the end of 6th hour is the actual parameter measured. This value is used as a relative measure of the chloride permeability.

Two 2 in.-thick slices were cut from the 95 x 150 mm (3.75 in. x 6 in.) cylindrical specimens at a given test age to use as test specimens for the chloride permeability test. The sides of the test specimens were coated with a rapid setting epoxy from Adhesive Engineering Company at San Carlos, CA. Then, one of test specimens was placed in a 1000 ml beaker in the desiccator, vacuumed, and kept under the vacuum for 3 hours. Next, the previously boiled deionized water was added to cover the specimen and the vacuum was maintained for another hour. Finally, air was allowed to reenter the desiccator, the test specimen was transferred to the beaker and soaked under water for 18 ± 1 hours. The second test specimen was prepared using the same procedure.

After having been soaked for 18 ± 1 hours, the test specimen was mounted onto the test cell with silicone rubber sealer. Next, one side (-) of the cell was filled with 3.0 percent NaCl solution, and the other side (+) of the cell was

filled with 0.3N NaOH solution. Then,  $60.0 \pm 0.1$  V DC current was applied to the test cell. The resulting current flow was recorded over a period of 6 hours and integrated to give the total charge passed through test specimen during this time.

All chloride permeability tests were performed using a Model 159 Chloride Permeability Test Set produced by RLC Instrument Co. in Akron, OH. All the measurements and integration were done automatically by this machine. Furthermore, the machine also provided a printout of time, current, and accumulated charge passed every 30 minutes, and automatically terminated the test at the end of six hours.

### 5.3.5 Dynamic Modulus of Elasticity

The dynamic modulus of elasticity of all specimens was determined using the fundamental transverse frequency method.

The instrument used to measure the fundamental transverse frequency was the Grindo-Sonic Meter (Type MK4x), manufactured by J.W. Lemmens, Inc. The measurements of the fundamental transverse frequency were made by following the instructions provided by the manufacturer. First, the supports were placed at the nodal zones of the test specimen. Next, the instrument's detector pin was placed in contact with the surface of the specimen. For maximum sensitivity, the detector pin was held in the direction of the vibrations. Finally, the surface of the specimen was stricken with a screwdriver handle, and the fundamental transverse frequency displayed on the instrument was recorded.

The recorded fundamental transverse frequency of the specimen was then transferred into a computer program provided by the manufacturer. This program was used to calculate the dynamic modulus of elasticity of the specimen. The dynamic modulus of elasticity was calculated based on the following formula (70):

$$\text{Dynamic E} = CWn^2$$

where: W = weight of specimen, kg (lb)  
 n = fundamental transverse frequency, Hz  
 C =  $0.00245 (L^3T/bt^3)$ ,  $s^2/m^2$  ( $s^2/in.^2$ ) for a prism  
 L = length of specimen, mm (in.)  
 t, b = dimensions of cross section of prism, in., t being in the direction in which it is driven  
 T = a correction factor which depends of the ratio of the radius of gyration, K ( $t/3.464$  for prism), to the length of the specimen, L, and on Poisson's ratio.

The measurements of the fundamental transverse frequencies were performed on the same 75 x 75 x 380 mm (3 x 3 x 15 in.) test beams which were later used for the flexural strength test.

### 5.3.6 Freeze-Thaw Resistance

The freeze-thaw resistance test for all specimens was done according to Procedure A of ASTM C 666 - 84. Test specimens were completely immersed in water at all times while they were subjected to freezing-and-thawing cycles. The freeze-thaw machine used for this test was manufactured by Logan Freeze-Thaw Mfg. Co. in Logan, Utah.

All the specimens were cured in the 100% relative humidity fog room for 14 days before testing. At the end of 14th day, the fundamental transverse frequency of the test beams at zero cycle of freezing-and-thawing was measured. Test specimens were then placed in the freeze-thaw machine and freezing-and-thawing cycles begin. Afterwards, the fundamental transverse frequency of the test beams was measured at intervals of every 30 cycles, at which time the specimen was at the end of the thawing stage. The testing continued for the full 300 cycles, as recommended by



ASTM C 666.

The fundamental transverse frequency of the test beams for the freeze-thaw resistance test was measured the same way as described in Section 5.3.5. However, the values measured from the freeze-thaw resistance test were used to calculate the relative dynamic modulus of elasticity, and the durability factor of the specimens, instead of the dynamic modulus of elasticity.

### 5.3.7 Splitting Bond Force

The purpose of this test was to determine the amount of force required to split a 100 mm (4 in.) cubic specimen, consisting of a 50 x 100 x 100 mm (2 x 4 x 4 in.) CPCC specimen binding with another 50 x 100 x 100 mm (2 x 4 x 4 in.) CPCC, PC10SSC, or PC20SSC specimen, as shown on Figure 5.2. No standard method was available to use as a guide for this test.

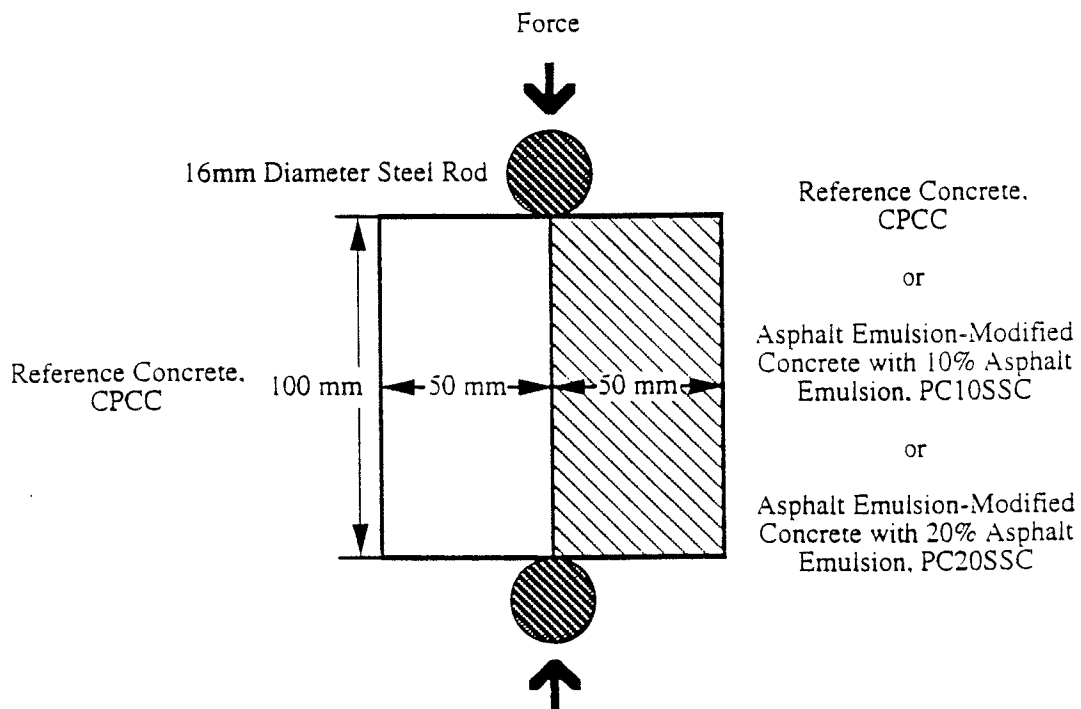


FIGURE 5.2 Technique Used to Measure the Splitting Bond Forces of CPCC-CPCC, CPCC-PC10SSC, and CPCC-PC20SSC Test Specimens

The splitting bond force test was performed on specimens at ages 7 and 28 days. All 100 x 100 x 100 mm (4 x 4 x 4 in.) cubic specimens were tested using the Satec hydraulic universal testing machine. Two 16 mm (5/8 in.) diameter steel rods were used as the contact points.

At the start of the splitting bond force test, a test specimen was placed in the center of the testing machine with molded surfaces facing the top and bottom crossheads of the testing machine respectively. Next, the steel rods were placed on the top and bottom of the specimen and aligned with the center of the specimen (the binding interface) as shown on Figure 5.2. Then, a small load was applied to the sample to secure the position of the steel rods and the specimen. The final loading of the specimen alignment was performed at this time. The loading was then applied at a rapid rate, up to approximately 50% of the breaking load. Then, a constant loading at a rate of 1 MPa/min (150 psi/min) was applied continuously to the cubic specimen until it split into two pieces. The maximum load applied was then recorded as the force required to split at the "binding interface" of the cubic specimen.

## 6. EXPERIMENTAL RESULTS

The study described in this chapter was carried out in two phases. During the first phase, which was the major part of this work, properties of the asphalt emulsion-modified concrete with superplasticizer were studied. In the second phase, the less intensive part of the study, a detraining agent was introduced into the asphalt emulsion-modified concrete to study its effects on the concrete's compressive strength and chloride permeability.

### 6.1 PROPERTIES OF FRESH CONCRETES

#### 6.1.1 Water-Cement Ratio

In developing the mix proportions for this study, the water:cement ratios of the reference concrete and the asphalt emulsion-modified concretes were set at 0.48 and 0.40 respectively. Superplasticizer was added to the asphalt-emulsion modified concrete mixes to acquire slumps of 75 to 150 mm (3 to 6 inches). Trial mixes were carried out to find the proper amount of superplasticizer needed in the asphalt emulsion-modified concrete mixes to yield the desired slump.

#### 6.1.2 Properties of Fresh Asphalt Emulsion-Modified Concretes with Superplasticizer

The properties of fresh asphalt emulsion-modified concretes with superplasticizer and those of fresh reference concrete (CPCC) are summarized in Table 6.1. Each slump value in the table represents an average of four measurements performed on separate batches of the same composition, while each air content value is an average of three measurements. Furthermore, the air contents reported in Table 6.1 are the actual air contents, that is, they are corrected for aggregate void space.

From the data presented in Table 6.1, it is clear that the addition of superplasticizer to the asphalt emulsion-modified concrete mixes greatly enhanced their initial workability. However, the slump reduction for the asphalt emulsion-modified concrete mixes 5 minutes after completion of mixing was greater than that of the reference concrete. The slump reduction 5 minutes after completion of mixing for CPCC, PC10SSC, and PC20SSC were 13%, 45%, and 27% respectively. Thus, incorporation of superplasticizer into asphalt emulsion-modified concrete mixes has provided good initial workability. However, this workability quickly diminished. In the case of the PC10SSC mix, the slump reduction was so severe that 5 minutes after completion of mixing its workability was considered undesirable.

As shown in Table 6.1, the air content of the asphalt emulsion-modified concrete mixes was much higher than that of the reference concrete. Also, the PC20SSC mix had a higher air content than the PC10SSC mix. Hence, the addition of SS-1h asphalt emulsion used in this study resulted in a concrete mix with very high air content. In

TABLE 6.1 Summary of Properties of Fresh Asphalt Emulsion-Modified Concretes with Superplasticizer and Fresh Reference Concrete

Mix	w:cm	Slump (mm)*		Air Content (%)
		S <sub>1</sub> **	S <sub>2</sub> **	
CPC	0.48	95	94	3.0
PC10SSC	0.40	100	56	10.0
PC20SSC	0.40	150	110	11.8

\* 1 mm = 0.0394 in.

\*\* S<sub>1</sub> is the slump immediately after completion of mixing;  
S<sub>2</sub> is the slump 5 minutes after completion of mixing.

addition, the air content increased with the increased dosage of the asphalt emulsion.

### 6.1.3 Properties of Fresh Asphalt Emulsion-Modified Concretes with Superplasticizer and Air Detraining Agent

The properties of fresh asphalt emulsion-modified concretes containing superplasticizer and air detraining agent are presented in Table 6.2. Each value in the table represents an average of two measurements performed on separate batches of the same composition. The air contents reported in this table are the actual air contents after correction for the aggregate void space.

TABLE 6.2 Summary of Properties of Fresh Asphalt Emulsion-Modified Concretes with Superplasticizer and Air Detraining Agent

Mix	w:cm	Slump (mm)*		Air Content (%)
		S <sub>1</sub> **	S <sub>2</sub> **	
PC10SSDC	0.40	75	50	3.60
PC20SSDC	0.40	135	96	6.00

\* 1 mm = 0.0394 in.

\*\* S<sub>1</sub> is the slump immediately after completion of mixing;  
S<sub>2</sub> is the slump 5 minutes after completion of mixing.

Comparing the results from Tables 6.1 and 6.2, it can be seen that at the same water:cement ratio, the addition of air detraining agent slightly reduced the workability of asphalt emulsion-modified concrete mixes. As seen in Table 6.2, the slump of PC10SSDC mix was only 75 mm (3 in.) when measured immediately after completion of mixing compare to 100 mm (4 in.) reported in Table 6.1 for the same mix but without the detraining agent. Furthermore, the slump was reduced to as low as 50 mm (2 in.) when measured 5 minutes after completion of mixing. Despite this low slump, the PC10SSDC mix was not difficult to place. The workability for PC20SSDC mix which contained more superplasticizer remained satisfactory throughout the entire placing and finishing operation.

As shown on Table 6.2, the addition of air detraining agent greatly reduced the air contents of asphalt emulsion-modified concrete mixes. By incorporating a very small amount of air detraining agent into a asphalt emulsion-modified concrete mix (0.1% by the weight of cement), the actual reduction in the air content was approximately 6%. As a result, the air content of PC10SSDC become as low as the one for CPC (~3%), and the air content of PC20SSDC was reduced to 6%. Therefore, it can be concluded that the addition of air detraining agent successfully eliminated most of extra air introduced by the emulsifying agent in an asphalt emulsion-modified concrete.

## 6.2 AIR CONTENT

The purpose of this experiment was to determine the air contents of hardened reference concrete, CPCC; hardened asphalt emulsion-modified concretes with superplasticizer, PC10SSC and PC20SSC; and hardened asphalt emulsion-modified concretes with superplasticizer and air detrainning agent, PC10SSDC and PC20SSDC. A summary of the test results presented in Table 6.3.

TABLE 6.3 Air Content of Hardened Reference Concrete, Asphalt Emulsion-Modified Concretes with Superplasticizer, and Asphalt Emulsion-Modified Concretes with Superplasticizer and Air Detrainning Agent

Mix	Air Content (%)
CPCC	2.2
PC10SSC	8.3
PC20SSC	10.1
PC10SSDC	2.8
PC20SSDC	4.3

The results shown in Table 6.3, air content of hardened concrete for all five type of mixes, was compared to their respective air content during the "fresh stage" shown in Tables 6.1 and 6.2. It has been observed that there were reduction in air content for hardened concretes ranging from 0.77% to 1.75%. Yet, hardened CPCC concrete still has the lowest air content, followed by PC10SSDC, PC20SSDC, PC10SSC, and PC20SSC concretes respectively.

The air contents of fresh PC10SSC and PC20SSC concrete mixes were high because the emulsifying agent from SS-1h asphalt emulsion entrained large amount of air in these mixes. The data presented in Table 6.3 clearly indicate that those excessive amount of air entrained by the emulsifying agent did not fade away as PC10SSC and PC20SSC concretes become mature; rather, the excess entrained air was retained and became the major part of air void system for these two concretes. Consequently, PC10SSC and PC20SSC concretes have relatively high porosity compared to the reference concrete.

The addition of air detrainning agent effectively eliminated large amount of air voids in the fresh asphalt emulsion-modified concrete mixes. As a result, the hardened asphalt emulsion-modified concretes with air detrainning agent, PC10SSDC and PC20SSDC, have lower content of air voids. As seen from Table 6.3, the air content of hardened PC10SSDC concrete is only about 0.6% more than that of the reference concrete and about 5.5% less compared to the air content of hardened PC10SSC concrete. In addition, hardened PC20SSDC concrete only has about twice the air compared to the hardened reference concrete, and approximately 5.8% less air than that of the hardened PC20SSC concrete.

## 6.3 STRENGTH

For compressive strength of CPCC, PC10SSC, and PC20SSC specimens, each strength value reported in Table 6.4 represents an average of the test results of five individual cylinders. Each compressive strength value reported in Table 6.5 for PC10SSDC and PC20SSDC specimens is an average of three individual test results. As mentioned in Section 5.2, flexural strength test was only performed on CPCC, PC10SSC, and PC20SSC specimens. Each flexural strength value reported in Table 6.6 for these three types of specimens is an average of the test results of three individual beams.

### 6.3.1 Compressive Strength of Asphalt Emulsion-Modified Concretes with Superplasticizer

Compressive strength test were carried out for the two asphalt emulsion-modified concretes (PC10SSC and PC20SSC)

TABLE 6.4 Compressive Strength of Asphalt Emulsion-Modified Concretes with Superplasticizer and Reference Concrete

Mix	Compressive Strength (MPa)* at:						
	1 day	3 days	7 days	28 days	90 days	180 days	360 days
CPCC	15.1	27.8	35.8	46.6	52.5	57.4	60.1
PC10SSC	13.9	23.0	26.5	29.5	35.2	37.0	37.3
PC20SSC	8.6	16.3	20.8	25.3	29.3	31.6	32.4

\* 1 MPa = 145 psi

TABLE 6.5 Compressive Strength of Asphalt Emulsion-Modified Concretes with Superplasticizer and Air Detraining Agent

Mix	Compressive Strength (MPa)* at:			
	1 day	3 days	7 days	28 days
PC10SSDC	20.0	30.7	35.3	41.4
PC20SSDC	12.0	22.4	24.8	28.4

\* 1 MPa = 145 psi

TABLE 6.6 Flexural Strength of Asphalt Emulsion-Modified Concretes with Superplasticizer and Reference Concrete

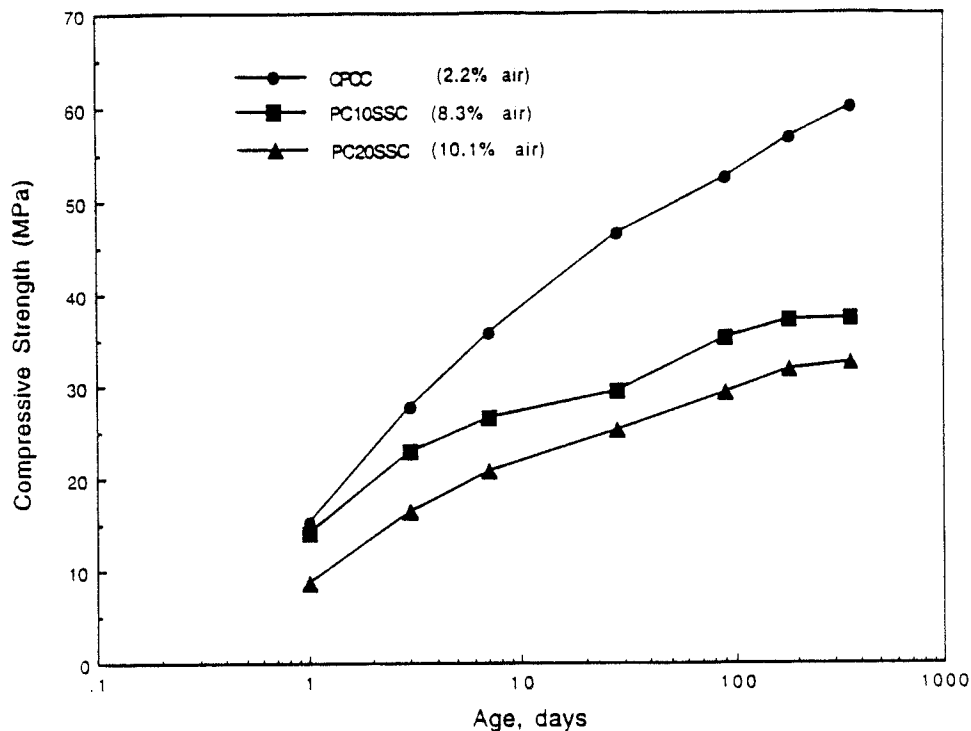
Mix	Flexural Strength (MPa)* at:						
	1 day	3 days	7 days	28 days	90 days	180 days	360 days
CPCC	5.6	8.0	9.4	9.6	9.6	9.9	10.2
PC10SSC	4.6	6.5	7.5	7.5	8.0	8.0	8.1
PC20SSC	2.8	3.8	5.1	5.7	5.8	6.1	6.2

\* 1 MPa = 145 psi

and the reference concrete (CPCC) at ages of 1, 3, 7, 28, 90, 180, and 360 days. A summary of the compressive strength test results is presented in Table 6.4 and graphically in Figure 6.1.

From Table 6.4 and Figure 6.1, it is apparent that the compressive strengths of the two asphalt emulsion-modified concretes are lower than that of the reference concrete at all ages. Furthermore, the difference between the compressive strength of the reference concrete and the two asphalt emulsion-modified concretes becomes greater with time.

Even though the water:cement ratios for PC10SSC and PC20SSC concretes are lower than the water:cement ratio of CPCC concrete (0.40 versus 0.48), their compressive strengths are lower than that of CPCC. The primary factor



**FIGURE 6.1** Compressive Strength versus Time for Asphalt Emulsion-Modified Concretes, PC10SSC and PC20SSC; and Reference Concrete, CPCC

that limited the compressive strength of the asphalt emulsion-modified concretes is their porosity. As seen in Table 6.3, the air contents of the hardened PC10SSC and PC20SSC concretes were 8.3% and 10.1% respectively, while the air content of the hardened reference concrete was only 2.2%. As a result, the compressive strengths of asphalt emulsion-modified concretes were considerably lower than that of the reference concrete.

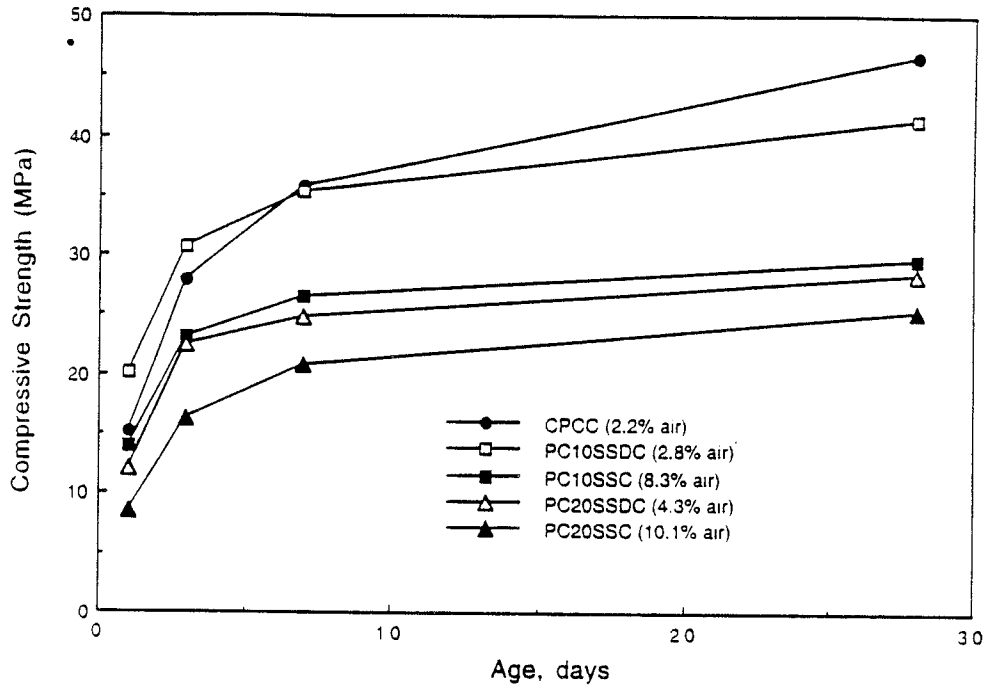
It is also evident that the compressive strength of concrete with only 10 percent of SS-1h asphalt emulsion is higher than the compressive strength of concrete with 20 percent of SS-1h asphalt emulsion. This is most likely related to the higher percent of air in the concrete with 20% of SS-1h asphalt emulsion.

### 6.3.2 Compressive Strength of Asphalt Emulsion-Modified Concretes with Superplasticizer and Air Detraining Agent

Compressive strength tests were performed on two asphalt emulsion-modified concretes containing superplasticizer and air detraining agent (PC10SSDC and PC20SSDC) at ages of 1, 3, 7, and 28 days. A summary of these test results is presented in Table 6.5. The same results along with the values of compressive strengths for CPCC, PC10SSC, and PC20SSC concretes are presented graphically in Figure 6.2.

As seen in Figure 6.2, incorporation of air detraining agent into asphalt emulsion-modified concrete greatly enhanced its compressive strength. With the addition of an air detraining agent, the early age compressive strength of PC10SSDC concrete was actually greater than that of the reference concrete. Also, the addition of an air detraining agent caused an increase in the compressive strength of PC20SSDC concrete to a level approximately equal to that of the PC10SSC concrete.

The addition of air detraining agent to asphalt emulsion-modified concrete mixes effectively reduced the air content of these mixes at the "fresh stage", as shown in Table 6.2. Hence, the amount of air voids in the hardened asphalt emulsion-modified concrete was reduced. As a result of air voids reduction, the compressive strength of the asphalt emulsion-modified concrete increased, especially at early ages.



**FIGURE 6.2** Compressive Strength versus Time for Asphalt Emulsion-Modified Concretes with Air Detraining Agent, PC10SSDC and PC20SSDC; Asphalt Emulsion-Modified Concretes without Air Detraining Agent, PC10SSC and PC20SSC; and Reference Concrete, CPCC

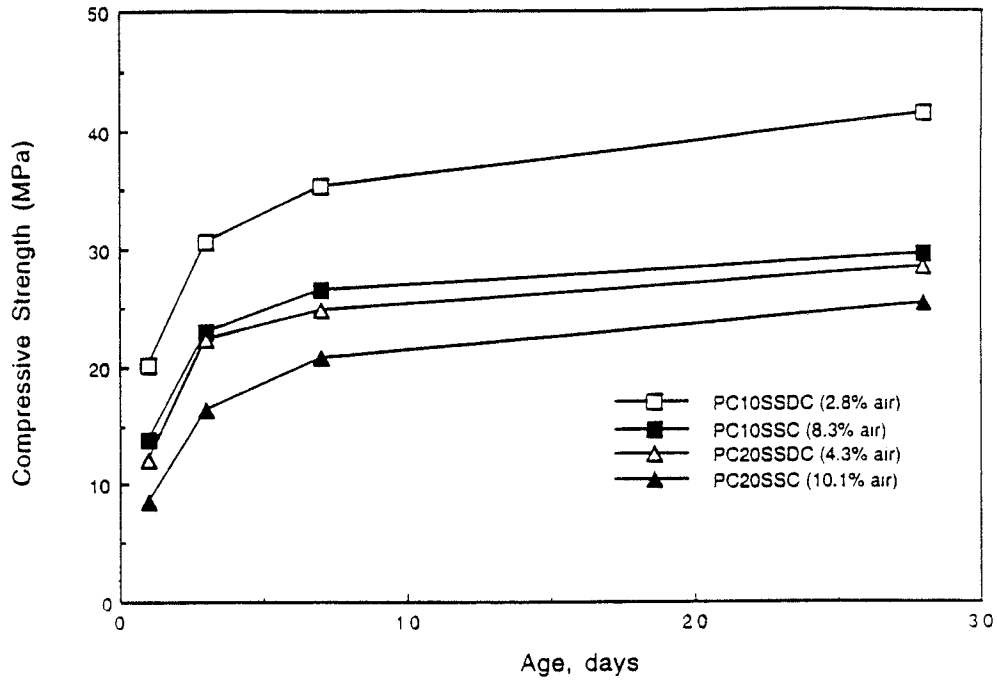
The compressive strength of PC10SSDC concrete at 28 days was lower than that of reference concrete. Such a result indicates that, in addition to being controlled by the amount of air voids present, the compressive strength of the asphalt emulsion-modified concrete is also reduced by the presence of asphalt emulsion itself. The degree to which the presence of asphalt emulsion may modify the hydration process of cement was not investigated in this study.

When comparing concretes with an equal asphalt emulsion content, the asphalt emulsion-modified concrete with a low air void content had higher compressive strength than the one with a high void content. This comparison is shown graphically in Figure 6.3.

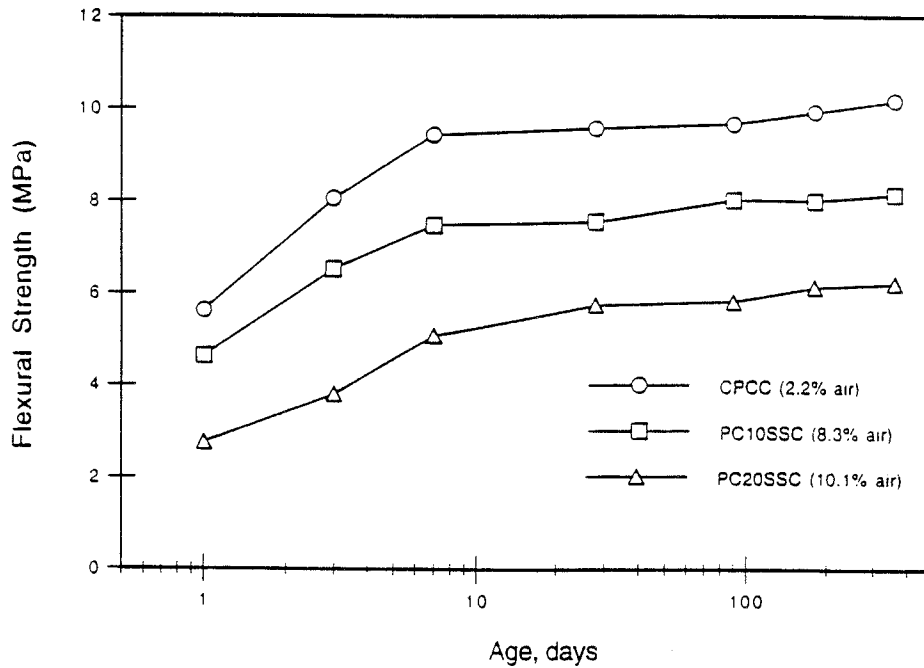
### 6.3.3 Flexural Strength of Asphalt Emulsion-Modified Concretes with Superplasticizer

Flexural strength tests were performed on the two asphalt emulsion-modified concretes (PC10SSC and PC20SSC) and the reference concrete (CPCC) at ages of 1, 3, 7, 28, 90, 180, and 360 days. A summary of the test results is presented in Table 6.6. The flexural strength results for all three concretes are presented graphically in Figure 6.4.

As indicated in Table 6.6 and Figure 6.4, both asphalt emulsion-modified concretes had lower flexural strengths than the reference concrete at all ages. However, it can be seen that the pattern of flexural strength development over time is different than the pattern of compressive strength development over time seen in Figure 6.1 and Table 6.4. For compressive strength, there is an almost linear increase with logarithm of time for the reference concrete over the whole period examined (1 year). For asphalt emulsion-modified concretes, the increase in compressive strength over time, while still substantial, occurs at a significantly reduced rate. In consequence, the difference between the compressive strength levels of the reference concrete and the asphalt emulsion-modified concretes progressively increased.



**FIGURE 6.3** Comparison of Compressive Strength versus Time between PC10SSDC and PC10SSC Concretes; and PC20 SSDC and PC20SSC Concrete



**FIGURE 6.4** Flexural Strength versus Time for Asphalt Emulsion-Modified Concretes, PC10SSC and PC20SSC; and Reference Concrete, CPCC



In contrast, Figure 6.4 shows that after 7 days there was little change in flexural strength levels of either the reference concrete or the asphalt emulsion-modified concretes. Thus, the difference in flexural strength levels remained relatively constant after 7 days, and there was not a progressive flexural strength penalty associated with the incorporation of the asphalt emulsion as time progressed.

Similarly to what was observed for compressive strength, higher contents of the SS-1h asphalt emulsion concrete system produced concretes with lower flexural strengths. This is because concrete with more asphalt emulsion had higher air content.

No experiments were performed on the effects of air detraining agent on the flexural strength of asphalt emulsion-modified concrete. However, based on the results with compressive strength, it would be reasonable to assume that addition of such agent would increase flexural strength as well.

#### 6.4 CHLORIDE ION PERMEABILITY

The chloride ion permeability (chloride permeability) of concrete was measured in accordance with AASHTO Designation T 277 - 83, "Rapid Determination of the Chloride Permeability of Concrete". This test was initially developed as an indicator of the effective resistance of saturated concrete to migration of chloride ions. The test results are evaluated using the presumed relationship between the chloride permeability and the charge passed as given in Table 1 of AASHTO Designation T 277 - 83. This table is reproduced as Table 6.7.

TABLE 6.7 Chloride Permeability Based on Charge Passed

Charge Passed (coulombs)	Chloride Permeability	Typical of
> 4,000	High	High water:cement ratio, conventional ( $\geq 0.6$ ) PCC
2,000~4,000	Moderate	Moderate water:cement ratio, conventional (0.4~0.5) PCC
1,000~2,000	Low	Low water cement ratio, conventional ( $< 0.4$ ) PCC
100~1,000	Very Low	Latex-modified concrete Internally sealed concrete
< 100	Negligible	Polymer impregnated concrete Polymer Concrete

##### 6.4.1 Chloride Ion Permeability of Asphalt Emulsion Modified-Concretes with Superplasticizer

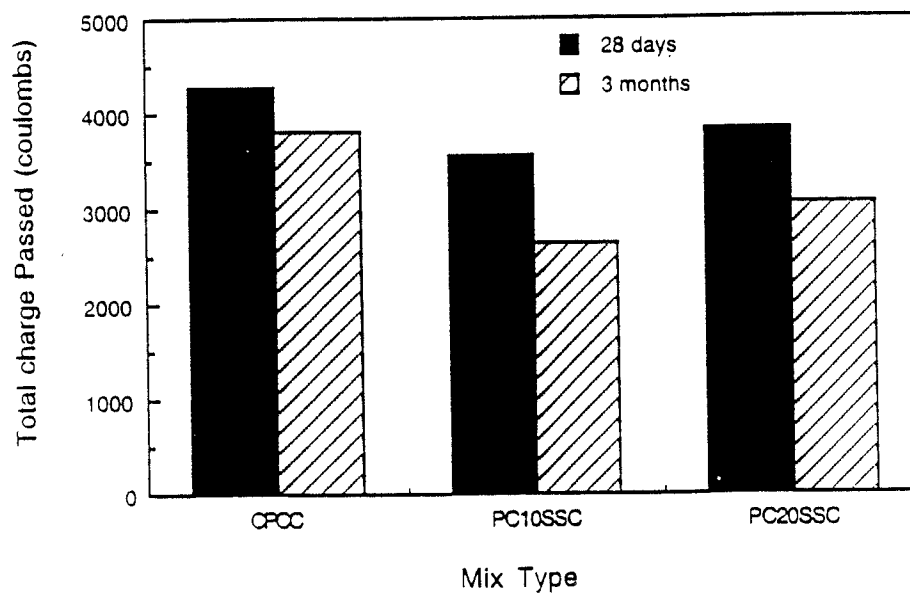
The test results for the two asphalt emulsion-modified concretes and the reference concrete at 28 days and 3 months are presented in Table 6.8. For 28-day test results, each value reported in Table 6.8 represents an average of four specimens while each value reported for 3 months is an average of the test results of two specimens. The chloride permeability results are also plotted schematically in Figure 6.5.

For the reference concrete, the average total charge passed at the 28-day test age was about 4700 coulombs. This puts the reference concrete into the "high" chloride permeability category according to AASHTO Designation T 277 - 83 classification ( $> 4000$  coulombs). The average total charge passed at 3 month test age fell to about 3800 coulombs. This puts the reference concrete into the "moderate" chloride permeability category of the AASHTO classification (2000~4000 coulombs). The average total charge of about 4000 coulombs is typical of conventional portland cement concrete with moderate water:cement ratio (0.4~0.5).

Originally, there was an expectation that by incorporating SS-1h asphalt emulsion into concrete mix the resulting asphalt emulsion-modified concrete would attain very low permeability, comparable to that of latex-modified

**Table 6.8 Results of Chloride Permeability Test on Asphalt Emulsion-Modified Concretes with Superplasticizer and Reference Concrete**

Mix	Total Charge Passed (coulombs) at:	
	28 days	3 months
CPCC	4726	3811
PC10SSC	3562	2636
PC20SSC	3838	3049



**FIGURE 6.5 Total Charge Passed in a Period of 6 Hours for Asphalt Emulsion-Modified Concretes, PC10SSC and PC20SSC; and Reference Concrete, CPCC at 28 Days and 3 Months**

concrete and polymer-impregnated concrete described in Section 2.4. However, the chloride permeability for the two asphalt emulsion-modified concretes were only slightly lower than that of reference concrete at both 28-day and 3-month test ages. Their chloride permeability at either 28-day or 3-month test ages all belonged to the "moderate" chloride permeability category of the AASHTO classification (2000–4000 coulombs).

Permeability of concrete is closely associated with porosity of concrete. Usually concrete with high amount of intrudable pores will also have a high permeability. Since asphalt emulsion-modified concretes have high air contents, their chloride permeability results were relatively high.

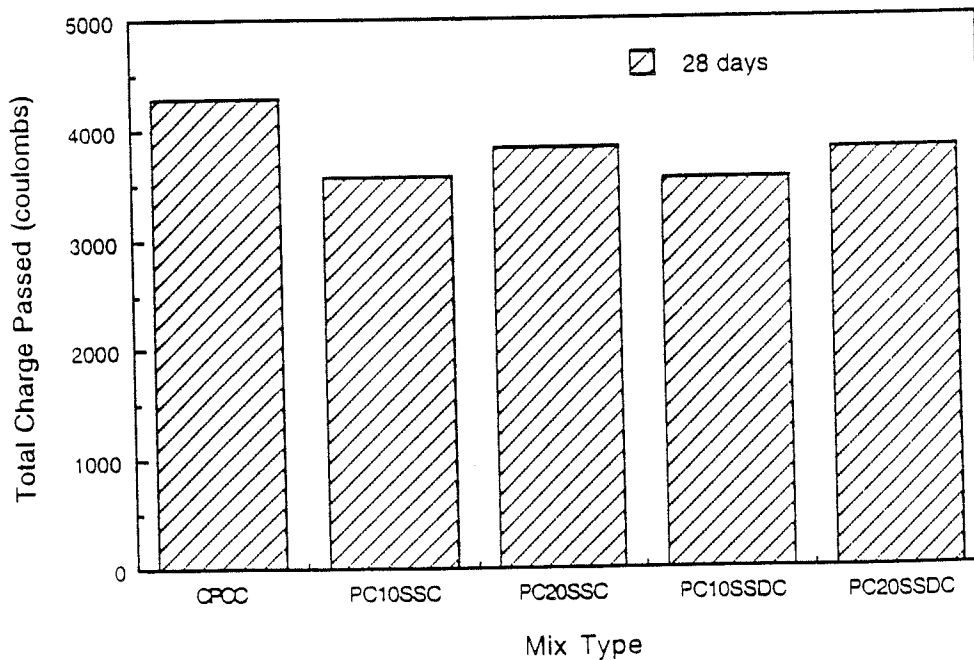
**6.4.2 Chloride Ion Permeability of Asphalt Emulsion-Modified Concretes with Superplasticizer and Air Detraining Agent**

The chloride permeability test was carried out on the two asphalt emulsion-modified concretes with superplasticizer and air detraining agent at age of 28 days and the test results are presented in Table 6.9. Each value reported in Table 6.9 represents an average of the test results of four individual specimens. The individual test results for the chloride permeability test are provided in Appendix C. The 28-day chloride permeability results for PC10SSDC and PC20SSDC concretes and CPCC, PC10SSC, and PC20SSC concretes are presented graphically in Figure 6.6.

As shown in Figure 6.6, the addition of an air detraining agent did not improve the chloride permeability of asphalt emulsion-modified concrete. The average total charge passed for the two asphalt emulsion-modified concretes with air detraining agent was only about 30 coulombs less than the average total charge for the two asphalt emulsion-modified concretes without air detraining agent. As a result, the chloride permeability of PC10SSDC and PC20SSDC concretes also belonged to the "moderate" category according to AASHTO classification.

**TABLE 6.9 Results of Chloride Permeability Test on Asphalt Emulsion-Modified Concretes with Superplasticizer and Air Detraining Agent**

Mix	Total Charge Passed (coulombs) at:	
	28 days	
PC10SSDC	3530	
PC20SSDC	3815	



**FIGURE 6.6 Total Charge Passed in a Period of 6 Hours for Asphalt Emulsion-Modified Concretes with Air Detraining Agent, PC10SSDC and PC20SSDC; Asphalt Emulsion-Modified Concretes without Air Detraining Agent, PC10SSC and PC20SSC; and Reference Concrete, CPCC at 28 Days**

As discussed earlier, the addition of an air detrainment agent greatly reduced the air content and enhanced the compressive strength of asphalt emulsion-modified concretes. This raises the question why did the addition of an air detrainment agent did not improve the chloride permeability of asphalt emulsion-modified concretes? Examinations by optical microscopy indicate that the addition of an air detrainment agent successfully eliminated the excessive amount of entrained air introduced by the emulsifying agent in asphalt emulsion. However, the continuous voids (intrudable pores) of the asphalt emulsion-modified concrete were not influenced by the addition of an air detrainment agent. Hence, even though the macro-porosity (air voids) of the asphalt emulsion-modified concrete was greatly reduced, its chloride permeability did not improve.

## 6.5 DYNAMIC MODULUS OF ELASTICITY

The dynamic modulus of elasticity of the concretes was determined using the fundamental transverse frequency method described in Section 5.3.5. The measurements of the fundamental transverse frequencies were performed on the same 75 x 75 x 380 mm (3 x 3 x 15 in.) test beams which were used for the flexural strength test. Thus, only CPCC, PC10SSC, and PC20SSC specimens were tested. The formula used to calculate the values of dynamic modulus of elasticity is provided in Section 5.3.5.

The values of dynamic modulus of elasticity calculated for all three concretes are presented in Table 6.10. Each value reported in Table 6.10 represents an average of results of three separate replicate specimens. The values of dynamic modulus of elasticity are also graphically presented in Figure 6.7.

TABLE 6.10 Dynamic Modulus of Elasticity of Asphalt Emulsion-Modified Concretes with Superplasticizer and Reference Concrete

Mix	Dynamic Modulus of Elasticity (MPa)* at:						
	1 day	3 days	7 days	28 days	90 days	180 days	360 days
CPCC	34.2	40.9	44.9	48.8	49.9	46.8	51.0
PC10SSC	28.7	34.4	35.9	38.3	38.7	36.0	39.3
PC20SSC	19.8	25.6	28.1	31.0	31.3	27.6	32.8

\* 1 MPa = 145 psi

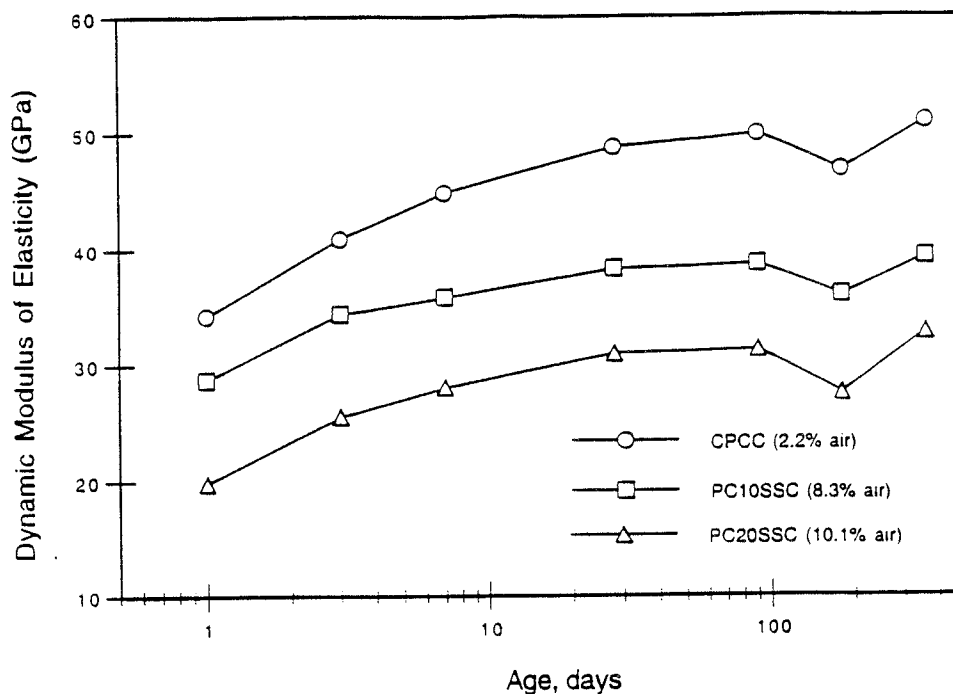
According to the data shown in Table 6.10 and Figure 6.7, it is clear that the dynamic modulus of elasticity ( $E_d$ ) of reference concrete was higher than that of both asphalt emulsion-modified concretes at all ages. Test results also indicated that the  $E_d$  of PC10SSC concrete was higher than the  $E_d$  of PC20SSC concrete. Hence, it can be concluded that the addition of SS-1h asphalt emulsion reduces the  $E_d$  of concrete and produces a more flexible material as compared to conventional portland cement concrete.

Furthermore, the degree of  $E_d$  reduction increases with an increased dosage of asphalt emulsion.

The pattern of development of  $E_d$  for all three concretes appears to be similar. The  $E_d$  values for all three concretes increased with respect to time except at test age of 180 days, where a sudden drop in the  $E_d$  values can be seen. This drop most likely represents a "bad" data point.

## 6.6 FREEZE-THAW RESISTANCE

The freezing and thawing resistance test was carried out for CPCC, PC10SSC, and PC20SSC concretes only. In this test, the fundamental transverse frequency of all specimens was measured before the first cycle of freezing and thawing. Then the measurements were repeated after every 30 cycles of freezing and thawing. The fundamental transverse frequencies were measured and used to calculate the relative dynamic modulus of elasticity,  $P_c$ , according



**FIGURE 6.7** Dynamic Modulus of Elasticity versus Time for Asphalt Emulsion-Modified Concretes, PC10SSC and PC20SSC; and Reference Concrete, CPCC

to the following equation (71):

$$P_c = (n_1^2/n^2) \times 100$$

where:  $P_c$  = relative dynamic modulus of elasticity, after  $c$  cycles of freezing and thawing, in percent  
 $n$  = fundamental transverse frequency at 0 cycle of freezing and thawing  
 $n_1$  = fundamental transverse frequency after  $c$  cycles of freezing and thawing.

According to the ASTM C 666 - 84 procedure, each specimen should continue to be tested until it has been subjected to 300 cycles of freezing and thawing or until its relative dynamic modulus of elasticity drops to 60% of the initial modulus, whichever occurs first. Then, the durability of the concrete is assessed by calculating the durability factor (DF) using the following equation:

$$DF = PN/M$$

where: DF = durability factor of the test specimen  
 $P$  = relative dynamic modulus of elasticity at  $N$  cycles, %  
 $N$  = number of cycles at which  $P$  reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less  
 $M$  = specified number of cycles at which the exposure is to be terminated.

The values of relative dynamic modulus of elasticity and durability factor for all three concretes are presented in Table 6.11. The relationship between the relative dynamic modulus of elasticity of all three concretes and the number of freezing and thawing cycles is presented graphically in Figure 6.8.

Table 6.11 Relative Dynamic Modulus of Elasticity and Durability Factor of Asphalt Emulsion-Modified Concretes with Superplasticizer and Reference Concrete

	CPCC	PC10SSC	PC20SSC
Number of Cycles	Relative Dynamic Modulus of Elasticity (%)		
0	100.0	100.0	100.0
30	96.9	98.0	98.5
60	97.6	98.7	99.2
90	97.2	99.7	99.5
120	94.4	99.5	99.3
150	85.3	99.4	99.2
180	68.3	98.8	98.7
210	42.0	98.1	98.3
240	N/A	97.6	98.2
270	N/A	97.2	97.8
300	N/A	96.9	97.7
Durability Factor (%)			
	41.0	96.9	97.7

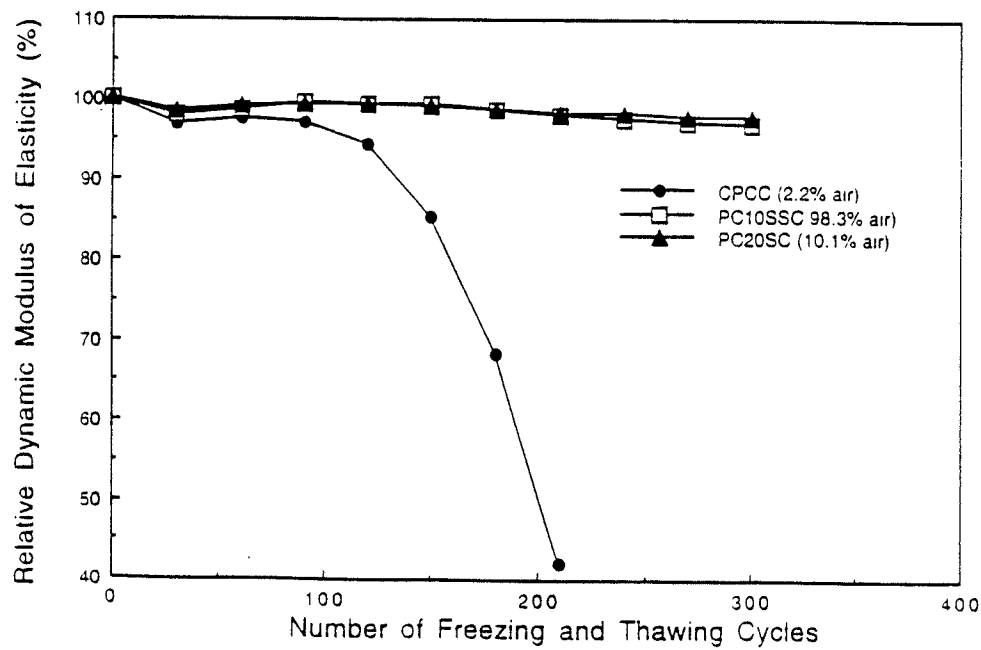


FIGURE 6.8 Relative Dynamic Modulus of Elasticity versus Number of Freezing and Thawing Cycles for Asphalt Emulsion-Modified Concretes, PC10SSC and PC20SSC; and Reference Concrete, CPCC

It is clear that the freezing and thawing resistance of asphalt emulsion-modified concretes is superior compared to that of the reference concrete. As seen in Table 6.11 and Figure 6.8, the relative dynamic modulus of elasticity of reference concrete reached near by 60% of its initial modulus after 180 cycles of freezing and thawing. After 210 cycles, the reference concrete's relative dynamic modulus of elasticity dropped below 60% of its initial modulus and this test was terminated. On the other hand, the relative dynamic modulus of elasticity for the two asphalt emulsion-modified concretes was much higher. For PC10SSC and PC20SSC concretes, their relative dynamic modulus of elasticity at end of 300 cycles was 96.9% and 97.7% respectively.

The durability of concrete can be assessed by the durability factor. Usually, a durability factor smaller than 40 means that the concrete is probably unsatisfactory with respect to freezing and thawing resistance; 40 to 60 is the durability factor range for concretes with doubtful performance; if the durability factor is above 60, the concrete is probably satisfactory (16). Since the durability factors for the asphalt emulsion-modified concretes are in the nineties, their resistance against freezing and thawing is expected to be satisfactory. The durability factor of reference concrete was only 41 ( $DF = 68.3 \times 180 + 300$ ), which is considerably lower than the durability factor of asphalt emulsion-modified concretes. As a result, its performance against freezing and thawing is expected to be much less satisfactory.

The primary factor that caused the performance of asphalt emulsion-modified concrete to be as satisfactory was their air voids. As mentioned earlier, emulsifying agent from the SS-1h asphalt emulsion entrained a large amount of air into fresh concrete mix. As a result, hardened asphalt emulsion-modified concrete contained many air voids, thus allowing the excess water in the concrete to move and freeze without causing any damage. The reference concrete had no entrained air and no extra spaces for water to move around during freezing. As a result, concrete cracked and become damaged.

The effects of a detraining agent on the freezing and thawing resistance of asphalt emulsion-modified concrete were not studied because the lack of SS-1h asphalt emulsion. However, this topic should be investigated in future studies.

## 6.7 SPLITTING BOND FORCE

The splitting bond test was performed on CPCC, PC10SSC, and PC20SSC concretes only. The purpose of this test was to determine the force required to split the "binding interface" of a CPCC-CPCC, CPCC-PC10SSC, or CPCC-PC20SSC cubic specimen. A detailed description of the experimental procedure for the splitting bond test is presented in Section 5.3.7.

The test results for the two asphalt emulsion-modified concretes and the reference concrete at 7 and 28 days are presented in Table 6.12. Each average value from Table 6.12 is plotted schematically in Figure 6.9.

At both 7 and 28 days, the force required to split the "binding interface" of the CPCC-CPCC specimen was highest, followed by that of the CPCC-PC10SSC specimen and the CPCC-PC20SSC specimen respectively. However, it was also observed from Table 6.12 and Figure 6.9 that the relative increase in the forces required to split the "binding interface" of CPCC-PC10SSC and CPCC-PC20SSC specimens at 28 days was much greater than that of CPCC-CPCC specimen. The relative increases in splitting bond force at 28 days for CPCC-CPCC, CPCC-PC10SSC, and CPCC-PC20SSC specimens were 5%, 30%, and 39% respectively. As a result, the splitting bond force for the CPCC-PC10SSC specimen at 28 days was almost as high as that of the CPCC-CPCC specimen.

Based on the results of this experiment, it can be concluded that:

- (1) the addition of SS-1h asphalt emulsion delays the bond development of concrete at early age;
- (2) the addition of SS-1h asphalt emulsion also reduces the "bonding force" of concrete to some extent.

TABLE 6.12 Splitting Bond Force Test Results for CPCC-CPCC, CPCC-PC10SSC, and CPCC-PC20SSC Specimens

Mix	Replicates	Splitting Bond Force (N)* at:	
		7 days	28 days
CPCC-CPCC	1	15524	15172
	2	14278	15933
	3	14545	15515
	AVERAGE	14781	15541
CPCC-PC10SSC	1	10453	15052
	2	12143	14283
	3	11876	15488
	AVERAGE	11489	14941
CPCC-PC20SSC	1	8763	11970
	2	9029	13295
	3	9163	12330
	AVERAGE	8985	12530

\* 1 N = 0.2248 lbf

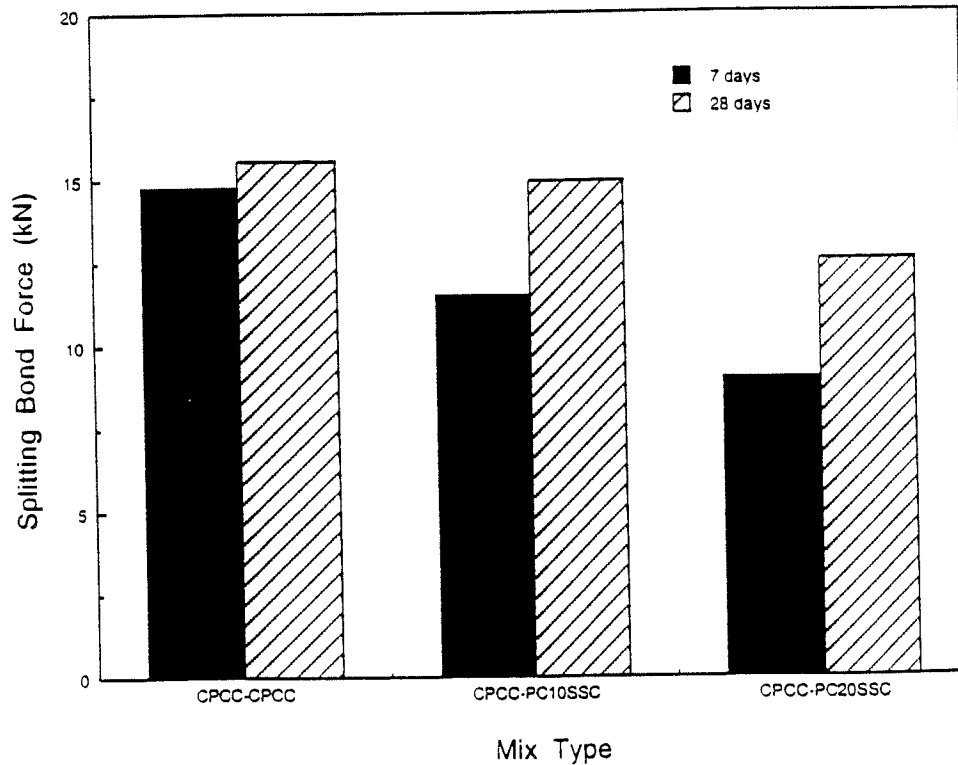


FIGURE 6.9 Average Splitting Bond Force Test Results for CPCC-CPCC, CPCC-PC10SSC, and CPCC-PC20SSC Specimens



## 7. SUMMARY AND GENERAL DISCUSSION

This chapter presents summary and general discussion of test results reported in Chapter 6 for each of the specific experiments.

### 7.1 PROPERTIES OF ASPHALT EMULSION-MODIFIED CONCRETES WITH SUPERPLASTICIZER

This section elaborates more about the test results presented in Chapter 6 for the two asphalt emulsion-modified concretes with superplasticizer, PC10SSC and PC20SSC.

#### 7.1.1 Workability

The workability of fresh concrete mixes decreased as the amount of SS-1h asphalt emulsion added to the mix increased. The addition of superplasticizer greatly enhanced the initially workability of the fresh asphalt emulsion-modified concrete mixes. However, this workability rapidly diminished with time as shown in Table 6.1. Also, for mixes with higher content of the SS-1h asphalt emulsion, more superplasticizer was needed to bring the mix to a desirable workability.

The fresh asphalt emulsion-modified concrete mixes were cohesive and unusually sticky, which made the consolidation somewhat unpleasant. Nevertheless, placing and finishing operations of asphalt emulsion-modified concrete mixes with superplasticizer were not seriously impaired. Also, no excessive bleeding and segregation was observed in these mixes.

#### 7.1.2 Air Content of Hardened Concretes

As discussed many times throughout this report, the air contents of asphalt emulsion-modified concretes were considerably high. According to the modified point-count results shown on Table 6.3, the air contents of PC10SSC and PC20SSC concretes were 8.3% and 10.1% respectively. The air content of reference concrete was only 2.2%. The air contents of hardened asphalt emulsion-modified concretes were high because the emulsifying agent in SS-1h asphalt emulsion lead to the formation of large amounts of air that subsequently entrained in fresh concrete mixes. The content of this entrained air did not diminish as the asphalt emulsion-modified concretes matured, rather, they constituted the major part of air void system for the asphalt emulsion-modified concrete. Therefore, air contents of asphalt emulsion-modified concretes were considerably higher compared to reference concrete's air content.

#### 7.1.3 Compressive Strength

Although the water:cement ratios of PC10SSC and PC20SSC concretes were lower than the water:cement ratio of reference concrete, the compressive strength of asphalt emulsion-modified concretes were lower compared to that of the reference concrete at all ages. Furthermore, it was found that the higher the asphalt emulsion content, the lower the compressive strength of the concrete.

As discussed in Section 6.3.1, the primary parameter that affected the compressive strength of asphalt emulsion-modified concretes was their air void content. A large amount of air was entrained into asphalt emulsion-modified concrete mixes by the emulsifying agent contained in SS-1h asphalt emulsion. As a result, the air content in hardened asphalt emulsion-modified concretes was also very high thus reducing their compressive strength below that of the reference concrete.

When the content of asphalt emulsion in a concrete increased, the amount of emulsifying agent mixed into the concrete increased as well. Consequently, more air was entrained into the concrete resulting in further reduction of

the compressive strength. This was the case for PC20SSC concrete.

#### 7.1.4 Flexural Strength

The flexural strength of asphalt emulsion-modified concretes was also lower than that of the reference concrete at all ages. Similarly to the compressive strength, an increased dosage of SS-1h asphalt emulsion somewhat reduced the flexural strength. But unlike the case of compressive strength test results, the pattern of the flexural strength development over time between reference concrete and asphalt emulsion-modified concretes remained quite constant as shown in Figure 6.4. Thus, the difference in flexural strength levels over time was smaller compared to the difference in compressive strength levels between reference concrete and asphalt emulsion-modified concretes.

One of the reasons that led to this smaller difference in flexural strength levels between the reference concrete and the asphalt emulsion-modified concretes was that the increase in flexural strength over time was much smaller than that of the compressive strength. Another reason likely contributed to this smaller difference between flexural strength of reference concrete and asphalt emulsion-modified concretes was that porosity has less effect on flexural strength than compressive strength (45, 49, 50). The emulsifying agent contained in the SS-1h asphalt emulsion caused large amount of air entrained into concrete mixes. Consequently, porosity of hardened asphalt emulsion-modified concretes become remarkably high and their strength reduced accordingly. However, it was discussed in Section 2.3 that an increase in porosity weakens the compressive strength of concrete more than its flexural strength (45).

#### 7.1.5 Chloride Ion Permeability

The chloride ion permeability (chloride permeability) of the asphalt emulsion-modified concretes are slightly lower than the chloride permeability of the reference concrete. However, the chloride permeability reduction capability of SS-1h asphalt emulsion was greatly limited due to the excessive air asphalt emulsion brought into concrete. Accordingly, the chloride permeability of both PC10SSC and PC20SSC concretes places them into the "moderate" category according to the AASHTO classification (2000~4000 coulombs).

Impermeability is usually associated with low porosity. Special concrete systems such as latex-modified concretes usually show excellent impermeability to chloride ions, being classified as "very low" permeability concrete according to the AASHTO classification (100~1000 coulombs). Mercury intrusion measurements on pastes incorporating the same dosage of latex as used in concrete were found to show very low intrudable porosity ( $0.15 \text{ cm}^3/\text{g}$ ) as early as 1 day after placing, and even lower intrudable porosity ( $0.10 \text{ cm}^3/\text{g}$ ) at 7 days (58). On the other hand, a concrete with high amount of pores, especially intrudable pores, would usually have high permeability. Those asphalt emulsion-modified concretes without air detraining agent have high porosity; the air contents of hardened PC10SSC and PC20SSC concretes were 8.3% and 10.1% respectively. Hence, the chloride permeability results for both PC10SSC and PC20SSC concretes were high, as expected.

#### 7.1.6 Dynamic Modulus of Elasticity

Asphalt emulsion is less stiff than cement paste or aggregate, so addition of asphalt emulsion to concrete produced a concrete system which is less stiff than conventional portland cement concrete. Accordingly, the elastic modulus of asphalt emulsion-modified concrete is lower than that of conventional portland cement concrete.

The results in Table 6.10 show that the dynamic modulus of elasticity of asphalt emulsion-modified concretes was lower than that of the reference concrete at all ages. Furthermore, dynamic modulus of elasticity of PC20SSC concrete was found to be still lower than PC10SSC concrete.

### 7.1.7 Freeze-Thaw Resistance

The excessive amount of air entrained into concrete by addition of SS-1h asphalt emulsion had one positive contribution -- it increased the freezing and thawing resistance of asphalt emulsion-modified concretes. The ability of asphalt emulsion to form the system of air voids provides empty space within the paste. During freezing, the excess water can move through this space and freeze without seriously damaging the concrete.

The results of freezing and thawing resistance tests showed that the durability factors of PC10SSC and PC20SSC concretes were 96.9% and 97.7% respectively, a difference of only 0.8%. This indicates that doubling the content of asphalt emulsion in concrete did not result in a more durable concrete. On the other hand, PC20SSC concrete has lower compressive and flexural strengths, and higher chloride permeability than PC10SSC concrete. Therefore, the overall properties of PC10SSC concrete seem to be superior to that of PC20SSC concrete.

### 7.1.8 Splitting Bond Force

By examining the results from the splitting bond force test, an assessment could be made about the bond strength of asphalt emulsion-modified concretes. At test age of 7 days, the force needed to split a "binding interface" between asphalt emulsion-modified concrete and reference concrete was relatively low. The splitting bond forces at test age of 28 days for CPCC-PC10SSC and CPCC-PC20SSC specimens were much higher; in case of CPCC-PC10SSC specimen, its splitting bond force at 28 days is almost as high as the force for CPCC-CPCC specimen.

Since the splitting bond forces for asphalt emulsion-modified concretes were lower than that of reference concrete, the bond strength of asphalt emulsion-modified concretes would probably be lower than the bond strength of reference concrete, especially at early ages. Also, since the splitting bond force of CPCC-PC10SSC specimen was higher than CPCC-PC20SSC specimen, it could be expected that the bond strength of an asphalt emulsion-modified concrete would probably decrease with the increased content of asphalt emulsion.

Another evidence which indicates that the bond strength of asphalt emulsion-modified concrete is probably lower than that of reference concrete is the air content. Air entrainment tends to reduce the bond strength because air voids tend to reduce the contact area between the mortar and the coarse aggregate (2). Hence, as the air content of a concrete increases, the contact area between the mortar and the coarse aggregate reduces resulting in the decrease of bond strength. The air contents of asphalt emulsion-modified concretes were considerably higher than the air content of reference concrete; hence, their bond strengths are probably lower compared to reference concrete.

## 7.2 PROPERTIES OF ASPHALT EMULSION-MODIFIED CONCRETES WITH SUPERPLASTICIZER AND AIR DETRAINING AGENT

As shown in Chapter 6, the incorporation of air detrainning agent provided beneficial effects to asphalt emulsion-modified concrete. This section contains more detailed discussion of the test results presented in Chapter 6 for the two asphalt emulsion-modified concretes with superplasticizer and air detrainning agent, PC10SSDC and PC20SSDC.

### 7.2.1 Effects of Air Detrainning Agent on Workability of Asphalt Emulsion-Modified Concretes

The addition of air detrainning agent slightly reduced the workability of asphalt emulsion-modified concretes. Given the same water:cement ratio and asphalt emulsion content, fresh asphalt emulsion-modified concrete mix with air detrainning agent has a slightly lower slump compared to fresh asphalt emulsion-modified concrete mix without air detrainning agent.

The primary reason behind the workability reduction of PC10SSDC and PC20SSDC concrete mixes is the reduction in their air content. Since entrained air generally improves the workability of fresh concrete by behaving as low-friction, elastic, fine aggregate thus reducing interactions between conventional solid aggregate particles as the

concrete is handled (2), a reduction in the air content will usually result in a decrease in the workability of fresh concrete. Therefore, the workability of fresh asphalt emulsion-modified concretes with air detrainning agent were little lower compared to those asphalt emulsion-modified concretes without air detrainning agent.

### 7.2.2 Effects of Air Detrainning Agent on Compressive Strength of Asphalt Emulsion-Modified Concretes

Incorporation of air detrainning agent into asphalt emulsion modified concrete definitely improved its compressive strength, especially at early ages. As shown in Figure 6.3, the compressive strength of asphalt emulsion-modified concrete with air detrainning agent is relatively higher than that without air detrainning agent at all test ages, given the same water:cement ratio and asphalt emulsion content.

Asphalt emulsion-modified concretes with air detrainning agent have higher compressive strength primarily because their air contents were much lower compared to those asphalt emulsion-modified concretes without air detrainning agent. Air detrainning agent successfully eliminated most of air which was entrained into fresh asphalt emulsion-modified concrete mixes by emulsifying agent from SS-1h asphalt emulsion. As a result, the hardened asphalt emulsion-modified concretes with air detrainning agent only have a small amount of air voids in them. As presented in Table 6.3, the air contents of hardened PC10SSDC and PC20SSDC concretes were 2.8% and 4.3% respectively.

Besides the air content, the amount of asphalt emulsion containing in a concrete affects the compressive strength of the concrete as well. The air content of hardened PC10SSC concrete was determined to be 8.3% and it is almost twice as much as the air content of PC20SSDC, 4.3%. However, at the same water:cement ratio, the compressive strength of PC20SSDC concrete was still a little lower than that of PC10SSC at all ages despite the fact that its air content was lower. Therefore, it can be concluded that SS-1h asphalt emulsion itself also moderately reduces the compressive strength of concrete. Furthermore, at the same water:cement ratio, the compressive strength of an asphalt emulsion-modified concrete is likely to decrease as the asphalt emulsion contained in it increases.

### 7.2.3 Effects of Air Detrainning Agent on Chloride Ion Permeability of Asphalt Emulsion-Modified Concretes

Unfortunately, the addition of an air detrainning agent did not significantly reduce the chloride permeability of asphalt emulsion-modified concretes. The chloride permeability of asphalt emulsion-modified concretes with air detrainning agent, PC10SSDC and PC20SSDC, still places these concretes into the "moderate" category in the AASHTO classification.

There was no significant reduction in chloride permeability of PC10SSDC and PC20SSDC concretes because the air voids that have been reduced in these concretes by the use of the air detrainning agent were discontinuous voids instead of continuous voids. Since the permeability reduction in concrete is primarily related to reduction of continuous voids (intrudable pores), a decrease in the amount of discontinuous voids would not affect concrete's permeability significantly. Examinations by optical microscopy indicate that the amount of discontinuous air voids within the asphalt emulsion-modified concretes were greatly reduced after air detrainning agent was added and resulted in lower air contents. However, it is believed that the continuous voids (intrudable pores) within these asphalt emulsion-modified concretes were not affected by the addition of air detrainning agent. Hence, their chloride permeability were not improved by the addition of air detrainning agent. Further studies are needed on this subject but were not part of this research program.

### 7.2.4 Summary of Effects of Air Detrainning Agent

It was found that incorporation of air detrainning agent into asphalt emulsion-modified concrete eliminated most of the excessive air caused by the emulsifying agent from SS-1h asphalt emulsion. Thus, hardened asphalt emulsion-modified concretes with air detrainning agent, PC10SSDC and PC20SSDC, have much less discontinuous air voids than those without air detrainning agent.

As a result of air content reduction, the workability of these fresh asphalt emulsion-modified concrete mixes was slightly reduced. However, there was no apparent difficulty in placing and finishing of these mixes. The compressive strength of these asphalt emulsion-modified concretes greatly increased. There was no significant reduction in the chloride permeability of these concretes.

## 8. FINDINGS, CONCLUSIONS, AND FUTURE RESEARCH NEEDS

This chapter is been divided into three sections. The first section describes the specific findings from this study. Based on the findings, a set of conclusions is presented in the second section. Finally, future research needs are listed in the third section.

### 8.1 FINDINGS

Based on the data presented previously, the individual findings from this study could be summarized as follows:

1. Addition of SS-1h asphalt emulsion greatly reduces the workability of concrete and superplasticizer must be added to fresh asphalt emulsion-modified concrete mixes in order to provide desirable workability and to achieve slumps of 75 to 150 mm (3 to 6 inches).
2. The air contents of fresh asphalt emulsion-modified concrete mixes were considerably higher than that of fresh reference concrete. High air contents were apparently caused by the emulsifying agent from SS-1h asphalt emulsion.
3. The air contents of hardened asphalt emulsion-modified concretes were considerably higher than the air content of hardened reference concrete.
4. The compressive strength of asphalt emulsion-modified concretes were considerably lower than the compressive strength of conventional portland cement concrete (the reference concrete) at all test ages.
5. The flexural strength of asphalt emulsion-modified concretes were also lower than that of conventional portland cement concrete at all test ages. The pattern of the flexural strength development over time between asphalt emulsion-modified concretes and conventional portland cement concrete remained quite constant.
6. The chloride permeability of asphalt emulsion-modified concretes at test age of 3 months is similar to that of the reference concrete and places these concretes in the "moderate" category of the AASHTO classification (2000~4000 coulombs).
7. Asphalt emulsion-modified concretes are less stiff than the conventional portland cement concrete since their dynamic modulus of elasticity is substantially lower than that of conventional portland cement concrete at all test ages.
8. Freeze-thaw resistance of asphalt emulsion-modified concretes was excellent. The durability factors of asphalt emulsion-modified concretes were above 95%.
9. The force needed to split a "binding interface" between an asphalt emulsion-modified concrete and a conventional portland cement concrete was lower than the force needed to split a "binding interface" between two conventional portland cement concretes at both 7 and 28-day test ages, but the force differences were much smaller at test age of 28 days.
10. Addition of air detraining agent effectively reduced the air contents of as-

phalt emulsion-modified concretes at both "fresh" and "hardened" stages.

11. Although the addition of air detraining agent slightly reduced the workability of asphalt emulsion-modified concrete mixes, there was no apparent difficulty in placing and finishing of these mixes.
12. Addition of air detraining agent greatly improved the compressive strength of asphalt emulsion-modified concretes at all test ages. The observed improvement in compressive strength was due to air content reduction of these asphalt emulsion-modified concretes.
13. Incorporation of air detraining agent did not significantly affect the chloride permeability of asphalt emulsion-modified concretes. The chloride permeability was not significantly improved because most of voids reduced by the detraining agent belonged to discontinuous voids rather than continuous voids.
14. Doubling the content of SS-1h asphalt emulsion resulted in an asphalt emulsion-modified concrete with lower compressive strength, flexural strength, and dynamic modulus of elasticity. Its durability remained about the same.

## 8.2 CONCLUSIONS

The primary objective of this study was to characterize an asphalt emulsion-modified concrete system with respect to properties that might be suitable for applications in pavements and bridge deck overlays. The effects of SS-1h asphalt emulsion on workability, strength, dynamic modulus of elasticity, chloride permeability, freeze-thaw resistance, and porosity of the concrete were investigated as part of this study.

The conclusions reached with respect to asphalt emulsion-modified concretes are as follows:

1. Superplasticizer must be added to fresh asphalt emulsion modified concrete mixes in order to achieve desirable workability, slump of 75 to 150 mm (3 to 6 inches).
2. Asphalt emulsion-modified concretes have considerably higher porosity than conventional portland cement concrete (reference concrete).
3. Asphalt emulsion-modified concretes have considerably lower compressive strength and flexural strength than conventional portland cement concrete.
4. Asphalt emulsion-modified concretes have lower dynamic modulus of elasticity than the conventional portland cement concrete, thus, asphalt emulsion-modified concretes are less stiff than conventional portland cement concrete.
5. The chloride permeability of asphalt emulsion-modified concretes without air detraining agent was not that significantly better than that of conventional portland cement concrete. All are classified as having "moderate" chloride permeability according to the AASHTO classification when tested after 3 months of wet curing.
6. Asphalt emulsion-modified concretes without air detraining agent have superior freezing and thawing resistance. Their durability factors and relative dynamic modulus of elasticity at the end of 300 cycles of freezing and thawing were all above 95%.

The above conclusions are based on studies involving two asphalt emulsion-modified concrete systems: asphalt emulsion-modified concrete with 10% of SS-1h asphalt emulsion by the weight of cement, PC10SSC; and asphalt emulsion-modified concrete with 20% of SS-1h asphalt emulsion by the weight of cement, PC20SSC. When the

asphalt emulsion content of the concrete was doubled, as in the case of PC20SSC concrete, its compressive strength, flexural strength, and dynamic modulus of elasticity decreased compared to concrete with only 10% asphalt emulsion. The chloride permeability and freeze-thaw resistance of concrete with 20% asphalt emulsion was about the same as that of concrete with 10% asphalt emulsion and its air content was slightly higher.

Studies on the effects of modifying the asphalt emulsion-modified concrete formulation by incorporating detraining agent led to the following conclusions:

7. Incorporation of air detraining agent without otherwise changing the formulation:
  - (a) slightly reduced the workability;
  - (b) significantly improved the compressive strength, especially at early ages;
  - (c) had no significant effects on the chloride permeability;
  - (d) significantly decreased the air content.

Once again, the above conclusions were reached from studies involving two asphalt emulsion-modified concrete systems with air detraining agent: PC10SSDC and PC20SSDC. In the case of PC20SSDC concrete, its compressive strength was lower and air content was higher compared to PC10SSDC concrete.

### 8.3 RECENT DEVELOPMENTS AND FUTURE RESEARCH NEEDS

The first stage of this report was a pioneer project that attempted to explore the mechanical properties and durability of asphalt emulsion-modified concrete system. All findings listed in the previous section were reached on the basis of test results performed on continuously moist cured samples. Although adequate, the test results for asphalt emulsion-modified samples were at best comparable or only marginally better than that obtained for plain, unmodified concrete. A critical analysis of these findings led to the conclusion that further modifications of both mix proportions and production techniques are needed if significant performance improvement was to be achieved. It was therefore decided to start the second phase of the investigation to explore the influence of different curing regime and addition of mineral admixtures on the properties of asphalt emulsion modified concrete.

In the new series of tests the samples were moist cured only for short initial period of 24 or 48 hours. This brief initial period of moist curing was followed by a period of air curing. This modified curing procedure accelerated the evaporation of water from concrete (including the water from asphalt emulsion) and speeded up the development of asphalt "film" throughout the microstructure of the concrete.

For comparative purposes, a second series of companion samples following the same curing regime as used in the first stage of the project (that is moist curing in the fog room) was also tested. These second series test results for moist cured samples are very similar to those obtained during the first part of the project. This indicates that asphalt emulsion modified concrete can be produced in a reproducible fashion, using the standard mixing and batching equipment. A limited number of tests have also been performed on samples containing the addition of both asphalt emulsion and either silica fume or class C fly ash at 10% by weight of cement replacement level.

The results obtained for air-cured samples with and without the mineral admixtures are presented in Figures 8.1 and 8.2. There were a total of four mixes prepared for this study. These mixes were as follows: a) conventional portland cement concrete (CPCC) as the first reference, b) asphalt emulsion-modified concrete with 10% of SS-1h asphalt emulsion, naphtalene sulfonate superplasticizer, and an air detraining agent (AEMC), c) conventional (10% of silica fume by wt. of cement) silica fume concrete with a naphtalene sulfonate superplasticizer (CPCSFC) as the second reference, d) asphalt emulsion-modified concrete with 10% of SS-1h asphalt emulsion, naphtalene sulfonate superplasticizer, silica fume and an air detraining agent (AEMSFC).

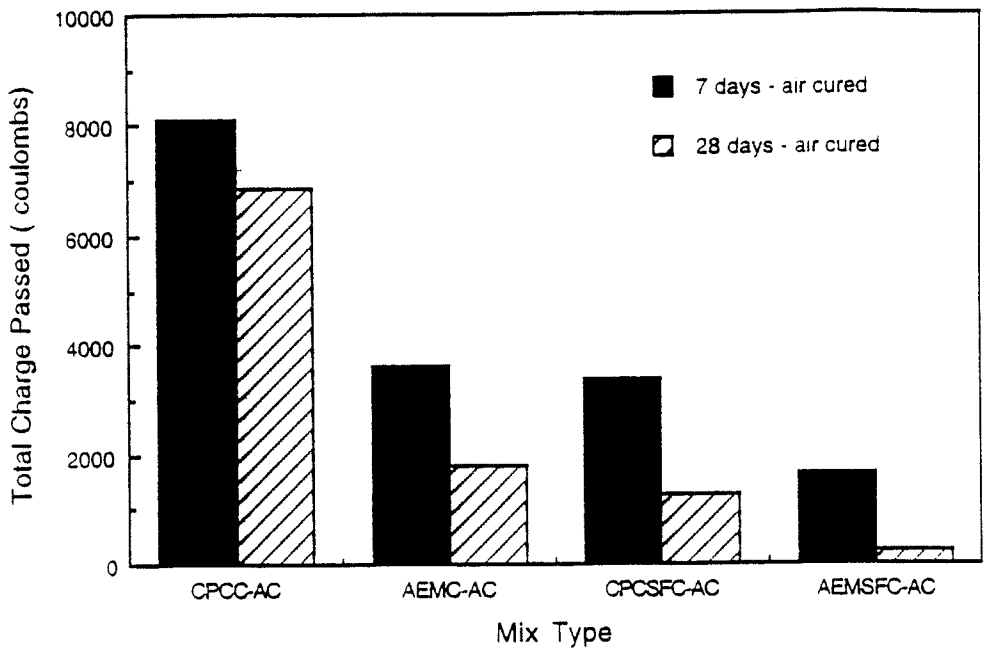


FIGURE 8.1. Rapid Chloride Permeability Results of Air-Cured Samples

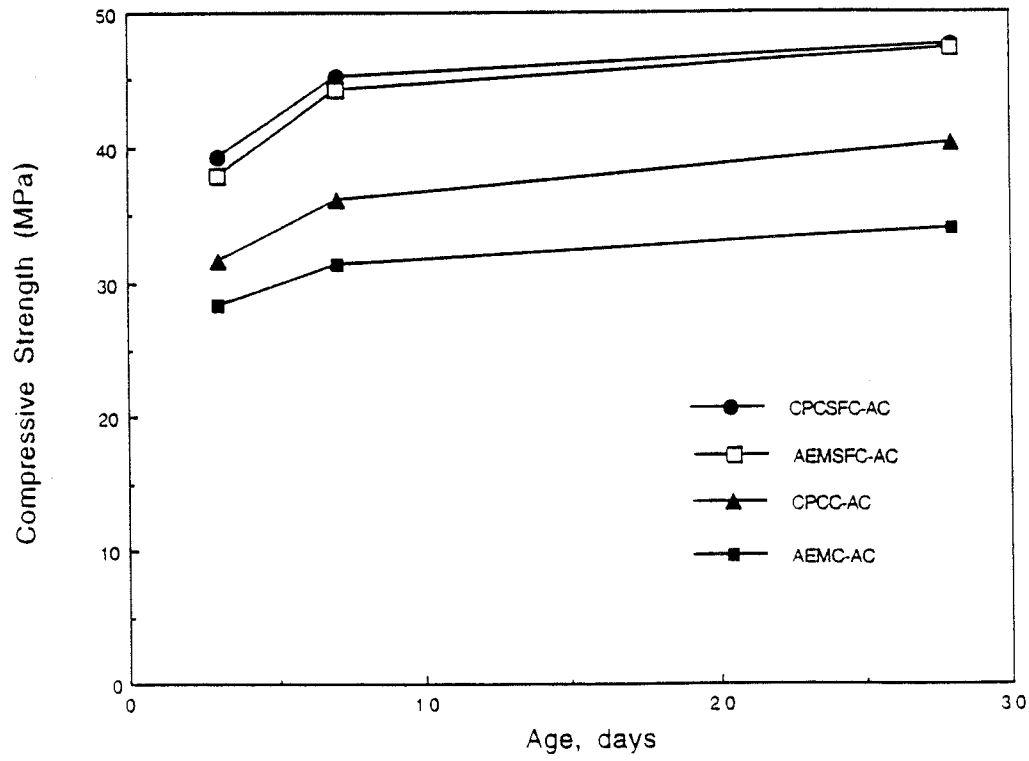


FIGURE 8.2. Compressive Strength Development of Air-Cured Samples



The results from rapid chloride permeability tests obtained for air-cured samples are superior to those obtained from wet-cured samples. This indicates that exposure of samples modified with asphalt emulsion to the environment which promotes the loss of water by evaporation is very beneficial to the properties of the final product. Even at relatively early age of 28 days the asphalt emulsion-modified samples reached the "low" chloride permeability category (1000 to 2000 coulombs according to AASTO T277) and practically matched the performance of the reference silica fume concrete. The most significant reduction of total charge passed in rapid chloride permeability test was observed in samples containing both silica fume and asphalt emulsion addition. After 56 days of air curing these samples were completely impenetrable (zero coulombs of charge).

Based on the critical analysis of data available to date the following topics are suggested for further investigation:

1. Effects of air curing on properties of asphalt emulsion-modified concrete.
2. Rate of hydration and degree of hydration of asphalt emulsion-modified concrete.
3. Continuity of pore systems of asphalt emulsion-modified concrete.
4. Effects of air detraining agent on freezing and thawing resistance of asphalt emulsion-modified concrete.
5. Effects of pozzolanic admixtures (fly ash and silica fume) on mechanical and durability properties of asphalt emulsion modified concretes.
6. Comparative studies of the asphalt emulsion modified concrete and latex modified concrete containing the same basic ingredients and cured under similar conditions. Such study will be helpful in assessing the effectiveness of the superplasticizing system in latex emulsion and provide quantitative data which can be used in development of comparable superplasticizing system for asphalt emulsions. Currently the asphalt emulsion manufacturer does not provide a superplasticizing system tailored for concrete.

## LIST OF REFERENCES

1. Roberts, F., Kandhal, P., Brown, E.R., Lee, D., and Kennedy, T., "*Hot Mix Asphalt Materials, Mixture Design and Construction*", NAPA Education Foundation, Lanham, Maryland, 1991, pp. 3, 16-19.
2. Mindess, S. and Young, J.F., *Concrete*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1981, pp 184-186, 344-349, 544-548, 615-628.
3. Coyne, L.D. and Ripple, R.M., "Emulsified Asphalt Mix Design and Construction", Proceedings, Association of Asphalt Paving Technologists Technical Sessions, E.L. Skok, Jr., ed., Phoenix, Arizona, February 10-12, 1975, *Asphalt Paving Technology*, Vol. 44, 1975, pp. 281-301.
4. Terrel, R.L. and Wang, C.K., "Early Curing Behavior of Cement Modified Asphalt Emulsion Mixtures", Proceedings, Association of Asphalt Paving Technologists Technical Sessions, E.L. Skok, Jr., ed., Oklahoma City, Oklahoma, February 15-17, 1971, *Asphalt Paving Technology*, Vol. 40, 1971, pp. 108-125.
5. Schmidt, R.J., Santucci, L.E. and Coyne, L.D., "Performance Characteristics of Cement-Modified Asphalt Emulsion Mixes", Proceedings, Association of Asphalt Paving Technologists Technical Sessions, E.L. Skok, Jr., ed., Houston, Texas, February 12-14, 1973, *Asphalt Paving Technology*, Vol. 42, 1973, pp. 300-319.
6. Energy Requirements Study, Letter DL-74-10 (5-16-74), *The Asphalt Institute*.
7. Sherman, G.B., Johnson, M.H., and Scrimsher, T., "An Experiment Using Emulsified Asphalt Cold Mix as a Surfacing Material", *Seventh Annual Nevada Street and Highway Conference*, Reno, Nevada, 1972.
8. Traxler, R., *Asphalt, Its Composition, Properties and Uses*, Reinhold Publishing Corporation, New York, 1961, pp. 157-175.
9. Goetz, W.H. and Wood, L.E., "Bituminous Materials and Mixtures", *Highway Engineering Handbook*, K.B. Wood, ed., McGraw-Hill Book Co., Inc., New York, 1960, Section 18, pp. 1-102.
10. American Society of Testing Materials, "*Standard Test Methods for Emulsified Asphalts*", ASTM D 244 - 91, Philadelphia, PA, 1991.
11. Day, A., "A Brief Consideration of Fundamental Concepts of Asphalt Emulsions", Proceedings, Association of Asphalt Technologists Technical Session, E.L. Skok, Jr., ed., *Asphalt Paving Technology*, Vol. 19, 1950, pp. 348-368.
12. Hutchision, C.B., "*Effect of Asphalt Composition on Asphalt Emulsion Viscosity*", Masters Thesis, Washington University, 1947.
13. Bland, M.R., "*Factors Determining Asphalt Emulsion Viscosity*", Senior Thesis, Washington University, 1947.
14. Kobayashi, M., Nakakuro, K. and Negami, S., "Frost Resistance of Superplasticized Concrete", Second International Conference on Superplasticizers in Concrete, V.M. Malhotra, ed., Ottawa, Canada, June 1981, *ACI Special Publication SP-68*, 1981, pp. 269-282.
15. Hattori, K., "Experiences with Mighty Superplasticizer in Japan", First International Symposium on Superplasticizers in Concrete, V.M. Malhotra, ed., Ottawa, Canada, May 1978, *ACI Special Publication SP-62*, 1978, pp. 37-66.
16. Neville, A.M., *Properties of Concrete*, John Wiley & Sons, Inc., New York, 1981, pp. 110-112, 741-742.
17. Ramachandran, V.S. and Malhotra, V.M., "Superplasticizers", Chapter 4 in *Concrete Admixtures Handbook*, V.S.

- Ramachandran, ed., Noyes Publications, Parkridge, New Jersey, 1984, pp. 211-264.
18. Rixom, M.R. and Mailvaganam, N.P., "*Chemical Admixtures for Concrete*", Second Edition, Chapter 1, E. and F.N. Spon Publishers, New York, 1986, pp. 1-91.
  19. Meyer, A., "Experiences with Mighty Superplasticizers in Germany", First International Symposium on Superplasticizers in Concrete, V.M. Malhotra, ed., Ottawa, Canada, May 1978, *ACI Special Publication SP-62*, 1978, pp. 21-36.
  20. Sellevold, E.J. and Radjy, F.F., "Condensed Silica Fume (Microsilica) in Concrete: Water Demand and Strength Development", Proceedings of the First International Conference on the Use of Fly Ash, Silica Fume, Slag & Other Mineral By-Products in Concrete, 1983, V.M. Malhotra, ed., *ACI SP-79*, 1983, pp. 677-694.
  21. Quon, D.H. and Malhotra, V.M., "Effect of Superplasticizer on Slump, Strength, and Degree of Conversion of High-Alumina Cement Concrete", Second International Conference on Superplasticizers in Concrete, V.M. Malhotra, ed., Ottawa, Canada, June 1981, *ACI Special Publication SP-68*, 1981, pp. 173-188.
  22. Mailvaganam, N.P., "Factors Influencing Slump Loss in Flowing Concrete", First International Symposium on Superplasticizers in Concrete, V.M. Malhotra, ed., Ottawa, Canada, May 1978, *ACI Special Publication SP-62*, 1978, pp. 389-404.
  23. Malhotra, V.M., "Superplasticizers: Their Effect on Fresh and Hardened Concrete", *CANMET Report*, Ottawa, Canada, 1979, 23 pages.
  24. Malhotra, V.M., "Performance of Superplasticizers in Concrete: Laboratory Investigation -- Part I", First International Symposium on Superplasticizers in Concrete, V.M. Malhotra, ed., Ottawa, Canada, May 1978, *ACI Special Publication SP-62*, 1978, pp. 209-244.
  25. Seabrook, P.T. and Malhotra, V.M., "Accelerated Strength Testing of Superplasticized Concrete and the Effect of Repeated Doses of Superplasticizers on Properties of Concrete", First International Symposium on Superplasticizers in Concrete, V.M. Malhotra, ed., Ottawa, Canada, May 1978, *ACI Special Publication SP-62*, 1978, pp. 263-292.
  26. Aignesberger, A. and Kern, A., "Use of Melamine Based Superplasticizer as a Water Reducer", Developments in the Use of Superplasticizer, *ACI SP-68*, 1981, pp. 61-80.
  27. Collepardi, M. and Corradi, M., "Influence of Naphthalene-Sulfonated Polymer Based Superplasticizers on the Strength of Ordinary and Lightweight Concretes", First International Symposium on Superplasticizers in Concrete, V.M. Malhotra, ed., Ottawa, Canada, May 1978, *ACI Special Publication SP-62*, 1978, pp. 315-336.
  28. Mukherjee, P.K. and Chojnacki, B., "Laboratory Evaluation of a Concrete Superplasticizing Admixture", First International Symposium on Superplasticizers in Concrete, V.M. Malhotra, ed., Ottawa, Canada, May 1978, *ACI Special Publication SP-62*, 1978, pp. 245-262.
  29. Brooks, J.J., Wainwright, P.J. and Neville, A.M., "Time-Dependent Properties of Concrete Containing a Superplasticizing Admixtures", First International Symposium on Superplasticized Concretes, V.M. Malhotra, ed., Ottawa, Canada, May 1978, *ACI Special Publication SP-62*, 1978, pp. 293-314.
  30. Mailvaganam, N.P., Bhagrath, R.S. and Shaw, K.L., "Sulfate Resistance of Mortars Containing Superplasticizers with Fly Ash or Blast Furnace Slag", Second International Conference on Superplasticizers in Concrete, V.M. Malhotra, ed., Ottawa, Canada, June 1981, *ACI Special Publication SP-68*, 1981, pp. 535-556.
  31. Tynes, W.O., "Investigation of Proprietary Admixtures", U.S. Army Waterways Experiment Station, *Technical Report C-77-1*, April 1977.

32. Ghosh, R.S. and Malhotra, V.M., "Use of Superplasticizers as Water-Reducers", *Cement, Concrete and Aggregates*, ASTM Vol. 1, No. 2, 1979, pp. 56-63.
33. Malhotra, V.M., "Effects of Repeated Dosage of Superplasticizers on Slump, Strength, and Freeze-Thaw Resistance of Concrete", *Materials and Constructions*, Vol. 14, No. 80, 1981, pp. 79-89.
34. Whiting, D., "Effects of High-Range Water Reducers on Some Properties of Fresh and Hardened Concrete", Portland Cement Association, *Research and Development Bulletin RD061.OT*, 1979.
35. Malhotra, V.M., "Superplasticizers in Concrete", *CANMET Report MRP/MSL 77-213(J)*, August 1977.
36. Roberts, L.M. and Scheiner, P., "Air Void System and Frost Resistance of Concrete Containing Superplasticizers", Second International Conference on Superplasticizers in Concrete, V.M. Malhotra, ed., Ottawa, Canada, June 1981, *ACI Special Publication SP-68*, 1981, pp. 189-214.
37. Lane, R.O. and Best, J.F., "Laboratory Studies on the Effects of Superplasticizers on the Engineering Properties of Plain and Fly Ash Concrete", First International Symposium on Superplasticizers in Concrete, V.M. Malhotra, ed., Ottawa, Canada, May 1978, *ACI Special Publication SP-62*, 1978, pp. 193-207.
38. Collepardi, M., Corradi, M. and Valente, M., "Low-Slump-Loss Superplasticized Concrete", *Proceedings, Transportation Research Record*, Symposium on Superplasticizers in Concrete, National Academy of Sciences, Washington, D.C., 1979, pp. 7-12.
39. Brooks, J.J., Wainwright, P.J. and Neville, A.M., "Time-Dependent Behavior of High-Early-Strength Concrete Containing a Superplasticizer", Second International Conference on Superplasticizers in Concrete, V.M. Malhotra, ed., Ottawa, Canada, June 1981, *ACI Special Publication SP-68*, 1981, pp. 81-100.
40. Popovics, S., "A Hypothesis Concerning the Effects of Macro-Porosity on Mechanical Properties of Concrete", SEM/RILEM International Conference, S.P. Shah and S.E. Swartz, ed., Houston, Texas, June 1987, *Fracture of Concrete and Rock*, 1989, pp. 170-174.
41. Popovics, S., *Concrete Making Materials*, McGraw-Hill Book Company, New York, and Hemisphere Publishing Corporation, Washington, 1979, p. 370.
42. Popovics, S., "New Formulas for the Prediction of the Effect of Porosity on Concrete Strength", *ACI Journal*, Proceedings Vol. 82, No. 2, March - April, 1985, pp. 136-146.
43. Gaynor, R.D., "High Strength Air-Entrained Concrete", *Joint Research Laboratory Publication No. 17*, March 1986, National Sand and Gravel Assn., National Ready Mixed Concrete Assn., Silver Spring, Md.
44. Wright, P.J.F., "Entrained Air in Concrete", *Proceeding Institution of Civil Engineers*, Part I, Vol. 2, No. 3, May 1953, pp. 337-358.
45. Popovics, S., "Effect of Porosity on the Strength of Concrete", *Journal of Materials*, JMLSA, Vol. 4, No. 2, June 1969, pp. 356-371.
46. Abrams, D.A., "Design of Concrete Mixtures", *Bulletin 1*, revised edition, Structural Materials Research Laboratory, Chicago, 1925.
47. Talbot, A.N., "A Proposed Method of Estimating the Density and Strength of Concrete and of Proportioning the Materials by the Experimental and Analytical Consideration of the Voids in Mortar and Concrete", *Proceedings, American Society for Testing and Materials*, Vol. 21, 1921, pp. 940-963.
48. Glanville, W.H., Collins, A.R. and Matthews, D.D., "The Grading of Aggregates and Workability of Concrete",

- Road Research Technical Paper No. 5*, Department of Scientific and Industrial Research and Ministry of Transport, London, 1938.
49. Kaplan, M.F., "Effects of Incomplete Consolidation on Compressive and Flexural Strength, Ultrasonic Pulse Velocity and Dynamic Modulus of Elasticity of Concrete", *Journal of the American Concrete Institute, Proceedings*, Vol. 56, March 1960, pp. 853-867.
  50. Gonnerman, H.F., "Tests of Concrete Containing Air-Entraining Portland Cements or Air-Entraining Materials Added to Batch at Mixer", *Journal of the American Concrete Institute, Proceedings*, Vol. 40, June 1944, pp. 447-508.
  51. Gowripalan, N., Cabrera, J.G., Cusens, A.R. and Wainwright, P.J., "Effect of Curing on Durability", *Concrete International*, Vol. 12, No. 4, April 1990, pp. 47-54.
  52. Nyame, B.K. and Illston, J.M., "Capillary Pore Structure and Permeability of Hardened Cement Paste", *Proceedings, 7th International Congress on the Chemistry of Cement*, Editions Septima, Paris, Vol. 1, 1980, pp. 181-185.
  53. Mehta, P.K. and Manmohan, D., "Pore Size Distribution and Permeability of Hardened Cement Pastes", *Proceedings, 7th International Congress on the Chemistry of Cement*, Editions Septima, Paris, Vol. 2, pp. 1-5.
  54. Hughes, D.C., "Pore Structure and Permeability of Hardened Cement Paste", *Magazine of Concrete Research*, London, Vol. 37, No. 133, December 1985, pp. 227-233.
  55. Walters, D.G., "What are Latexes?", *Concrete International*, Vol. 9, No. 4, April 1987, pp. 44-47.
  56. Anonymous, "Latex-Modified Concrete", *Indian Concrete Journal*, Vol. 62, No. 6, June 1988, pp. 278-279.
  57. Kuhlmann, L.A., "Performance History of Latex-Modified Concrete Overlays", Applications of Polymer Concrete, *ACI SP-69*, 1981, pp. 123-144.
  58. Sheng, Qizhong, "*Study of Modifications of Latex-Modified Concrete System*", Doctor of Philosophy Thesis, Purdue University, May 1990, pp. 5-12.
  59. Kuhlmann, L.A., "Application of Styrene-Butadiene Latex Modified Concrete", *Concrete International*, Vol. 9, No. 12, December 1987, pp. 48-53.
  60. Kuhlmann, L.A., "Latex Modified Concrete for the Repair and Rehabilitation of Bridges", *The International Journal of Cement Composites and Lightweight Concrete*, Vol. 7, No. 4, November 1985, pp. 217-233.
  61. Bentur, A., "Properties of Polymer Latex-Cement Composites", *The International Journal of Cement Composites and Lightweight Concrete*, Vol. 4, No. 1, February 1982, pp. 57-65.
  62. Popovics, S., "Strength Losses of Polymer-Modified Concretes under Wet Conditions", Polymer Modified Concrete, D.W. Fowler, ed., *ACI SP-99*, 1987, pp. 165-189.
  63. Riley, V.R. and Razl, I., "Polymer Additives for Cement Composites: A Review", *Composites*, Vol. 5, No. 1, January 1974, pp. 27-33.
  64. Ohama, Y., "Chapter 7, Polymer-Modified Mortars and Concretes", *Concrete Admixtures Handbook*, Properties, Science and Technology, V.S. Ramachandran, ed., Noyes Publications, Park Ridge, New Jersey, 1984, pp. 341.
  65. Clear, K.C. and Chollar, B.H., "*Styrene-Butadiene Latex Modifiers for Bridge Deck Overlay Concrete*", Interim Report, FHWA-RD-78-35, 1987, p. 36.

66. Kukacka, L.E., Ausker, A., Colombo, P., Fontana, J. and Steinberg, M., "Introduction to Concrete-Polymer Materials", Report No. FHWA-RD-75-507, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1975.
67. Dikeou, J.T., Kukacka, L.E., Backstorm, J.E. and Steinberg, E., "Polymerization Makes Tougher Concrete", *Journal of American Concrete Institute*, Vol. 66, October 1969, pp. 829-839.
68. Auskern, A. and Horn, W., "Some Properties of Polymer-Impregnated Cements and Concretes", *Journal of American Ceramic Society*, 1971, pp. 282-285.
69. Manning, D.G. and Hope, B.B., "The Effect of Porosity on the Compressive Strength and Elastic Modulus of Polymer-Impregnated Concrete", *Cement and Concrete Research*, 1971, pp. 631-644.
70. American Society of Testing Materials, "Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens", *ASTM C 215 - 85*, Philadelphia, PA, 1987.
71. American Society of Testing Materials, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing", *ASTM C 666 - 84*, Philadelphia, PA, 1987.

