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16. Abstract

A two-part laboratory experimental program was conducted to evaluate strength and durability of various concrete mix designs. In Part I of the study, the influence of using grade 120 ground granulated blast furnace slag (GGBFS) on the strength and durability properties of concrete was evaluated. GGBFS was used to replace portland cement at replacement rates ranging from 0 to 75 percent. Other test variables included the use of cements with different alkali contents, fly ash, silica fume, and Type K cement. Strength testing included compressive strength, flexural strength, and splitting tensile strength. Durability testing included freeze-thaw resistance, shrinkage testing, rapid chloride ion penetration testing, and abrasion resistance testing. Based on the test results, the addition of GGBFS at rates as high as 55 percent of the total cementitious material resulted in strengths that, after 14 days, equaled or exceeded those of the baseline concrete mix. The incorporation of GGBFS in the concrete mix significantly improved the resistance to chloride ion penetration. In Part II of the study, the influence of coarse aggregate size on the strength and durability of the ODOT Class C mix designs was evaluated. Coarse aggregate sizes included #57, #467, and #357. The ODOT high performance concrete mix designs were also included in the study. Test results are presented in tabular and graphical formats.

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RESEARCH PROJECT
"EVALUATION OF PORTLAND CEMENT CONCRETES CONTAINING GROUND GRANULATED BLAST FURNACE SLAG"
STATE JOB NO. 14559(0)

FINAL REPORT

Submitted to:

Ohio Department of Transportation
and
Federal Highway Administration

Prepared by:

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Prepared in cooperation with the
Ohio Department of Transportation and the
U.S. Department of Transportation, Federal Highway Administration

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DISCLAIMER STATEMENT

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Acknowledgments

The research reported herein was sponsored by the Ohio Department of Transportation under Agreement No. 7516 in cooperation with the Federal Highway Administration. The liaison representatives from the Ohio DOT were Mr. Roger Green, Mr. Keith Keeran, Mr. Jim Barnhart, and Mr. Lloyd Welker. Their suggestions and guidance during the course of the project are sincerely appreciated.

Throughout this project, several graduate students participated in the project, and several of them used various segments of the project as the subject material for their thesis. The graduate research assistants involved in the project include Marcia C. Belcher, Yunhong Gao, Luyi Yan, James E. Whitt, Jai Du, David M. Vovak, Nikhila N. Naik, and Thomas McDonnell. In addition, these individuals were assisted by numerous undergraduate research assistants who helped with the many laborious tasks involved in making and testing the large quantity of concrete involved in this project. Together, these research assistants produced and tested more than 136,000 kilograms (300,000 pounds) of concrete in the lab. In the process of doing so, this amount of material was handled a minimum of six times. In some tests procedures, it was handled many times more. The effort of every individual who assisted in this research project is greatly appreciated.

Several manufacturers provided materials at no cost or at reduced cost and/or paid the cost of shipping the materials to the University of Akron. This support of the project is appreciated.

The Office of Research Services and Sponsored Programs at the University of Akron provided tuition waivers for the graduate students involved in the project and also shared in the cost of this project through under-recovery of indirect costs associated with the project. This support is acknowledged and appreciated.

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INTRODUCTION

This research project was conducted in two separate parts. The initial project was appropriately titled "Evaluation of Portland Cement Concretes Containing Ground Granulated Blast Furnace Slag." The second part of the project is the result of a significant expansion of the scope and budget of the original project to address additional concrete related issues of interest to the Ohio Department of Transportation. The original title is inadequate to reflect the true scope of the revised project. Since the total project consists of two distinct parts, the report is divided into two primary sections. Part I presents the portion of the project corresponding to the initial scope of work, and Part II presents the portion of the project corresponding to the additional scope of work that was added during the course of the project. The research objectives of the two parts of the project are presented here to provide an overview of the complete project. The details of the two parts of the project and the corresponding results and conclusions are presented in subsequent sections of this report.

RESEARCH OBJECTIVES

PART I – INFLUENCE OF GGBFS ON THE STRENGTH AND DURABILITY OF CONCRETE

The primary objectives of Part I of the research project are to investigate the strength, durability, and workability of concretes containing ground granulated blast furnace slag (GGBFS) as a partial replacement for portland cement. The research focuses on the use of Grade 120 GGBFS.

The specific objectives of the research investigation are to:

1) evaluate the strength, durability, and workability of several concretes containing different percentages of GGBFS as a partial replacement for portland cement,
2) evaluate the strength, durability, and workability of concretes with 15% of the portland-GGBFS combination replaced with Class C fly ash and with Class F fly ash,
3) evaluate the strength, durability, and workability of standard ODOT Class S and Micro-Silica concretes,
4) compare the properties of concretes containing GGBFS to those of ODOT Class S and Micro-Silica concretes,
5) evaluate the length change due to drying for ODOT High Performance Concretes used in ODOT construction projects,
6) evaluate the chloride permeability of ODOT High Performance Concretes used in ODOT construction projects,
7) monitor the concrete temperatures during curing at project sites where ODOT High Performance Concrete is being used,

8) establish guidelines for the specification and use of GGBFS as a partial replacement for portland cement,

9) specify and/or establish test procedures for the evaluation and acceptance of GGBFS and concretes containing GGBFS, and

10) evaluate the economics of using concretes containing GGBFS.

PART II – INFLUENCE OF COARSE AGGREGATE SIZE ON THE STRENGTH AND DURABILITY OF CONCRETE

The primary objectives of Part II of the research project are to: 1) investigate the strength and durability of several concrete mixes based on the standard ODOT Class C concrete mix and incorporating various coarse aggregate sizes and various mix options allowed by the ODOT specifications, 2) evaluate the strength and durability characteristics of several concrete mixes similar to the four High Performance Concrete mixes of Proposal Note 350 but with lower cement factors, and 3) to evaluate the strength and durability characteristics of the ODOT Silica Fume Concrete Overlay Mix and variations of that mix with a reduced silica fume content or with a reduced portland cement and silica fume content.

The specific objectives of Part II of the research project are as follows.

I. Evaluate the strength and durability of the following twelve laboratory-prepared concrete mixes.

   a) ODOT Class C concrete with coarse aggregate size number 57
   b) ODOT Class C concrete with coarse aggregate size number 57, Option 1
   c) ODOT Class C concrete with coarse aggregate size number 57, Option 2
   d) ODOT Class C concrete with coarse aggregate size number 57, Option 3

   e) ODOT Class C concrete with coarse aggregate size number 467
   f) ODOT Class C concrete with coarse aggregate size number 467, Option 1
   g) ODOT Class C concrete with coarse aggregate size number 467, Option 2
   h) ODOT Class C concrete with coarse aggregate size number 467, Option 3

   i) ODOT Class C concrete with coarse aggregate size number 357
   j) ODOT Class C concrete with coarse aggregate size number 357, Option 1
   k) ODOT Class C concrete with coarse aggregate size number 357, Option 2
   l) ODOT Class C concrete with coarse aggregate size number 357, Option 3

II. Develop new mix designs that are similar to the four mixes of the ODOT High Performance Concrete (HPC) Proposal Note, but with a reduced cementitious content. The target properties of the new mix formulations are: a) good workability, finishability, and pumpability, b) approximately 41.3 MPa (6000 psi) compressive strength at 28 days, c) results from 28-day rapid chloride permeability tests similar to those for the current high performance concrete mixes, d) good resistance to freeze-thaw cycles, and e) length change due to drying characteristics similar to those for the current high performance concrete mixes.

The concretes involved in this task include the following:

a) ODOT HPC Mix 1 (fly ash)
b) ODOT HPC Mix 2 (GGBFS)
c) ODOT HPC Mix 3 (fly ash and silica fume)
d) ODOT HPC Mix 4 (GGBFS and silica fume)

e) Revised ODOT HPC Mix 1 (fly ash)
f) Revised ODOT HPC Mix 2 (GGBFS)
g) Revised ODOT HPC Mix 3 (fly ash and silica fume)
h) Revised ODOT HPC Mix 4 (GGBFS and silica fume)

III. Evaluate the strength and durability of the following four laboratory prepared concrete mixes which are the ODOT Micro-Silica Concrete Overlay Mixes and variations of that mix with a reduced silica fume content or with a reduced portland cement and silica fume content.

a) ODOT Silica Fume Overlay Mix (317.5 kg (700 lbs) portland, 31.8 kg (70 lbs) silica fume)
b) Revised Overlay Mix (317.5 kg (700 lbs) portland, 23.8 kg (52.5 lbs) silica fume)
c) Revised Overlay Mix (317.5 kg (700 lbs) portland, 15.9 kg (35.0 lbs) silica fume)
d) Revised Overlay Mix (272.2 kg (600 lbs) portland, 13.6 kg (30.0 lbs) silica fume)

PART I – INFLUENCE OF GGBFS ON THE STRENGTH AND DURABILITY OF CONCRETE

RESEARCH PROGRAM

The research presented herein is primarily a laboratory experimental evaluation of the properties of portland cement concretes containing GGBFS at different replacement rates. The influence of the alkali content of the portland cement on the properties of the concrete containing the portland cement and GGBFS is also investigated. Testing is also performed on standard ODOT Class S, Micro-Silica, and shrinkage compensated concretes for comparison with the properties of the concretes containing GGBFS. The term Micro-Silica concrete is used by ODOT to refer to its standard concrete containing silica fume that is normally used for bridge deck overlay applications. Although Micro-Silica is actually a trademark name for a particular brand of silica fume, it is used in this report to be consistent with the terminology used by the ODOT to refer to its overlay concrete mix. The concrete mixes evaluated during this study include:

1) ODOT Class S concrete containing medium alkali portland cement,
2) ODOT Class S concrete containing shrinkage compensating portland cement,
3) ODOT Micro-Silica Modified concrete,
4) concretes similar to ODOT Class S concrete containing medium alkali portland cement where GGBFS is used to replace portland cement at the replacement rates of 25, 35, 45, 55, and 70 percent,
5) concretes similar to ODOT Class S concrete containing high alkali portland cement where GGBFS is used to replace portland cement at the replacement rates of 35 and 55 percent,
6) concretes similar to ODOT Class S concrete containing low alkali portland cement where GGBFS is used to replace portland cement at the replacement rates of 35 and 55 percent,
7) concretes similar to ODOT Class S concrete containing shrinkage compensating portland cement where GGBFS is used to replace portland cement at the replacement rates of 35 and 55 percent,
8) concretes similar to ODOT Micro-Silica Modified concrete where GGBFS is used to replace portland cement at the replacement rates of 35 and 55 percent,
9) concretes similar to ODOT Class S concrete containing medium alkali portland cement were GGBFS is used to replace portland cement at the replacement rates of 35 and 55 percent, and 15 percent of the GGBFS-portland combination replaced with Class C fly ash, and

10) concretes similar to ODOT Class S concrete containing medium alkali portland cement with GGBFS used to replace portland cement at the replacement rates of 35 and 55 percent, and 15 percent of the GGBFS-portland combination replaced with Class F fly ash.

For each of the concrete mix designs, the tests performed on the concrete in its plastic state include: 1) slump, 2) air content, 3) unit weight, and 4) temperature. The tests performed on the hardened concrete include: 1) compressive strength testing performed at 1, 3, 7, 14, 28, and 90 days of age, 2) splitting tensile strength at testing performed at 7 and 28 days of age, 3) flexural strength testing performed at 7 and 28 days of age, 4) rapid chloride permeability testing performed at 28 days of age, 5) freeze-thaw durability testing, 6) length change due to drying, and 7) abrasion resistance testing.

MATERIALS

The materials used to produce the concrete mixes for this study are the same as those normally used in the commercial production of ready-mix concrete. The manufacturer, and the brand name if applicable, for each of the component materials is given below. The mix designations that contained a particular component are also included.

Portland Cement Four different portland cements were used in the study. The cements referred to as low alkali, medium alkali and high alkali portland cement all meet the requirements for Type I portland cement prescribed by ASTM C 150. They have alkali contents that are considered as low, medium, and high relative to the portland cements that are commonly found in the Ohio market. The low alkali cement used in the S35SLA and S55SLA concrete mixes was produced by the Lafarge Cement Company and meets the requirements for both Type I and Type II cement. The medium alkali cement used in the SnnS series, the SnnSC series, the SnnSF series, and the MSnnS series was produced by Holnam, Inc. The high alkali cement used in the S35SHA and S55SHA concrete mixes was produced by Southdown, Inc., Fairborn, Ohio. The Type K shrinkage compensating cement used in the SnnSK series meets the requirements of ASTM C 845 for Type K cement and was produced by Southdown, Inc., Fairborn, Ohio.

GGBFS The ground granulated blast furnace slag (GGBFS) used in the study meets the requirements for Grade 120 GGBFS prescribed by ASTM C 989. The GGBFS was provided by Koch Minerals Co., from their Weirton, WV plant. The GGBFS segment of Koch Minerals Co. has since been sold to Holnam, Inc. Typical values for the specific gravity and Blaine fineness of the Grade 120 GGBFS produced by Koch Minerals Co. are 2.89 and 450 to 650 m^2/kg, respectively.

Silica Fume Silica fume meeting the requirements of AASHTO M 309-90 was used in the concrete mixes in the MS group. The silica fume used in the study was MB-SF marketed by Master Builders, Inc., Cleveland, Ohio. The specific gravity of the silica fume used in proportioning the concrete mixes was 2.2.

Fly Ash Class C fly ash and Class F fly ash meeting the requirements of ASTM C 618 were used in the SnnSC and SnnSF series concrete mixes. A specific gravity value of 2.5 for the fly ashes was used in proportioning the concrete mixes.

Coarse Aggregate A crushed limestone coarse aggregate with a #57 gradation was used for all of the mixes in the S group, and a crushed limestone coarse aggregate with a #8 gradation was used in the mixes in the MS series. The #57 coarse aggregate was divided into four particle size groups and recombined in the proper proportions for each batch of concrete to insure that all of the batches of concrete have the same coarse aggregate gradation. Two sources of coarse aggregate were used in the study. In the early part of the study, aggregate from the Rogers Group was used. This aggregate was later found to cause poor resistance to freeze-thaw cycles. Once this problem was discovered, the coarse aggregate source was changed, and an aggregate from Drummond Island, Michigan was used for the remainder of the study. The SSD specific gravity and the absorption values for the aggregated are presented in Table 1.

Fine Aggregate Natural concrete sand from Hill Top Sand and Gravel was used for the fine aggregate. The sand meets the gradation requirements of ASTM C 33, but some samples tested had fineness modulus values that were slightly higher than allowed by ASTM C 33. All of the samples tested did meet the gradation requirements of section 703.02 of the ODOT specifications. The specific gravity and absorption values are reported in Table 1.

Table 1) Specific Gravity and Absorption Values for the Aggregates Used in the Study.

Aggregate Gradation	Source	Specific Gravity SSD	Absorption (percent)
#57	Rogers Group	2.61	1.70
#57	Drummond Island	2.78	0.55
#8	Rogers Group	2.59	2.27
Fine Aggregate	Hill Top Sand and Gravel	2.56	2.00

Water Water for the concrete mixes was taken from the municipal water system of Akron, Ohio.

Air Entraining Admixtures Two different air-entraining admixtures were used in the study. Micro-Air, produced by Master Builders, Cleveland, Ohio, was used in all of the concrete mixes except the S70S concrete mixes. For the S70S mix, the slump values were usually about 1 inch, and the Micro-Air admixture was not able to entrain the desired air content. For the S70S concrete mixes, EucoAir was used as the air-entraining admixture. EucoAir is a product of Euclid Chemical Co. of Cleveland, Ohio, and is designed specifically for use in concrete mixtures in which it is difficult to produce entrained air.

Water Reducing Admixture RheoBuild 2000, a high-range water reducing admixture produced by Master Builders, Inc., Cleveland, Ohio, was used in all of the concrete mixes in the MS group.

MIX PROPORTIONS

Part I of the project involved twenty-three different concrete mix designs. Of these, the concrete for eighteen of the mix designs was prepared in the laboratory using multiple batches per mix design, and the concrete for the remaining five mix designs was obtained from ODOT construction projects. Throughout the report, the results and the discussion are arranged in the same sequence for all of the test types. The twenty-three mix designs can be divided into three broad groups as follows: 1) the "S" group consists of fifteen mixes having batch proportions based on ODOT Class S concrete, 2) the "MS" group consists of three mix designs having batch proportions based on ODOT Micro-Silica concrete, and 3) the "O" group consists of concrete obtained from ODOT construction projects. Each of these primary groups is described further in the following sections, and details of the mix proportions for the mixes prepared in the laboratory are presented in Table 2.

"S" group All of the concretes in this group contain 424.2 kg/m^3 (715 lb/yd^3) of cementitious material, #57 crushed limestone as the coarse aggregate, and a water:cement ratio of 0.42. The target values for air content and slump are 6±2 percent and 7.6±2.5 centimeters (3±1 inches), respectively. The control mix of this group is the S00S mix, which is proportioned according to the standard ODOT Class S mix design. There are six different replacement values of GGBFS, four types of cement, and two types of fly ash used in this group. This group can be further divided into subgroups as follows.

SnnS series A medium alkali Portland cement was used in this series. The only variable within the SnnS series is the GGBFS replacement percentage. The GGBFS replacement percentage is indicated by the nn values in the nnS portion of the mix identification label. GGBFS replacement percentages of 0, 25, 35, 45, 55, and 70 were used. The remaining mixes in the Class S group resemble the mixes in the SnnS series with variations in the portland cement used and whether or not a particular fly ash is used.

SnnSC and SnnSF series Fly ash was used for these mixes at 15 percent by weight of the total cementitious mixture (cement + slag + fly ash). The percent replacement of portland cement with GGBFS coincides with the other mixes (35 and 55). The SnnSC series contains Class C fly ash, and the SnnSF series contains Class F fly ash.

Table 2) Concrete mix proportions for the laboratory-prepared mixes tested during Part I of the project.

Concrete Mix	Total Cementitious kg/m^3 (lb/yd^3)	Portland Cement kg/m^3 (lb/yd^3)	GGBFS kg/m^3 (lb/yd^3)	Silica Fume kg/m^3 (lb/yd^3)	Fly Ash kg/m^3 (lb/yd^3)	w/c	Comments
S00S	424.2 (715.0)	424.2 (715.0)				0.42	med. alkali Type I
S25S	424.2 (715.0)	318.2 (536.6)	106.1 (178.8)			0.42	med. alkali Type I
S35S	424.2 (715.0)	275.7 (464.8)	148.5 (250.3)			0.42	med. alkali Type I
S45S	424.2 (715.0)	233.3 (393.3)	109.9 (321.8)			0.42	med. alkali Type I
S55S	424.2 (715.0)	190.9 (321.8)	233.3 (393.3)			0.42	med. alkali Type I
S70S	424.2 (715.0)	127.3 (214.5)	296.9 (500.5)			0.42	med. alkali Type I
S00SK	424.2 (715.0)	424.2 (715.0)				0.42	Type K
S35SK	424.2 (715.0)	275.7 (464.8)	148.5 (250.3)			0.42	Type K
S55SK	424.2 (715.0)	190.9 (321.8)	233.3 (393.3)			0.42	Type K
S35SLA	424.2 (715.0)	275.7 (464.8)	148.5 (250.3)			0.42	low alkali Type I
S55SLA	424.2 (715.0)	190.9 (321.8)	233.3 (393.3)			0.42	low alkali Type I
S35SHA	424.2 (715.0)	275.7 (464.8)	148.5 (250.3)			0.42	high alkali Type I
S55SHA	424.2 (715.0)	190.9 (321.8)	233.3 (393.3)			0.42	high alkali Type I
S35SC	424.2 (715.0)	234.4 (395.0)	126.2 (212.7)		63.6 (107.3)	0.42	med. alkali Type I + Class C ash
S35SF	424.2 (715.0)	234.4 (395.0)	126.2 (212.7)		63.6 (107.3)	0.42	med. alkali Type I + Class C ash
MS00S	456.8 (770.0)	415.3 (700.0)		41.5 (70.0)		0.33	med. alkali Type I + silica fume
MS35S	456.8 (770.0)	269.9 (455.0)	145.4 (245.0)	41.5 (70.0)		0.33	med. alkali Type I + silica fume
MS55S	456.8 (770.0)	186.9 (315.0)	228.4 (385.0)	41.5 (70.0)		0.33	med. alkali Type I + silica fume

w/c = (water):(total cementitious) ratio

SnnSK series This series consisted of three levels of GGBFS replacement (0, 35, and 55%) and contained Type K shrinkage compensating cement.

SnnSHA and SnnSLA series Two levels of GGBFS replacement (35 and 55%) were used for this series. The primary purpose of this series was to investigate the influence of different cement alkali contents on the properties of the concrete. High alkali cement was used for the SnnSHA series, and low alkali cement was used for the SnnSLA series.

"MS" group The concretes in this group all contain 41.5 kg/m^3 (70 lbs/yd^3) of silica fume and 415.3 kg/m^3 (700 lb/yd^3) of either cement or cement plus GGBFS. The coarse aggregate used for these mixes was #8 crushed limestone, and a water: (cement + GGBFS) ratio of 0.36 was used. The target values for air content and slump are 8$\pm$2 percent and 15$\pm$5 centimeters (6$\pm$2 inches), respectively. The control mix of this group is the MS00S mix, which is proportioned according to the standard ODOT Micro-Silica concrete mix design. The MS letters are used to represent Micro-Silica which is a particular brand of silica fume. The term Micro-Silica is used to be consistent with the terms used by ODOT. Its use does not imply any significance beyond that. Three different percent replacement values of GGBFS were tested (0, 35, and 55) with a medium alkali cement.

"O" group All of the concretes in this group were obtained from ODOT construction projects. The concrete labeled OS is a standard ODOT Class S concrete, and the concrete labeled OK is from a project where the use of Type K cement was specified. The concrete mixes labeled OHPC2 and OHPC4 were obtained from ODOT construction projects involving ODOT High Performance Concrete mixes using mix options 2 and 4 respectively. The concrete mix labeled as OMS was obtained from an ODOT project where ODOT micro-silica concrete was specified.

TEST METHODS

The raw materials used in preparation of the concrete mixes in the lab were stored in the lab at room temperature. The aggregates were maintained at moisture contents slightly above their respective absorption moisture contents. The #57 coarse aggregate was initially screened into several size ranges and stored in separate bins. The amount of each size range required to produce the desired gradation was weighed out for each batch of concrete to prevent variations in the particle size distribution due to segregation. The fine aggregate and the #8 coarse aggregate are small enough in particle size that, when kept moist, segregation is not a problem.

The laboratory-prepared concrete mixes were made using a laboratory mixer with a manufacturer's rated capacity of 0.255 m^3 (9 ft^3). The practical working capacity of the mixer is about 0.170 to 0.184 m^3 (6.0 to 6.5 ft^3). For each batch of concrete, a 0.014 m^3 (0.5 ft^3) butter mix having the same mix proportions as the batch of concrete being prepared was mixed in the mixer first. After mixing of the butter mix was complete, it was discharged from the mixer and discarded. The cement paste and aggregate that stayed in the mixer was left in the mixer to compensate for the material that will remain in the mixer when the actual test batch is discharged.

The loading of the actual test mix into the mixer began immediately after discharging the butter mix. The coarse aggregate and water were placed in the mixer first and were mixed for a few seconds to wet the aggregate. The fine aggregate, with the air-entraining admixture on it, was added next. The mixer was placed into the normal mixing position and started. As soon as the sand, water, and coarse aggregate were well blended, the cement was added, followed immediately by any slag, silica fume, and fly ash present in the mix being prepared. Once all of materials were in the mixer, the start time was noted. The mixer was then operated for 3 minutes and stopped. This was followed by 3 minutes of rest and an additional 2 minutes of mixing. After the final 2-minute mixing period, the concrete was discharged into a pan capable of holding the entire batch, and the concrete was remixed with shovels to eliminate any segregation that may have taken place as the concrete was discharged into the pan. Following the remixing of the concrete in the pan, tests were performed in accordance with ASTM C 143, ASTM C 231, ASTM C 138, and ASTM C 1064, to determine the slump, air content, unit weight, and temperature of the concrete. If these test results were within the desired ranges, specimens were molded for testing.

Each of the mix designs in Part I of the study were prepared a minimum of five times, and a particular mix design was never prepared more than once on a given day. A typical group of specimens from a batch of concrete included: 1) twelve 152x152 mm (6x12 inch) cylindrical specimens for compression testing of two specimens at each of the six test ages, 2) two 152x152 mm (6x12 inch) cylindrical specimens for splitting tensile testing at 7 and 28 days of age, 3) two 152x152x610 mm (6x6x24 inch) beams for flexural testing at 7 and 28 days of age, and 4) additional specimens as needed for freeze-thaw durability testing, rapid chloride permeability testing, abrasion resistance testing, length change testing, and 90-day chloride ponding tests.

The specimen mold filling and consolidation was done in accordance with applicable ASTM standards. After casting, all the molded cylinder specimens were covered with plastic caps, and all the molded beams were covered with plastic sheets. The specimens were left undisturbed in the casting room until the following day. On the day following mixing, the specimens were demolded, numbered, and transferred either to a concrete curing room or to a lime-saturated water bath meeting the requirements of ASTM C 551. All of the concrete specimens were made and cured in accordance with ASTM C 192.

The strength testing was conducted in one of two different compression machines. During the earlier stages of the project, a compression-testing machine with a 1.33 MN (300 kip) capacity was used. This machine was later replaced by a machine with a 2.22 MN (500 kip) capacity that was used for the remainder of the testing program. Before testing, the compression test specimens were capped with a high-strength sulfur-based capping compound in accordance with ASTM C 617. They were tested in accordance with ASTM C 39. The load was applied continuously at a constant rate of about 267 kN (60,000 pounds) per minute until specimen failure.

The splitting tensile strength was determined according to ASTM C 496. The load was applied continuously at a rate of about 80 kN (18,000 pounds) per minute until the specimen failed. The splitting tensile strength is computed from the formula:

$$T = 2P/(\pi LD)$$

where: T = splitting tensile strength in psi,
P = applied load at failure in pounds,
L = length of the specimen in inches, and
D = diameter of the specimen in inches.

The flexural strength was measured by using a simple beam with the load applied at the third-points in accordance with ASTM C 78. The test beams were loaded at a rate of about 8 kN (1,800 pounds) per minute. Flexural strength is expressed in terms of the modulus of rupture, which is computed from the maximum applied load using the flexural formula:

$$R = PL/(bd^2)$$

where: R = modulus of rupture in psi,
P = maximum applied load in pounds,
L = span length in inches,
b = width of the specimen in inches, and
d = depth of the specimen in inches.

For rapid chloride permeability testing, 102x203 mm (4x8 inch) plastic cylinder molds were used to cast the specimens. After 24 hours in ambient laboratory conditions, the specimens were demolded and transferred to a moist-curing room meeting ASTM C 192 specifications until the time of testing.

Rapid chloride permeability testing was performed at 28 days. After removal from the moist-curing room, a two-inch slice was cut from the top of each specimen and the circumferential sides were coated with epoxy. After the epoxy coating cured to a tack-free condition, the samples were conditioned and tested in accordance with ASTM C 1202 Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration.

The current in the test circuit is monitored over a six-hour period and the current (amperes) is plotted as a function of time. The area under the resulting curve represents the charge in coulombs (ampere•seconds) passed through the specimen during the test. Since 102 mm (4 inch) diameter specimens were used during Part I of this study, and the standard specification sample diameter is 95 mm (3.75 inches), an adjustment was made by multiplying the measured values of charge passed by the ratio of the cross-sectional areas ($3.75^2/4^2$). Once the average corrected value in coulombs passed was determined for a particular concrete mix design, the chloride ion penetration resistance of the concrete could be determined using Table 3.

Table 3) Penetrability rating chart for interpretation of rapid chloride permeability test results (Whiting, 1981).

Chloride Permeability Rating	Charge Passed (coulombs)	Type of Concrete
High	4,000	high w/c ratios (>0.6)
Moderate	2,000 to 4,000	moderate w/c ratios
Low	1,000 to 2,000	low w/c ratios (<0.4)
Very Low	100 to 1,000	latex modified concrete
Negligible	100	polymer concrete

The length change testing was conducted according to ASTM C 157 Length Change of Hardened Hydraulic-Cement Mortar and Concrete. This test measures the change in length of the concrete specimen caused by factors other than temperature and applied load. The length change behavior of each of the lab-prepared concrete mixes evaluated during Part I of the project was evaluated using standard 3x3x11.25 inch specimens. For the concrete mixes obtained from ODOT construction projects, tests were performed on standard 76x76x286 mm (3x3x11.25 inch) specimens and special 76x102x381 mm (3x4x15 inch) specimens commonly used by ODOT.

The influence of the amount of GGBFS used as a portland cement replacement on the abrasion resistance of the concrete was evaluated in accordance with ASTM 944 Abrasion Resistance of Concrete or Mortar Surfaces by the Rolling-Cutter Method. The SnnS series of concrete mixes was used for this evaluation. Each test involved exposing three test specimens to the abrasion process and recording the weight loss due to abrasion. Two such tests were performed for each mix in the SnnS series.

The freezing and thawing resistance testing was performed in accordance with ASTM C 666. After a 14-day cure, the specimens were brought to the control temperature of 4.4±1.7°C (40±3°F). Once this temperature was reached, the initial transverse frequency of each specimen was measured along with the weight and dimensions of each specimen. The specimens were placed into the freezing and thawing apparatus for the test to begin. The cycles of freezing and thawing were recorded to monitor the number of cycles and the temperature of the reference specimen. Removal of the sample for measurements of the transverse frequency occurred at intervals not exceeding 36 cycles of freezing and thawing throughout the test period.

At the completion of testing, the transverse frequency can be plotted with respect to the number of freeze-thaw cycles. Figure 1 shows typical results for two different specimens tested during this project. The data for specimen S35S is typical of a specimen that would be considered resistant to damage caused by freeze-thaw cycles. After 300 cycles, this specimen has a durability factor of 93. The data for specimen S55S is typical of a concrete that would be considered as having low resistance to damage caused by freeze-thaw cycles. For this specimen, the relative dynamic modulus of elasticity decreased to 60% at about 238 cycles. According to ASTM C 666, the test is complete when the relative dynamic modulus of elasticity drops to 60%. The durability factor for this specimen is 48.

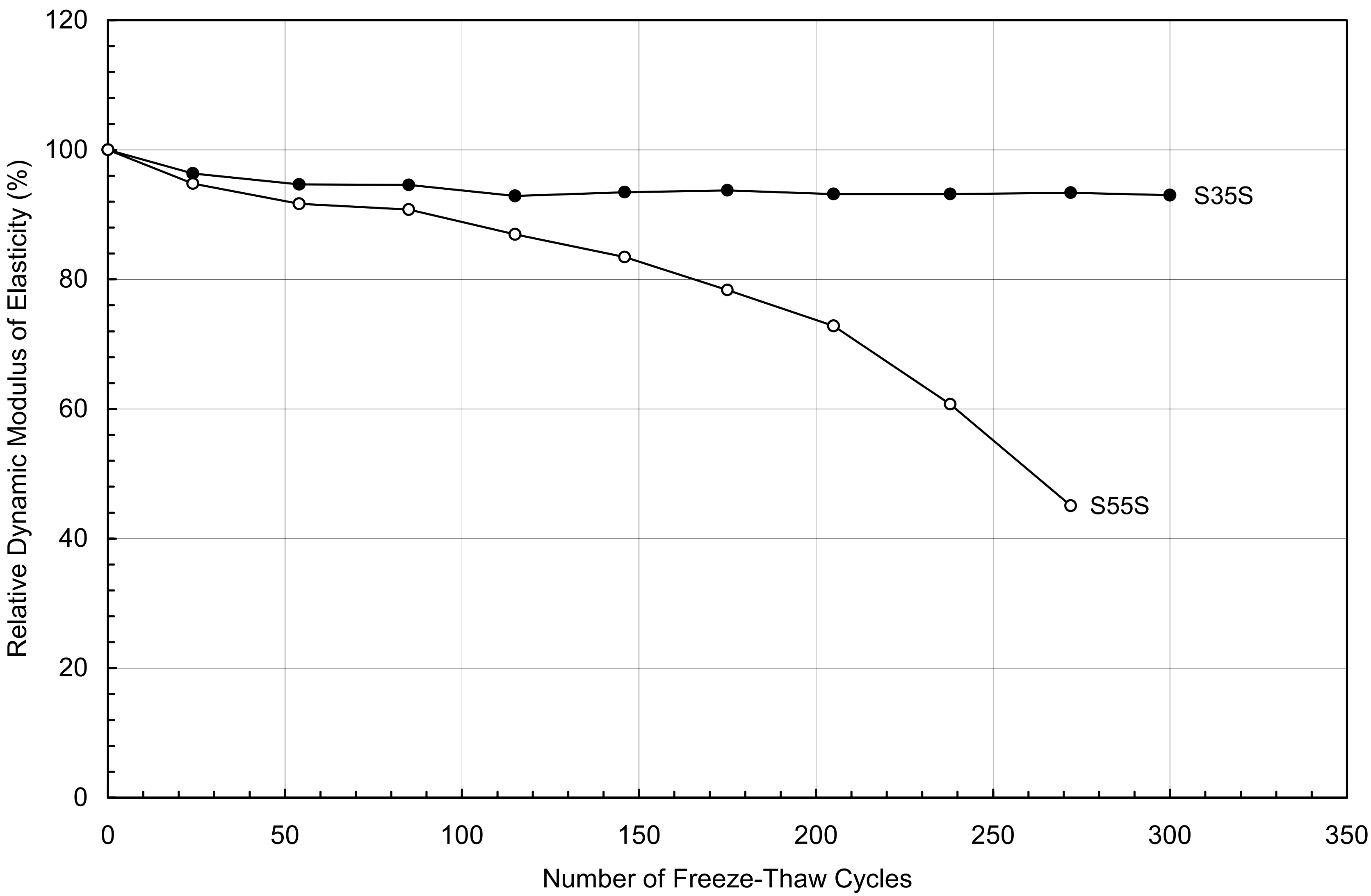

Figure 1) Typical results for two different concrete specimens tested using Method A of ASTM 666.

PROPERTIES OF THE PLASTIC CONCRETE

After each batch of concrete was discharged from the mixer into the pan, it was remixed with shovels to eliminate any segregation that may have taken place as the concrete was discharged from the mixer. Upon completion of the remixing operation, tests were performed to determine the air content, slump, unit weight and temperature of the concrete. For the concrete mixes in the "S" group, the primary concern at this stage was to insure that the air content was within the desired range. For the "S" group of mixes, the water:cement ratio of 0.42 was selected early in the project based on trial batches. Since the primary objective of the testing of this group of mixes was to determine the influence of the material combinations and proportions, it was undesirable to use water-reducing admixtures in some of the mixes and not in others. For these mixes, the slump values were recorded for completeness of the documentation and they were not used as an acceptance criterion for a particular mix. The dosage of the air-entraining admixture required to produce the desired air content for each mix was determined through a trial-and-error process.

For the mixes in the "MS" group, a water-reducing admixture must be used to produce a workable concrete mix. In these mixes, both the slump and the air content values were used as acceptance criteria for each batch of concrete. The required dosages for the air-entraining admixture and the water reducer were determined for each concrete mix design through a trial-and-error process. If either the slump or the air content for a particular batch of concrete was not within the desired range, the batch of concrete was discarded without making any specimens for testing.

The results of the tests performed on the fresh concrete are presented in Table 4. Even though batch weights and material uniformity is carefully controlled in the laboratory environment, several batches of concrete were discarded throughout the project because the air content was not within the expected range. As indicated by the data in Table 4, the air content values do vary within the acceptable range. The unit weight values are relatively consistent and in agreement with the calculated values. The agreement between the calculated unit weight and the measured unit weight is simply the result of accurately knowing the mix proportions, the air content, and the specific gravity values of the individual materials in the concrete mix.

Table 4) Summary of test results for tests performed on the fresh concrete mixes prepared during Part I of the project.

Concrete Mix	Mix Date	Slump cm (inch)	Air Content (percent)	Density Mg/m^3	Unit Weight (pcf)	Temperature °C (°F)
S00S	06/03/94	9.0 (3 1/2)	6.8	2.26	141	23.0 (74)
	06/13/94	12.0 (4 3/4)	7.3	2.26	141	24.5 (76)
	07/13/94	9.0 (3 1/2)	6.0	2.27	142	25.5 (78)
	09/01/94	11.5 (4 1/2)	5.2	2.30	143	24.0 (75)
	12/29/94	12.5 (5)	6.2	2.30	143	19.5 (67)
	02/03/95	9.0 (3 1/2)	4.8	2.36	147	19.0 (66)
	07/10/95	7.5 (3)	5.0	2.37	148	24.5 (76)
	07/31/96	7.0 (2 3/4)	4.9	2.36	147	23.5 (74)
S25S	06/03/94	7.5 (3)	5.0	2.29	143	23.0 (74)
	06/08/94	9.0 (3 1/2)	5.7	2.26	141	23.5 (74)
	06/13/94	10.0 (4)	6.2	2.26	141	24.5 (76)
	08/22/94	9.5 (3 3/4)	5.8	2.27	142	26.0 (79)
	12/29/94	10.0 (4)	7.5	2.25	141	18.0 (64)
	02/03/95	12.0 (4 3/4)	7.0	2.30	144	18.5 (65)
	07/10/95	6.5 (2 1/2)	5.5	2.35	147	24.0 (75)
	07/31/96	10.0 (4)	7.2	2.27	142	23.5 (74)
S35S	07/13/94	9.0 (3 1/2)	7.0	2.24	140	24.0 (76)
	07/18/94	9.5 (3 3/4)	6.6	2.25	140	25.0 (77)
	07/23/94	6.5 (2 1/2)	5.0	2.31	144	24.5 (76)
	08/22/94	9.0 (3 1/2)	5.7	2.26	141	26.5 (80)
	12/26/94	11.5 (4 1/2)	8.0	2.21	138	19.0 (66)
	02/03/95	16.0 (6 1/4)	7.5	2.29	143	19.0 (66)
	07/10/95	7.5 (3)	7.0	2.32	145	24.0 (75)
	11/07/95	7.5 (3)	7.2	0.00	0	20.0 (68)
	07/31/96	9.5 (3 3/4)	7.8	2.27	142	22.0 (72)
S45S	06/03/94	6.5 (2 1/2)	4.5	2.30	143	23.0 (74)
	06/08/94	8.5 (3 1/4)	6.0	2.26	141	23.0 (73)
	06/13/94	7.5 (3)	5.9	2.28	142	23.5 (74)
	08/22/94	8.5 (3 1/4)	6.3	2.26	141	25.5 (78)
	12/26/94	9.0 (3 1/2)	7.2	2.24	140	19.5 (67)
	02/04/95	7.5 (3)	7.2	2.29	143	18.0 (64)
	07/12/95	6.5 (2 1/2)	6.9	2.32	145	24.0 (75)
	08/02/96	5.5 (2 1/4)	6.5	2.31	144	22.0 (72)

Table 4 cont.) Summary of test results for tests performed on the fresh concrete mixes prepared during Part I of the project.

Concrete Mix	Mix Date	Slump cm (inch)	Air Content (percent)	Density Mg/m^3	Unit Weight (pcf)	Temperature °C (°F)
S55S	07/13/94	5.0 (2)	5.4	2.29	143	24.0 (75)
	07/18/94	5.5 (2 1/4)	5.0	2.29	143	24.0 (75)
	07/23/94	5.0 (2)	5.2	2.29	143	24.0 (76)
	08/22/94	5.0 (2)	5.3	2.28	143	25.0 (77)
	12/26/94	5.0 (2)	5.5	2.28	143	18.5 (65)
	02/04/95	2.5 (1)	6.0	2.33	145	18.0 (64)
	07/12/95	2.5 (1)	5.8	2.32	145	23.5 (74)
	11/07/95	4.0 (1 1/2)	5.5	2.34	146	18.0 (64)
	08/06/96	4.0 (1 1/2)	4.5	2.35	147	20.0 (68)
S70S	09/10/94	5.5 (2 1/4)	5.2	2.27	142	23.0 (73)
	09/16/94	4.5 (1 3/4)	4.4	2.29	143	24.0 (75)
	12/19/94	5.0 (2)	7.4	2.21	138	19.0 (66)
	12/26/94	7.5 (3)	7.6	2.21	138	20.0 (68)
	12/29/94	6.5 (2 1/2)	6.4	2.25	141	19.5 (67)
	02/04/95	5.5 (2 1/4)	7.5	2.28	142	18.5 (65)
	07/12/95	4.5 (1 3/4)	7.2	2.28	142	23.5 (74)
	11/07/95	5.0 (2)	7.0	2.32	145	19.0 (66)
	08/02/96	6.5 (2 1/2)	8.0	2.26	141	21.0 (70)
S35SC	03/30/95	14.0 (5 1/2)	7.7	2.27	142	20.0 (68)
	07/19/95	11.5 (4 1/2)	7.1	2.30	144	26.5 (80)
	07/21/95	10.0 (4)	7.3	2.29	143	26.0 (79)
	12/20/95	12.0 (4 3/4)	6.5	2.32	145	17.5 (63)
	12/27/95	9.5 (3 3/4)	6.0	2.32	145	16.0 (61)
	12/29/95	16.5 (6 1/2)	7.7	2.26	141	
	07/12/96	15.0 (6)	7.0	2.28	142	21.0 (70)
S35SF	03/23/95	11.5 (4 1/2)	5.5	2.33	145	20.5 (69)
	03/30/95	11.5 (4 1/2)	6.2	2.31	144	19.5 (67)
	07/19/95	10.0 (4)	6.9	2.30	143	27.0 (81)
	07/21/95	9.5 (3 3/4)	6.7	2.29	143	25.0 (77)
	12/20/95	11.5 (4 1/2)	6.5	2.32	145	17.5 (63)
	12/27/95	10.0 (4)	6.0	2.31	144	14.5 (58)
	12/29/95	16.0 (6 1/4)	7.8	2.30	144	

Table 4 cont.) Summary of test results for tests performed on the fresh concrete mixes prepared during Part I of the project.

Concrete Mix	Mix Date	Slump cm (inch)	Air Content (percent)	Density Mg/m^3	Unit Weight (pcf)	Temperature °C (°F)
S00SK	03/23/95	2.5 (1)	5.4	2.36	147	22.0 (72)
	03/30/95	2.5 (1)	5.7	2.34	146	21.5 (71)
	07/14/95	4.0 (1 1/2)	5.0	2.39	149	29.0 (84)
	12/29/95	2.0 (0 3/4)	7.4	2.30	144	22.0 (72)
	01/16/96	3.0 (1 1/4)	7.6	2.29	143	22.0 (72)
	02/01/96	4.0 (1 1/2)	6.9	2.29	143	19.5 (67)
	07/17/96	4.0 (1 1/2)	7.2	2.29	143	22.0 (72)
S35SK	08/02/94	5.5 (2 1/4)	4.7	2.31	144	26.0 (79)
	08/07/94	5.5 (2 1/4)	4.4	2.32	145	25.0 (77)
	08/12/94	7.0 (2 3/4)	4.5	2.32	145	25.0 (77)
	09/01/94	7.0 (2 3/4)	5.0	2.27	141	24.0 (75)
	12/22/94	5.0 (2)	5.8	2.28	142	22.0 (72)
	12/20/95	5.0 (2)	7.5	2.28	142	18.0 (65)
	07/17/96	5.0 (2)	5.5	2.31	144	22.0 (72)
S55SK	09/10/94	2.5 (1)	4.0	2.31	144	24.5 (76)
	01/16/95	2.0 (0 3/4)	7.1	2.30	144	20.0 (68)
	02/09/95	4.0 (1 1/2)	8.0	2.26	141	19.0 (66)
	03/16/95	5.0 (2)	7.0	2.29	143	22.0 (72)
	02/01/96	5.5 (2 1/4)	7.6	2.28	143	19.0 (66)
	07/12/96	6.5 (2 1/2)	5.5	2.30	144	21.0 (70)
S35SHA	07/28/94	9.0 (3 1/2)	6.2	2.28	142	24.5 (76)
	08/02/94	7.5 (3)	5.2	2.30	143	25.5 (78)
	08/07/94	8.5 (3 1/4)	5.5	2.29	143	24.5 (76)
	09/01/94	8.5 (3 1/4)	6.6	2.29	143	24.0 (75)
	12/22/94	9.5 (3 3/4)	6.6	2.26	141	20.0 (68)
	02/28/96	11.0 (4 1/4)	6.3	2.31	144	17.5 (64)
	03/02/96	11.0 (4 1/4)	7.9	2.26	141	17.0 (63)
S55SHA	07/28/94	4.0 (1 1/2)	4.4	2.32	145	25.0 (77)
	08/12/94	5.0 (2)	5.3	2.27	142	24.5 (76)
	09/10/94	5.0 (2)	5.4	2.27	142	24.0 (75)
	12/19/94	6.5 (2 1/2)	8.0	2.21	138	20.5 (69)
	12/29/94	7.5 (3)	5.0	2.31	144	18.5 (65)
	03/02/96	8.5 (3 1/4)	6.4	2.32	145	18.5 (65)
	03/08/96	9.5 (3 3/4)	6.3	2.30	143	17.5 (63)

Table 4 cont.) Summary of test results for tests performed on the fresh concrete mixes prepared during Part I of the project.

Concrete Mix	Mix Date	Slump cm (inch)	Air Content (percent)	Density Mg/m^3	Unit Weight (pcf)	Temperature °C (°F)
S35SLA	07/18/94	9.0 (3 1/2)	5.4	2.29	143	24.5 (76)
	07/23/94	8.5 (3 1/4)	5.4	2.29	143	24.0 (76)
	07/28/94	9.0 (3 1/2)	5.6	2.28	142	24.5 (76)
	09/01/94	10.0 (4)	6.0	2.18	136	23.0 (73)
	12/19/94	5.5 (2 1/4)	4.0	2.34	146	18.0 (64)
	03/19/96	10.0 (4)	7.4	2.28	142	19.5 (67)
	03/21/96	15.0 (6)	7.2	2.28	142	12.0 (54)
S55SLA	07/18/94	5.0 (2)	5.8	2.27	142	24.0 (75)
	07/23/94	5.0 (2)	5.3	2.29	143	23.5 (74)
	09/10/94	5.5 (2 1/4)	6.0	2.26	141	23.0 (73)
	09/30/94	6.5 (2 1/2)	4.8	2.29	143	22.0 (72)
	12/19/94	7.0 (2 3/4)	6.1	2.27	142	18.5 (65)
	02/15/96	9.0 (3 1/2)	6.7	2.29	143	16.0 (61)
	03/19/96	7.5 (3)	6.0	2.32	145	17.5 (64)
MS00S	01/12/95	14.0 (5 1/2)	7.5	2.30	144	22.0 (72)
	01/16/95	13.5 (5 1/4)	8.5	2.26	141	23.5 (74)
	01/26/95	14.0 (5 1/2)	8.3	2.26	141	20.0 (68)
	02/09/95	16.5 (6 1/2)	9.0	2.23	139	20.0 (68)
	03/16/95	17.0 (6 3/4)	10.0	2.18	136	23.5 (74)
	07/02/96	19.5 (7 3/4)	10.0	2.24	140	21.5 (71)
	07/05/96	11.5 (4 1/2)	6.5	2.31	144	21.5 (71)
MS35S	01/12/95	16.5 (6 1/2)	9.0	2.23	140	21.0 (70)
	01/16/95	14.5 (5 3/4)	8.0	2.25	141	20.5 (69)
	01/26/95	16.0 (6 1/4)	8.0	2.25	141	19.0 (66)
	02/09/95	16.5 (6 1/2)	7.5	2.27	142	19.0 (66)
	03/09/95	16.5 (6 1/2)	8.2	2.25	141	20.0 (68)
	07/01/96	17.0 (6 3/4)	8.0	2.30	144	21.0 (70)
	07/05/96	19.0 (7 1/2)	10.0	2.23	139	21.5 (71)
MS55S	01/12/95	18.5 (7 1/4)	7.5	2.27	142	21.0 (70)
	01/16/95	13.5 (5 1/4)	6.6	2.29	143	20.0 (68)
	01/26/95	19.5 (7 3/4)	8.0	2.25	140	18.0 (64)
	02/09/95	16.0 (6 1/4)	6.9	2.27	142	18.5 (65)
	03/09/95	12.5 (5)	8.0	2.28	142	21.0 (70)
	07/02/96	18.5 (7 1/4)	9.5	2.26	141	21.5 (71)
	07/05/96	14.0 (5 1/2)	8.5	2.29	143	21.5 (71)

Table 4 cont.) Summary of test results for tests performed on the fresh concrete mixes prepared during Part I of the project.

Concrete Mix	Mix Date	Slump cm (inch)	Air Content (percent)	Density Mg/m^3	Unit Weight (pcf)	Temperature °C (°F)
OK	08/29/95	3.0 (1 1/4)	4.5			31.0 (88)
	08/29/95	4.0 (1 1/2)	3.8			30.0 (86)
OHPC2	08/11/95	20.5 (8)	12.0			21.0 (70)
	08/11/95	21.5 (8 1/2)	11.5			21.0 (70)
	10/12/95	1.5 (0 1/2)	2.5			21.0 (70)
	10/12/95	1.5 (0 1/2)	3.6			22.0 (72)
OMS	08/14/95	9.5 (3 3/4)	8.0			31.5 (89)
	08/14/95	10.0 (4)	6.4			32.5 (91)
	08/16/95	14.0 (5 1/2)	7.8			31.5 (89)
	08/16/95	14.0 (5 1/2)	6.7			31.0 (88)

STRENGTH PROPERTIES

The presentation of the strength test results is divided into three sections as follows: 1) compressive strength, 2) modulus of rupture, and 3) splitting tensile strength. For each of these strength categories, a table containing the average strength for each concrete mix at each test age is presented. In each category, the summary table is followed by several graphs illustrating the influence of specific mix proportion variables on the strength parameter under consideration. The average strength values contained in the summary tables are calculated from several individual test results. In general, the compressive strength average values are based on ten or more individual test results per concrete mix design. The average strength values for splitting tensile strength and modulus of rupture are based on five or more individual test results per concrete mix design.

COMPRESSIVE STRENGTH

In most cases, compressive strength testing consisted of ten or more individual compression tests for each of the six test ages for each mix design evaluated during Part I of the study. There are a small number of exceptions caused by an insufficient number of specimens in some cases and by testing errors or omissions in other cases. The individual test results are presented in Table A-1 in Appendix A. That table also contains the average strength for each test age for each concrete mix design. The average strength values from Table A-1 are summarized in Table 5 and form the basis for the remainder of the discussion regarding the influence of the mix design variables on the compressive strength of the resulting concrete. Much of the information contained in Table 5 is presented graphically in a series of figures to facilitate comparisons within specific groups of the concrete mix designs.

In each of these figures, the data for the S00S concrete mix is presented as the leftmost bar in each group of bars in the figures. This mix design represents the standard ODOT Class S concrete mix, and serves as the baseline for comparison of many of the other mix designs evaluated in this study. Within each group of bars on a figure, the sequence of the mixes represented by the bars is the same as the sequence of the mixes as it is displayed in the legend near the top of the figure.

The average compressive strength values for the concrete mixes in the SnnS series are presented in Figure 2 for six different test ages. Mixes in the SnnS series differ only in the percent of portland cement replaced by GGBFS in the mix. The nn value in the mix name indicates the replacement rate. The data indicate that at specimen ages of 7 days or less, the compressive strength decreases significantly as the percentage of GGBFS in the mix increases. At specimen ages of 14 days and more, the concrete mixes GGBFS replacement rates of 25% to 55% had compressive strengths that were about equal to, or slightly greater than the strength of the S00S baseline mix. For the concrete mix with a GGBFS replacement rate of 70%, the strength at all ages is clearly less than all of the other mixes within this group. This data suggests that if only compressive strength is considered, GGBFS replacement rates of up to 55% are reasonable unless strength at 7 days or less is critical.

Table 5) Compressive strength data for the concrete mixes evaluated during Part I of the project.

Concrete Mix	Average Compressive Strength, MPa (psi)					
	Specimen Age					
	1 days	3 days	7 days	14 days	28 days	90 days
S00S	12.81 (1857)	25.38 (3681)	32.55 (4721)	36.20 (5251)	41.09 (5960)	47.45 (6882)
S25S	9.40 (1364)	20.72 (3006)	29.91 (4338)	39.72 (5761)	44.22 (6414)	52.40 (7600)
S35S	6.99 (1014)	17.29 (2508)	26.43 (3833)	37.08 (5379)	41.27 (5986)	48.63 (7053)
S45S	5.64 (818)	16.10 (2335)	26.69 (3872)	38.18 (5537)	42.69 (6191)	51.17 (7421)
S55S	4.44 (645)	14.01 (2032)	26.00 (3772)	38.03 (5516)	43.03 (6241)	50.17 (7277)
S70S	1.94 (282)	8.45 (1226)	19.06 (2765)	30.08 (4362)	34.45 (4997)	39.84 (5778)
S35SC	3.87 (562)	10.33 (1498)	19.00 (2755)	28.59 (4147)	35.44 (5141)	40.16 (5824)
S35SF	3.36 (487)	10.44 (1515)	17.75 (2574)	27.77 (4028)	35.85 (5200)	42.10 (6106)
S00SK	10.65 (1545)	27.46 (3983)	30.77 (4463)	33.39 (4843)	37.83 (5487)	41.90 (6078)
S35SK	11.84 (1718)	23.22 (3367)	33.27 (4825)	42.62 (6181)	45.80 (6643)	51.97 (7538)
S55SK	5.02 (728)	13.43 (1948)	25.82 (3745)	36.97 (5362)	42.40 (6149)	48.32 (7009)
S35SHA	9.27 (1344)	20.60 (2988)	32.22 (4674)	40.97 (5942)	47.68 (6916)	51.08 (7409)
S55SHA	5.13 (745)	15.52 (2251)	30.22 (4383)	41.94 (6083)	49.55 (7186)	50.24 (7286)
S35SLA	9.13 (1324)	20.37 (2954)	32.13 (4660)	41.55 (6027)	48.02 (6965)	55.38 (8032)
S55SLA	5.49 (797)	14.91 (2163)	28.82 (4181)	37.13 (5385)	44.47 (6450)	50.76 (7362)
MS00S	21.32 (3093)	38.55 (5591)	51.22 (7429)	61.23 (8880)	64.28 (9323)	67.12 (9735)
MS35S	10.81 (1568)	30.30 (4395)	47.65 (6911)	63.99 (9281)	62.03 (8996)	69.82 (10126)
MS55S	5.89 (855)	25.15 (3648)	42.42 (6153)	58.61 (8501)	58.04 (8418)	65.63 (9519)
OS	21.13 (3065)	32.03 (4646)	35.78 (5189)	39.37 (5711)	42.79 (6206)	48.78 (7074)
OK	14.18 (2057)	21.77 (3157)	25.79 (3740)	27.92 (4049)	30.53 (4429)	33.27 (4826)
OHPC2	22.61 (3279)	31.20 (4525)	38.71 (5615)	45.27 (6566)	50.08 (7264)	58.07 (8422)
OHPC4	10.13 (1470)	21.01 (3047)	30.07 (4361)	36.76 (5332)	40.50 (5874)	44.06 (6390)
OMS	27.56 (3998)	36.73 (5327)	45.04 (6532)	51.34 (7447)	55.10 (7992)	57.39 (8323)

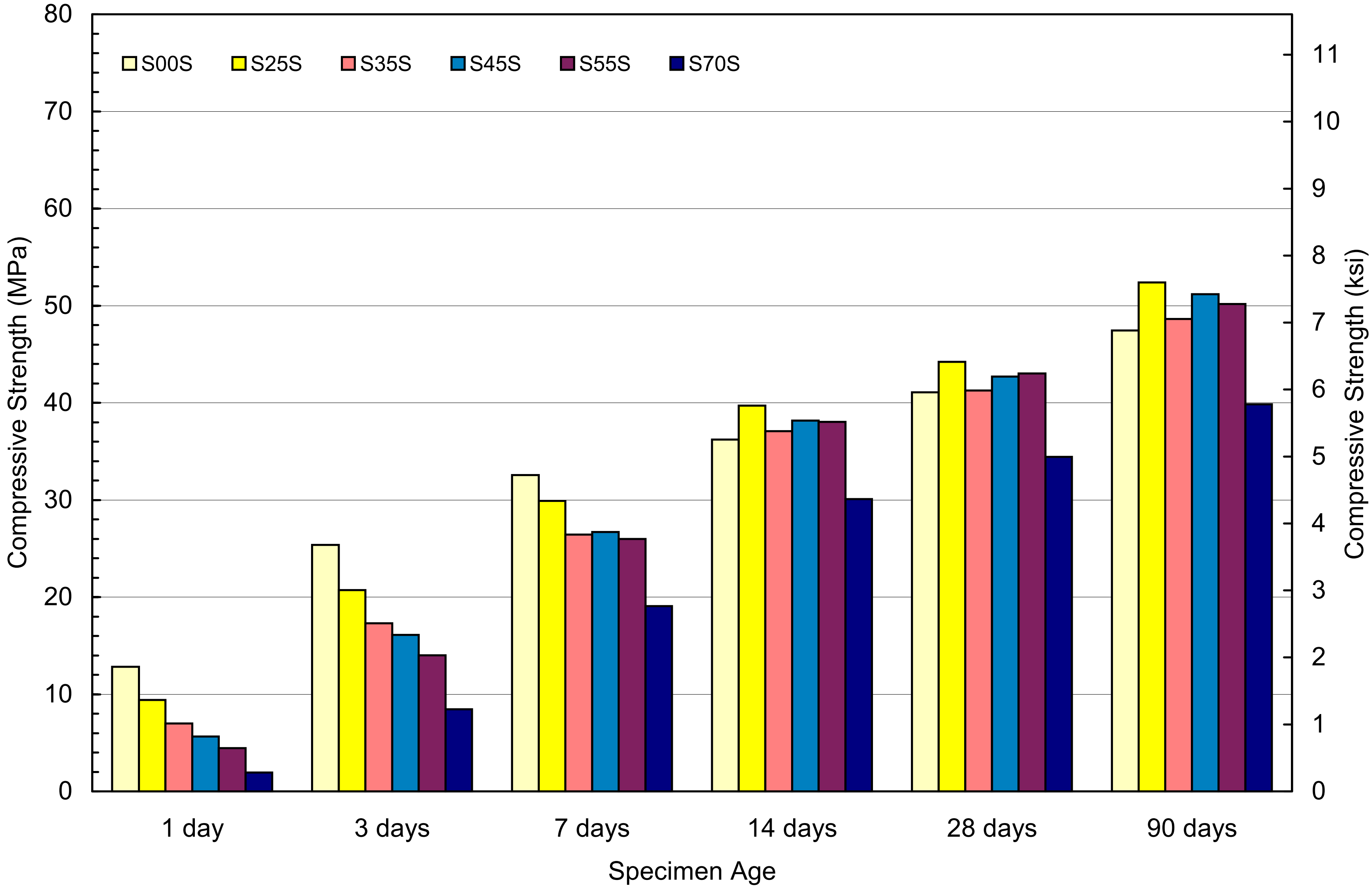

Figure 2) Comparison of the average compressive strength values for the concrete mixes in the SnnS series.

In Figure 3, the compressive strength data for the two mixes containing fly ash are presented along with that for the S00S baseline mix. In the S35SC and S35SF mixes, 35 percent of the portland cement is replaced by GGBFS, and 15 percent of the portland-GGBFS combination is replaced by either Class C or Class F fly ash. The test results indicate that the compressive strength of the two mixes containing both fly ash and GGBFS is less than that of the baseline mix at all ages. The difference is most significant at early ages and becomes less significant as the specimen age increases. The type of fly ash used in these concrete mixes had no significant influence on the resulting compressive strength.

The strength data for the concrete mixes containing the Type K shrinkage compensating cement are presented in Figure 4 along with the data for the S00S baseline mix. Mix S00SK is identical to mix S00S except that medium alkali portland cement is used in mix S00S, and Type K cement is used in mix S00SK. Comparing the compressive strength data for these two mixes indicates that at specimen ages of 14 days or more, the use of Type K cement results in slightly lower strength than the use of Type I cement. At earlier ages, the strengths of the two mixes are almost identical. The influence of replacing cement with GGBFS when Type K cement is involved is very similar to that observed when Type I portland cement is used. At early ages, the strength tends to decrease as the GGBFS proportion is increased. At ages of 14 days or more, the incorporation of GGBFS results in strengths that are noticeably higher than those for the mix containing Type K cement without GGBFS.

The influence of the alkali content of the portland cement on the strength of concretes containing GGBFS and portland cement was evaluated using a high alkali Type I cement and a low alkali Type I cement. For both of these cements, concrete mix designs involving GGBFS at 35 and 55 percent replacement were evaluated. The compressive strength data for these concretes and for the S00S baseline mix are presented in Figure 5. The influence of the GGBFS loading on strength of the concrete that was observed for the medium alkali cement also appears to be present for both the high and low alkali cements. At specimen ages of 7 days or less, the strength tends to be decreased as the GGBFS loading is increased. At specimen ages of 14 days or more, the strength of the specimens containing GGBFS exceeded that of the baseline mix. From the data in Figure 5, there are 12 direct comparisons that can be made to evaluate the influence of the alkali content of the cement on the compressive strength of concretes containing GGBFS and Type I portland cement at the same GGBFS loading. Of these 12 comparisons, 9 indicate that the alkali content of the cement has virtually no influence on the strength of the concrete containing the GGBFS-portland combination. Of the remaining three cases, one case indicates that the use of low alkali cement results in higher strength. The other two cases suggest the opposite. Based on this data, it appears that the alkali content of the portland cement has little, if any, influence on the strength of the concrete involving GGBFS and Type I portland cement.

The compressive strength data for the MSnnS series is presented in Figure 6 along with the data for the S00S baseline mix. The strength of the MS00S mix is clearly higher than that of the S00S mix at all ages. This is expected because the water:

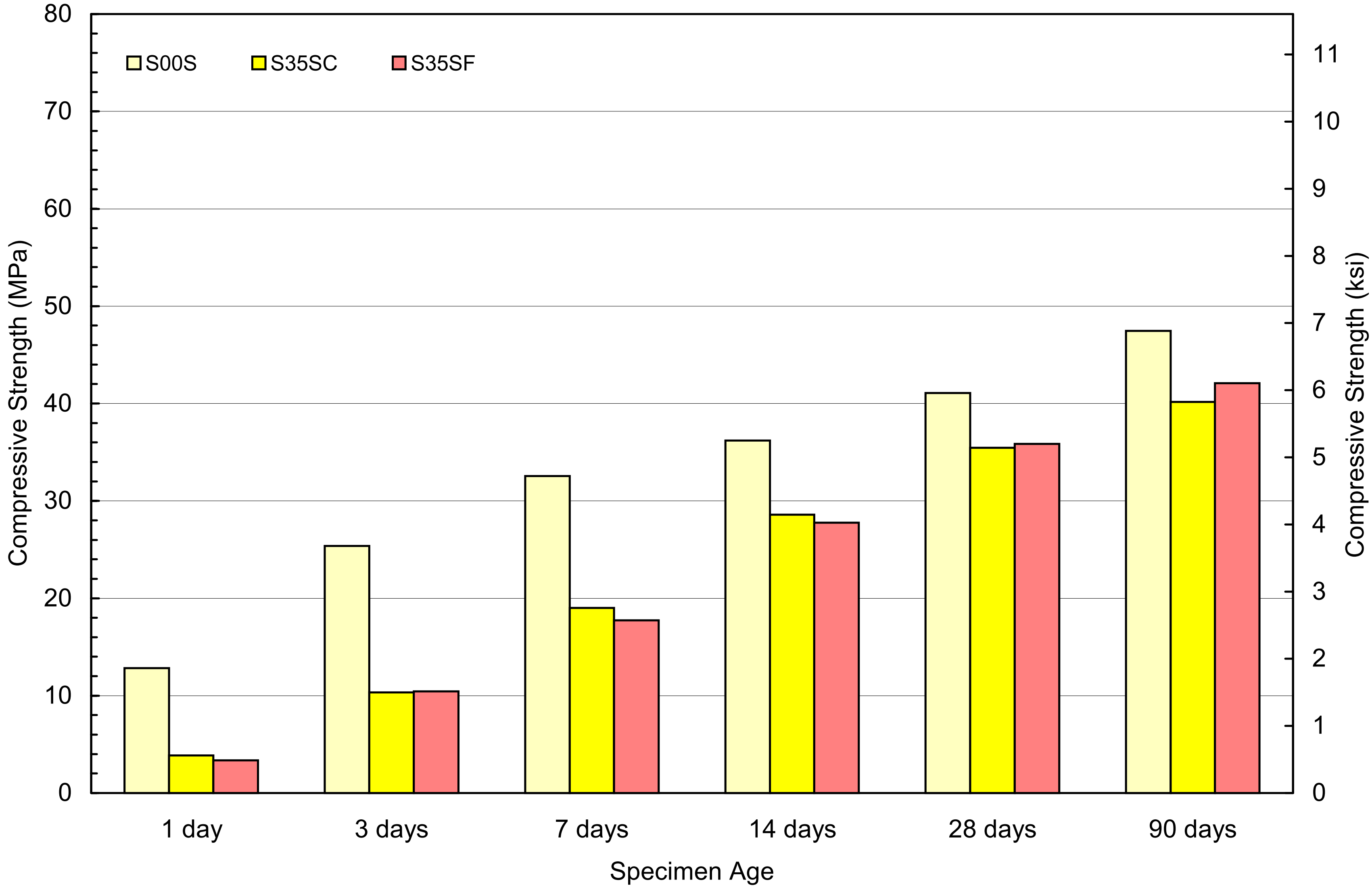

Figure 3) Comparison of the average compressive strength values for the S35SC and S35SF concrete mixes containing fly ash and GGBFS.

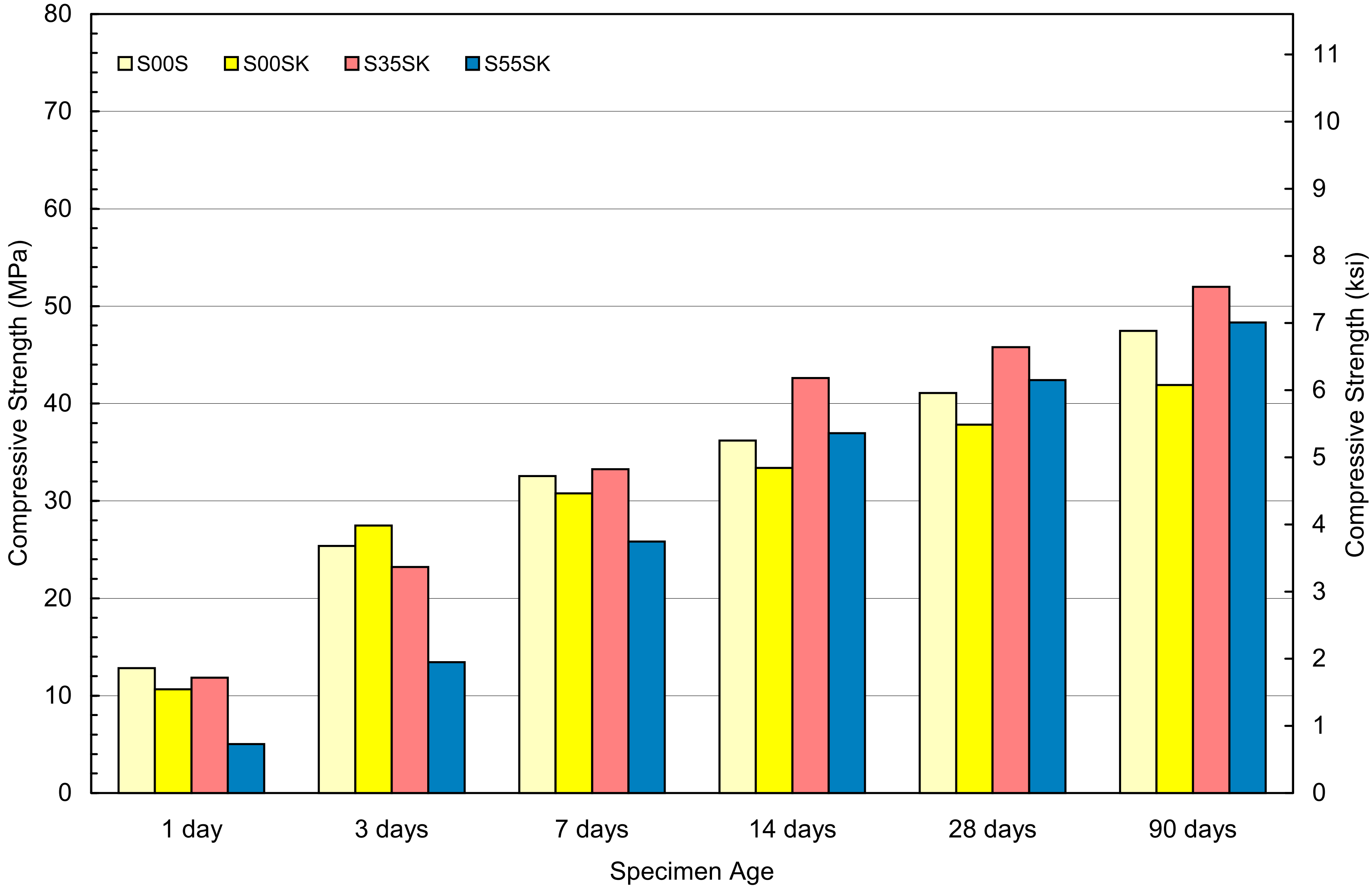

Figure 4) Comparison of the average compressive strength values for the concrete mixes in the SnnSK series containing Type K cement.

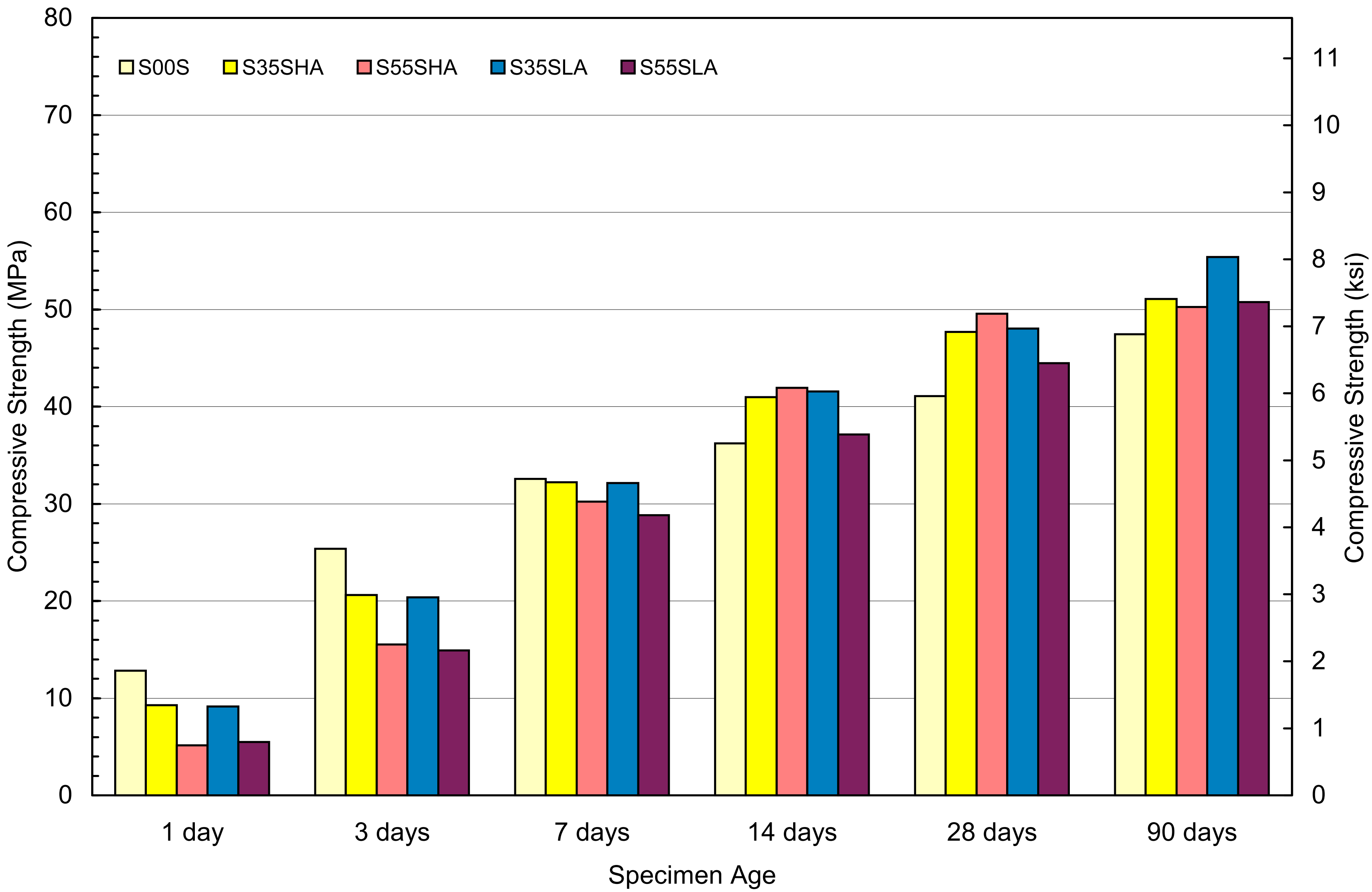

Figure 5) Comparison of the average compressive strength values for the concrete mixes in the SnnSHA series and the SnnSLA series.

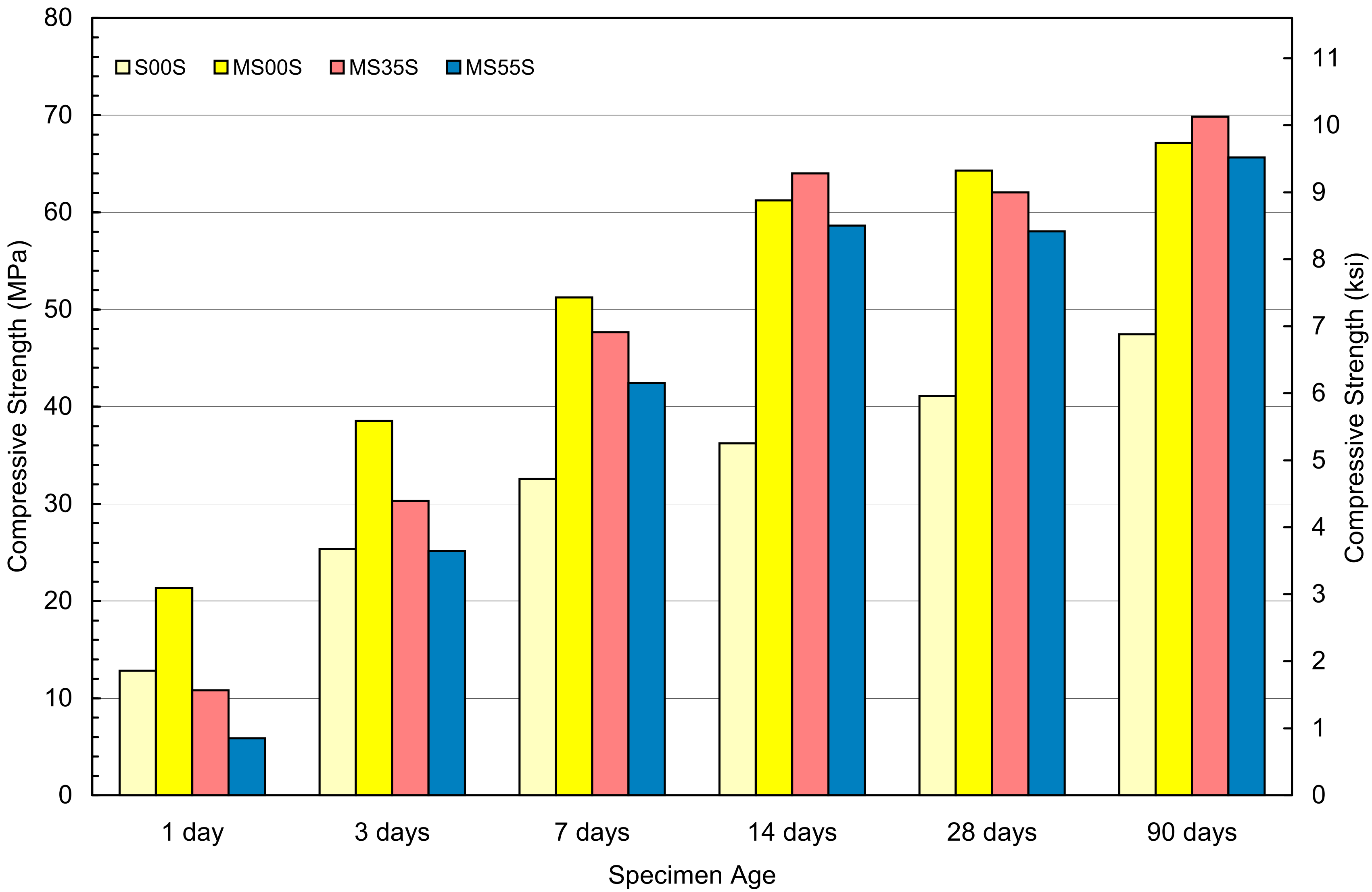

Figure 6) Comparison of the average compressive strength values for the concrete mixes in the MSnnS series.

cement ratio of the S00S mix is 0.42 and the water to cementitious materials ratio for the mixes in the MSnnS series is about 0.33. In addition, micro-silica and a water reducer are incorporated in the MSnnS mixes. All of these factors are known to result in increased compressive strength of the concrete. Within the MSnnS series, the influence of the GGBFS is similar to that observed in the other mix groups. At specimen ages of 7 days or less, the compressive strength clearly decreases as the GGBFS loading is increased. At specimen ages of 14 days or more, the compressive strength of the mix containing GGBFS at a replacement rate of 35 percent is about the same as that for the micro-silica concrete mix without GGBFS. Increasing the GGBFS loading from 35 percent to 55 percent results in a slight reduction in the compressive strength for the MSnnS series of mix designs.

The compressive strength data for five concrete mixes obtained from ODOT construction projects are presented in Figure 7 along with the compressive strength data for the S00S baseline mix. The compressive strength of OS concrete mix from the field was greater than that of the corresponding mix prepared in the lab (S00S) at all test ages. At 28 and 90 days, the difference is slight, but at the earlier ages the sample from the field is significantly stronger than the lab prepared specimen. This difference may be partially due to different ambient temperature conditions at early ages. The lab samples are in a temperature-controlled lab, and the field samples are stored at the construction site for the first 12 to 18 hours. Since the samples were collected during the summer months, the outdoor temperatures were significantly higher than the average lab temperature. Since OS concrete was placed by pumping, it's likely that a water-reducing admixture was used to improve workability of the concrete. The water-reducing admixture is likely to result in faster strength gain at early ages.

Except for the first day, the compressive strength of the OK mix is less than that of the S00S baseline mix. For the lab-prepared concretes, the use of Type K cement also resulted in strengths that were less than those of the S00S baseline mix, but the difference between the two mixes was smaller for the lab-prepared mixes. Samples of two high performance concrete mixes were obtained from ODOT construction projects. OHPC2 is a concrete mix based on ODOT high performance concrete mix option 2 using portland cement and GGBFS, and OHPC4 is a concrete mix based on ODOT high performance concrete mix option 4 using portland cement, GGBFS, and silica fume. At all test ages, the strength of OHPC4 is significantly less than that of OHPC2. Because of the similarity in the two mix designs and the presence of silica fume in OHPC4, the two mixes should have similar strength development, and the OHPC4 mix would normally be expected to have a higher strength than the OHPC2 mix. The reason for the unexpected behavior is not clear, but it may have to do with normal variability between suppliers and natural variability in the data. The field specimens were collected from a limited number of projects and may not be representative.

The OMS concrete was collected from an ODOT construction project. The strength of this mix is greater than all of the other mixes in Figure 7 at all ages except at 90 days. At the 90-day test age, the strengths of mixes OMS and OHPC2 are essentially the same. The relatively high strength of the OMS mix is expected because of its low water:cement ratio and the incorporation of silica fume in the mix.

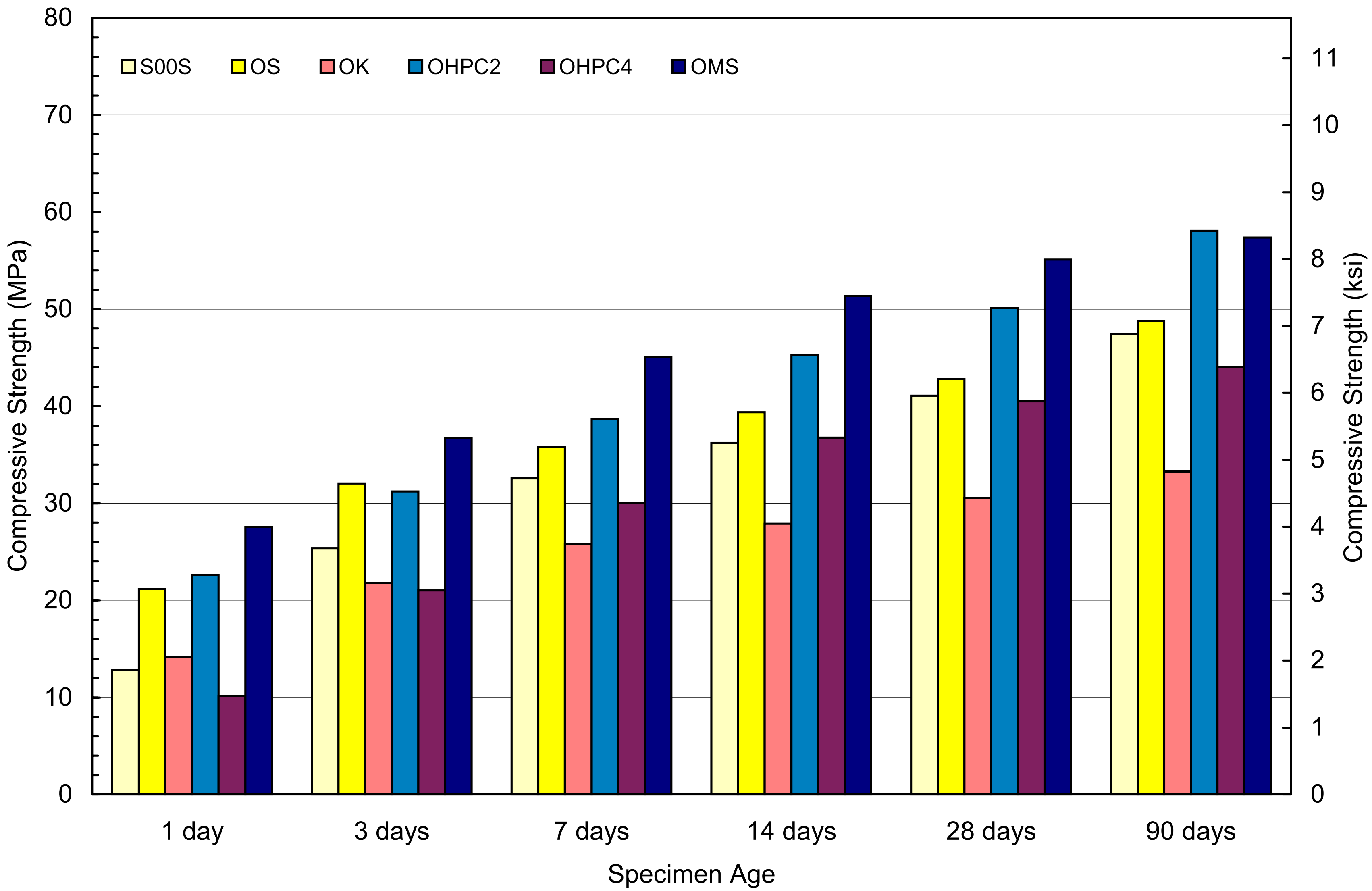

Figure 7) Comparison of the average compressive strength values for the concrete mixes obtained from ODOT construction projects.

MODULUS OF RUPTURE

In most cases, flexural strength testing consisted of five or more individual flexural strength tests for both test ages for each mix design evaluated during Part I of the study. There are a small number of exceptions caused by an insufficient number of specimens in some cases and by testing errors or omissions in other cases. The individual test results are presented in Table A-2 in Appendix A. That table also contains the average strength for each test age for each concrete mix design. The average strength values from Table A-2 are summarized in Table 6. Table 6 also includes the corresponding average compressive strength for each concrete mix at the corresponding test ages.

Table 6 also contains values of the factor m that were calculated by dividing the modulus of rupture by the square root of the compressive strength. Note that this factor is not dimensionless and that its value depends on the units of the strength values used in its calculation. Values are given in the table for both US customary units and for metric units. The Commentary for ACI 318 indicates that the ratio of the modulus of rupture to the square root of the compressive strength is approximately 0.62 for strengths expressed in MPa (7.5 for strengths in psi) for normal weight concrete. For the concrete mixes represented in Table 6, the values of this ratio for strengths in MPa range from 0.72 to 1.10 at 7 days and from 0.79 to 1.13 at 28 days. These values indicate that the flexural strengths of the concretes in Part I of the project exceed those that would be predicted by the equation recommended by ACI for approximating modulus of rupture based on the compressive strength of the concrete.

The modulus of rupture data contained in Table 6 is presented graphically in a series of figures to facilitate comparisons within specific groups of the concrete mix designs. The order and organization of the figures is identical to that used to present the compressive strength data except that flexural strength testing was only performed at 7 and 28 days rather than at the six different test ages used for compressive strength testing.

Figure 8 contains the modulus of rupture data for the SnnS series of concrete mixes. Within this group of mixes, the amount of GGBFS used to replace portland cement is the only variable. At the 7-day age, the modulus of rupture decreases slightly as the amount of GGBFS in the mix increases. At the 28-day age, the modulus of rupture values are virtually identical except that the modulus of rupture for mix S70S is slightly less than for the other mixes.

Based on the data in Figure 9, when 15 percent of the GGBFS-portland mixture is replaced with fly ash, the type of fly ash used appears to have no significant effect on the modulus of rupture of the concrete. This is consistent with the observation made earlier relative to compressive strength for these two mixes. The incorporation of GGBFS and fly ash did result in modulus of rupture values at the 7-day test age that were clearly less than those for the S00S baseline mix. At the 28-day age, the modulus of rupture values for the S35SC and S35SF mixes are essentially the same as the modulus of rupture for the S00S baseline mix.

Table 6) Modulus of rupture data for the concrete mixes evaluated during Part I of the project.

Concrete Mix	7-day Strength Data			28-day Strength Data		
	Average Modulus of Rupture MPa (psi)	Average Compressive Strength MPa (psi)	m	Average Modulus of Rupture MPa (psi)	Average Compressive Strength MPa (psi)	m
S00S	4.93 (715)	32.55 (4721)	0.86 (10.41)	6.07 (880)	41.09 (5960)	0.95 (11.40)
S25S	5.05 (733)	29.91 (4338)	0.92 (11.13)	6.25 (907)	44.22 (6414)	0.94 (11.33)
S35S	4.55 (660)	26.43 (3833)	0.89 (10.66)	6.01 (871)	41.27 (5986)	0.94 (11.26)
S45S	4.70 (681)	26.69 (3872)	0.91 (10.94)	6.12 (888)	42.69 (6191)	0.94 (11.29)
S55S	4.71 (683)	26.00 (3772)	0.92 (11.12)	6.12 (888)	43.03 (6241)	0.93 (11.24)
S70S	3.81 (553)	19.06 (2765)	0.87 (10.52)	5.67 (823)	34.45 (4997)	0.97 (11.64)
S35SC	3.89 (564)	19.00 (2755)	0.89 (10.75)	5.87 (851)	35.44 (5141)	0.99 (11.87)
S35SF	3.83 (555)	17.75 (2574)	0.91 (10.94)	5.84 (847)	35.85 (5200)	0.98 (11.75)
S00SK	5.02 (728)	30.77 (4463)	0.90 (10.90)	5.75 (834)	37.83 (5487)	0.93 (11.26)
S35SK	5.40 (783)	33.27 (4825)	0.94 (11.27)	6.87 (996)	45.80 (6643)	1.02 (12.22)
S55SK	4.10 (594)	25.82 (3745)	0.81 (9.71)	6.74 (978)	42.40 (6149)	1.04 (12.47)
S35SHA	5.24 (760)	32.22 (4674)	0.92 (11.12)	6.28 (911)	47.68 (6916)	0.91 (10.95)
S55SHA	4.62 (670)	30.22 (4383)	0.84 (10.12)	6.18 (897)	49.55 (7186)	0.88 (10.58)
S35SLA	5.44 (789)	32.13 (4660)	0.96 (11.56)	6.63 (962)	48.02 (6965)	0.96 (11.53)
S55SLA	4.76 (690)	28.82 (4181)	0.89 (10.67)	5.85 (848)	44.47 (6450)	0.88 (10.56)
MS00S	6.21 (900)	51.22 (7429)	0.87 (10.44)	7.67 (1112)	64.28 (9323)	0.96 (11.52)
MS35S	6.02 (873)	47.65 (6911)	0.87 (10.50)	7.59 (1101)	62.03 (8996)	0.96 (11.61)
MS55S	5.41 (785)	42.42 (6153)	0.83 (10.01)	7.35 (1066)	58.04 (8418)	0.96 (11.62)
OS	5.03 (729)	35.78 (5189)	0.84 (10.12)	5.86 (850)	42.79 (6206)	0.90 (10.79)
OK	3.68 (534)	25.79 (3740)	0.72 (8.73)	4.38 (635)	30.53 (4429)	0.79 (9.54)
OHPC2	6.83 (991)	38.71 (5615)	1.10 (13.22)	6.98 (1013)	50.08 (7264)	0.99 (11.89)
OHPC4	5.93 (860)	30.07 (4361)	1.08 (13.02)	7.18 (1041)	40.50 (5874)	1.13 (13.58)
OMS	5.38 (781)	45.04 (6532)	0.80 (9.66)	6.03 (875)	55.10 (7992)	0.81 (9.79)

$m = (\text{modulus of rupture}) / (\text{compressive strength})^{0.5}$

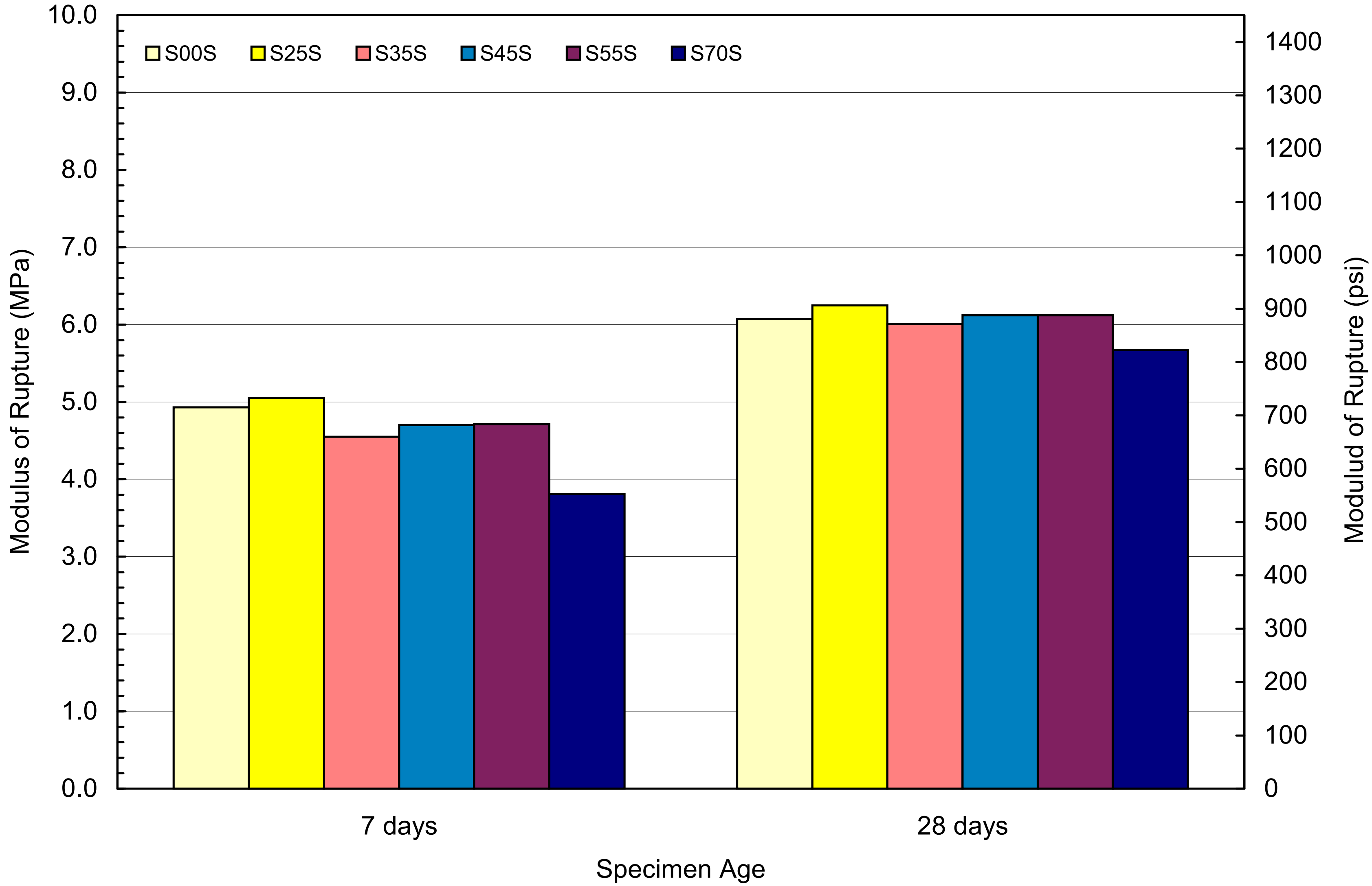

Figure 8) Comparison of the average modulus of rupture values for the concrete mixes in the SnnS series.

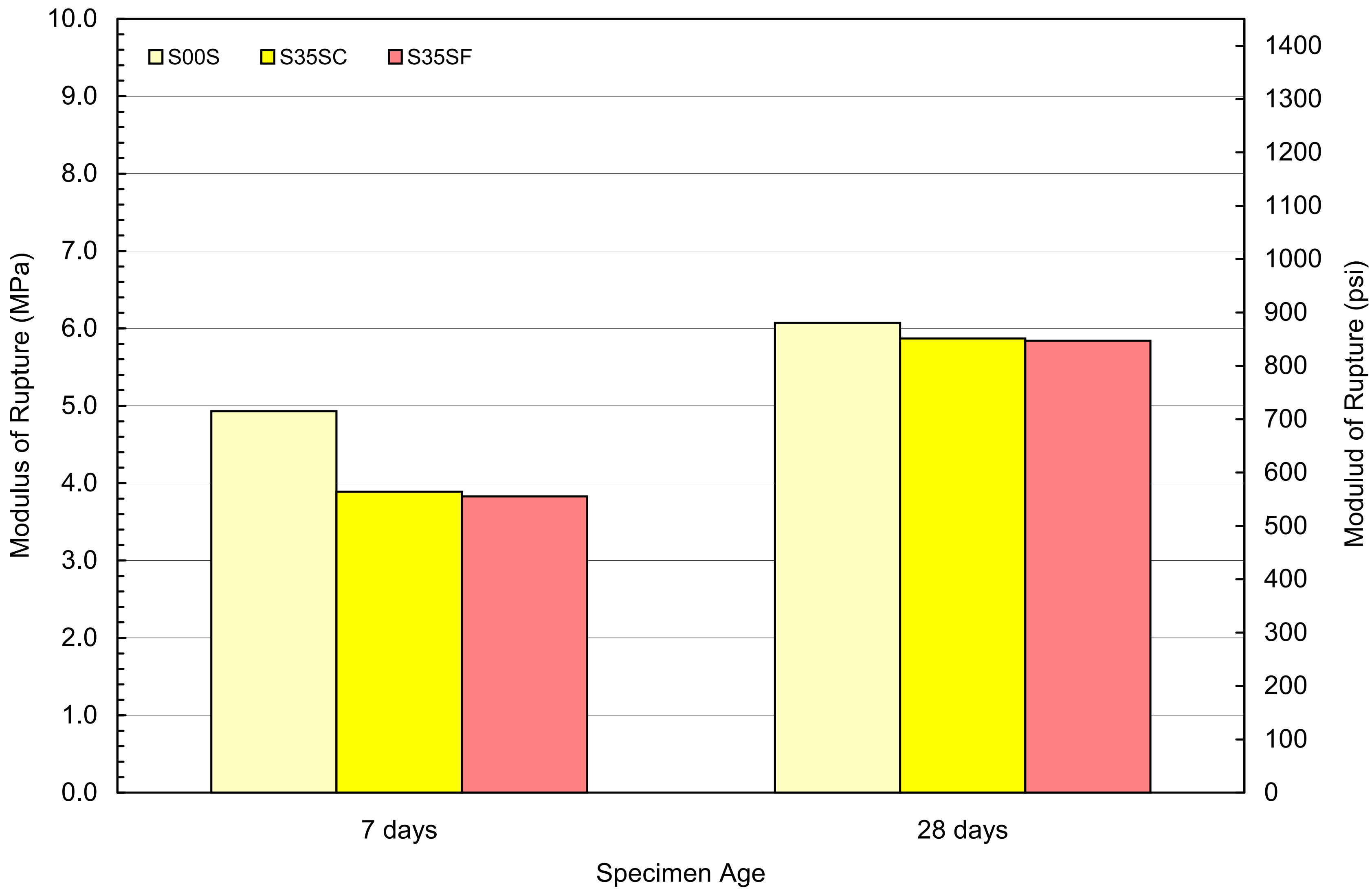

Figure 9) Comparison of the average modulus of rupture values for the S35SC and S35SF concrete mixes containing fly ash and GGBFS.

The modulus of rupture data for the mixes containing Type K cement are presented in Figure 10 along with the data for the S00S baseline mix. The mix designs for mixes S00S and S00SK are the same except that medium alkali portland cement is used in S00S and Type K cement is used in S00SK. For each of the test ages, the modulus of rupture values for these two mixes are almost identical. The modulus of rupture values for the mixes containing GGBFS with the Type K cement exceed those of the S00SK mix and the S00S baseline mix in all cases except for the mix containing 55 percent GGBFS at the 7-day test.

The data on the influence of the alkali content of Type I portland cement on the modulus of rupture of concretes containing GGBFS at replacement rates of 35 and 55 percent are presented in Figure 11. Based on this data, the alkali content of the cement appears to have very little, if any, influence on the modulus of rupture of the concrete mixes involving the GGBFS-portland blends. At the 7-day test age, the modulus of rupture values for the mixes containing 55 percent GGBFS are slightly less than those for the corresponding mixes containing 35 percent GGBFS. At the 28-day specimen age, the modulus of rupture values for the two mixes containing the high alkali portland cement are almost identical. At the same test age and for the mixes containing the low alkali cement, the modulus of rupture value is slightly less when the GGBFS replacement rate is 55 percent than when the replacement rate is 35 percent.

Figure 12 contains the modulus of rupture data for the micro-silica group of concrete mixes and for the S00S baseline mix. As discussed in the compressive strength section, the MS00S concrete mix is expected to be noticeably stronger than the S00S baseline mix. The expected strength difference between these two mixes is evident in Figure 12. For the three mixes in the MS series, the modulus of rupture decreases as the amount of GGBFS in the concrete mix increases. The amount of decrease in the modulus of rupture with increasing GGBFS loading is less for the 28-day test age than for the 7-day test age.

The modulus of rupture values for the concrete mixes collected from ODOT construction projects are compared to each other and to the S00S baseline mix in Figure 13. The S00S mix and the OS mix are both basic ODOT Class S concrete mixes and should have comparable strengths. The data indicate that the modulus of rupture values for these two mixes are almost identical at each of the two test ages. The modulus of rupture values for the high performance mixes (OHPC2 and OHPC4) are clearly greater than those for the S00S baseline mixes at both the 7-day and the 28-day test ages. The modulus of rupture values for the ODOT micro-silica mix appear to be similar to those of the S00S baseline mix.

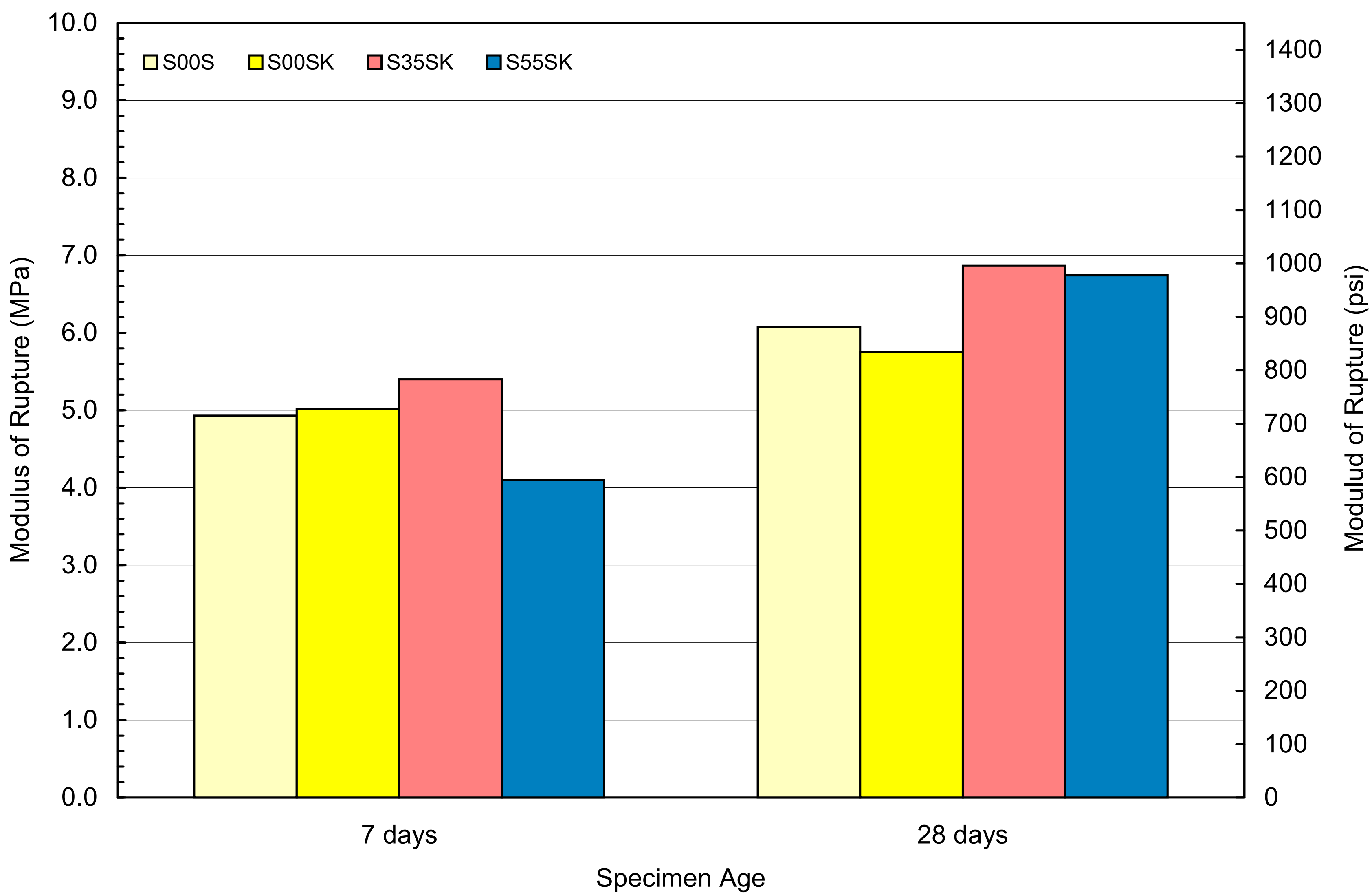

Figure 10) Comparison of the average modulus of rupture values for the concrete mixes in the SnnSK series containing Type K cement.

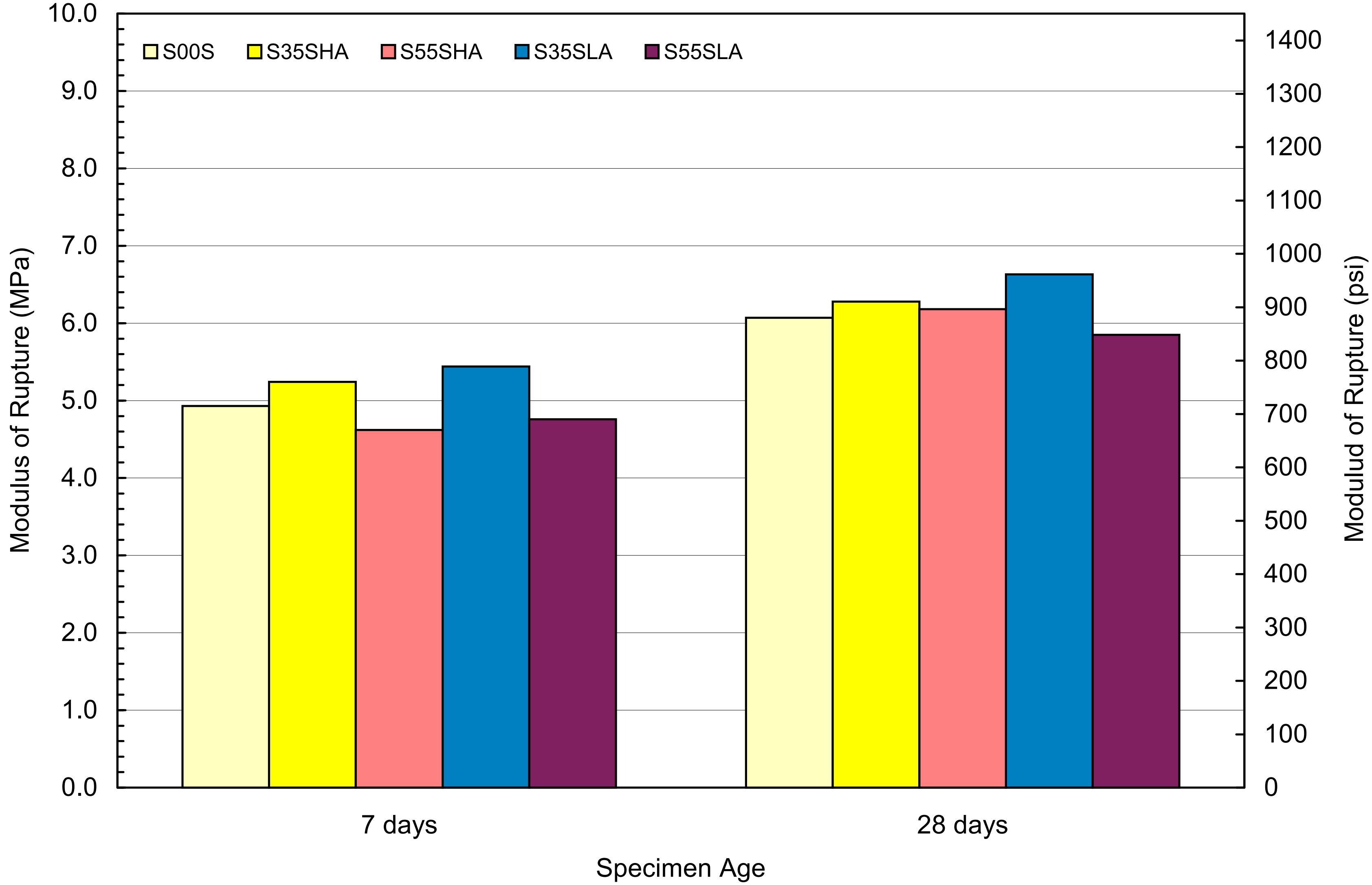

Figure 11) Comparison of the average modulus of rupture values for the concrete mixes in the SnnSHA series and the SnnSLA series.

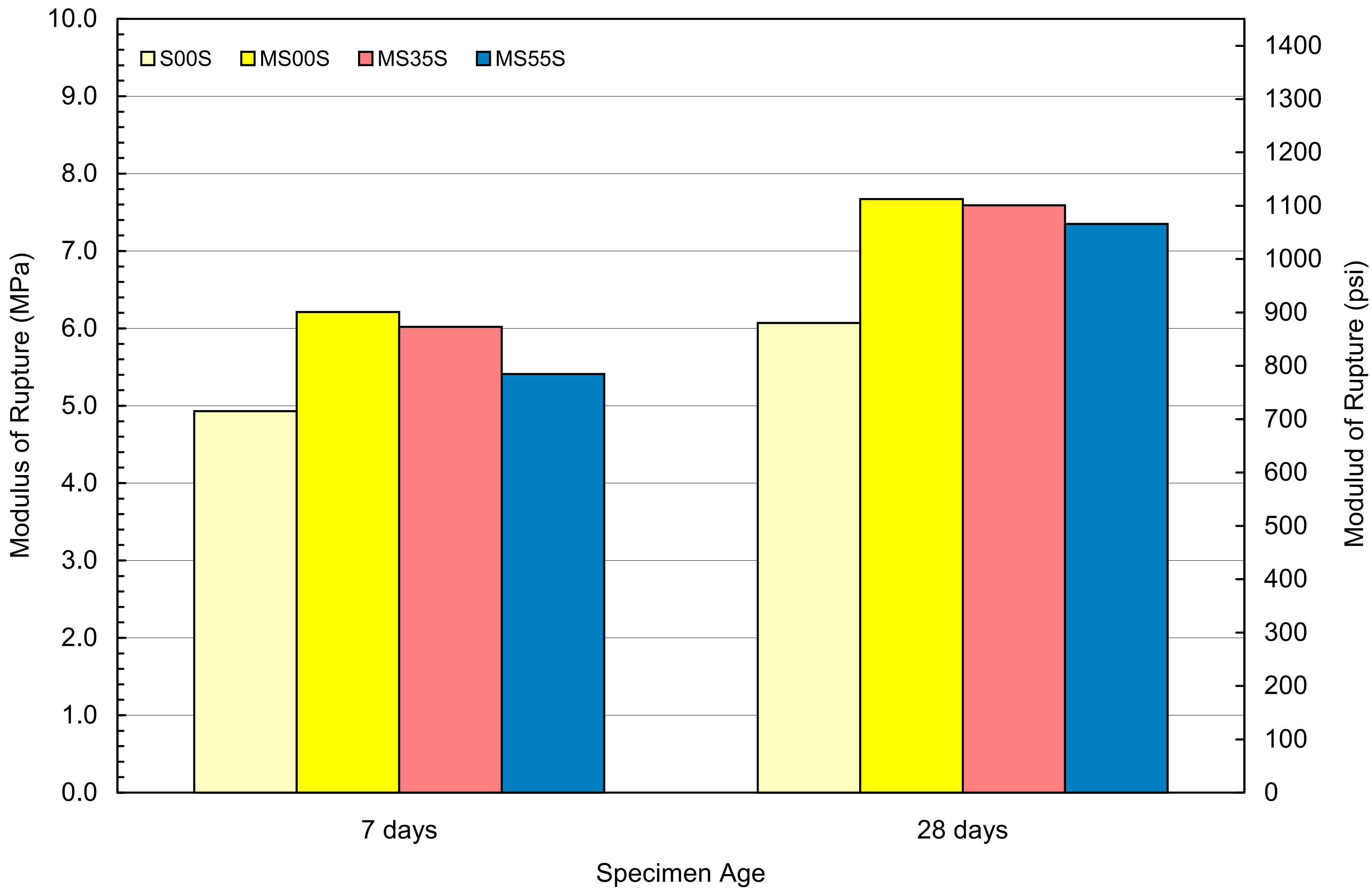

Figure 12) Comparison of the average modulus of rupture values for the concrete mixes in the MSnnS series.

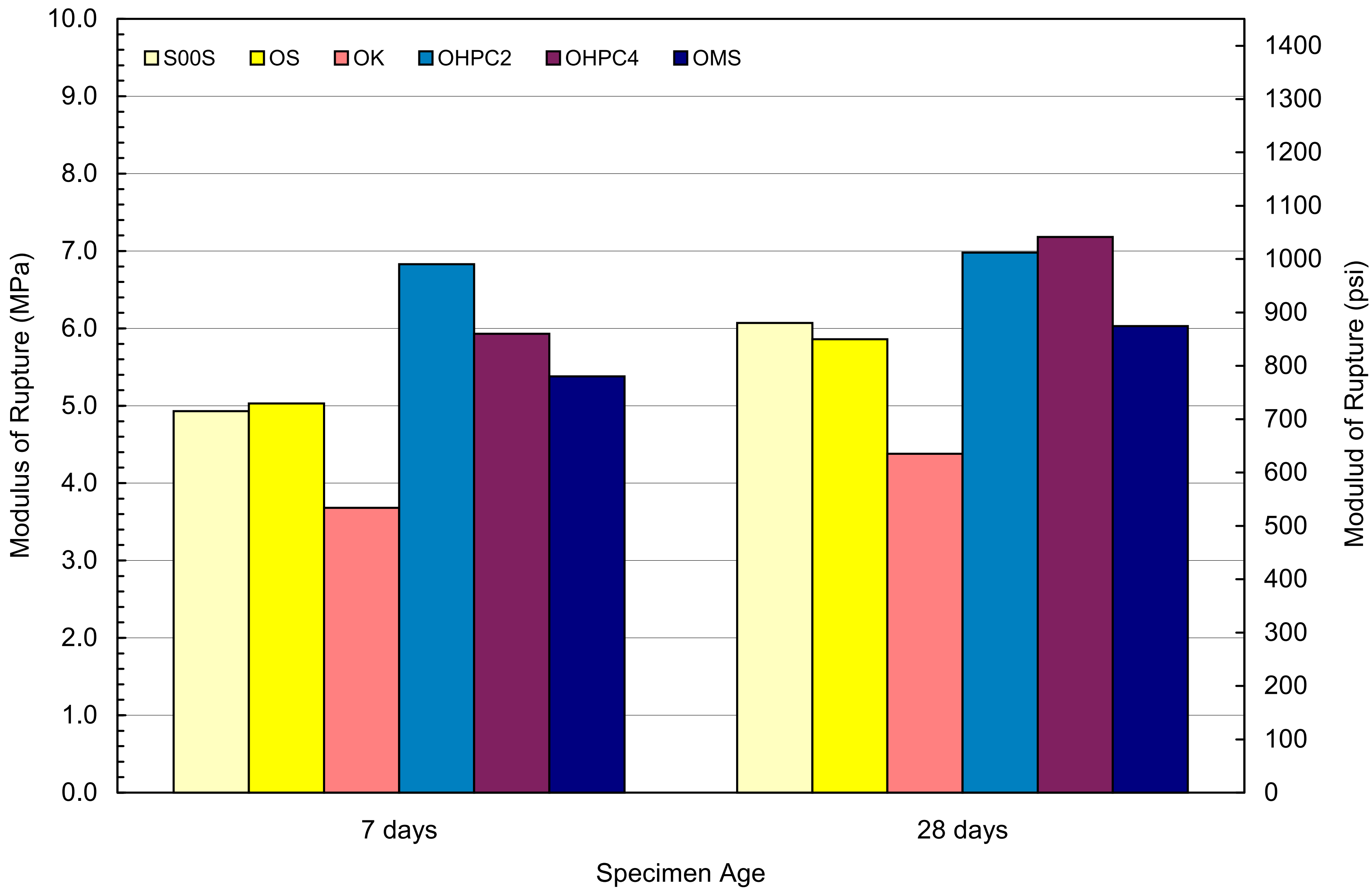

Figure 13) Comparison of the average modulus of rupture values for the concrete mixes obtained from ODOT construction projects.

SPLITTING TENSILE STRENGTH

In most cases, the splitting tensile strength testing consisted of five or more individual compression tests for both test ages for each mix design evaluated during Part I of the study. There are a small number of exceptions caused by an insufficient number of specimens in some cases and by testing errors or omissions in other cases. The individual test results are presented in Table A-3 in Appendix A. That table also contains the average strength for each test age for each concrete mix design. The average splitting tensile strength values from Table A-3 are summarized in Table 7. Table 7 also includes the corresponding average compressive strength for each concrete mix at the corresponding test ages. For the laboratory-prepared concrete mixes, each splitting tensile strength test specimen came from a different batch of concrete.

Table 7 also contains values of the factor m that were calculated by dividing the splitting tensile strength by the square root of the compressive strength. Note that this factor is not dimensionless and that its value depends on the units of the strength values used in its calculation. Values are given in the table both for US customary units and for metric units. The Commentary for ACI 318 indicates that the ratio of the splitting tensile strength to the square root of the compressive strength is approximately 0.56 for strengths expressed in MPa (6.7 for strengths in psi) for normal weight concrete. For the concrete mixes represented in Table 7, the values of this ratio for strengths in MPa range from 0.49 to 0.67 at 7 days and from 0.52 to 0.68 at 28 days. These values indicate that, in general, the splitting tensile strengths of the concretes in Part I of the project are approximately the same as those that would be predicted by the equation recommended by ACI for approximating splitting tensile strength based on the compressive strength of the concrete.

The modulus of rupture data contained in Table 7 is presented graphically in a series of figures to facilitate comparisons within specific groups of the concrete mix designs. The order and organization of the figures is identical to that used to present the modulus of rupture data.

The splitting tensile strength data for the SnnS series of mixes is presented in Figure 14. At the 7-day test age, the splitting tensile strength decreases as the amount of GGBFS loading in the mix increases from zero in S00S to 70 percent in S70S. This influence of GGBFS on the splitting tensile strength is very similar to that reported for compressive strength and modulus of rupture. At the 28-day test age, the use of GGBFS appears to either have no effect on the splitting tensile strength or to result in a slight increase in the strength.

For the mixes containing fly ash and GGBFS, the data presented in Figure 15 indicate that there is little difference between the splitting tensile strength when Class C fly ash is used versus that when Class F fly ash is used. Again, this is consistent with the findings for this group of mixes relative to the compressive strength and the modulus of rupture values. At the 7-day test age, the splitting tensile strength values for both the S35SC and S35SF mixes are clearly less than that for the S00S baseline mix. At the

Table 7) Splitting tensile strength data for the concrete mixes evaluated during Part I of the project.

Concrete Mix	7-day Strength Data			28-day Strength Data		
	Average Splitting Tensile Strength MPa (psi)	Average Compressive Strength MPa (psi)	m	Average Splitting Tensile Strength MPa (psi)	Average Compressive Strength MPa (psi)	m
S00S	3.67 (532)	32.55 (4721)	0.64 (7.74)	3.90 (566)	41.09 (5960)	0.61 (7.33)
S25S	3.49 (507)	29.91 (4338)	0.64 (7.70)	4.37 (633)	44.22 (6414)	0.66 (7.90)
S35S	3.23 (468)	26.43 (3833)	0.63 (7.56)	3.88 (563)	41.27 (5986)	0.60 (7.28)
S45S	3.19 (463)	26.69 (3872)	0.62 (7.44)	4.47 (648)	42.69 (6191)	0.68 (8.24)
S55S	3.12 (453)	26.00 (3772)	0.61 (7.38)	4.19 (608)	43.03 (6241)	0.64 (7.70)
S70S	2.60 (377)	19.06 (2765)	0.60 (7.17)	3.88 (563)	34.45 (4997)	0.66 (7.96)
S35SC	2.14 (310)	19.00 (2755)	0.49 (5.91)	3.27 (474)	35.44 (5141)	0.55 (6.61)
S35SF	2.14 (310)	17.75 (2574)	0.51 (6.11)	3.81 (553)	35.85 (5200)	0.64 (7.67)
S00SK	3.07 (445)	30.77 (4463)	0.55 (6.66)	3.47 (504)	37.83 (5487)	0.56 (6.80)
S35SK	3.57 (518)	33.27 (4825)	0.62 (7.46)	4.60 (667)	45.80 (6643)	0.68 (8.18)
S55SK	2.99 (434)	25.82 (3745)	0.59 (7.09)	4.05 (587)	42.40 (6149)	0.62 (7.49)
S35SHA	3.39 (492)	32.22 (4674)	0.60 (7.20)	4.43 (643)	47.68 (6916)	0.64 (7.73)
S55SHA	3.15 (457)	30.22 (4383)	0.57 (6.90)	4.43 (643)	49.55 (7186)	0.63 (7.58)
S35SLA	3.50 (507)	32.13 (4660)	0.62 (7.43)	4.59 (666)	48.02 (6965)	0.66 (7.98)
S55SLA	3.14 (455)	28.82 (4181)	0.58 (7.04)	4.40 (638)	44.47 (6450)	0.66 (7.94)
MS00S	4.79 (695)	51.22 (7429)	0.67 (8.06)	5.29 (768)	64.28 (9323)	0.66 (7.95)
MS35S	4.65 (674)	47.65 (6911)	0.67 (8.11)	4.88 (708)	62.03 (8996)	0.62 (7.46)
MS55S	4.09 (593)	42.42 (6153)	0.63 (7.56)	4.34 (630)	58.04 (8418)	0.57 (6.87)
OS	3.61 (523)	35.78 (5189)	0.60 (7.26)	3.85 (559)	42.79 (6206)	0.59 (7.10)
OK	2.83 (410)	25.79 (3740)	0.56 (6.70)	2.87 (416)	30.53 (4429)	0.52 (6.25)
OHPC2	3.76 (545)	38.71 (5615)	0.60 (7.27)	4.64 (673)	50.08 (7264)	0.66 (7.90)
OHPC4	2.72 (395)	30.07 (4361)	0.50 (5.98)	3.66 (531)	40.50 (5874)	0.58 (6.93)
OMS	3.97 (576)	45.04 (6532)	0.59 (7.13)	4.27 (619)	55.10 (7992)	0.58 (6.92)

m = (splitting tensile strength) / (compressive strength)$^{0.5}$

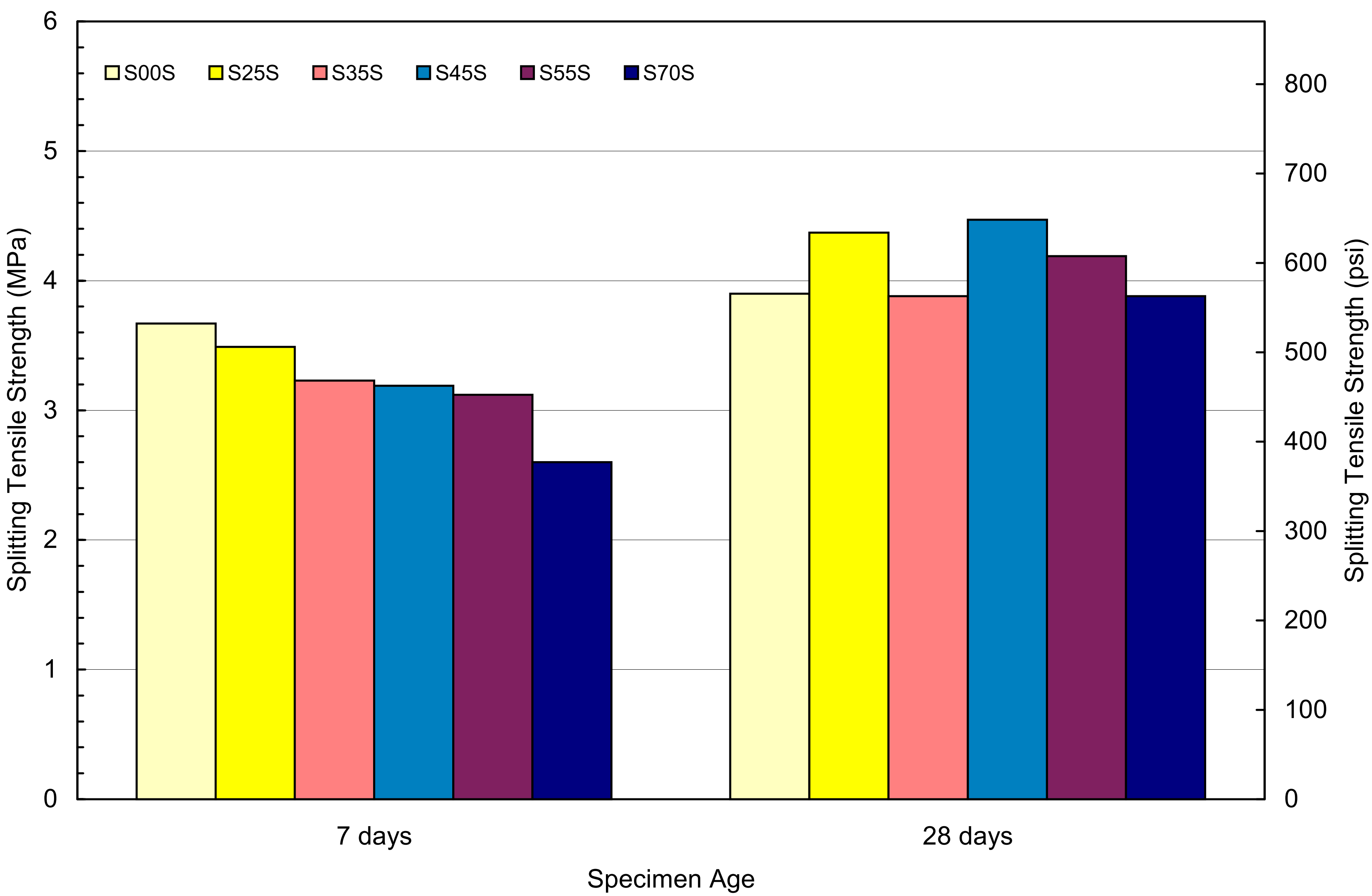

Figure 14) Comparison of the average splitting tensile strength values for the concrete mixes in the SnnS series.

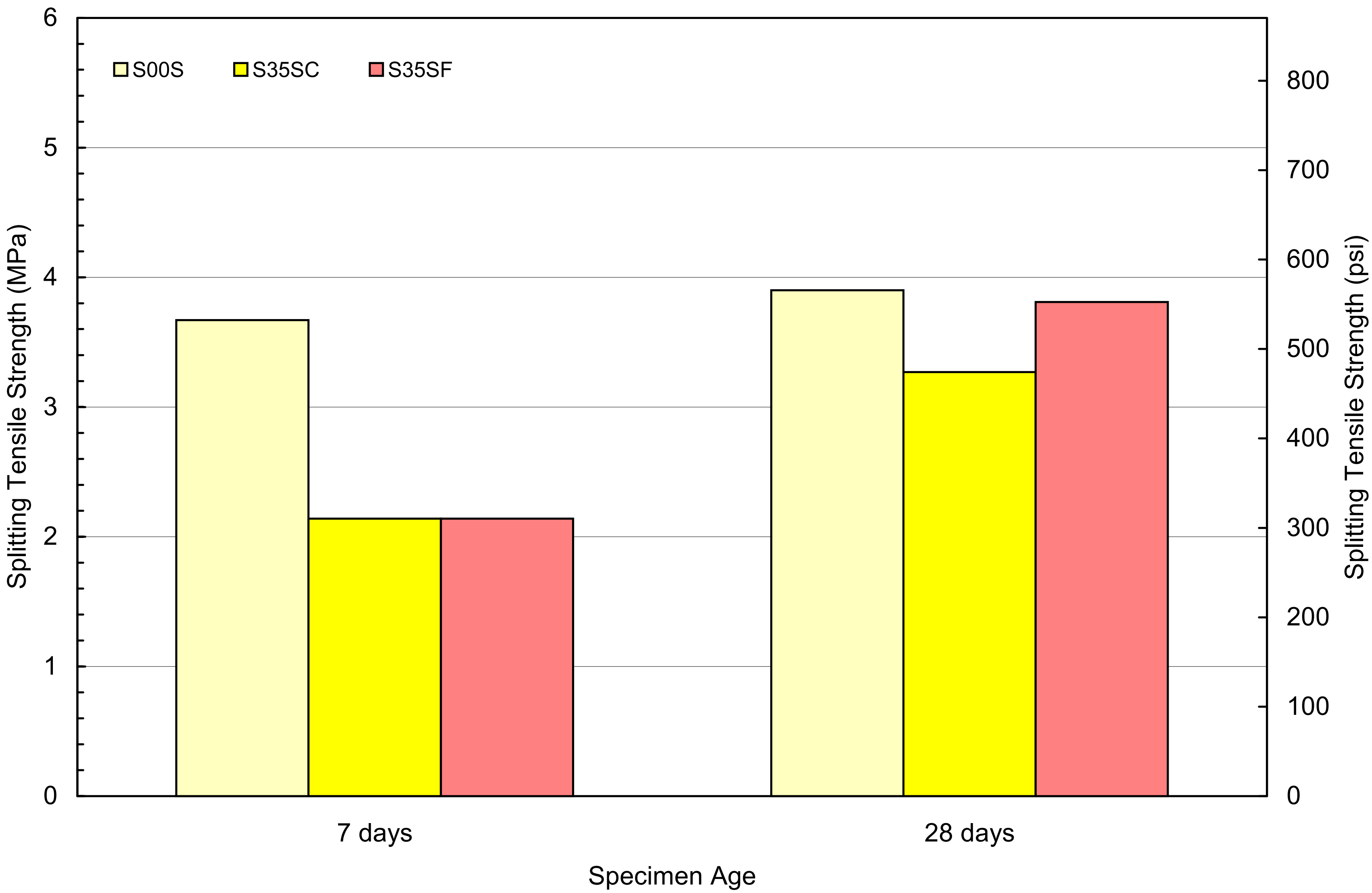

Figure 15) Comparison of the average splitting tensile strength values for the S35SC and S35SF concrete mixes containing fly ash and GGBFS.

28-day test age, the splitting tensile strength of mix S35SC is noticeably less than that for the S00S baseline mix, while the strength the S35SF mix is about the same as that for the S00S baseline mix.

The splitting tensile strength data for the mixes containing Type K cement are presented in Figure 16 along with the data for the S00S baseline mix. The mix designs for mixes S00S and S00SK are similar except that medium alkali portland cement is used in S00S and Type K cement is used in S00SK. For each of the test ages, the splitting tensile strength value for the S00SK mix is less than that for the S00S baseline mix. The splitting tensile strength values for the mixes containing GGBFS with the Type K cement are about the same as or greater than those for the S00SK mix.

The data on the influence of the alkali content of Type I portland cement on the splitting tensile strength of concretes containing GGBFS at replacement rates of 35 and 55 percent are presented in Figure 17. Based on this data, the alkali content of the cement appears to have very little, if any, influence on the splitting tensile strength of the concrete mixes involving the GGBFS-portland blends. At the 7-day test age, the splitting tensile strength values for the mixes containing 55 percent GGBFS are slightly less than those for the corresponding mixes containing 35 percent GGBFS, and the strengths for both groups are less than that for the S00S baseline mix. At the 28-day specimen age, the splitting tensile strength values for the four mixes containing the GGBFS-portland blend are nearly equal to each other and slightly higher than the splitting tensile strength of the S00S baseline mix.

Figure 18 contains the splitting tensile strength data for the micro-silica group of concrete mixes and for the S00S baseline mix. As discussed in the compressive strength section, the MS00S concrete mix is expected to be noticeably stronger than the S00S baseline mix. The expected strength difference between these two mixes is evident in Figure 18. For the three mixes in the MS series, the splitting tensile strength decreases as the amount of GGBFS in the concrete mix increases. The effect of GGBFS loading on the splitting tensile strength is very similar to its effect on the modulus of rupture discussed earlier.

The splitting tensile strength values for the concrete mixes collected from ODOT construction projects are compared to each other and to the S00S baseline mix in Figure 19. The S00S mix and the OS mix are both basic ODOT Class S concrete mixes and should have comparable strengths. The splitting tensile strength values for these two mixes are almost identical at each of the two test ages. The splitting tensile strength values for mixes OHPC2 and OMS are about the same as or greater than those for the S00S baseline mixes at both the 7-day and the 28-day test ages. The splitting tensile strength values for the OHPC4 are less than that of the S00S mix at both test ages.

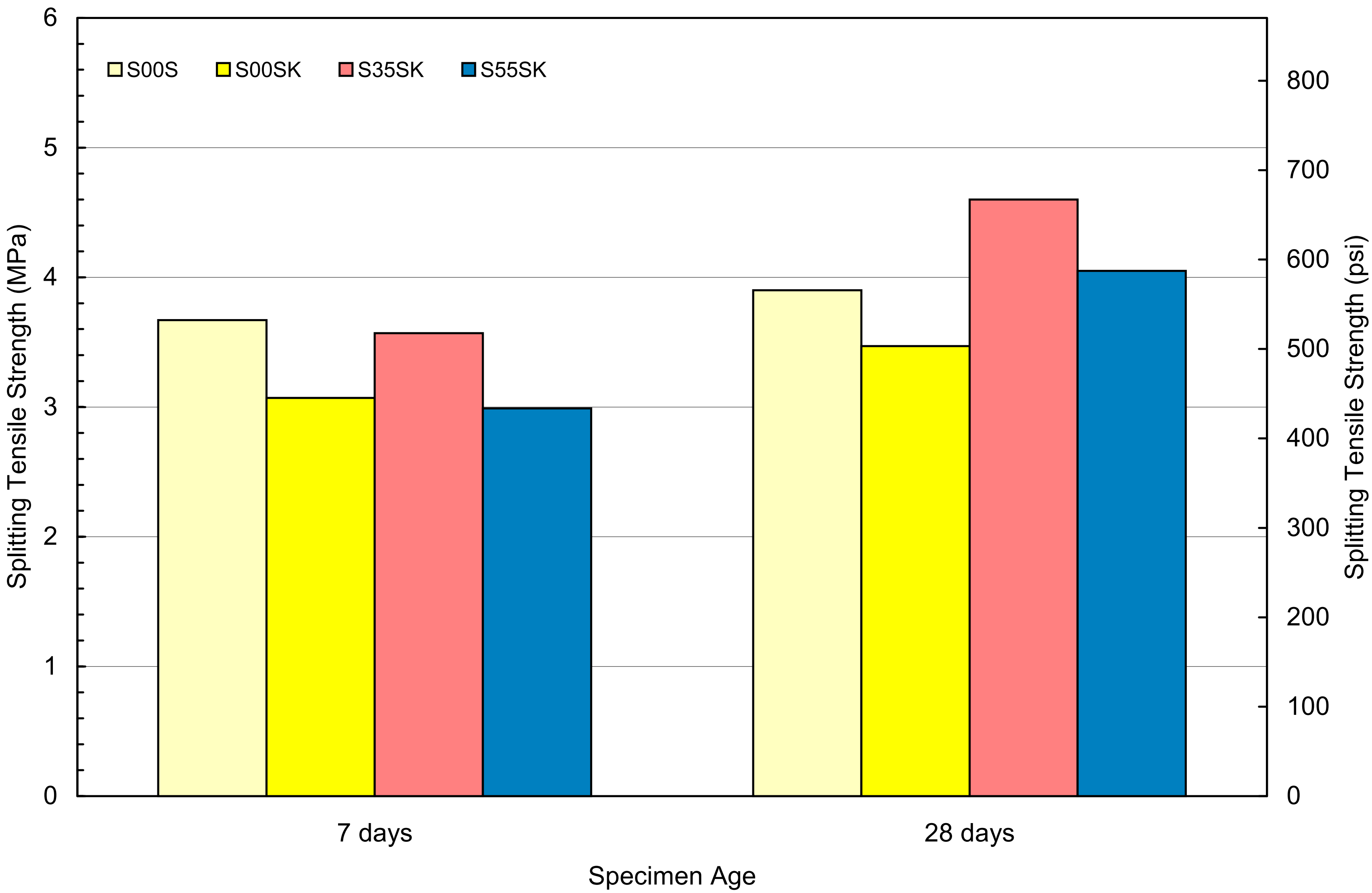

Figure 16) Comparison of the average splitting tensile strength values for the concrete mixes in the SnnSK series containing Type K cement.

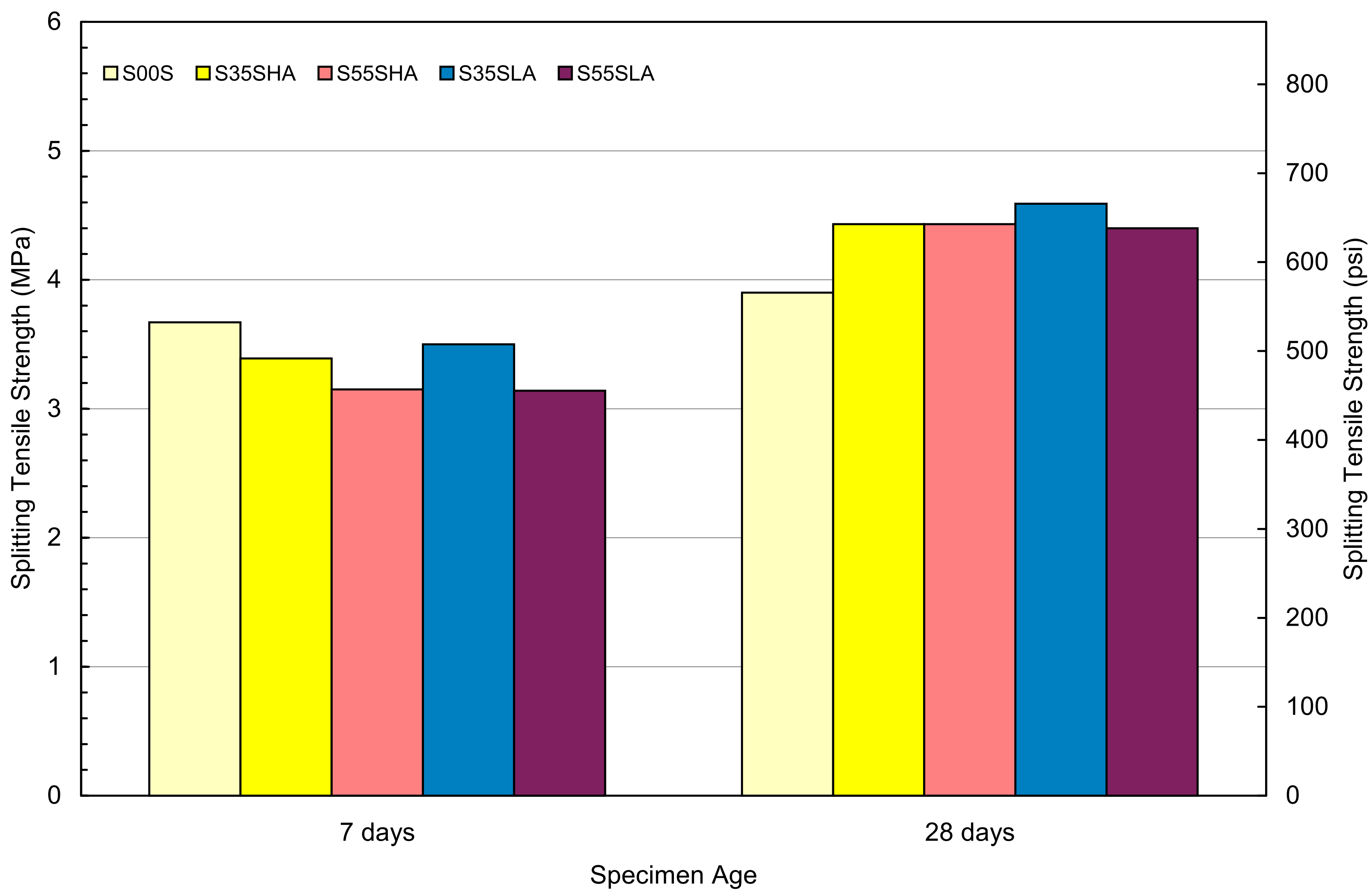

Figure 17) Comparison of the average splitting tensile strength values for the concrete mixes in the SnnSHA series and the SnnSLA series.

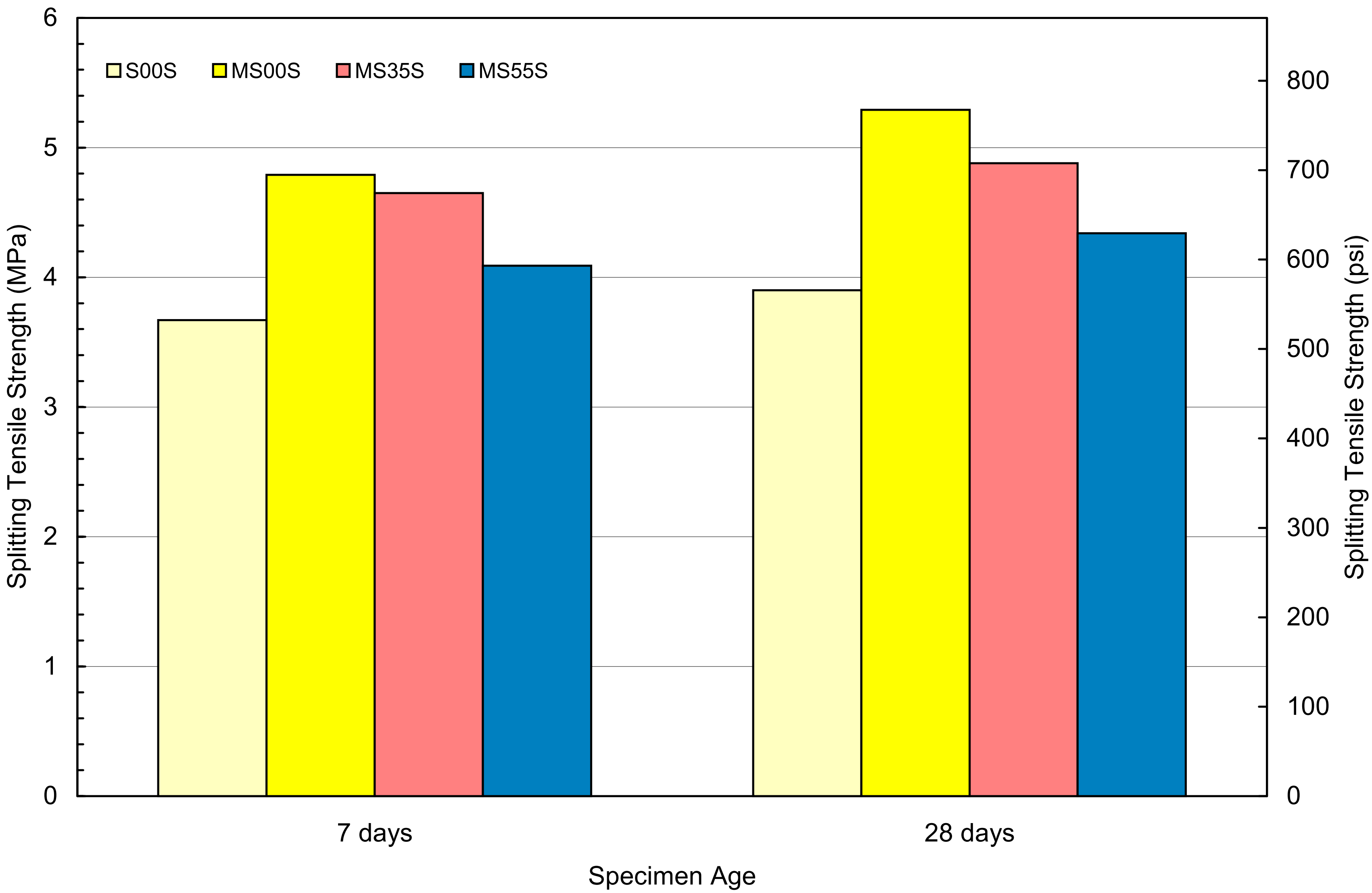

Figure 18) Comparison of the average splitting tensile strength values for the concrete mixes in the MSnnS series.

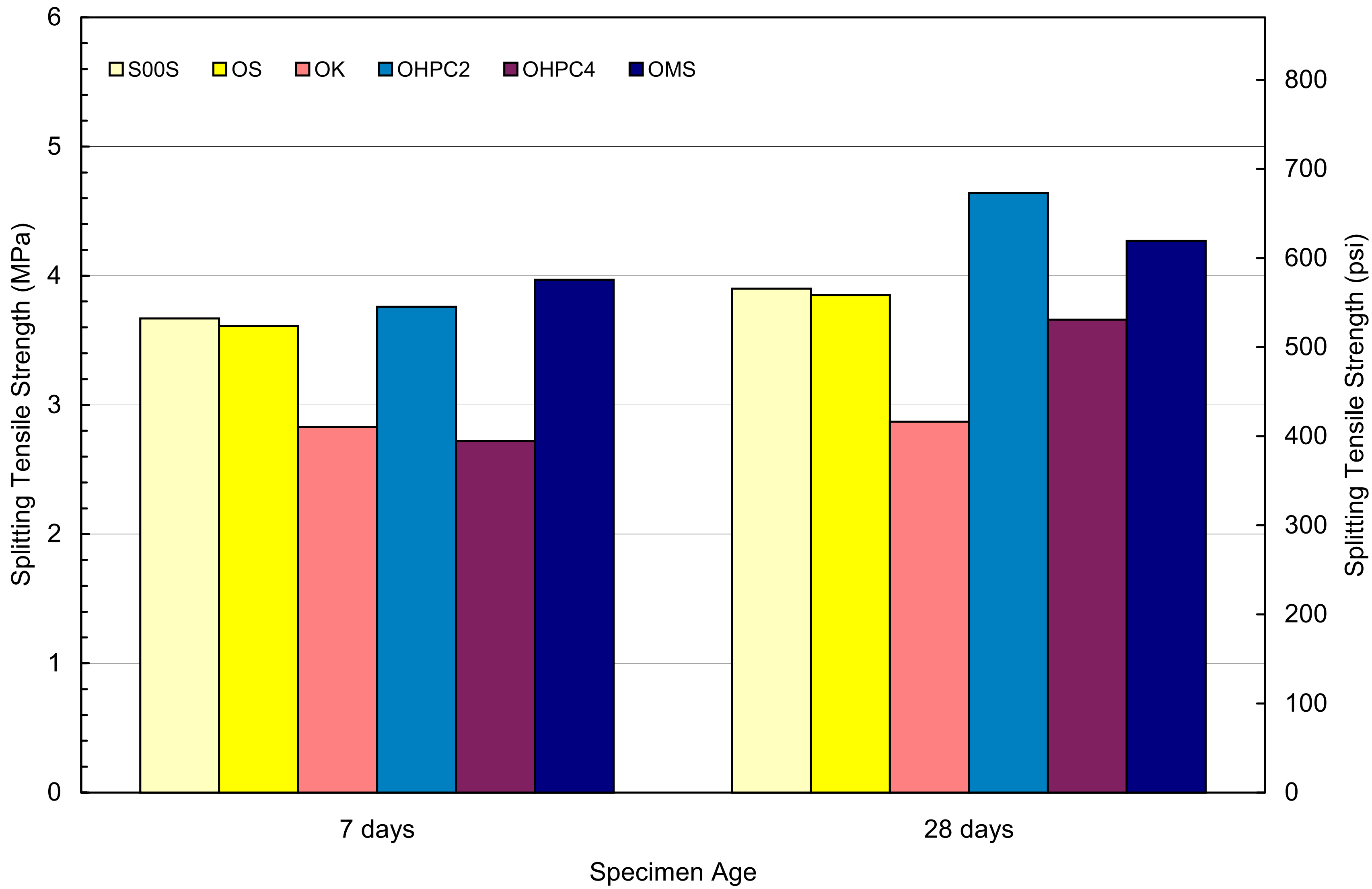

Figure 19) Comparison of the average splitting tensile strength values for the concrete mixes obtained from ODOT construction projects.

DURABILITY PROPERTIES

CHLORIDE PERMEABILITY

For the lab-prepared concrete mixes, four rapid chloride permeability tests were performed for each of the mixes. The tests were performed in accordance with ASTM C 1202 Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. The tests were performed on specimens that were cast in 102 mm (4 inches) diameter specimens. The standard specimen size is 95.3 mm (3.75 inches) in diameter. The results from the lab tests were corrected by multiplying by an area correction factor of 0.879 which is the ratio of the two specimen areas. The area-corrected test results for each test are reported in Table 8 along with the average for each mix type. The rightmost column in Table 8 contains the chloride permeability rating of the concrete according to ASTM 1202. The values of the average area-corrected charge passed reported in the table form the basis for Figures 20 and 21, which are used to compare the performance of the different mixes.

The average values of the area-corrected charge passed for the lab-prepared concrete mixes evaluated during Part I of the study are shown graphically in Figure 20. Based on these test results, the incorporation of GGBFS in the concrete mix has a clear and significant influence on the charge passed during the rapid chloride permeability test. For the SnnS series, the charge passed during the test decreases significantly as the amount of GGBFS in the concrete increases. For the S00S concrete with no GGBFS, the average area-corrected charge passed is 3670 coulombs while the average area-corrected charge passed for the concrete mix containing 70 percent GGBFS (S70S) is 588 coulombs. This corresponds to an 84 percent reduction in the charge passed during the test and a change in the chloride permeability rating from moderate to very low.

The results for the SnnSK series and the MSnnS series indicate a similar influence of incorporating GGBFS on the average area-corrected charge passed during the test. For these two groups of concrete mixes, the range of GGBFS loadings is less than that used for the SnnS series, but the influence of the GGBFS on the test results is still very clear. In the SnnSK series, the average area-corrected charge passed during the test decreases from 3271 coulombs to1168 coulombs and the GGBFS loading increases from 0 in mix S00SK to 55 percent in mix S55SK. This corresponds to 64 percent reduction in the charge passed. For the mixes in the MSnnS series, the influence of GGBFS on the average area-corrected charge passed is less noticeable because the value for MS00S is already quite low. The reduction in the charge passed as a result of incorporating GGBFS at 55% compared to no GGBFS in the mix is still about 40 percent.

The data from S35S, S55S, the SnnSLA series, and the SnnSHA series can be used to evaluate the influence of the alkali content of the cement used in combination with the GGBFS and the resistance of the concrete to chloride ion penetration. Based on the average area-corrected charge passed for these concrete mixes, there does not appear to be a consistent relationship between the charge passed and the alkali content of the cement involved.

The influence of incorporating fly ash into the concrete mix on the average area-corrected charge passed can be evaluated by comparing the results for mixes S35SC and S35SF to those of the other mixes containing 35 percent GGBFS (S35S, S35SHA, S35SLA, and S35SK). Based on this comparison, the use of 15% fly ash resulted in the lowest average area-corrected charge passed for concretes within the comparison group. The most direct comparison is between S35S and the two mixes containing fly ash. In this case, the test results indicate a clear reduction in the charge passed as a result of incorporating the fly ash into the mix. The results for the two different classes of fly ash are virtually identical.

Table 8) Area-corrected charge passed during the rapid chloride permeability test for concrete mixes evaluated during Part I of the project.

Concrete Mix	Charge Passed (coulombs)					Chloride Permeability Rating
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Average	
S00S	3592	3592	3762	3734	3670	moderate
S25S	2822	3154	2306	2715	2749	moderate
S35S	2527	2297	2038	2297	2290	moderate
S45S	1098	1177	1157	1064	1124	low
S55S	1072	1104	801	810	947	very low
S70S	621	684	521	524	588	very low
S35SC	1521	1410	1462	1657	1513	low
S35SF	1726	1341	1448	1423	1484	low
S00SK	2904	3496	3265	3419	3271	moderate
S35SK	1726	1543	1878	1438	1646	low
S55SK	1340	1320	979	1032	1168	low
S35SH	2272	2401	1470	1973	2029	moderate
S55SH	1550	1537	1516	1385	1498	low
S35SL	1848	1806	1768	1749	1793	low
S55SL	1033	1086	707	817	911	very low
MS00S	428	414	541	541	482	very low
MS35S	332	362	312	340	337	very low
MS55S	282	267	300	294	286	very low
OS	3579	2974	3583	2919	3264	moderate
OK	3592	3592	3592	3592	3592	moderate
OHPC2	2319	2357	2871	3104	2663	moderate
OHPC4	1595	1482			1539	low
OMS	706	744	693	824	742	very low

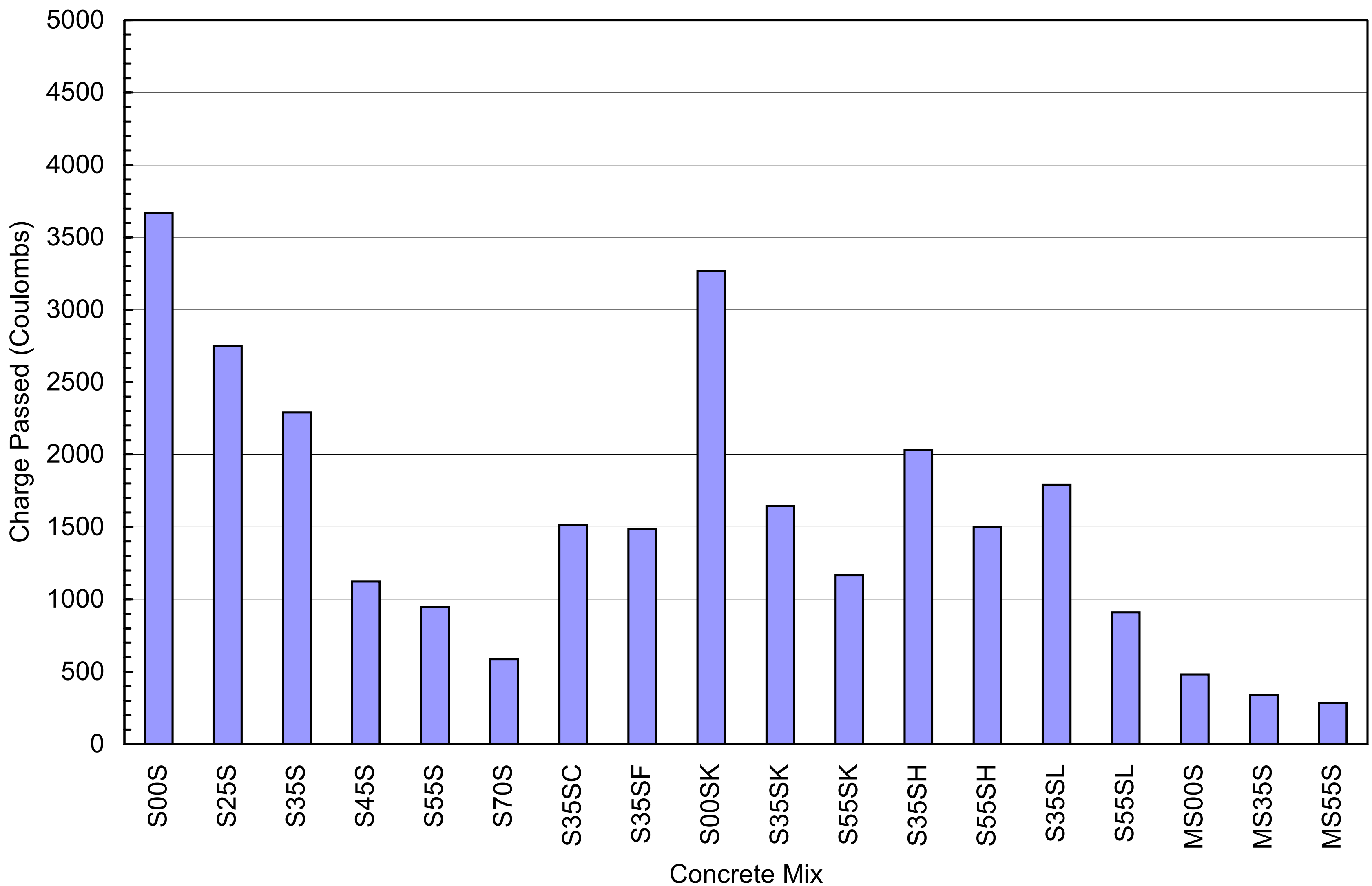

Figure 20) Average area-corrected charge passed during the rapid chloride permeability test for lab-prepared concrete mixes evaluated during Part I of the project.

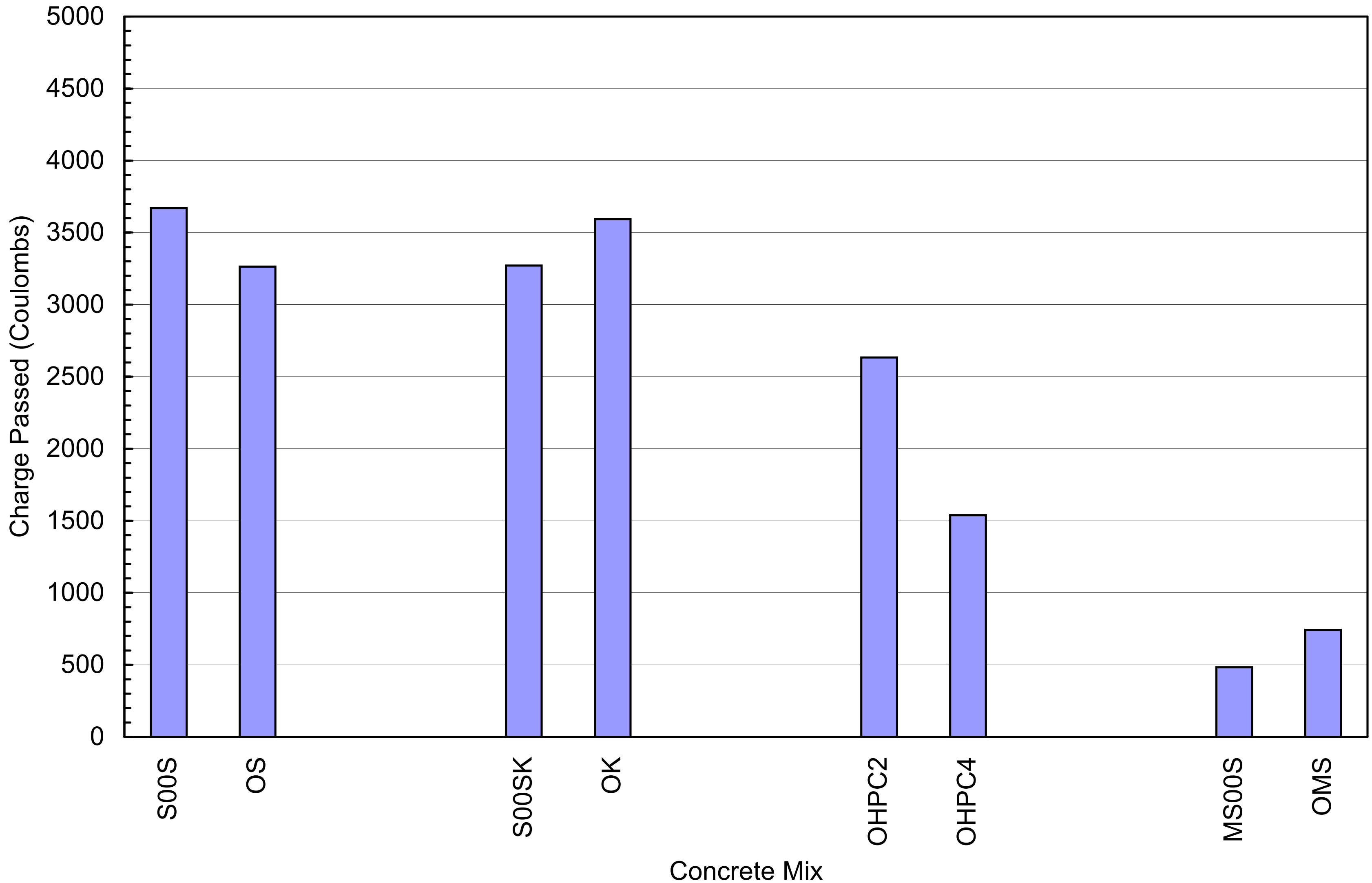

Figure 21) Average area-corrected charge passed during the rapid chloride permeability test for concrete mixes from ODOT construction projects and selected lab-prepared concrete mixes evaluated during Part I of the project.

As a group, the MSnnS series is the most resistant to chloride ion penetration. This is expected due to the lower water:cement ratio and the incorporation of silica fume in these mixes.

The rapid chloride permeability test results for the five concrete mixes obtained from ODOT construction projects are presented in Figure 21 along with the results of three comparable concrete mixes prepared in the lab (S00S, S00SK, and MS00S). Comparing the results of concrete mixes OS, OK and OMS obtained from ODOT projects with their comparable lab-prepared concrete mixes indicates that the performance of the lab-prepared concrete is very similar to that of the corresponding concrete collected from the ODOT projects. As noted earlier, the best resistance to chloride ion penetration is exhibited by mixes with low water:cement ratios and silica fume. This is evidenced in Figure 21 by the performance of concrete mixes MS00S and OMS.

LENGTH CHANGE

The length change of concrete caused by factors other than temperature and applied load is determined using ASTM 157 Length Change of Hardened Hydraulic-Cement Mortar and Concrete. The length change behavior of each of the lab-prepared concrete mixes evaluated during Part I of the project was evaluated using standard 3x3x11.25 inch specimens. For the concrete mixes obtained from ODOT construction projects, tests were performed on standard 76x76x286 mm (3x3x11.25 inch) specimens and special 76x102x381 mm (3x4x15 inch) specimens commonly used by ODOT. The test results for the standard-size specimens are presented in Table 9, and the results for the larger specimens are presented in Table 10. In both of the tables, the individual test results are presented for each concrete mix, and the average of the test results for each mix is presented in the rightmost column.

Table 9) Length change after 64 weeks of drying for the 286 mm (11.25 inch) long specimens for the concrete mixes evaluated during Part I of the project.

Concrete Mix	Length Change After 64 Weeks of Drying (percent)					
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Average
S00S	0.043	0.037	0.035	0.043	0.042	0.040
S25S	0.036	0.042	0.037	0.042	0.035	0.038
S35S	0.040	0.041	0.043	0.047	0.043	0.043
S45S	0.035	0.034	0.036	0.040	0.042	0.037
S55S	0.036	0.047	0.043	0.046	0.037	0.042
S70S	0.032	0.046	0.041	0.036	0.047	0.040
S35SC	0.030	0.033	0.030	0.030		0.031
S35SF	0.040	0.025	0.025	0.023		0.028
S00SK	0.034	0.036				0.035
S35SK	0.026	0.044	0.032	0.031	0.030	0.033
S55SK	0.028	0.036	0.028	0.029	0.021	0.028
S35SHA	0.033	0.034	0.031	0.030		0.032
S55SHA	0.030	0.037	0.034	0.034	0.034	0.034
S35SLA	0.036	0.048	0.042	0.035		0.040
S55SLA	0.032	0.045	0.042	0.034		0.038
MS00S	0.033	0.034	0.036	0.038		0.035
MS35S	0.038	0.037	0.036	0.039		0.038
MS55S	0.035	0.041	0.039			0.038
OS	0.045	0.050	0.034	0.037		0.042
OK	0.048	0.043				0.046
OHPC2	0.045	0.044	0.029	0.036		0.039
OHPC4	0.038	0.035				0.037
OMS	0.057	0.060	0.044	0.045		0.052

Table 10) Length change after 64 weeks of drying for the 381 mm (15 inch) long specimens for the concrete mixes obtained from ODOT construction projects.

Concrete Mix	Length Change After 64 Weeks of Drying (percent)				
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Average
OS	0.036	0.037	0.036	0.051	0.040
OK	0.055	0.056			0.056
OHPC2	0.063	0.065	0.058	0.065	0.063
OHPC4	0.057	0.052			0.055
OMS	0.049	0.059	0.049	0.057	0.054

The values of average length change in these two tables are the basis for the comparisons presented in Figures 22 and 23. Figure 22 is used to compare the results of the length change tests for the lab-prepared mixes, and Figure 23 is used to compare the results of the tests performed on concrete obtained from ODOT construction projects using two different specimen sizes.

For the concrete mixes in the SnnS series, the amount of GGBFS incorporated into the concrete mixes ranges from zero to 70 percent. For these concrete mixes, there is no apparent correlation between the amount of GGBFS present in the concrete and the amount of length change that occurs.

The results for the SnnSK series and those for the MSnnS series are contradictory with respect to the suggested influence of GGBFS on the results of the length change test. The data for the SnnSK series indicates that the length change decreases slightly as GGBFS loading is increased from zero to 55 percent. For the MS00S series, the data indicate a slight trend in the opposite direction. The trends for these two groups are small and in opposite directions and there is no apparent correlation between the amount of GGBFS and the length change behavior within the SnnS series. Based on these facts, it appears that the incorporation of GGBFS into the concrete as a replacement for portland cement has very little, if any, influence on the length change behavior of the concrete.

The length change values for the two concrete mixes incorporating GGBFS and fly ash (S35SC and S35SF) are among the lowest values recorded for any of the mixes evaluated. The particular class of fly ash used in combination with the portland cement and the GGBFS does not appear to have a significant influence on the length change behavior of the resulting concrete.

A comparison of the data for the SnnSHA series using high alkali cement and data for the SnnSLA series containing low alkali cement suggests that the concretes containing the high alkali cement have slightly less shrinkage than those containing the low alkali cement. However, when concrete mixes S35S and S55S containing medium alkali cement are included in the comparison, the correlation between alkali content and length change behavior breaks down.

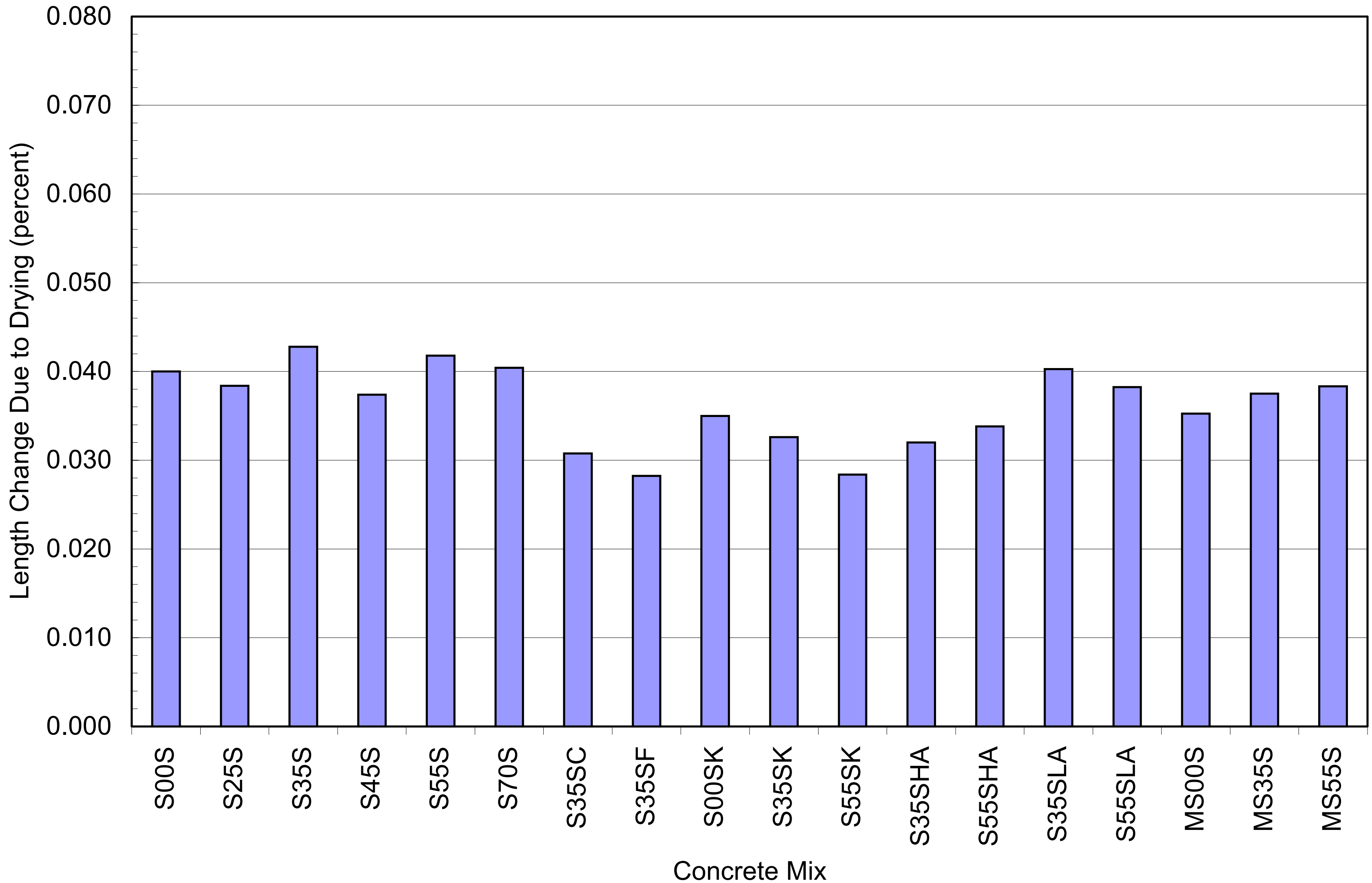

Figure 22) Length change after 64 weeks of drying for the lab-prepared concrete mixes evaluated during Part I of the project.

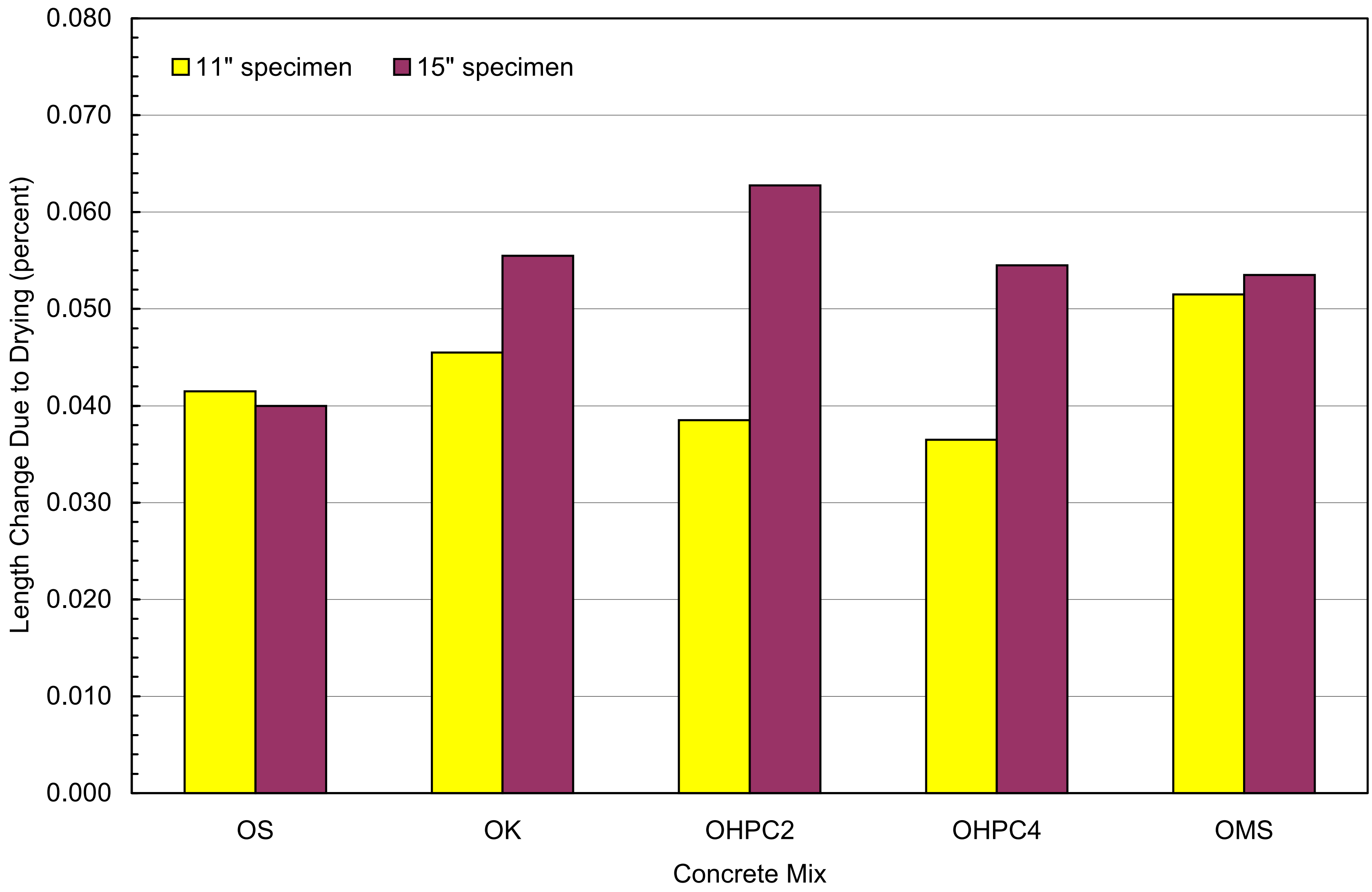

Figure 23) Length change after 64 weeks of drying for two different specimen sizes for the concrete mixes obtained from ODOT construction projects during Part I of the project.

Although there are some differences in the length change behaviors reported in Figure 22, the differences do not appear to be significant and are attributed to natural variations in test results and materials rather than the result of differences in the concrete mix designs. The length change measured using ASTM C 157 is often primarily due to length change due to drying of the concrete. Length change of concrete due to drying is primarily a function of the paste volume of the concrete mix and the water:cement ratio of the concrete. Within the broad grouping of the "S" mixes in the study, the water:cement ratio is constant at 0.42, and the volume of cement paste is nearly constant. The only differences in the volume of the cement paste are those arising from differences in the specific gravities of the different materials constituting the cement paste in the different concrete mixes. The influence of the slightly higher paste volume in the MSnnS series is apparently offset by the influence of the lower water:cement ratio compared to the "S" group of mixes. As a result, the length change behavior of the MSnnS series does not appear to be significantly different from that of the concrete mixes in the "S" group.

The length change data for the two different specimen sizes for the concrete mixes obtained from ODOT construction projects are presented in Figure 23. The results from the tests involving the two different specimen sizes are in good agreement in only two of the five cases. In two of the remaining three cases, there is a significant difference between the results of the tests on the different specimen sizes. The reason for the difference between the results for the different specimen sizes is not apparent. The cross-sectional area of the longer specimen is 33% larger than that of the smaller specimen. If specimen size has an influence on the test results, the specimen with the larger cross-sectional area should dry slower, and at the end of the test, if there is a difference in the length change, the larger specimen should have a lower length change. However, the differences in the test data are opposite from this expectation. Otherwise, the data for the standard-size specimens are similar to the data for the corresponding lab-prepared specimens.

ABRASION RESISTANCE

The influence of replacing portland cement with various amounts of GGBFS on the resistance to abrasion of the concrete was evaluated using the concrete mixes in the S00S series. The concrete mixes in the S00S series differ from one another only in the percent of the portland cement replaced by GGBFS. The GGBFS replacement rates range from 0 to 70 percent. For each of the concrete mixes in the S00S series, two abrasion resistance tests were conducted according to ASTM 944 Abrasion Resistance of Concrete or Mortar Surfaces by the Rolling-Cutter Method. Each test involves exposing three test specimens to the abrasion process and recording the weight loss due to abrasion. The results for each test specimen are presented in Table 11 along with the test average and the mix average. The test average is the average weight loss of the three specimens for that test, and the mix average is the average of the two test averages for that concrete mix.

The average values of weight loss due to abrasion for the six concrete mixes in the S00S series are shown graphically in Figure 24. For GGBFS replacement percentages of 45 or less, the GGBFS replacement rate appears to have little, if any, influence on the abrasion resistance of the concretes containing GGBFS-portland blends. For GGBFS replacement rates of 55 and 70 percent, the resistance to abrasion increases with increasing GGBFS content.

Table 11) Weight loss due to abrasion for the S00S series of concrete mixes evaluated during Part I of the Project.

Conc. Mix	Test No.	Weight Loss Due to Abrasion (grams)				
		Specimen 1	Specimen 2	Specimen 3	Test Average	Mix Average
S00S	1	1.46	1.40	1.33	1.40	1.28
S00S	2	0.70	1.38	1.37	1.15	
S25S	1	1.55	2.30	1.61	1.82	1.80
S25S	2	1.69	2.03	1.58	1.77	
S35S	1	0.96	0.91	0.93	0.93	1.13
S35S	2	1.28	1.56	1.14	1.33	
S45S	1	1.26	1.59	1.52	1.46	1.60
S45S	2	1.67	1.63	1.89	1.73	
S55S	1	2.19	1.35	1.15	1.56	2.10
S55S	2	1.93	3.81	2.17	2.64	
S70S	1	2.33	3.02	2.20	2.52	2.99
S70S	2	3.21	3.76	3.41	3.46	

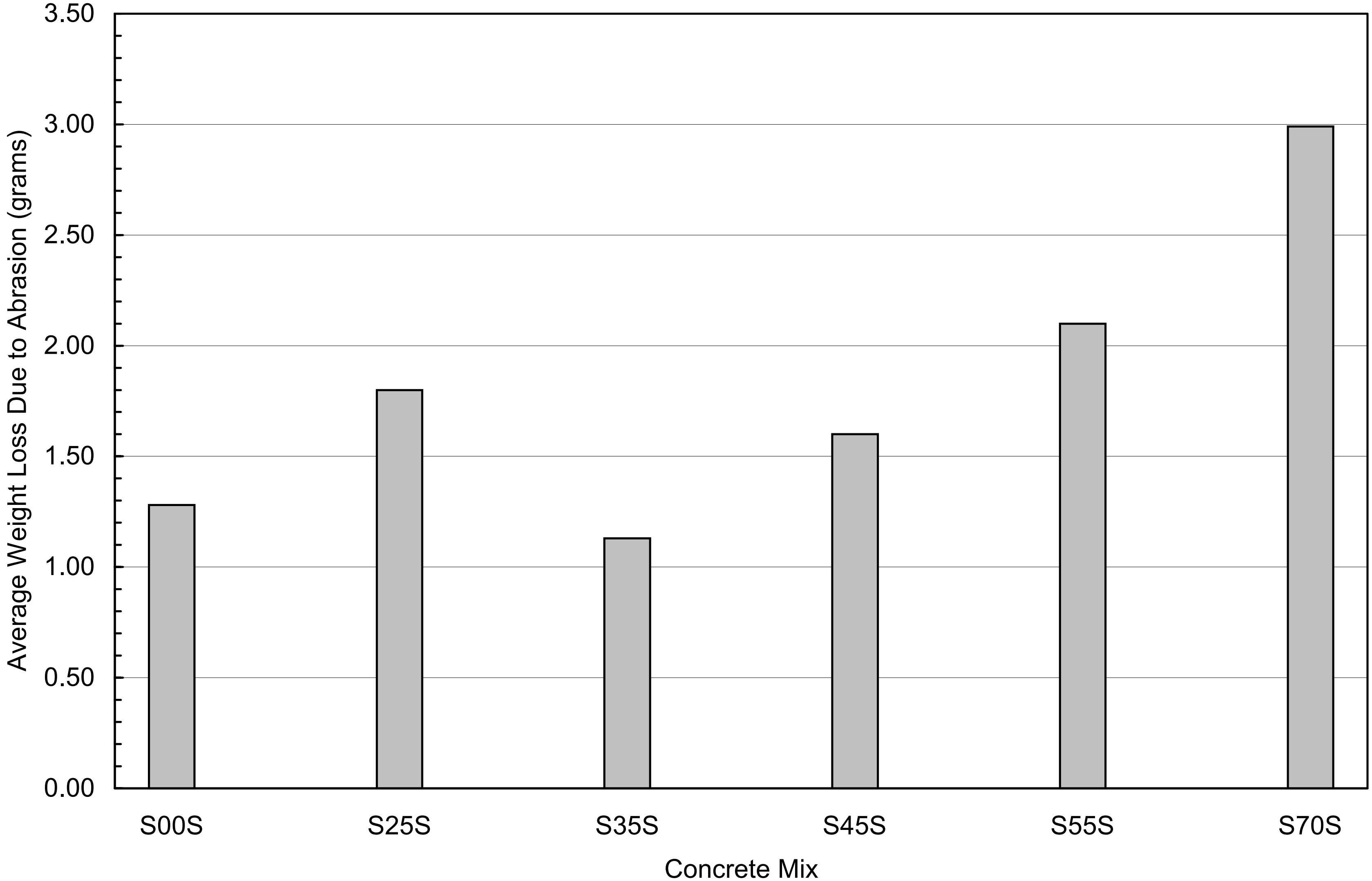

Figure 24) Average weight loss due to abrasion for the six concrete mixes in the S00S series.

FREEZE-THAW DURABILITY

The freeze-thaw durability of the concrete mixes was evaluated using method A of ASTM C 666. In this method, the specimen remains submerged in water during both the freezing and the thawing cycles. The test specimens were cured in a lime-saturated water bath for 14 days prior to testing. On the fourteenth day, the dimensions, weight, and initial fundamental transverse frequency were recorded prior to placing the test specimen into the freeze-thaw cabinet. In accordance with ASTM C 666, the specimens were evaluated at intervals not exceeding 36 cycles of freezing and thawing. The testing of each specimen continued until either it was exposed to 300 cycles of freezing and thawing or until the relative dynamic elastic modulus of the specimen dropped below 60%. The relative dynamic modulus is calculated using the following equation.

$$P_c = \frac{n_1^2}{n^2} \times 100$$

where: P_c = relative dynamic modulus of elasticity after c cycles of freezing and thawing,
n = fundamental transverse frequency at zero cycles of freezing and thawing, and
n_1 = fundamental transverse frequency after c cycles of freezing and thawing.

At the end of the test, the durability factor for the specimen is calculated as:

$$DF = \frac{PN}{M}$$

where: DF = durability factor of the specimen,
P = relative dynamic modulus of elasticity of the specimen at N cycles of freezing and thawing,
N = the lesser of the number of cycles at which P reaches 60% or 300 (the number of cycles at which the exposure to freezing and thawing is to be terminated), and
M = 300, the specified number of cycles at which the exposure to freezing and thawing is to be terminated.

Within Part I of the study, the objective was to determine the influence, if any, of the amount of GGBFS used as a portland cement replacement on the freeze-thaw durability of the concrete. Multiple specimens of the lab-prepared concrete mixes and the concrete mixes obtained from ODOT construction projects were subjected to the freeze-thaw durability test procedure. For each test, the initial and final fundamental transverse frequency values and the air content for the concrete mix are reported in Table 12 along with the calculated values of the durability factor. For each concrete mix, the individual test results are used to calculate the average durability factor for the mix. The average durability factors are used to compare the various concrete mixes.

Table 12) Results of freeze-thaw durability testing for concrete mixes evaluated during Part I of the project.

Concrete Mix	Initial Fundamental Transverse Frequency	Final Fundamental Transverse Frequency	Air Content (percent)	Number of Freeze-Thaw Cycles	Durability Factor	Average Durability Factor
S00S	2160	2094	4.8	300	94	98
	2160	2141	4.8	300	98	
	2049	2048	5.0	300	100	
	2184	2160	5.0	300	98	
S25S	2091	2034	7.0	300	95	95
	2097	2069	7.0	300	97	
	2107	2019	5.5	300	92	
	2145	2089	5.5	300	95	
S35S	2081	2036	7.5	300	96	92
	2093	2019	7.5	300	93	
	2110	1955	7.2	300	86	
	2076	2002	7.2	300	93	
S45S	2105	1962	7.2	300	87	90
	2062	1972	7.2	300	91	
	2094	1992	6.9	300	90	
	2112	2011	6.9	300	91	
S55S	2110	1640	6.0	278	56	56
	2120	1807	6.0	300	73	
	2115	1648	5.5	238	48	
	2112	1630	5.5	230	46	
S70S	2029	1915	7.5	300	89	89
	2019	1915	7.5	300	90	
	2080	1964	7.0	300	89	
	2094	1937	7.0	300	86	
S35SC	2097	1984	6.5	300	90	87
	2078	1978	6.5	300	91	
	2121	1927	6.0	300	83	
	2127	1932	6.0	300	83	
S35SF	2022	1783	6.5	300	78	71
	2107	1626	6.5	279	55	
	2046	1826	6.0	300	80	
	2080	1767	6.0	300	72	

Table 12 cont.) Results of freeze-thaw durability testing for concrete mixes evaluated during Part I of the project.

Concrete Mix	Initial Fundamental Transverse Frequency	Final Fundamental Transverse Frequency	Air Content (percent)	Number of Freeze-Thaw Cycles	Durability Factor	Average Durability Factor
S00SK	2048	2010	7.2	300	96	93
	2076	2020	7.2	300	95	
	2063	1978	7.5	300	92	
	2071	1964	7.5	300	90	
S35SK	2064	1630	5.5	300	62	59
	2088	1620	5.5	275	55	
S55SK	2037	1969	8.0	300	93	94
	2026	2001	8.0	300	98	
	2050	1977	7.6	300	93	
	2041	1967	7.6	300	93	
S35SHA	2049	1585	6.3	290	58	78
	2057	1587	6.3	290	58	
	2036	2004	7.9	300	97	
	2031	2029	7.9	300	100	
S55SHA	2103	2019	6.4	300	92	93
	2085	1974	6.4	300	90	
	2110	2039	6.3	300	93	
	2100	2044	6.3	300	95	
S35SLA	2085	2054	7.4	300	97	95
	2120	2060	7.4	300	94	
	2100	2030	7.2	300	93	
	2082	2030	7.2	300	95	
S55SLA	2066	1657	6.7	300	64	69
	2067	1789	6.7	300	75	
	2121	1764	6.0	300	69	
MS00S	2130	2076	10.0	300	95	94
	2099	2036	10.0	300	94	
	2161	2086	6.5	300	93	
	2191	2098	6.5	300	92	
MS35S	2145	2070	8.0	300	93	93
	2129	2058	8.0	300	93	
	2083	2029	10.0	300	95	
	2067	1959	10.0	300	90	

Table 12 cont.) Results of freeze-thaw durability testing for concrete mixes evaluated during Part I of the project.

Concrete Mix	Initial Fundamental Transverse Frequency	Final Fundamental Transverse Frequency	Air Content (percent)	Number of Freeze-Thaw Cycles	Durability Factor	Average Durability Factor
MS55S	2100	1940	9.5	300	85	86
	2113	1950	9.5	300	85	
	2080	1934	8.5	300	86	
	2065	1947	8.5	300	89	
OS	1942	1504		251	50	32
	2009	1556		167	33	
	2072	1605		57	11	
	2012	1558		167	33	
OK	1841	1437	3.8	258	52	57
	1856	1565	4.5	258	61	
OHPC2	2078	1610	11.5	127	25	21
	2058	1505	12.0	151	27	
	2109	1634	2.5	77	15	
	2099	1626	3.6	78	16	
OHPC4	1953	1760		300	81	84
	1933	1807		300	87	
OMS	1955	1514	8.0	290	58	57
	1980	1534	6.4	200	40	
	1887	1563	7.8	300	69	
	2026	1570	6.7	300	60	

If the number of freeze thaw cycles reported in Table 12 is less than 300, it indicates that the relative dynamic modulus of elasticity for the specimen decreased to less than 60 percent before the specimen had been subjected to 300 cycles of freezing and thawing. According to ASTM 666, this constitutes the end of the test.

The high rate of temperature change and the fact that the concrete specimen is kept saturated during the test when method A of ASTM 666 is used results in a test that is considered to be particularly severe. Under field conditions, the concrete is rarely kept saturated at all times, and the rate of change in temperature in the field is usually much slower than that used in the lab procedure. Neville (1996) offered the following guidance for the interpretation of durability factors obtained from tests performed according to method A of ASTM 666. A durability factor less than 40 is probably unsatisfactory with respect to frost resistance; 40 to 60 is the range for concretes with doubtful performance; and above 60, the concrete is probably satisfactory. Other interpretations include: durability factors above 80 indicate very high freeze-thaw damage resistance and durability factors between 60 and 80 indicate that the concrete will likely give satisfactory field performance.

The average durability factors for the lab-prepared concrete mixes are presented in Figure 25. Of the 18 lab-prepared concrete mixes, all but five of the mixes had average durability factors that were above 80 indicating very high resistance to damage caused by freezing and thawing cycles. Of the remaining five concrete mixes, one had a durability factor of 78, which is at the high end of the range of 60 to 80, and probably indicates that the field performance of that concrete mix will be satisfactory. Of the remaining four mixes, two had durability factors less than 60 putting them in the category of doubtful resistance to damage caused by freezing and thawing cycles. As will be discussed later, these performance deficiencies are attributed to insufficient entrained air rather than to the composition of the concrete mixes.

For the concrete mixes in the SnnS series, all of the mixes except the S55S mix had durability factors that were clearly above 80. The low durability factor for the S55S mix is not believed to be the result of replacing 55 percent of the portland cement with ground granulated blast furnace slag. For the SnnS series of concrete mixes, as the amount of GGBFS is increased, the slump of the concrete decreased and the amount of air-entraining admixture required to produce the desired air content increased. Both of these are typical for grade 120 GGBFS. The dosage of the air-entraining agent used in mixes S00S through S55S increased progressively. The desired amount of entrained air could not be produced in the S70S mix using the same admixture, so a different air-entraining admixture was used in S70S. The slumps for the S55S mix were in the 2.5 to 5.1 cm (1 to 2 inch) range. As slump values get lower, the amount of entrapped air generally increases. As a result, as slump decreases and the amount of entrapped air increases, there is less entrained air for a given total air content. For the low slump of the S55S concrete mix, the total air contents of 5.5 and 6.0 percent for the freeze-thaw specimens may not have provided adequate protection from freeze-thaw related damage. If this is accepted as the reason for the relatively poor and inconsistent behavior of the S55S mix, then the amount of GGBFS present in the concrete mix

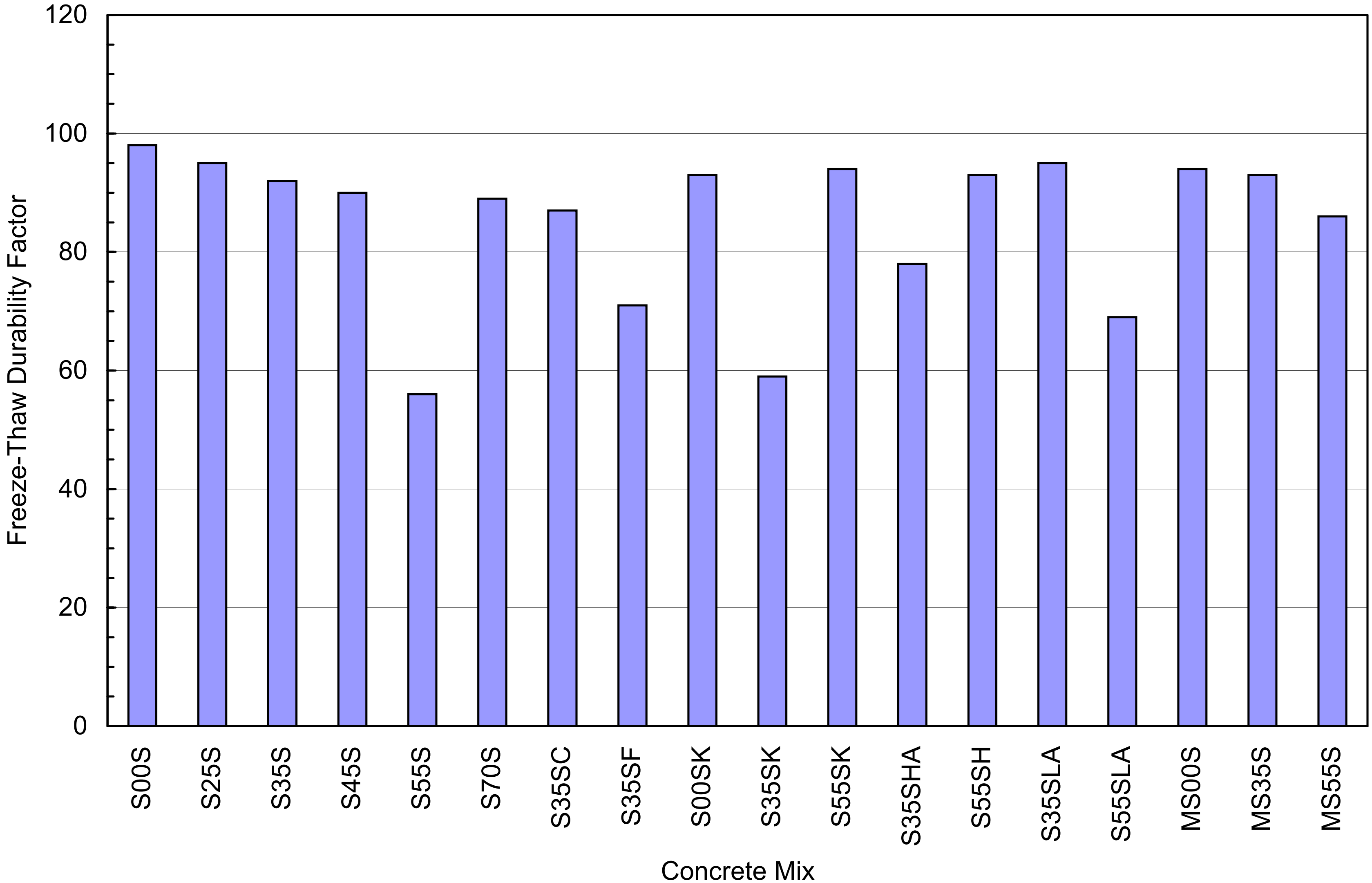

Figure 25) Average freeze-thaw durability factors for the lab-prepared concrete mixes evaluated during Part I of the project.

appears to have only a very slight influence on freeze-thaw durability factor of the concrete. Furthermore, if adequate levels of entrained air are present, GGBFS replacement rates of up to 70 percent appear to result in concretes that are very resistant to damage due to freezing and thawing cycles.

The relatively low durability factors of the S35SK mix is also attributed to insufficient entrained air. For these specimens the total air content was 5.5%. The other two mixes involving Type K cement had higher air contents, and both the S00SK and S55SK mixes had durability factors in excess of 90. Based on the similarity between the average durability factors for the S00SK mix and the S55SK mix, the amount of GGBFS used in conjunction with the Type K cement appears to have no significant influence on freeze-thaw durability of the concrete.

All three of the concrete mixes in the MSnnS series have average freeze-thaw durability factors that are well within the range of 80 to 100 for concretes that are very resistant to damage caused by freeze-thaw cycles. The durability factor does appear to decrease slightly as the amount of GGBFS increases, but the effect is very small and all three of the mixes are considered to be very resistant to damage caused be freeze-thaw cycles.

The average durability factors for the concretes obtained from ODOT construction projects are presented in Figure 26 along with data for the corresponding lab-prepared concrete mixes where appropriate. The durability factors for concrete obtained from the ODOT projects is surprisingly low. For the OK mix and for two specimens of the OHPC2 mix, the air contents were undesirably low and probably contributed to the poor performance of those specimens. Two of the OHPC2 specimens had air contents of 11.5 and 12 percent, and the durability factors for these specimens were 25 and 27, respectively. The air contents of the other mixes are within an acceptable range. Therefore, it is unlikely that the poor performance of these concrete mixes is the result of insufficient entrained air. The quality of the coarse aggregate is known to be a significant factor in the freeze-thaw durability of concrete and may have contributed to the poor performance of the concrete mixes obtained from ODOT projects.

Testing of the specimens obtained from ODOT projects was conducted in parallel with the testing of lab-prepared concrete specimens. The same personnel performed the tests on both groups of specimens, and the same equipment was used. Therefore, it is unlikely that variations in equipment performance or testing technique are significant factors contributing to the lower than expected durability factors.

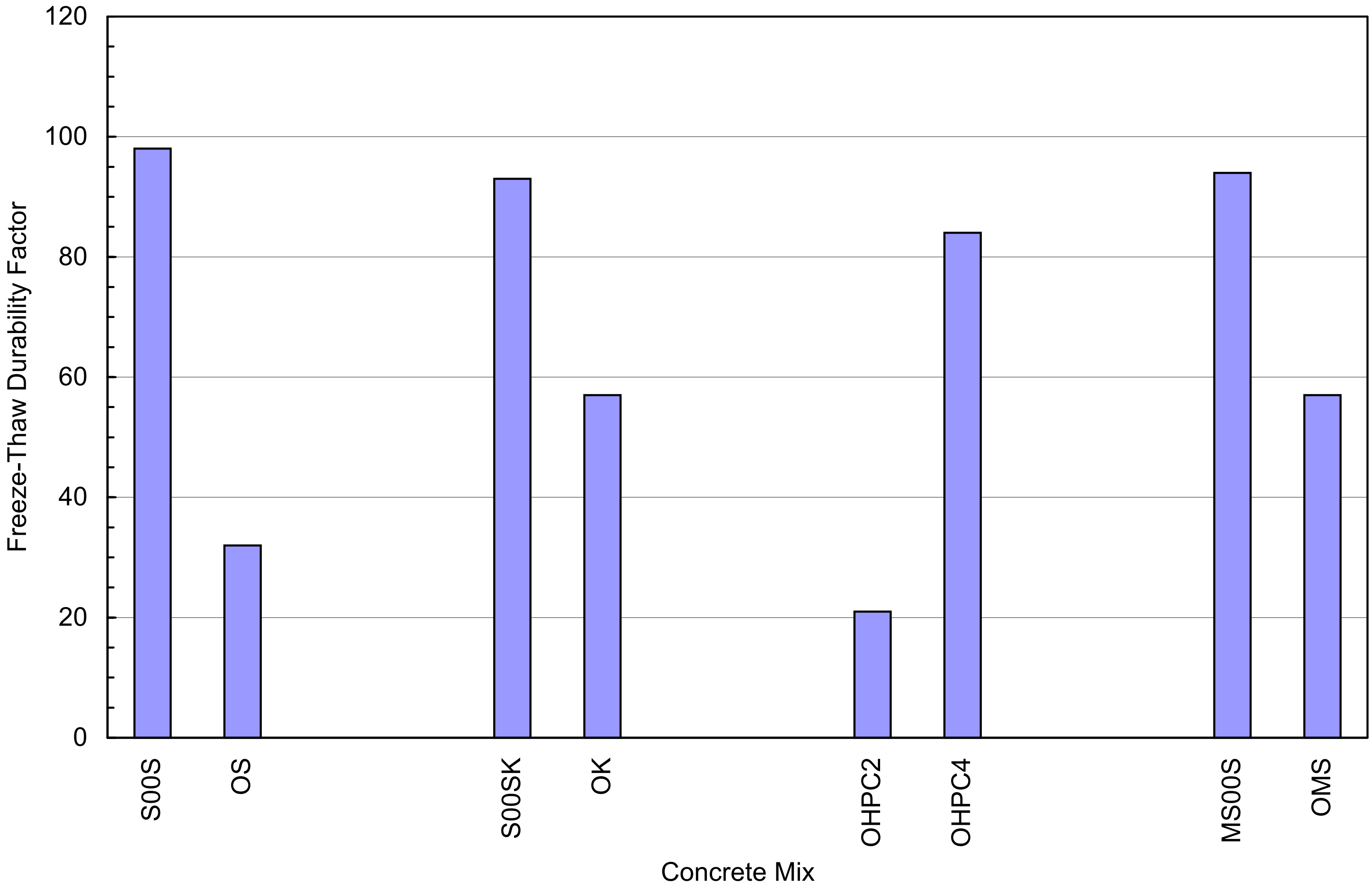

Figure 26) Average freeze-thaw durability factors for concrete mixes from ODOT construction projects and for selected lab-prepared concrete mixes evaluated during Part I of the project.

RECOMMENDATIONS FOR USE AND SPECIFICATION OF GGBFS

Based on the results from testing performed during Part I of the study, quality ODOT Class S concrete can be produced using GGBFS as a partial replacement for portland cement at replacements rates as high as 55 percent. The resulting concrete exhibited good strength and durability characteristics provided that the concrete was properly air-entrained to insure resistance to damage caused by freeze-thaw cycles. Replacement rates greater than 55 percent are not recommended for normal applications. There may be special cases where replacement rates greater than 55 percent are appropriate.

The specification, testing, and evaluation of concretes containing GGBFS can be done using the same methods commonly used for normal portland cement concrete. In some cases, such as the determination of chloride content in concrete, minor modification of the standard test procedure is necessary.

ASTM specifications are available for GGBFS (ASTM C989-99 Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars) and for GGBFS-portland blended cements (ASTM C595-02 Standard Specification for Blended Hydraulic Cements).

ECONOMIC CONSIDERATIONS

Based on telephone interviews with several major producers of ready-mix concrete in the state of Ohio, there is only a very minor cost difference between concrete produced with portland cement and a comparable concrete mix design involving a blend of portland cement and GGBFS. In terms of the material costs, GGBFS is generally priced slightly below the price of Type I portland cement.

A significant portion of the cost per cubic yard of concrete delivered to the project site is in the cost of production (storage, batching, mixing, plant overhead) and the cost of transportation of the concrete to the project site (personnel and equipment). As a result, the small price difference between portland cement and GGBFS generally results in either a slight decrease in cost per cubic yard of concrete or no significant difference in the cost. Factors such as additional equipment for storage and handling may impact cost on a supplier-by-supplier basis. Some producers have reduced or eliminated the use of fly ash in their concrete production in order to free up equipment for handling GGBFS.

PART II – INFLUENCE OF COARSE AGGREGATE SIZE ON THE STRENGTH AND DURABILITY OF CONCRETE

RESEARCH PROGRAM

Part II of the project is primarily an experimental investigation of the strength and durability of several concrete mixes containing various concrete making materials in various proportions. The interest is mainly in identifying concrete mix proportions that can lead to the economic production of highly durable concrete having the required strength and workability characteristics. Each of the concrete mix types were subjected to a series of laboratory tests to determine their strength, durability, and workability characteristics. The mixes have been divided into three groups based on the composition of the concrete.

For each of the concrete mixes, the number of specimens needed for testing required about 14 to 16 cubic feet of concrete per mix type. The maximum batch size of the mixing equipment available at the University of Akron is about 6 cubic feet. Based on this and the desirability of preparing a particular mix design on different days to include normal variations in materials, laboratory conditions, and workmanship, each mix design was prepared on a minimum of three separate days. Typically, several different mixes were prepared on a particular day. The frequency of mixing was controlled by the time required to clean the molds between uses and the need to control the production rate so that the testing capacity will not be exceeded at some future date.

The concrete mixes were prepared in the laboratory, and the specimens were subjected to the test program outlined in Table 13.

Table 13) Testing program for the concrete mixes evaluated during Part II of the study.

Test	ASTM Test Procedure Reference	AASHTO Test Procedure Reference	Number of Specimens per Batch	Minimum Number of Batch Mixes Sampled for this Test	Minimum Number of Specimens Tested per Concrete Mix
Comp. Strength, 7-day	C 39	T 22	3	3	9
Comp. Strength, 28-day	C 39	T 22	3	3	9
Comp. Strength, 90-day	C 39	T 22	3	3	9
Flexural Strength, 7-day	C 78	T 97	1	3	3
Flexural Strength, 28-day	C 78	T 97	1	3	3
Rapid Cl Perm., 28-day	C 1202	T 277	2	3	6
Rapid Cl Perm., 90-day	C 1202	T 277	2	3	6
Ponding Cl Permeability	- -	T 259	4	1	4
Freeze-Thaw Resistance	C 666	T 161	1	3	3
Length Change	C 157	T 160	1	3	3
Air Void System Analysis	C 457	- -	1	3	3

The test program includes two major areas of complimentary assessments. For the evaluation of resistance to chloride ion penetration, the rapid permeability test and the 90-day ponding chloride penetration test were used. To assess resistance to damage caused by freeze-thaw cycles for each concrete, tests included freeze-thaw durability testing (ASTM 666), total air content, and characterization of the air void system using microscopic examination techniques.

Use of the 90-day ponding test to assess the resistance to chloride ion penetration is believed to be a more reliable and more quantitative approach than the rapid chloride permeability test. However, the 90-day ponding test requires considerably more time and effort than the rapid chloride permeability test, and for that reason is less popular for routine implementation. The information from this research program allows an assessment of whether or not it is appropriate to use the rapid chloride permeability test to compare the performance of concretes involving the range of materials used in the proposed study. It will also provide information on the relative influence of various concrete-making materials on the results of the rapid chloride permeability test.

As part of the rapid chloride permeability testing grogram, the mixes involving large coarse aggregate require specimens larger than the normal specimen size for this test. To allow comparisons between the results from tests using larger-than-normal specimens and those from tests involving the standard specimen size, tests were performed using standard sized cores from mini-slabs cast in the lab. These tests are in addition to the testing for all of the large coarse aggregate mixes that were done using larger-than-normal specimens. This was done for a representative group of the mixes involving the larger-than-normal coarse aggregate. Six mixes were selected for this testing. For each of the selected mix designs, six specimens were tested at 28 days of age and six specimens were tested at 90 days of age.

MATERIALS

The materials used to produce the concrete mixes for Part II of the study are the same as those normally used in the commercial production of ready-mix concrete. The manufacturer, and the brand name if applicable, for each of the component materials is given below. The mix designations that contained a particular component are also included.

Portland Cement The portland cement used for the concrete mixes in Part II of the study was all obtained from Holnam, Inc. in one shipment.

GGBFS The ground granulated blast furnace slag (GGBFS) used in Part II of the study meets the requirements for Grade 120 GGBFS prescribed by ASTM C 989. The GGBFS was provided by Holnam, Inc. from its plant in Weirton, WV. Typical values for the specific gravity and Blaine fineness of the Grade 120 GGBFS produced by Holnam, Inc. are 2.89 and 450 to 650 m^2/kg, respectively.

Silica Fume Silica fume meeting the requirements of AASHTO M 309-90 was used in the concrete mixes HP3 and HP4 and in the mixes in the SF group. The silica fume used in the study was MB-SF marketed by Master Builders, Inc., Cleveland, Ohio. The specific gravity of the silica fume used in proportioning the concrete mixes was 2.2.

Fly Ash Class C fly ash was used in the C series of concrete mixes under ODOT mix potion 1 (mixes C31, C41, C51) and in the high performance mixes HP1 and HP3. A specific gravity value of 2.5 for the fly ash was used in proportioning the concrete mixes.

Coarse Aggregate Four different sizes of crushed limestone coarse aggregate were used in Part II of the study. All of the coarse aggregate was obtained from National Lime and Stone from its Carey, OH quarry. The four aggregate gradations used were 357, 467, 57, and 8. The size of coarse aggregate used in each mix is reported in the section on mix proportions. The specific gravity and absorption values are presented in Table 14.

Fine Aggregate Natural concrete sand from Allied Corporation's Plant #3 was used for all of the concrete mixes in Part II of the study. The sand meets the gradation requirements of ASTM C 33 and section 703.02 of the ODOT specifications. The fineness modulus for the sand is 2.95, and the specific gravity and absorption values are reported in Table 14.

Water Water for the concrete mixes was taken from the municipal water system of Akron, Ohio.

Air Entraining Admixtures Micro-Air, produced by Master Builders, Cleveland, Ohio, was used in all of the concrete mixes in Part II of the study.

Water Reducing Admixture RheoBuild 2000, a high-range water reducing admixture produced by Master Builders, Inc., Cleveland, Ohio, was used in all of the concrete mixes in the MS group.

Table 14) Specific gravity and absorption values for the aggregates used in Part II of the study.

Aggregate Gradation	Source	Specific Gravity SSD	Absorption (percent)
#357	National Lime and Stone	2.65	1.42
#467	National Lime and Stone	2.65	1.48
#57	National Lime and Stone	2.65	1.54
#8	National Lime and Stone	2.69	1.80
Fine Aggregate	Allied Group, Plant #3	2.55	2.15

MIX PROPORTIONS

Part II of the project involved evaluating twenty-four different concrete mix designs. Of these, extensive testing was performed on nineteen of the mixes. The five mixes that were not extensively tested were among the seven modified mixes presented in the proposal for the project. Of these seven modified mixes, five were found to produce concrete that lacked cohesion and was too harsh for field implementation. For these five mixes, several trial batches were prepared using different admixture dosages and fine aggregate to coarse aggregate ratios in an attempt to arrive at a suitable mix design with the intended amount of cementitious material. None of these attempts produced concrete with suitable workability characteristics. As a result, the proposed modified forms of the ODOT High Performance Concretes (HP1-R, HP2-R, HP3-R, and HP4-R) and concrete mix SF630 were eliminated from further evaluation. The primary objective of these mixes was to evaluate mixes similar to the ODOT High Performance Concrete mixes and the ODOT Micro-Silica Concrete mix but with about 15% less cementitious material. These modified mix designs proved to be unworkable. The nineteen mix designs that were involved in the complete testing program of Phase II of the project can be divided into three broad groups as follows: 1) the "C" group consists of twelve mixes having batch proportions based on ODOT Class C concrete, 2) the "HP" group consists of four ODOT High Performance Concrete mixes, and 3) the "SF" group consists of three concrete mixes containing portland cement and silica fume. Each of these primary groups is described further in the following sections, and details of the mix proportions for the mixes prepared in the laboratory are presented in Table 15.

"C" Group All of the concretes in this group are proportioned according to the requirements for standard ODOT Class C concrete or one of the three associated mix options. A water:cement ratio of 0.48 is used for all of the mixes in this group. The target values for air content and slump are 6±2 percent and 2.5±2.5 centimeters (1±1 inches), respectively. The control mix of this group is the C50 mix which is proportioned according to the standard ODOT Class C mix design using #57 coarse aggregate. The other mixes involve two larger sizes of coarse aggregate and the different mix design options for Class C concrete. Within the C group, the mix naming convention is Cnm where n indicates the coarse aggregate size, and m indicates the mix option. For the coarse aggregate sizes, 3 indicates #357 coarse aggregate, 4 indicates #467 coarse aggregate, and 5 indicates #57 coarse aggregate. For the mix options, 0 indicates the standard Class C mix proportions, and 1, 2, and 3 indicate the mix proportions of mix options 1, 2, and 3, respectively. The C group can be subdivided according to the coarse aggregate gradation used as follows:

> C3 series The C3 series consists of four concrete mixes using #357 coarse aggregate and proportioned according to the requirements for ODOT Class C concrete and the corresponding three mix design options. The concrete mixes in this series are C30, C31, C32, and C33.

Table 15) Concrete mix proportions for the mixes tested during Part II of the study.

Concrete Mix	Total Cementitious kg/m^3 (lb/yd^3)	Portland Cement kg/m^3 (lb/yd^3)	GGBFS kg/m^3 (lb/yd^3)	Silica Fume kg/m^3 (lb/yd^3)	Fly Ash kg/m^3 (lb/yd^3)	w/c	Coarse Aggregate Gradation
C30	356.0 (600.0)	356.0 (600.0)				0.48	357
C31	356.0 (600.0)	302.6 (510.0)			53.4 (90.0)	0.48	357
C32	326.3 (550.0)	326.3 (550.0)				0.48	357
C33	356.0 (600.0)	302.6 (510.0)	53.4 (90.0)			0.48	357
C40	356.0 (600.0)	356.0 (600.0)				0.48	467
C41	356.0 (600.0)	302.6 (510.0)			53.4 (90.0)	0.48	467
C42	326.3 (550.0)	326.3 (550.0)				0.48	467
C43	356.0 (600.0)	302.6 (510.0)	53.4 (90.0)			0.48	467
C50	356.0 (600.0)	356.0 (600.0)				0.48	57
C51	356.0 (600.0)	302.6 (510.0)			53.4 (90.0)	0.48	57
C52	326.3 (550.0)	326.3 (550.0)				0.48	57
C53	356.0 (600.0)	302.6 (510.0)	53.4 (90.0)			0.48	57
HP1	415.3 (700.0)	314.4 (530.0)			100.9 (170.0)	0.38	8
HP2	415.3 (700.0)	290.7 (490.0)	124.6 (210.0)			0.38	8
HP3	391.6 (660.0)	284.8 (480.0)		17.8 (30.0)	89.0 (150.0)	0.40	8
HP4	415.3 (700.0)	284.8 (480.0)	112.7 (190.0)	17.8 (30.0)		0.40	8
SF630	373.8 (630.0)	356.0 (600.0)		17.8 (30.0)		0.32	8
SF735	436.1 (735.0)	415.3 (700.0)		20.8 (35.0)		0.32	8
SF752	446.4 (752.5)	415.3 (700.0)		31.1 (52.5)		0.32	8
SF770	456.8 (770.0)	415.3 (700.0)		41.5 (70.0)		0.32	8

w/c = (water):(total cementitious) ratio

C4 series The C4 series consists of four concrete mixes using #467 coarse aggregate and proportioned according to the requirements for ODOT Class C concrete and the corresponding three mix design options. The concrete mixes in this series are C40, C41, C42, and C43.

C5 series The C5 series consists of four concrete mixes using #57 coarse aggregate and proportioned according to the requirements for ODOT Class C concrete and the corresponding three mix design options. The concrete mixes in this series are C50, C51, C52, and C53.

"HP" Group This group consists of four concrete mixes proportioned according to the requirements for ODOT High Performance Concrete. The coarse aggregate for these mixes is #8 crushed limestone.

"SF" Group Originally there were four concrete mixes in this group. The SF630 concrete mix was eliminated from further evaluation after trial batches indicated that the mix design did not produce workable concrete. The remaining three mixes each contain portland cement at 415.3 kg/m^3 (700 lb/yd^3) and various amounts of silica fume. The silica fume loadings are 20.8, 31.1, and 41.5 kg/m^3 (35, 52.5, and 70 lb/yd^3) for concrete mixes SF735, SF752, and SF770, respectively.

TEST METHODS

The test methods for compression strength, flexural strength, rapid chloride permeability, freeze-thaw resistance, and length change used for Part II of the project are essentially the same as those used for Part I of the project. The only significant differences are in the number of specimens tested per concrete mix for the various tests and in some cases, the size of the specimens used. For Part II of the testing program, the information regarding the number of specimens was presented in Table 13. The information relative to specimen size is presented along with the test results. The two test procedures used during Part II of the testing program, that were not used during Part I of the testing program, are the 90-day chloride ponding test and the air void system analysis. These two procedures are presented below.

For the 90-day chloride ponding test, one set of specimens consists of four 305x305x152 mm (12x12x6 inch) concrete blocks. Three of the blocks are ponded with the chloride solution, and the fourth block is not exposed to the chloride solution and serves as the reference specimen. For six of the concrete mixes in Part II of the study, three sets of specimens were evaluated. Each specimen set came from a separate batch of concrete. For the remaining concrete mixes, one set of specimens was used

The specimens were cast and moist-cured for 14 days. The slabs were then removed from the moist curing room to a drying room meeting the requirements of AASHTO T 160 Length Change of Mortar, and Concrete. At 29 days of age, the top 3.2 mm (0.125 inch) of each slab was removed by grinding. Solution dams were applied and the specimens were returned to the drying room. At 42 days of age, a 3% sodium chloride solution was applied to the top of each ponding specimen to a depth of about 13 mm (0.5 inch). The control samples were kept on a shelf above the ponded samples to prevent accidental chloride contamination.

After 90 days of ponding, samples were taken from the slabs at depth intervals of 1.6 to 12.7 mm (0.0625 to 0.5 inch) and 12.7 to 25.4 mm (0.5 to 1.0 inch). A Gilson HM-343 Sample Drilling Assembly was used to collect pulverized samples at these depths. The drilling device has a vertically mounted hammer drill with a 51 mm (2 inch) diameter core bit. As the powder is transported upward by the outer helical threads of the drill bit, a small vacuum hose attached to a filter bag collects the sample. The drill bit was cleaned with methanol between each sampling.

The samples were labeled according to their mix types and placed in plastic bags. The collected powder was further ground using a mortar and pestle until the entire sample passed a No. 50 sieve.

Total chloride ion content may be determined by one of several different methods prescribed by AASHTO T 260. The method utilized in this study was Procedure A, Total Ion and Water-Soluble Ion by Potentiometric Titration or Ion Selective Electrode.

A 10.0-gram sample of pulverized powder was weighed and placed into a 100 ml beaker. Hot distilled water (25 ml) was added to the powder, followed by several drops of nitric acid. Three milliliters of hydrogen peroxide were added to any samples from mixes containing GGBFS. (ASTM C 114, Standard Test Methods for Chemical Analysis of Hydraulic Cement, states that the hydrogen peroxide addition is necessary to oxidize any sulphide sulfur, which may interfere with chloride determination.) The mixture was stirred to break up any dry lumps of powder. A pH-measuring electrode was placed into the liquid, and nitric acid was added drop wise until a pH value between 3.2 and 4.5 was achieved. The beaker was then covered with a watch glass, placed on an electric hot plate, and boiled for one minute. The mixture was then filtered into a 250 ml beaker through double filter paper (No. 41 over No. 40). The filter paper was rinsed with hot distilled water until a total volume of 125 to 150 ml was collected. The liquid was then covered and allowed to cool to room temperature.

Once the solution was cooled to room temperature, 4 ml of 0.01N NaCl was added to adjust the ionic strength. Thus, an adequate chloride concentration was induced so that an incrementally defined titration curve could be achieved. The solution was then titrated with 0.01 Ag NO_3 to the first endpoint utilizing a Mettler Toledo DL25 titrator with a chloride ion selective electrode.

The chloride electrode consisted of a sensing element bonded into an epoxy body. When the sensing element is in contact with a solution containing chloride ions, an electrode potential develops across the sensing element. This potential, which depends on the level of free chloride ions in solution, is measured against a constant reference potential, and corresponds to the level of chloride ions in solution. The response of the electrode varies with respect to the logarithm of the activity of the chloride ions. The Nernst equation is a mathematical description of the electrode behavior:

$$E = E_0 + 2.3\frac{RT}{nF}\log A$$

where: E_0 = electrode reference potential,
R = gas constant (8.314J/deg/mol.),
T = temperature in Kelvin,
n = charge of the ion including sign,
F = Faraday constant (96,500 coulombs), and
A = activity of the ionic species being measured.

The endpoint of the titration corresponds to the inflection point of the titration curve. The volume of titrant (silver nitrate) required to reach the endpoint is then used to calculate the quantity of chloride in solution using the following equation:

$$\%Cl^- = \frac{3.5453\left[V \cdot N_{AgNO_3} - 4ml \cdot N_{NaCl}\right]}{10g}$$

where: 3.5453 = atomic weight of chloride,

V = volume of silver nitrate corresponding to the endpoint of the titration,
N_{AgNO3} = normality of the silver nitrate, and
N_{NaCl} = normality of the sodium chloride.

The percent chloride was then multiplied by the unit weight of the mix to determine the amount of chloride present per cubic yard of concrete. Baseline values were determined by taking the average chloride content between the top and bottom samples from the control specimens. All of the ponded sample chloride contents were then corrected by subtracting the baseline chloride content value. If the subtraction of the baseline chloride content resulted in a negative value, the chloride content was reported as zero.

The air void analyses were performed on specimens that were cut from 152x305 mm (6x12 inch) concrete specimens using a diamond saw. Each specimen was then polished and evaluated in accordance with ASTM C 457. The modified point-count method (procedure B) of ASTM C457 was used.

PROPERTIES OF THE PLASTIC CONCRETE

After each batch of concrete was discharged from the mixer into the pan, it was remixed with shovels to eliminate any segregation that may have taken place as the concrete was discharged from the mixer. Upon completion of the remixing operation, tests were performed to determine the air content, slump, unit weight and temperature of the concrete. For the concrete mixes in the "C" group, the primary concern at this stage was to insure that the air content was within the desired range. For the "C" group of mixes, the water:cement ratio of 0.48 was selected early in the project based on trial batches. Since the primary objective of the testing of this group of mixes was to determine the influence of the different coarse aggregate sizes and the different mix options on the properties of the concrete, it was undesirable to use water-reducing admixtures in some of the mixes and not in others. For these mixes, the slump values were recorded for completeness of the documentation and they were not used as an acceptance criterion for a particular mix. The dosage of the air-entraining admixture required to produce the desired air content for each mix was determined through a trial-and-error process.

For the mixes in the "SF" and "HP" groups, a water-reducing admixture was used to produce a workable concrete mix. In these mixes, both the slump and the air content values were used as acceptance criteria for each batch of concrete. The required dosages for the air-entraining admixture and the water reducer were determined for each concrete mix design through a trial-and-error process. If either the slump or the air content for a particular batch of concrete was not within the desired range, the batch of concrete was discarded without making any specimens for testing.

The results of the tests performed on the fresh concrete are presented in Table 16. Even though batch weights and material uniformity is carefully controlled in the laboratory environment, several batches of concrete were discarded throughout the project because the air content was not within the expected range. As indicated by the data in Table 16, the air content values do vary within the acceptable range. The unit weight values are relatively consistent and in reasonable agreement with the calculated values. The agreement between the calculated unit weight and the measured unit weight is simply the result of accurately knowing the mix proportions, the air content, and the specific gravity values of the individual materials in the concrete mix.

Table 16) Summary of test results for tests performed on the fresh concrete mixes prepared during Part II of the project.

Concrete Mix	Mix Date	Slump cm (inch)	Air Content (percent)	Density Mg/m^3	Unit Weight (pcf)	Temperature °C (°F)	Batch Ref. No.
C30	08/05/97	11.5 (4 1/2)	6.6	2.29	143	26.0 (79)	001
	08/07/97	9.5 (3 3/4)	6.6	2.29	143	23.0 (73)	002
	08/19/97	13.5 (5 1/4)	7.0	2.25	141	24.5 (76)	003
	04/29/98	9.5 (3 3/4)	5.4	2.34	146	22.0 (72)	004
	09/25/98	8.5 (3 1/4)	7.0	2.28	142	28.0 (82)	005
	10/02/98	5.0 (2)	6.5	2.32	145	24.0 (75)	006
C31	08/05/97	16.5 (6 1/2)	6.0	2.30	143	26.5 (80)	007
	08/14/97	16.5 (6 1/2)	7.4	2.25	140	25.5 (78)	008
	08/21/97	18.5 (7 1/4)	6.2	2.29	143	24.5 (76)	009
	03/04/98	19.0 (7 1/2)	5.5	2.32	145	20.0 (68)	010
	05/06/98	11.5 (4 1/2)	4.5	2.37	148	24.5 (76)	011
	09/25/98	17.0 (6 3/4)	7.2	2.26	141	26.0 (79)	012
	10/02/98	9.5 (3 3/4)	6.6	2.28	143	23.5 (74)	013
C32	08/07/97	4.5 (1 3/4)	6.6	2.30	144	22.0 (72)	014
	08/21/97	7.0 (2 3/4)	8.0	2.24	140	24.0 (75)	015
	09/03/97	4.0 (1 1/2)	6.4	2.31	144	24.0 (75)	016
	05/06/98	4.5 (1 3/4)	7.2	2.30	143	23.0 (73)	017
	09/25/98	5.0 (2)	7.2	2.30	144	27.0 (81)	018
	10/02/98	2.5 (1)	7.6	2.28	142	23.5 (74)	019
C33	02/25/98	12.5 (5)	7.5	2.22	139	22.0 (72)	020
	03/04/98	8.5 (3 1/4)	7.5	2.28	142	20.0 (68)	021
	09/18/98	8.5 (3 1/4)	6.8	2.27	142	25.0 (77)	022
	10/02/98	8.5 (3 1/4)	7.0	2.29	143	23.5 (74)	023
	06/07/99	9.0 (3 1/2)	6.4	2.27	142	23.5 (75)	024
C40	07/17/97	11.5 (4 1/2)	6.8	2.28	143	25.5 (78)	025
	08/12/97	7.0 (2 3/4)	5.6	2.32	145	22.0 (72)	026
	08/26/97	16.0 (6 1/4)	8.5	2.22	138	24.0 (75)	027
	09/16/97	4.5 (1 3/4)	5.8	2.34	146	24.5 (76)	028
	02/09/98	10.0 (4)	6.3	2.30	144	21.0 (70)	029
	02/11/98	12.5 (5)	7.0	2.28	143	20.0 (68)	030
	02/18/98	10.0 (4)	5.8	2.31	144	22.0 (72)	031
	04/29/98	9.5 (3 3/4)	6.0	2.34	146	24.5 (76)	032
	09/18/98	3.0 (1 1/4)	6.4	2.30	144	24.5 (76)	033
	12/04/98	4.5 (1 3/4)	6.0	2.32	145	26.0 (79)	034

Table 16 cont.) Summary of test results for tests performed on the fresh concrete mixes prepared during Part II of the project.

Concrete Mix	Mix Date	Slump cm (inch)	Air Content (percent)	Density Mg/m^3	Unit Weight (pcf)	Temperature °C (°F)	Batch Ref. No.
C41	07/24/97	18.0 (7)	7.6	2.25	140	24.5 (76)	035
	08/12/97	8.5 (3 ¼)	5.6	2.32	145	23.5 (74)	036
	09/03/97	17.0 (6 ¾)	7.4	2.25	141		037
	02/04/98	12.5 (5)	5.9	2.34	146	19.0 (66)	038
	02/09/98	11.5 (4 ½)	5.4	2.33	145	18.5 (65)	039
	02/11/98	12.5 (5)	5.5	2.33	146	22.0 (72)	040
	04/29/98	15.0 (6)	5.5	2.35	147	20.5 (69)	041
	09/18/98	6.5 (2 ½)	5.5	2.33	146	24.5 (76)	042
	12/04/98	9.0 (3 ½)	6.8	2.29	143	26.0 (79)	043
C42	07/31/97	4.5 (1 ¾)	7.0	2.29	143	23.5 (74)	044
	08/14/97	2.5 (1)	5.8	2.32	145	23.5 (74)	045
	08/26/97	8.5 (3 ¼)	8.5	2.21	138		046
	09/09/97	5.0 (2)	5.5	2.32	145	23.9 (75)	046a
	02/04/98	10.0 (4)	7.0	2.31	144	19.0 (66)	047
	02/09/98	4.5 (1 ¾)	6.8	2.32	145	19.5 (67)	048
	04/29/98	4.0 (1 ½)	6.0	2.33	146	22.0 (72)	049
	05/06/98	5.5 (2 ¼)	7.0	2.30	144	21.0 (70)	050
	12/04/98	1.5 (1/2)	6.2	2.33	146	26.5 (80)	051
C43	07/31/97	12.5 (5)	8.0	2.23	139	24.5 (76)	052
	02/04/98	9.5 (3 ¾)	6.5	2.29	143	20.5 (69)	053
	02/09/98	7.0 (2 ¾)	6.8	2.31	144	20.0 (68)	054
	02/18/98	12.5 (5)	8.5	2.21	138	21.0 (70)	055
	02/25/98	12.5 (5)	8.5	2.23	139	21.0 (70)	056
	04/29/98	6.5 (2 ½)	5.7	2.34	146	23.0 (73)	057
	05/06/98	11.0 (4 ¼)	7.4	2.25	140	23.5 (74)	058
C50	07/10/97	7.0 (2 ¾)	6.6	2.30	143	23.5 (74)	059
	07/17/97	7.0 (2 ¾)	6.0	2.30	144	24.5 (76)	060
	07/22/97	7.0 (2 ¾)	6.6	2.29	143	24.5 (76)	061
	09/23/97	6.5 (2 ½)	5.5	2.33	145		062
	09/30/97	5.0 (2)	6.0	2.31	144	24.0 (75)	063
	10/14/97	7.0 (2 ¾)	6.6	2.30	143		064
	12/16/98	6.5 (2 ½)	7.2	2.29	143	21.0 (70)	065
	03/12/99	5.5 (2 ¼)	9.0	2.27	142	20.0 (68)	066
	04/22/99	8.5 (3 ¼)	6.8	2.29	143	22.5 (73)	067
	04/29/99	6.5 (2 ½)	6.4	2.27	141	22.0 (71)	068

Table 16 cont.) Summary of test results for tests performed on the fresh concrete mixes prepared during Part II of the project.

Concrete Mix	Mix Date	Slump cm (inch)	Air Content (percent)	Density Mg/m^3	Unit Weight (pcf)	Temperature °C (°F)	Batch Ref. No.
C51	07/02/97	14.0 (5 1/2)	5.0	2.32	145	24.5 (76)	069
	07/08/97	10.0 (4)	5.0	2.33	145	24.0 (75)	070
	07/10/97	12.5 (5)	6.2	2.28	143	25.5 (78)	071
	07/22/97	14.0 (5 1/2)	7.2	2.26	141	24.5 (76)	072
	07/24/97	15.0 (6)	6.8	2.27	142	24.5 (76)	073
	04/22/99	14.0 (5 1/2)	6.4	2.29	143	21.5 (71)	074
	04/29/99	12.0 (4 3/4)	6.8	2.27	142	20.5 (69)	075
	11/23/99	13.5 (5 1/4)	7.2	2.28	142	23.5 (74)	076
	12/22/99	9.0 (3 1/2)	6.8	2.30	144	20.0 (68)	077
	12/29/99	16.0 (6 1/4)	6.8	2.37	148	19.5 (67)	078
C52	07/02/97	3.0 (1 1/4)	6.4	2.33	146	24.0 (75)	079
	07/08/97	2.5 (1)	6.6	2.32	145	22.0 (72)	080
	07/15/97	3.0 (1 1/4)	6.4	2.31	144	24.5 (76)	081
	08/19/97	2.5 (1)	5.8	2.34	146		082
	12/16/98	3.0 (1 1/4)	8.3	2.26	141	21.5 (71)	083
	03/12/99	4.5 (1 3/4)	9.5	2.30	144	18.0 (64)	084
	04/29/99	4.5 (1 3/4)	6.2	2.31	144	20.5 (69)	085
	05/24/99	0.5 (1/4)	6.2	2.33	145	22.5 (72)	086
	06/01/99	2.0 (3/4)	6.2	2.32	145	25.5 (78)	087
	11/23/99	3.0 (1 1/4)	7.4	2.29	143	23.0 (73)	088
	12/22/99	3.0 (1 1/4)	6.0	2.32	145	19.0 (66)	089
	12/29/99	2.5 (1)	6.2	2.32	145	19.0 (66)	090
C53	07/02/97	6.5 (2 1/2)	6.5	2.30	143	24.0 (75)	091
	07/08/97	8.5 (3 1/4)	6.6	2.29	143	24.5 (76)	092
	07/15/97	6.5 (2 1/2)	6.4	2.29	143	24.5 (76)	093
	08/21/97	5.5 (2 1/4)	6.0	2.30	143	25.5 (78)	094
	09/23/97	9.0 (3 1/2)	6.0	2.30	143	27.0 (81)	095
	09/30/97	5.5 (2 1/4)	6.2	2.31	144	22.0 (72)	096
	10/14/97	6.5 (2 1/2)	7.0	2.29	143	22.0 (72)	097
	05/24/99	5.0 (2)	6.8	2.29	143	22.5 (73)	098
	06/01/99	5.5 (2 1/4)	6.8	2.30	143	25.0 (77)	099
	06/07/99	7.0 (2 3/4)	6.8	2.28	143	24.5 (76)	100
	12/29/99	9.0 (3 1/2)	8.0			18.0 (64)	101

Table 16 cont.) Summary of test results for tests performed on the fresh concrete mixes prepared during Part II of the project.

Concrete Mix	Mix Date	Slump cm (inch)	Air Content (percent)	Density Mg/m^3	Unit Weight (pcf)	Temperature °C (°F)	Batch Ref. No.
HP1	09/19/96	12.5 (5)	9.0	2.21	138	21.0 (70)	102
	09/26/96	12.0 (4 3/4)	6.5	2.31	144	20.0 (68)	103
	10/01/96	16.0 (6 1/4)	8.5	2.25	140		104
HP2	09/19/96	20.5 (8)	7.0			22.0 (72)	105
	09/26/96	16.5 (6 1/2)	6.0	2.32	145	20.0 (68)	106
	10/01/96	15.0 (6)	8.0	2.28	142	21.0 (70)	107
HP3	10/10/96	20.5 (8)	6.0	2.36	147	21.0 (70)	108
	10/15/96	17.0 (6 3/4)	7.0	2.31	144	21.0 (70)	109
	10/17/96	16.5 (6 1/2)	5.0	2.37	148	22.0 (72)	110
HP4	10/29/96	11.5 (4 1/2)	6.8	2.33	145	20.0 (68)	111
	10/31/96	13.5 (5 1/4)	7.0	2.34	146	20.5 (69)	112
	11/05/96	12.5 (5)	7.0	2.31	145	18.0 (64)	113
SF735	11/14/96	11.5 (4 1/2)	6.0	2.34	146	19.5 (67)	114
	11/19/96	11.5 (4 1/2)	6.5	2.30	144	23.0 (73)	115
	01/06/00	21.5 (8 1/2)	7.0	2.32	145	21.5 (71)	116
SF752	10/24/96	16.0 (6 1/4)	8.0	2.36	147	21.0 (70)	117
	10/29/96	19.0 (7 1/2)	7.0	2.34	146	20.0 (68)	118
	11/05/96	19.0 (7 1/2)	5.5	2.35	147	20.0 (68)	119
SF770	10/10/96	16.5 (6 1/2)	9.0	2.24	140	21.0 (70)	120
	10/15/96	13.5 (5 1/4)	8.0	2.27	142	21.5 (71)	121
	10/17/96	20.5 (8)	9.0	2.26	141	20.5 (69)	122
	11/05/96	15.0 (6)	7.0	2.31	144	20.5 (69)	123
	11/14/96	9.5 (3 3/4)	5.5	2.36	147	19.5 (67)	124

STRENGTH PROPERTIES

The presentation of the strength test results is divided into two sections as follows: 1) compressive strength, and 2) modulus of rupture. For both of the strength categories, a table containing the average strength for each concrete mix at each test age is presented. In each category, the summary table is followed by graphs illustrating the influence of specific mix proportion variables on the strength parameter under consideration. The average strength values contained in the summary tables are calculated from several individual test results. In general, the compressive strength average values are based on 9 or more individual test results per concrete mix design. The average modulus of rupture values are based on three or more individual test results per concrete mix design.

COMPRESSIVE STRENGTH

In most cases, compressive strength testing consisted of nine or more individual compression tests for each of the three test ages for each mix design evaluated during Part II of the study. There are a small number of exceptions caused by an insufficient number of specimens in some cases and by testing errors or omissions in other cases. The individual test results are presented in Table B-1 in Appendix B. That table also contains the average strength for each test age for each concrete mix design. The average strength values from Table B-1 are summarized in Table 17 and form the basis for the remainder of the discussion regarding the influence of the mix design variables on the compressive strength of the resulting concrete. Much of the information contained in Table 17 is presented graphically in a series of figures to facilitate comparisons within specific groups of the concrete mix designs.

The compressive strength data for the concrete mixes in the C group of mixes is presented in Figure 27. The data in this figure are presented in three major groups based on the specimen age when the compression testing was performed. Within each of these test age groups, there are four groups of three for the four mix variations, and for each mix option there are three bars corresponding to the three different coarse aggregate sizes used in the study.

For the concrete mixes containing the #57 coarse aggregate, mix option 1 (C51) which substitutes 53.4 kg/m^3 (90 lbs/yd^3) of fly ash for portland cement consistently has the lowest strength of the four mix options. On average, the compressive strength of the concrete mixes containing the #57 coarse aggregate tend to be slightly higher than those of the corresponding concrete mixes containing the larger coarse aggregate. However, in some specific cases the difference in strength is small or the concrete mixes with the larger coarse aggregate have the greater strength. Based on this observation, it appears that for the aggregate sizes tested, the size of the coarse aggregate has little influence on the compressive strength of the concrete. The strengths of comparable mixes containing the #367 and the #467 are remarkably similar in most of the cases. The various mix options also appear to produce concretes with very similar compressive strength.

Table 17) Compressive strength data for the concrete mixes evaluated during Part II of the project.

Concrete Mix	Average Compressive Strength, MPa (psi)		
	Specimen Age		
	7 days	28 days	90 days
C30	29.91 (4338)	37.54 (5445)	43.53 (6313)
C31	29.30 (4250)	40.67 (5898)	44.84 (6503)
C32	27.70 (4017)	35.36 (5129)	41.81 (6064)
C33	25.58 (3710)	35.24 (5111)	40.37 (5855)
C40	28.92 (4195)	40.70 (5903)	43.51 (6310)
C41	29.31 (4251)	39.60 (5743)	45.32 (6573)
C42	31.79 (4610)	38.27 (5550)	41.16 (5969)
C43	26.23 (3804)	37.80 (5482)	41.84 (6069)
C50	33.41 (4845)	41.31 (5992)	47.90 (6947)
C51	27.75 (4025)	36.66 (5317)	44.02 (6384)
C52	31.87 (4623)	41.94 (6083)	45.84 (6649)
C53	30.79 (4465)	43.72 (6341)	48.45 (7027)
HP1	36.36 (5274)	46.46 (6738)	51.82 (7516)
HP2	39.66 (5752)	58.14 (8433)	63.74 (9244)
HP3	45.29 (6569)	62.56 (9074)	69.72 (10112)
HP4	38.07 (5522)	60.61 (8791)	67.02 (9721)
SF735	56.61 (8211)	69.00 (10007)	78.27 (11352)
SF752	52.26 (7579)	70.58 (10236)	74.86 (10858)
SF770	49.39 (7163)	62.41 (9052)	68.62 (9953)

In order to determine whether the differences in compressive strength illustrated in Figure 27 are statistically significant, various pairs of test data sets were compared using the t-test comparison method. The results of t-tests comparisons performed on pairs of concrete mixes having the same coarse aggregate size but involving different Class C mix options are presented in Table 18. All of the t-tests were performed using a significance level of 0.05. In Table 18, "ND" indicates that according to the t-test using a significance level of 0.05, there is no difference between the compressive strength data for the two mix options being compared with that particular aggregate size at that particular specimen age. In 32 of the 54 possible comparisons, the t-test comparison indicated that there was no significant difference in the compressive strength based on the mix option used. At all test ages, the Standard Class C concrete mix with #57 coarse aggregate had greater compressive strength than the corresponding mix based on Option 1. The Standard Class C mix with #357 coarse aggregate also outperformed the corresponding mix based on mix Option 2. Mix option 1 with #357 coarse aggregate had higher compressive strengths than the corresponding mix based on Option 3 at all test ages. Other tendencies are less consistent. Overall, there does not appear to be a single mix option that consistently results in higher compressive strength relative to the other mix options.

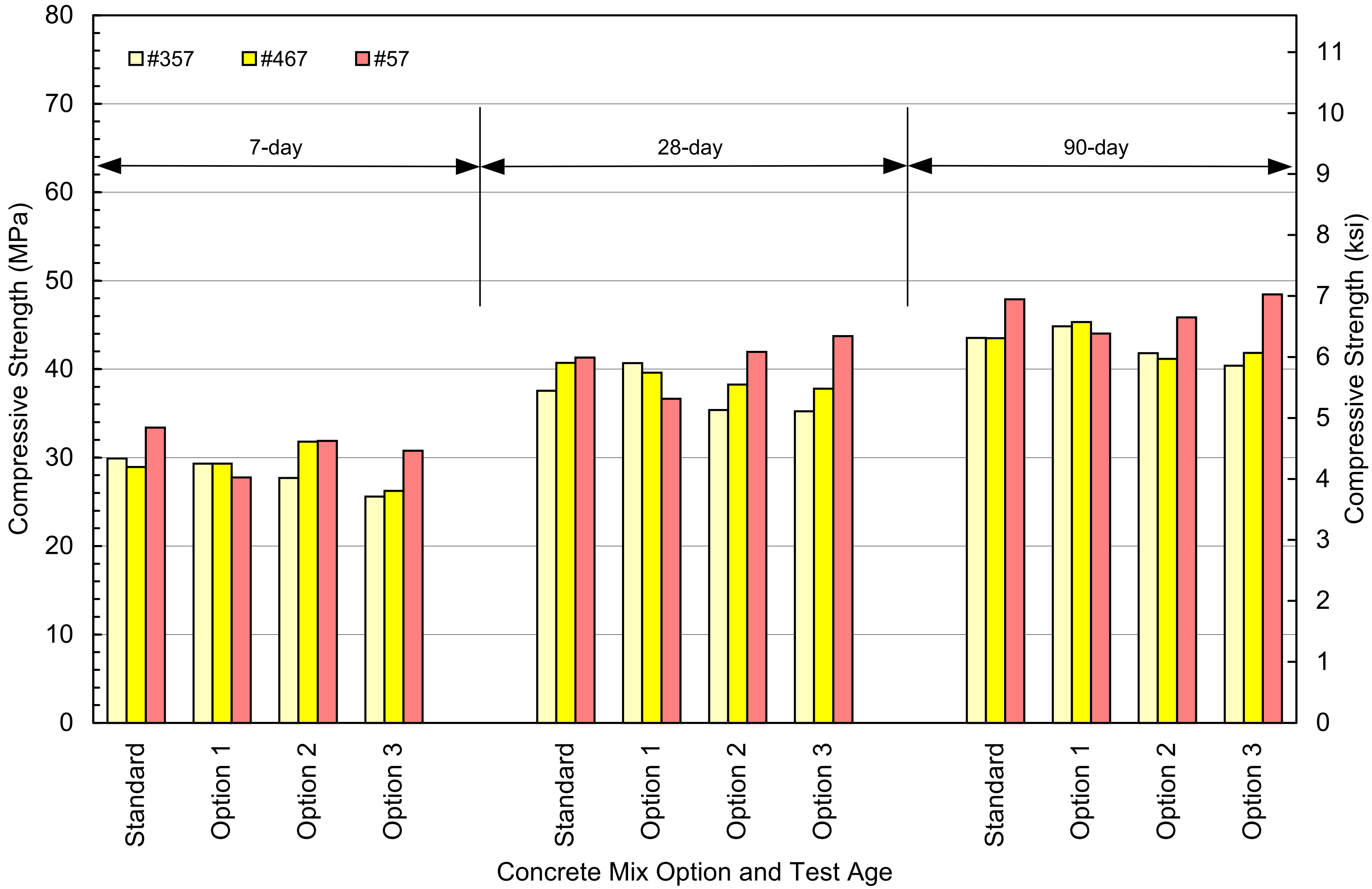

Figure 27) Average compressive strength data for the C group of concrete mixes evaluated during Part II of the study.

The results of t-test comparisons for compressive strength data for concrete mixes involving the same mix option and tested at the same age are presented in Table 19. Based on these comparisons, there is relatively strong evidence that the compressive strength of the mixes with #57 coarse aggregate is greater than that for the corresponding mixes with #357 coarse aggregate. Similarly, the mixes with #57 coarse aggregate also tend to have higher compressive strength than the corresponding mixes using #467 coarse aggregate.

The compressive strength data for the four ODOT High Performance Concrete mixes are presented in Figure 28. The data indicate that high performance mix HP3 has the greatest strength of the four mixes at all of the test ages, and mix HP1 has the lowest strength of the group. The strength of mixes HP2, HP3 and HP4 are fairly similar at 28 and 90 days.

Table 18) Summary of t-test comparisons conducted to evaluate the influence of ODOT Class C mix option on compressive strength.

Coarse Aggregate Size	Test Age (days)	Comparisons Involving Various Class C Mix Options					
		S vs. 1	S vs. 2	S vs. 3	1 vs. 2	1 vs. 3	2 vs. 3
357	7	ND	S > 2	S > 3	ND	1 > 3	2 > 3
467	7	ND	ND	ND	ND	ND	2 > 3
57	7	S > 1	ND	S > 3	1 < 2	1 < 3	ND
357	28	S < 1	ND	S > 3	1 > 2	1 > 3	ND
467	28	ND	ND	ND	ND	ND	ND
57	28	S > 1	ND	ND	1 < 2	1 < 3	2 < 3
357	90	ND	ND	S > 3	ND	1 > 3	ND
467	90	ND	ND	ND	ND	ND	ND
57	90	S > 1	ND	ND	ND	1 < 3	2 < 3

Notes: ND indicates that based on a two-sample t-test using a significance level of 0.05, there is No Difference between the two sets of data in the comparison.
S indicates Class C concrete mixes based on the Standard mix proportions.
1 indicates Class C concrete mixes based on mix option 1.
2 indicates Class C concrete mixes based on mix option 2.
3 indicates Class C concrete mixes based on mix option 3.

Table 19) Summary of t-test comparisons conducted to evaluate the influence of coarse aggregate size on compressive strength.

Mix Option	Test Age (days)	Comparisons based on Coarse Aggregate Size		
		# 357 vs. # 467	# 357 vs. # 57	# 467 vs. # 57
Standard	7	ND	# 357 < # 57	# 467 < # 57
Option 1	7	ND	ND	ND
Option 2	7	# 357 < # 467	# 357 < # 57	ND
Option 3	7	ND	# 357 < # 57	# 467 < # 57
Standard	28	# 357 < # 467	# 357 < # 57	ND
Option 1	28	ND	# 357 > # 57	ND
Option 2	28	# 357 < # 467	# 357 < # 57	# 467 < # 57
Option 3	28	ND	# 357 < # 57	# 467 < # 57
Standard	90	ND	# 357 < # 57	# 467 < # 57
Option 1	90	ND	ND	ND
Option 2	90	ND	# 357 < # 57	# 467 < # 57
Option 3	90	ND	# 357 < # 57	# 467 < # 57

Notes: ND indicates that based on a two-sample t-test using a significance level of 0.05, there is No Difference between the two sets of data in the comparison.
357 indicates Class C concrete mixes with # 357 coarse aggregate.
467 indicates Class C concrete mixes with # 467 coarse aggregate.
57 indicates Class C concrete mixes with # 57 coarse aggregate.

The mixes in the SF group all contain 415.3 kg/m^3 (700 lb/yd^3) of portland cement. The only variable in these mixes is the amount of silica fume present -- mix SF770 contains silica fume at 41.5 kg.m^3 (70 lb/yd^3), mix SF752 contains silica fume at 31.1 kg.m^3 (52.5 lb/yd^3), and mix SF735 contains silica fume at 20.8 kg.m^3 (35 lb/yd^3). The compressive strength data for these mixes are presented in Figure 29. For the range of silica fume dosages evaluated, the compressive strength of these concrete mixes tends to increase as the amount of silica fume decreases. The only exception to this trend is for the 28-day test age when the compressive strength of the SF735 mix is slightly less than that for the SF752 mix.

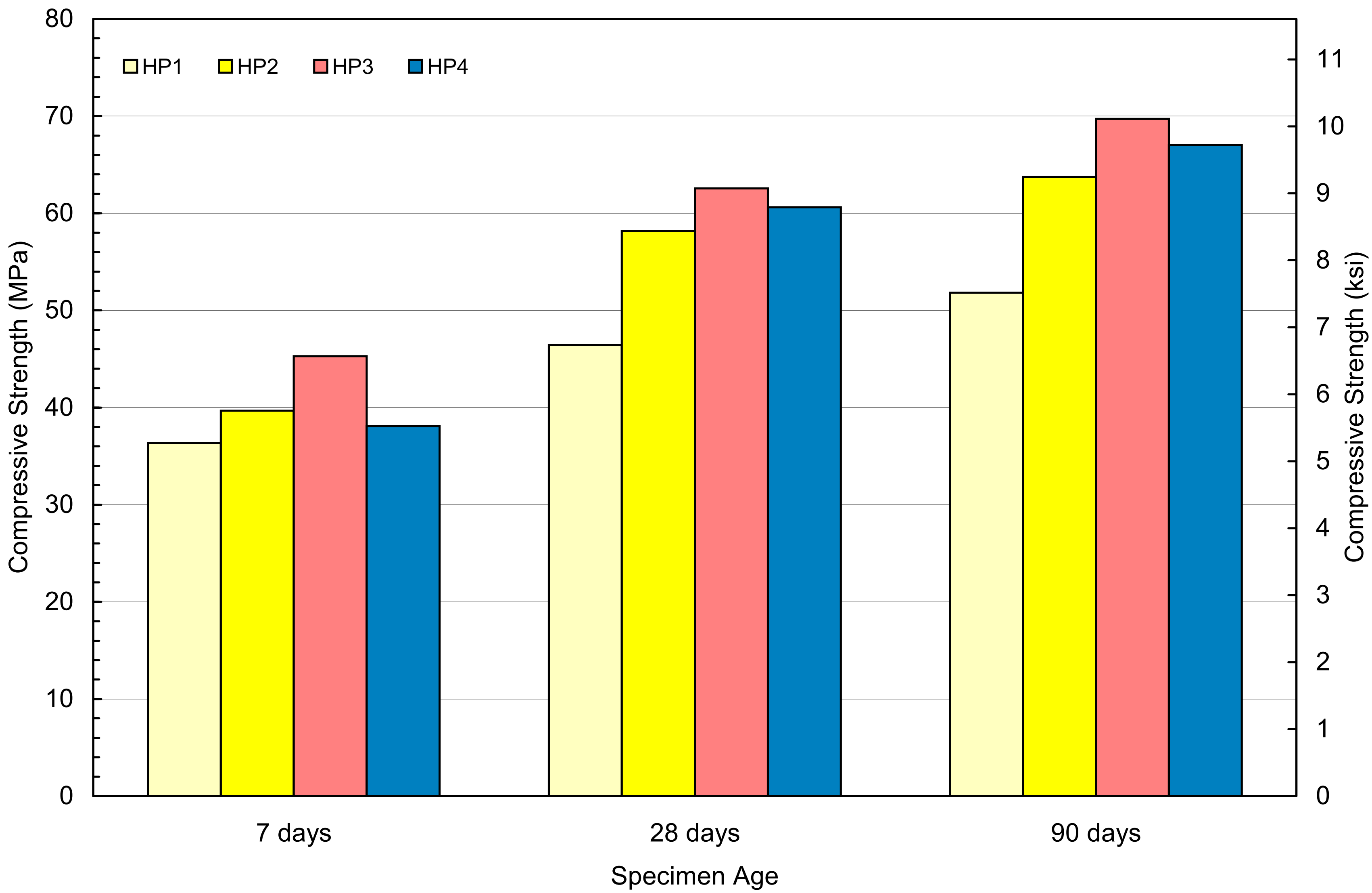

Figure 28) Average compressive strength data for the HP group of concrete mixes evaluated during Part II of the study.

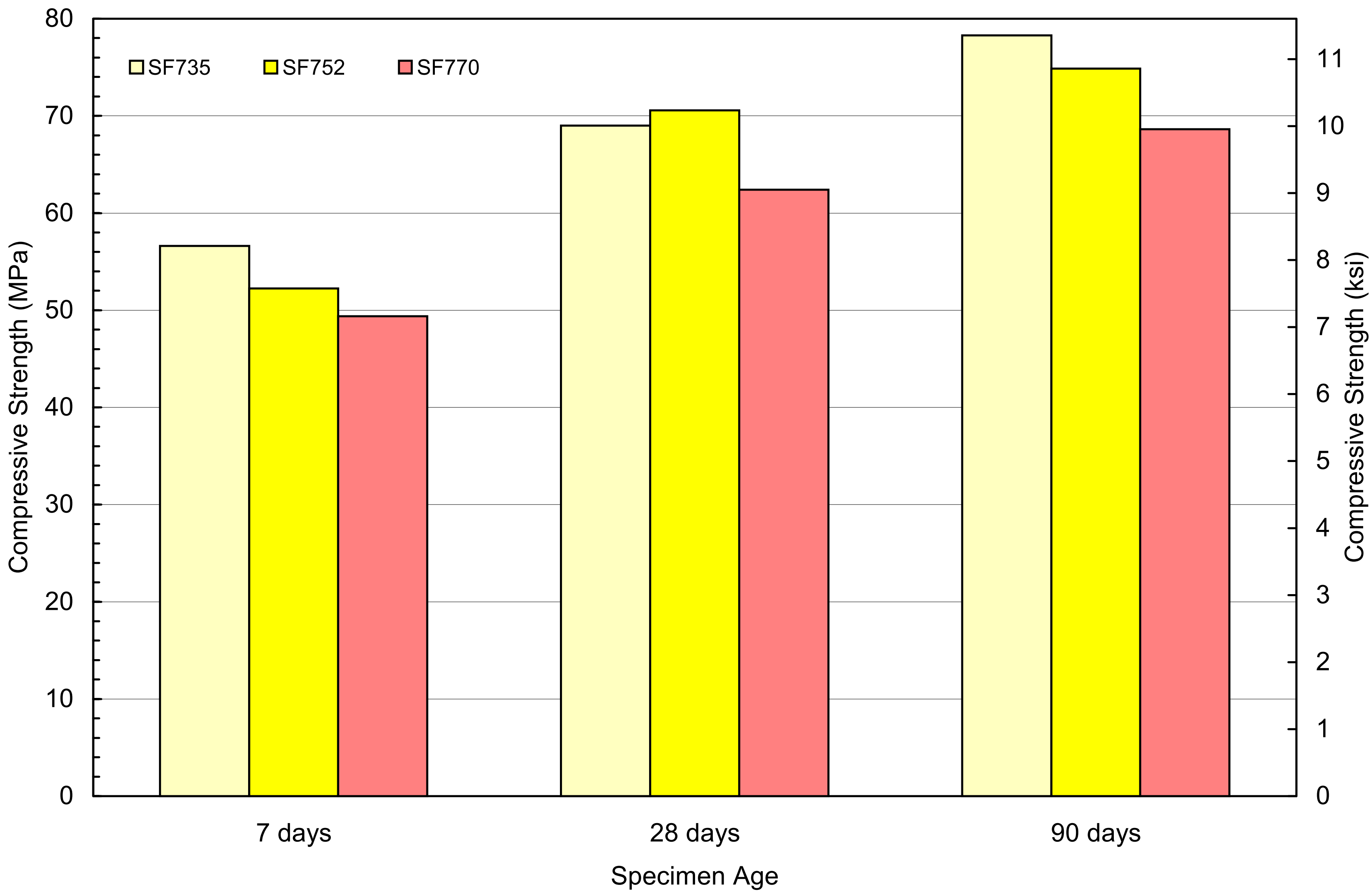

Figure 29) Average compressive strength data for the SF group of concrete mixes evaluated during Part II of the study.

MODULUS OF RUPTURE

Flexural strength testing consisted of three or more individual flexural strength tests for both test ages for each mix design evaluated during Part II of the study. The individual test results are presented in Table B-2 in Appendix B. That table also contains the average strength for each test age for each concrete mix design. The average strength values from Table B-2 are summarized in Table 20. Table 20 also includes the corresponding average compressive strength for each concrete mix at the corresponding test ages.

Table 20 also contains values of the factor m that were calculated by dividing the modulus of rupture by the square root of the compressive strength. Note that this factor is not dimensionless and that its value depends on the units of the strength values used in its calculation. Values are given in the table for both US customary units and for metric units. The Commentary for ACI 318 indicates that the ratio of the modulus of rupture to the square root of the compressive strength is approximately 0.62 for strengths expressed in MPa (7.5 for strengths in psi) for normal weight concrete. For the concrete mixes represented in Table 20, the values of this ratio for strengths in MPa range from 0.76 to 0.99 at 7 days and from 0.82 to 0.97 at 28 days. These values indicate that the flexural strengths of the concretes in Part II of the project exceed those that would be predicted by the equation recommended by ACI for approximating modulus of rupture based on the compressive strength of the concrete.

The modulus of rupture data contained in Table 20 is also presented graphically in Figures 30 and 31 to facilitate comparisons within specific groups of the concrete mix designs. Figure 30 contains the modulus of rupture data for the testing at 7 days, and Figure 31 contains the data for the testing at 28 days. With few exceptions, the relationships between the modulus of rupture values for the nineteen concrete mixes are the same at the 7-day test age and the 28-day test age. As expected, for each concrete mix, the modulus of rupture increases noticeably from the 7-day test results to the 28-day test results. Since the general appearance of the 7-day data is very similar to that of the 28-day data, the remainder of the discussion focuses on the 28-day test results.

The first three groups of bars in Figure 31 represent the modulus of rupture data for the Class C concrete mixes. The three groups correspond to the three coarse aggregate sizes evaluated in the study. For the range of coarse aggregates evaluated, the size of the coarse aggregate appears to have only a slight effect on the modulus of rupture values at the specimen age of 28 days. The modulus of rupture of the concrete mixes containing the #57 coarse aggregate tend to be slightly higher than those of the mixes containing the larger coarse aggregate. There is some indication that the standard mix may have modulus of rupture values that are slightly greater than those for any of the three mix options. However, the difference in the modulus of rupture value is small in two of the three cases and reversed in the third case. Based on these observations, it appears that neither the coarse aggregate size nor the mix option used have a significant influence on the resulting modulus of rupture. This conclusion is also valid for the 7-day test results presented in Figure 30.

Table 20) Modulus of rupture data for the concrete mixes evaluated during Part II of the project.

Concrete Mix	7-day Strength Data			28-day Strength Data		
	Average Modulus of Rupture MPa (psi)	Average Compressive Strength MPa (psi)	m	Average Modulus of Rupture MPa (psi)	Average Compressive Strength MPa (psi)	m
C30	4.32 (627)	29.91 (4338)	0.79 (9.52)	5.40 (783)	37.54 (5445)	0.88 (10.61)
C31	4.30 (623)	29.30 (4250)	0.79 (9.56)	5.32 (771)	40.67 (5898)	0.83 (10.04)
C32	4.27 (620)	27.70 (4017)	0.81 (9.78)	5.26 (763)	35.36 (5129)	0.88 (10.65)
C33	4.24 (615)	25.58 (3710)	0.84 (10.10)	5.15 (747)	35.24 (5111)	0.87 (10.45)
C40	4.69 (680)	28.92 (4195)	0.87 (10.50)	5.36 (777)	40.70 (5903)	0.84 (10.11)
C41	4.36 (633)	29.31 (4251)	0.81 (9.71)	5.58 (810)	39.60 (5743)	0.89 (10.69)
C42	4.27 (620)	31.79 (4610)	0.76 (9.13)	5.36 (778)	38.27 (5550)	0.87 (10.44)
C43	4.00 (580)	26.23 (3804)	0.78 (9.40)	5.18 (752)	37.80 (5482)	0.84 (10.16)
C50	4.81 (698)	33.41 (4845)	0.83 (10.03)	5.86 (850)	41.31 (5992)	0.91 (10.98)
C51	4.47 (648)	27.75 (4025)	0.85 (10.21)	5.62 (815)	36.66 (5317)	0.93 (11.18)
C52	4.30 (623)	31.87 (4623)	0.76 (9.16)	5.33 (773)	41.94 (6083)	0.82 (9.91)
C53	4.47 (648)	30.79 (4465)	0.81 (9.70)	5.76 (835)	43.72 (6341)	0.87 (10.49)
HP1	5.25 (762)	36.36 (5274)	0.87 (10.49)	6.14 (890)	46.46 (6738)	0.90 (10.84)
HP2	5.08 (737)	39.66 (5752)	0.81 (9.72)	6.88 (998)	58.14 (8433)	0.90 (10.87)
HP3	5.61 (813)	45.29 (6569)	0.83 (10.03)	6.96 (1010)	62.56 (9074)	0.88 (10.60)
HP4	4.95 (718)	38.07 (5522)	0.80 (9.66)	6.78 (983)	60.61 (8791)	0.87 (10.48)
SF735	6.72 (975)	56.61 (8211)	0.89 (10.76)	7.71 (1118)	69.00 (10007)	0.93 (11.18)
SF752	7.19 (1043)	52.26 (7579)	0.99 (11.98)	8.17 (1185)	70.58 (10236)	0.97 (11.71)
SF770	6.38 (926)	49.39 (7163)	0.91 (10.94)	7.09 (1028)	62.41 (9052)	0.90 (10.80)

m = (modulus of rupture) / (compressive strength)$^{0.5}$

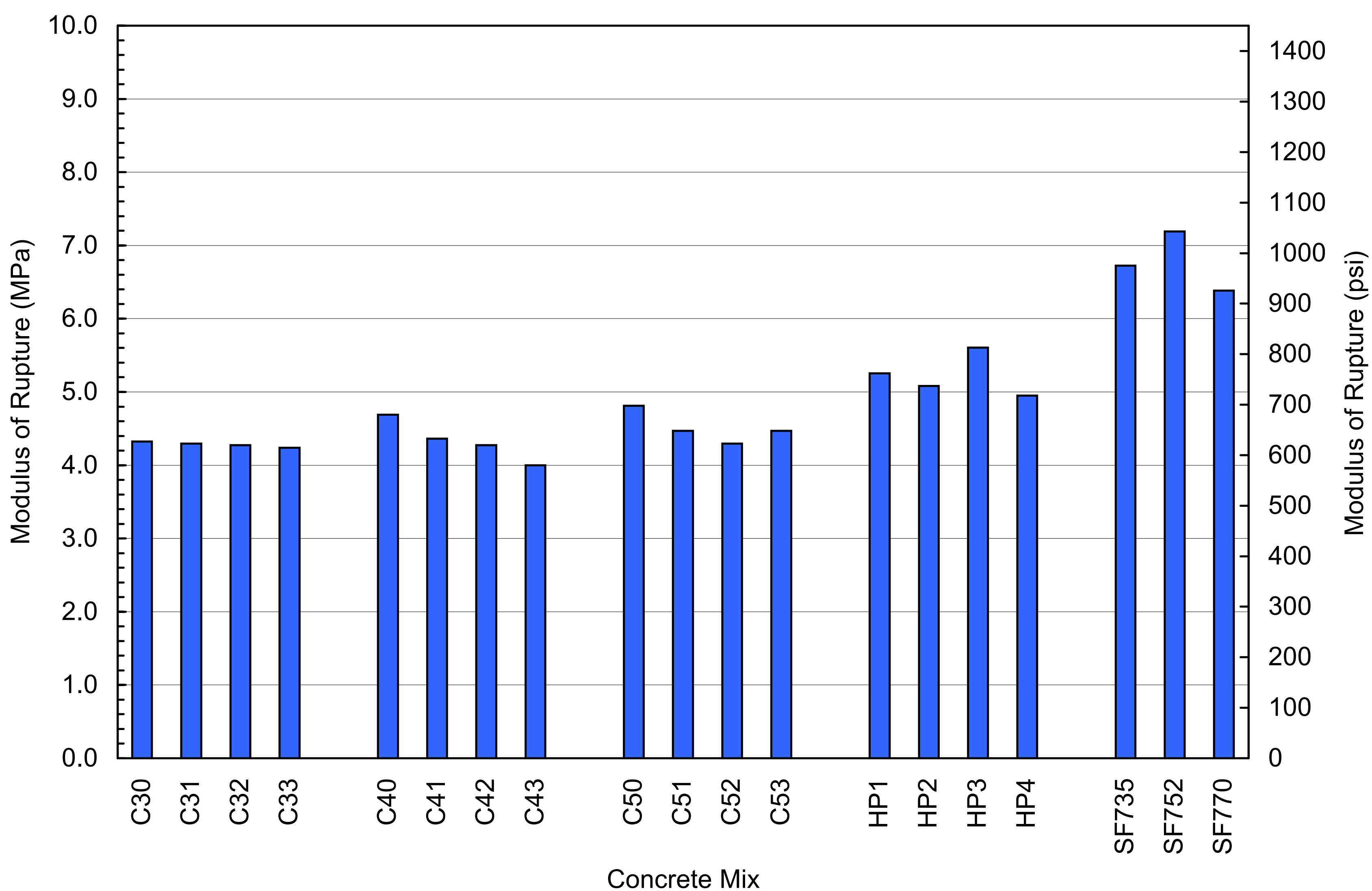

Figure 30) Average 7-day modulus of rupture data for the concrete mixes evaluated during Part II of the study.

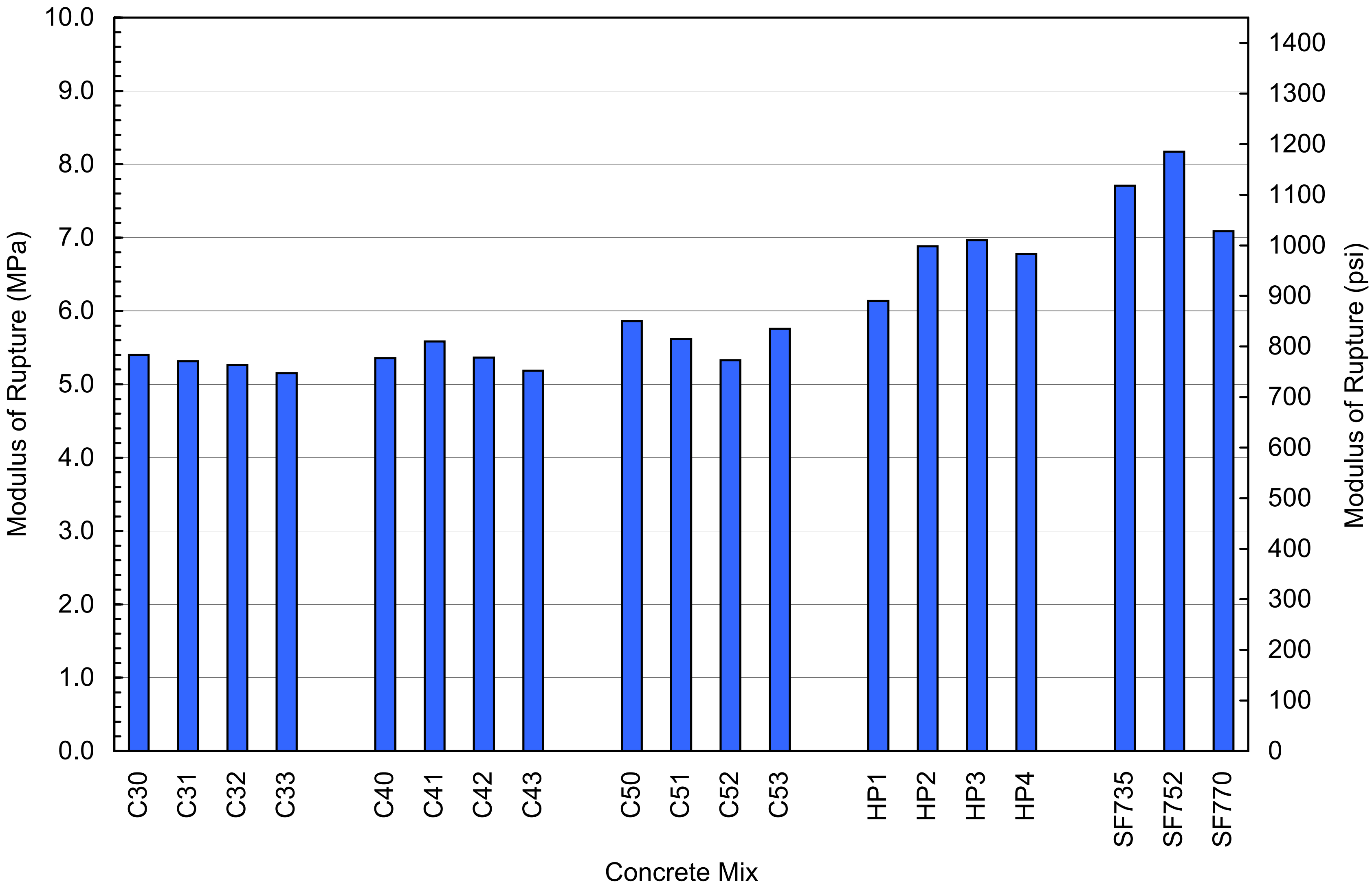

Figure 31) Average 28-day modulus of rupture data for the concrete mixes evaluated during Part II of the study.

For the four mixes in the high performance group (HP), their modulus of rupture values are slightly greater than those for the mixes in the Class C group. This is as expected due to the differences in the water:cement ratios for these two groups. Considering the data for both test ages, there is no clear relationship between the mix design and the resulting modulus of rupture. One observation that holds for both test ages is that the HP3 mix had the highest modulus of rupture values for this group of mixes. However, the difference in the modulus of rupture values for the HP3 mix and the HP2 and HP4 mixes is small at the 28-day test age.

The relative performance within the SF group of mixes is the same at both test ages. The SF752 had the highest modulus of rupture within this group, and the SF770 mix had the lowest modulus of rupture within the group. Overall, the SF group exhibited the highest modulus of rupture values of all of the concrete mixes evaluated during Part II of the study. Since these mixes have the lowest water:cement ratio of all of the mixes evaluated, they are expected to have the best strength performance.

In order to determine whether the differences in the modulus of rupture values illustrated in Figures 30 and 31 are statistically significant, various pairs of test data sets were compared using the t-test comparison method. The results of t-test comparisons performed on pairs of concrete mixes having the same coarse aggregate size but involving different Class C mix options are presented in Table 21. All of the t-tests were performed using a significance level of 0.05. In Table 21, "ND" indicates that according to the t-test using a significance level of 0.05, there is no difference between the modulus of rupture data for the two mix options being compared with that particular aggregate size at that particular specimen age. There is no significant difference between the two sets of data being compared in 34 of the 36 possible comparisons. Based on these comparisons, there is no consistent evidence that any one of the mix options is superior to the others in terms of the modulus of rupture of the concrete.

The t-test comparison method was also used to evaluate the significance of differences in the modulus of rupture data for mixes with different coarse aggregate size but based on the same Class C mix option and tested at the same age. A summary of these comparisons is presented in Table 22. In 20 of the 24 possible comparisons, the results of the t-test comparison indicate that there is no significant difference in the modulus of rupture data. Three of the four cases where there is a difference in the modulus of rupture data involve the standard Class C mix and #57 coarse aggregate. In these cases, the use of #57 coarse aggregate resulted in higher modulus of rupture values than those produced by concretes containing the larger size coarse aggregate.

Overall, the various ODOT Class C mix options and the coarse aggregate sizes evaluated seem to have very little influence on the modulus of rupture value of the concrete. This conclusion is consistent with the earlier observations made based on the graphical presentation of the data.

Table 21) Summary of t-test comparisons conducted to evaluate the influence of ODOT Class C mix option on modulus of rupture.

Coarse Aggregate Size	Test Age (days)	Comparisons Involving Various Class C Mix Options					
		S vs. 1	S vs. 2	S vs. 3	1 vs. 2	1 vs. 3	2 vs. 3
357	7	ND	ND	ND	ND	ND	ND
467	7	ND	ND	ND	ND	ND	ND
57	7	ND	S > 2	S > 3	ND	ND	ND
357	28	ND	ND	ND	ND	ND	ND
467	28	ND	ND	ND	ND	ND	ND
57	28	ND	ND	ND	ND	ND	ND

Notes: ND indicates that based on a two-sample t-test using a significance level of 0.05, there is No Difference between the two sets of data in the comparison.
S indicates Class C concrete mixes based on the Standard mix proportions.
1 indicates Class C concrete mixes based on mix option 1.
2 indicates Class C concrete mixes based on mix option 2.
3 indicates Class C concrete mixes based on mix option 3.

Table 22) Summary of t-test comparisons conducted to evaluate the influence of coarse aggregate size on modulus of rupture.

Mix Option	Test Age (days)	Comparisons based on Coarse Aggregate Size		
		# 357 vs. # 467	# 357 vs. # 57	# 467 vs. # 57
Standard	7	ND	# 357 < # 57	ND
Option 1	7	ND	ND	ND
Option 2	7	ND	ND	ND
Option 3	7	ND	ND	ND
Standard	28	ND	# 357 < # 57	# 467 < # 57
Option 1	28	ND	ND	ND
Option 2	28	ND	ND	ND
Option 3	28	ND	# 357 < # 57	ND

Notes: ND indicates that based on a two-sample t-test using a significance level of 0.05, there is No Difference between the two sets of data in the comparison.
357 indicates Class C concrete mixes with # 357 coarse aggregate.
467 indicates Class C concrete mixes with # 467 coarse aggregate.
57 indicates Class C concrete mixes with # 57 coarse aggregate.

DURABILITY PROPERTIES

The durability related properties of the concrete mixes evaluated during Part II of the study include resistance to damage caused by freeze-thaw cycles, resistance to chloride ion penetration, and length change. The test results relating to each of these issues are presented in the following sections.

CHLORIDE PENETRATION RESISTANCE

Resistance to chloride penetration was evaluated using two test methods for each of the concrete mixes evaluated during Part II of the study. The rapid chloride permeability test (ASTM 1202) was performed on specimens of two different sizes for the concrete mixes in the C group and on standard size specimens for the concrete mixes in the HP and SF concrete mix groups. Each of the concrete mixes was also evaluated using the 90-day chloride ponding test (AASHTO 259).

For the concrete mixes in the C3n and C4n groups, the nominal maximum size for the coarse aggregate is 51 mm (2 inches) and 38 mm (1.5 inches), respectively. The generally accepted practice is for the least dimension of a test specimen to be at least three times the nominal maximum size of the coarse aggregate. For this reason, there was concern regarding the appropriateness of using standard 95 mm (3.75 inch) diameter specimens for the rapid chloride permeability testing of the C3n and C4n concrete mixes.

RAPID CHLORIDE PERMEABILITY TEST

Rapid chloride permeability testing was performed according to ASTM 1202 for each concrete mix evaluated during Part II of the study. For the concrete mixes in the C3n and C4n groups, the nominal maximum size for the coarse aggregate is 51 mm (2 inches) and 38 mm (1.5 inches), respectively. The generally accepted practice is for the least dimension of a test specimen to be at least three times the nominal maximum size of the coarse aggregate. For this reason, there was concern regarding the appropriateness of using standard 95 mm (3.75 inch) diameter specimens for the rapid chloride permeability testing of the C3n and C4n concrete mixes. For all of the concrete mixes in the C group, rapid chloride permeability testing was done using the standard 95 mm (3.75 inch) diameter specimens and larger specimens having a diameter of 162 mm (6 inches). For the C5n group of concrete mixes, the nominal maximum size of the coarse aggregate is 25 mm (1 inch), and the size of the standard rapid chloride permeability test specimen is suitable.

At the beginning of the testing program, the logic was to perform testing on both of the specimen sizes mentioned above for all of the concrete mixes in the C group of concrete mixes. Doing so would allow an evaluation of the influence of specimen size on the test results for the C5n group of concrete mixes where both specimen sizes are appropriate relative to the size of the coarse aggregate. Using this information and similar comparisons for the concrete mixes involving the larger coarse aggregate, the appropriateness of using standard cored 95 mm (3.75 inch) diameter specimens for the concrete mixes involving the #357 and #467 coarse aggregate could be evaluated. As discussed in the following sections, this didn't work as intended because the results of the larger specimens are believed to be erroneous due to the much larger current during these tests that resulted in high specimen temperatures.

For the concrete mixes in the C group of concrete mixes, rapid chloride permeability testing was conducted at specimen ages of 28 days and 90 days. The test results for the 28-day testing are presented in Table 23, and the results for the 90-day testing are presented in Table 24. In both cases, three tests were performed for each concrete mix for each of the two specimen sizes. The tables include the individual test results and the average charge passed for each concrete type for each specimen size. Where appropriate, the values presented in the tables have been corrected to account for non-standard specimen size according the ASTM 1202. This is done by multiplying the test result by the ratio of the cross-sectional area of the standard size specimen to the cross-sectional area of the actual test specimen.

At the 28-day test age, the area corrected charge passed for the larger specimens ranged from 3938 to 12273 coulombs. Prior to applying the area correction, this range was from about 10,000 to 31,000 coulombs. These high currents coupled with the reduced surface area to volume ratio for the larger specimens resulted in excessive temperatures in nearly all of the rapid chloride permeability tests performed on the larger specimens. In several cases, the solutions in the test cell began to boil prior to completion of the test. When a specimen experiences a significant increases in temperature, it is usually accompanied by a significant increase in the current being drawn by the test specimen during the course of the test. This has a direct influence on the resulting coulomb value calculated for that test. For tests performed on normal concrete mixes on standard size specimens, the temperature of the specimen typically increases slightly in the early part of the test and then remains relatively constant for the remainder of the test, and the current being drawn by the test specimen is relatively constant throughout the test. Based on these observations, the test results for the 162 mm (6 inches) diameter specimens are considered to be invalid. They are included only for completeness of the reporting of the testing effort and should not be relied upon in evaluating the performance of the concrete mixes.

The average values for the rapid chloride permeability testing performed at 28 days for the concrete mixes in the C group are presented in Figure 32. As mentioned earlier, the data for the 162 mm (6 inches) diameter specimens is included for completeness of the report, but it should not be used to evaluate the performance of various concrete mixes. The results of tests performed on standard size specimens indicate that for each of the three aggregate sizes, the concrete mixes based on ODOT option 3 have the highest resistance to chloride ion penetration as indicated by the rapid chloride permeability test. Otherwise, there does not appear to be any clear significant influence of mix option on the charge passed during the test. The data presented in Figure 32 can be used to evaluate the influence of coarse aggregate size on the resistance of the concrete to chloride penetration. There is some indication that, as the

Table 23) Results of rapid chloride permeability testing performed at 28 days for the C group of concrete mixes evaluated during Part II of the study.

Concrete Mix	Area-Corrected Charge Passed (Coulombs)			
	Specimen Size and Type			
	3.75" Cored	6" Cast	Average for 3.75" Cored	Average for 6" Cast
C30	3992	7314	5455	8247
	7077	8369		
	5297	9057		
C31	3236	5958	4646	9251
	5258	12273		
	5444	9521		
C32	5303	6855	5727	7131
	6578	7438		
	5300	7099		
C33	3320	5629	3390	5541
	3642	4985		
	3207	6008		
C40	3793	6905	4742	8120
	5719	11758		
	4714	5696		
C41	3675	5463	3882	5764
	4472	7150		
	3499	4680		
C42	3742	5980	4141	7438
	4728	8580		
	3954	7753		
C43	3158	4209	3284	4396
	3407	4780		
	3288	4198		
C50	4082	5637	4279	6282
	3892	6255		
	4864	6954		
C51	3780	5324	3941	5312
	3347	4352		
	4695	6261		
C52	4080	5217	4139	5494
	3453	4689		
	4883	6576		
C53	2831	3938	3061	4189
	3235	4058		
	3118	4572		

Table 24) Results of rapid chloride permeability testing performed at 90 days for the C group of concrete mixes evaluated during Part II of the study.

Concrete Mix	Area-Corrected Charge Passed (Coulombs)			
	Specimen Size and Type			
	3.75" Cored	6" Cast	Average for 3.75" Cored	Average for 6" Cast
C30	2555	4608	3167	4707
	4246	4352		
	2701	5162		
C31	2265	3575	2664	4969
	2787	5523		
	2940	5808		
C32	3659	4835	3758	4993
	4276	5132		
	3339	5012		
C33	1726	2477	1511	2598
	1493	2193		
	1315	3124		
C40	2124	3936	2937	4487
	3717	5879		
	2970	3645		
C41	2573	3715	2339	3623
	2415	4719		
	2029	2434		
C42	2545	3349	2509	4535
	2411	5062		
	2570	5195		
C43	1547	2020	1755	2152
	1976	2294		
	1743	2141		
C50	2490	3157	2653	3989
	2647	3941		
	2821	4868		
C51	2155	2768	2309	3179
	1674	2698		
	3099	4070		
C52	2734	3652	2648	3223
	2037	2532		
	3174	3485		
C53	1472	1851	1467	2226
	1682	2313		
	1247	2515		

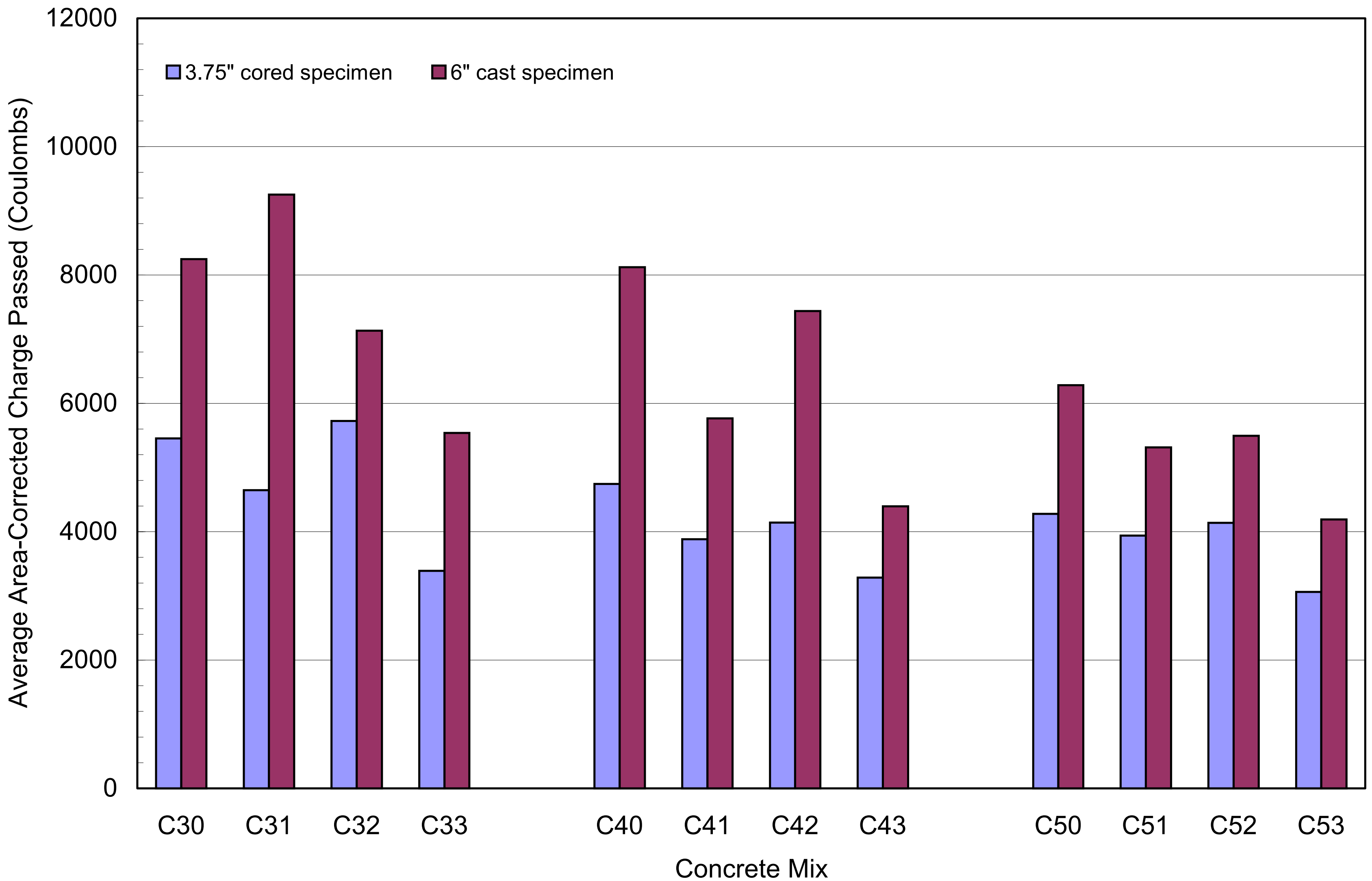

Figure 32) Rapid chloride permeability test results for the C group of concrete mixes for two different specimen sizes tested at 28 days of age.

size of the coarse aggregate increases, the resistance to chloride penetration decreases slightly. The decrease is relatively small in most cases, and in some cases there appears to be no relationship between the size of the coarse aggregate and the charge passed during the test.

The results of tests performed at the 90-day specimen age are presented in Figure 33. As discussed earlier, the data for tests involving 162 mm (6 inches) diameter specimens is believed to be invalid. The following discussion is based on the results of the tests performed on the 95 mm (3.75 inch) diameter specimens. As was the case for the 28-day test results, for each aggregate size, the concrete based on ODOT mix option 3 had the lowest charge passed, indicating the highest resistance to chloride penetration. According to Whiting's rating system, all three of the concrete mixes involving ODOT mix option 3 are assigned a chloride permeability rating of low. The remaining mixes fall into the category of moderate chloride permeability (2000 to 4000 coulombs). The influence of coarse aggregate size on chloride penetration resistance seems to be very slight if any at all. There is some indication that, as the nominal size of the coarse aggregate increases, there is a slight increase in the charge passed during the test. The difference is small and may not be significant considering the normal variability in the test results and the accuracy of the method.

The influence of specimen age on the charge passed during the test can be evaluated by comparing the data in Figures 32 and 33 for the tests performed using the standard 95 mm (3.75 inch) diameter specimens. This comparison indicates that for each particular concrete mix, there is a significant reduction in the charge passed during the test at 90 days compared to the charge passed during the test conducted at 28 days. This decrease in coulombs passed during the test as the specimen age increases is as expected and is well documented in the technical literature.

In order to determine whether the differences in the values of charge passed illustrated in Figures 32 and 33 are statistically significant, various pairs of test data sets were compared using the t-test comparison method. The results of t-test comparisons performed on pairs of concrete mixes having the same coarse aggregate size but involving different Class C mix options are presented in Table 25. All of the t-tests were performed using a significance level of 0.05. In Table 25, "ND" indicates that according to the t-test using a significance level of 0.05, there is no difference between the area-corrected charge passed data for the two mix options being compared with that particular aggregate size at that particular specimen age. There is no significant difference between the two sets of data being compared in 29 of the 36 possible comparisons. The results summarized in Table 25 indicate that mix option 3 may tend to be more resistant to chloride ion penetration than mix option 2. Otherwise, the results of the t-test comparisons indicate that there is no consistent evidence that any of the mix options is superior to the others in terms of resistance to chloride ion penetration.

The t-test comparison method was also used to evaluate the significance of differences in the area-corrected charge passed for mixes with different coarse aggregate size but based on the same Class C mix option and tested at the same age. A summary of these comparisons is presented in Table 26. In 22 of the 24 possible

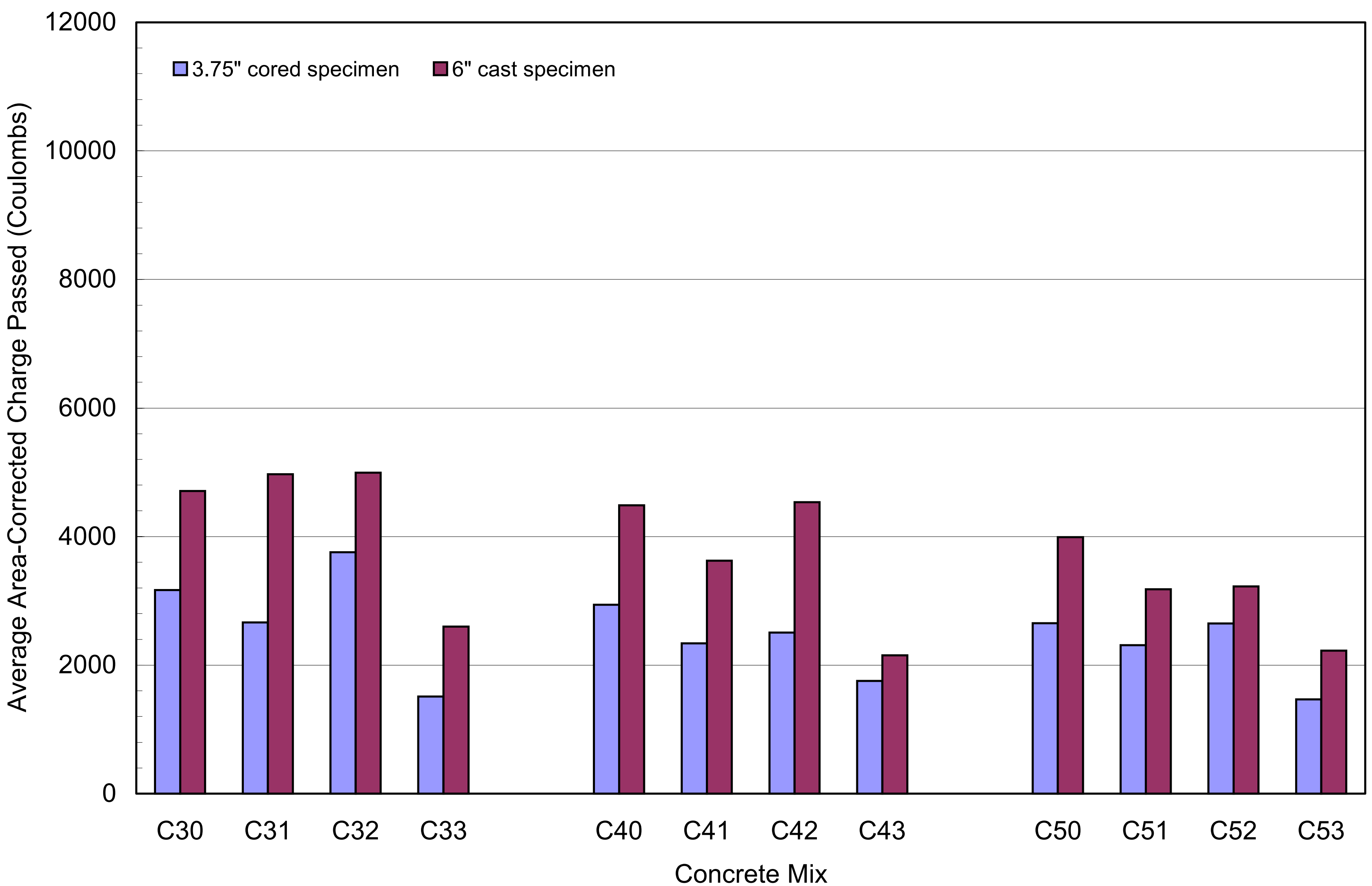

Figure 33) Rapid chloride permeability test results for the C group of concrete mixes for two different specimen sizes tested at 90 days of age.

comparisons, the results of the t-test comparison indicate that there is no significant difference in the area-corrected charge passed data. The two cases where there is a difference in the area-corrected charge passed indicate that, for mix option 2, the specimens with #467 coarse aggregate are more resistant to chloride ion penetration than those with #357 coarse aggregate.

Table 25) Summary of t-test comparisons conducted to evaluate the influence of ODOT Class C mix option on the results of rapid chloride permeability tests.

Coarse Aggregate Size	Test Age (days)	Comparisons Involving Various Class C Mix Options					
		S vs. 1	S vs. 2	S vs. 3	1 vs. 2	1 vs. 3	2 vs. 3
357	28	ND	ND	ND	ND	ND	2 > 3
467	28	ND	ND	ND	ND	ND	ND
57	28	ND	ND	S > 3	ND	ND	ND
357	90	ND	ND	ND	1 < 2	1 > 3	2 > 3
467	90	ND	ND	ND	ND	ND	2 > 3
57	90	ND	ND	S > 3	ND	ND	ND

Notes: ND indicates that based on a two-sample t-test using a significance level of 0.05, there is No Difference between the two sets of data in the comparison.
S indicates Class C concrete mixes based on the Standard mix proportions.
1 indicates Class C concrete mixes based on mix option 1.
2 indicates Class C concrete mixes based on mix option 2.
3 indicates Class C concrete mixes based on mix option 3.

Table 26) Summary of t-test comparisons conducted to evaluate the influence of coarse aggregate size on the results of rapid chloride permeability tests.

Mix Option	Test Age (days)	Comparisons based on Coarse Aggregate Size		
		# 357 vs. # 467	# 357 vs. # 57	# 467 vs. # 57
Standard	28	ND	ND	ND
Option 1	28	ND	ND	ND
Option 2	28	# 357 > # 467	ND	ND
Option 3	28	ND	ND	ND
Standard	90	ND	ND	ND
Option 1	90	ND	ND	ND
Option 2	90	# 357 > # 467	ND	ND
Option 3	90	ND	ND	ND

Notes: ND indicates that based on a two-sample t-test using a significance level of 0.05, there is No Difference between the two sets of data in the comparison.
357 indicates Class C concrete mixes with # 357 coarse aggregate.
467 indicates Class C concrete mixes with # 467 coarse aggregate.
57 indicates Class C concrete mixes with # 57 coarse aggregate.

Overall, the various ODOT Class C mix options and the coarse aggregate sizes evaluated seem to have very little influence on the resistance to chloride ion penetration of the concrete as indicated by the rapid chloride permeability test.

The results of the rapid chloride permeability tests performed on specimens from the HP and SF groups of concrete mixes are presented in Table 27. All of the concrete mixes in these two groups have #8 crushed limestone as the coarse aggregate, and all of the rapid chloride permeability testing for these mixes was performed using 4-inch diameter specimens cast in plastic cylinder molds. The results have been corrected to account for non-standard specimen size according the ASTM 1202. This is done by multiplying the test result by the ratio of the cross-sectional area of the standard size specimen to the cross-sectional area of the actual test specimen. For each concrete mix, six individual tests were performed at each of the two test ages. The average values presented in Table 27 form the basis for Figure 34.

The data presented in Figure 34 indicate that for a particular concrete mix, there is a significant reduction in the charge passed for the test conducted at 90 days compared to the charge passed for the test conducted at 28 days. As mentioned earlier, this is as expected.

For the concrete mixes in the HP group, the test results indicate that there is a significant difference in the resistance to chloride penetration depending on the particular mix option. HP4 is proportioned according to ODOT's High Performance Concrete mix option 4 as indicated in Table 15, and is the only concrete mix in the group with a chloride permeability rating of very low (100 to 1000 coulombs) at the 28-day test age. At the 28-day test age, concrete mix HP3 is in the low chloride permeability category (1000 to 2000 coulombs), and concrete mixes HP3 and HP4 are in the moderate chloride permeability category (2000 to 4000 coulombs). At the 90-day test age, both the HP3 and HP4 concrete mixes are about in the middle of the very low chloride permeability category. At the same test age, concrete mixes HP1 and HP2 have chloride permeability ratings on the low side of the low category, just above the 1000 coulomb mark that separates the low permeability category from the very low permeability category.

For the mixes in the SF group, the primary variable is the amount of silica fume in the mix. This is indicated by the last two digits of the mix name, which corresponds to the silica fume dosage in pounds per cubic yard of concrete. All three of these mixes contain 415.3 kg/m^3 (700 lb/yd^3) of portland cement. Other mix proportion details are presented in Table 15. At the 28-day test age, there is no clear relationship between the amount of silica fume in the concrete and the resulting charge passed during the rapid chloride permeability test. At the 90-day test age, all three of the concrete mixes had test results indicating a chloride permeability rating of very low. Concrete mixes SF752 and SF770 appear to be slightly more resistant to chloride penetration than mix SF735. However, considering the test method and its normal interpretation, the difference may not be significant.

Table 27) Results of rapid chloride permeability testing for the HP and SF groups of concrete mixes evaluated during Part II of the study.

Concrete Mix	Area-Corrected Charge Passed (Coulombs)					
	28-day Test Results			90-day Test Results		
	Test 1	Test 2	Average	Test 1	Test 2	Average
HP1	3291	2900	3156	1107	1096	1064
	2929	3229		991	1101	
	3140	3449		1045	1046	
HP2	1775	1809	2073	1092	1121	1104
	1915	1765		985	1100	
	2537	2637		1131	1195	
HP3	1723	1681	1707	550	601	530
	1484	1671		524	610	
	1915	1765		483	409	
HP4	863	861	888	528	497	490
	902	896		488	513	
	896	910		435	478	
SF735	1325	1287	1266	797	853	841
	1257	1228		780	926	
	1235	1265		862	827	
SF752	759	802	809	495	567	506
	965	997		511	476	
	658	674		483	502	
SF770	1008	1216	1072	504	499	518
	976	998		478	432	
	1110	1122		589	606	

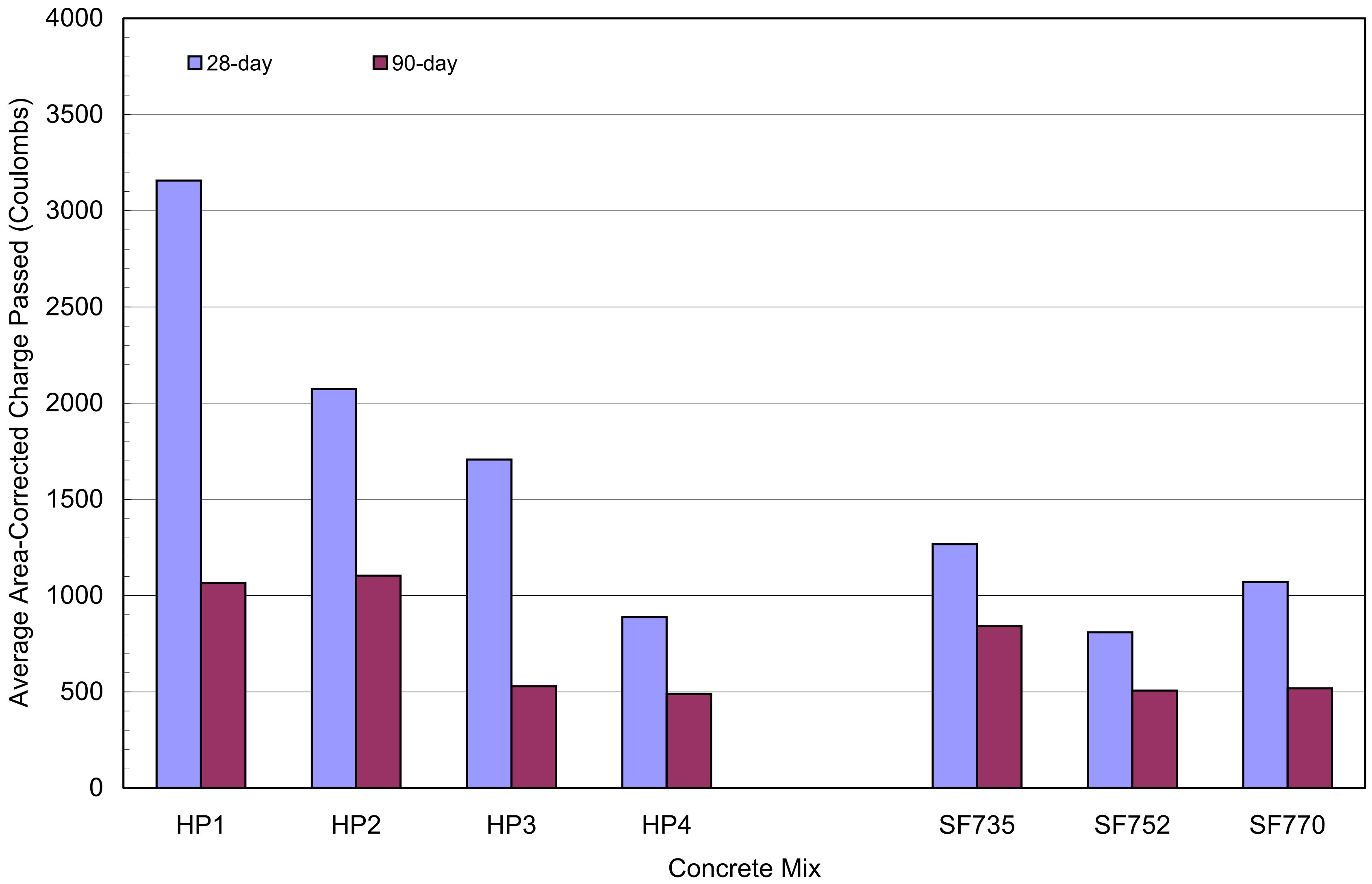

Figure 34) Rapid chloride permeability test results for the HP and SF groups of concrete mixes tested at 28 and 90 days of age.

90-DAY PONDING TEST

To further evaluate the resistance to chloride penetration of the concrete mixes evaluated during Part II of the study, 90-day chloride ponding tests were performed according to AASHTO T 259. For each concrete mix in the C group of mixes, one test set consisting of three chloride ponded specimens and one non-ponded baseline specimen were used. For the concrete mixes in the HP and SF groups, six mixes were selected for an expanded testing program using three sets of four specimens per concrete mix. For the remaining concrete mix in these groups, one set of four test specimens was used. After the 90-day ponding period, the chloride content of each specimen was determined for sampling depth intervals of 1.6 to 12.7 mm (0.0625 to 0.5 inch) and 12.7 to 25.4 mm (0.5 to 1.0 inch).

For the concrete mixes in the C group, the results for the upper sampling depth are presented in Table 28, and the results for the lower sampling depth are presented in Table 29. In both of these tables, the results for each of the four specimens are presented for each concrete mix. The amount of chloride that penetrates the concrete is indicated in the last column. This value is determined by taking the average of the chloride content values for each of the three specimens that were ponded with the chloride solution and subtracting the chloride content for the baseline specimen that was not subjected to the chloride ponding. These values are presented in Figure 35 for both the upper and lower sample depths.

The penetration of chloride ions into the concrete is the result of capillarity, hydraulic conductivity, and ionic diffusion. The effects of capillarity are the most important in the partially desiccated upper portion of the concrete. At greater depths below the surface, the hydraulic conductivity and ionic diffusion mechanisms are the dominant transport mechanisms. These factors contribute to the relatively large variability in the test results for the samples from the upper level sampling depth. For the upper sample depth, the data in Figure 35 indicate that the standard Class C concrete mix and the Class C mix using option 2 are somewhat more resistant to chloride penetration than the mixes involving mix options 1 and 4. However, for the samples obtained from the lower sampling depth, the data indicate that neither the mix option nor the size of coarse aggregate have a significant influence on the amount of chloride penetrating the concrete.

As noted in the previous section, all of the concretes in this group have relatively low resistance to chloride penetration as indicated by the rapid chloride ion permeability test. This is confirmed by the fact that for all of the specimens in this group, the chloride content at the lower sampling depth after the 90-day ponding test exceeded the 0.78 kg/m^3 (1.32 lb/yd^3) threshold value established by AASHTO. The AASHTO threshold value of 0.78 kg/m^3 (1.32 lb/yd^3) is often referenced as the chloride content at which corrosion of steel in concrete is likely to begin.

The results of the 90-day ponding tests conducted on specimens of concrete from the HP and SF concrete mixes are presented in Table 30 for samples from the upper sampling depth and in Table 31 for samples from the lower sampling depth.

Table 28) Chloride content data for the 90-day chloride ponding test for the upper sample depth of 1.6 to 12.7 mm (0.0625 to 0.5 inch) for the C group of concrete mixes.

Concrete Mix	Chloride Content (kg/m^3)				
	Ponded Specimen 1	Ponded Specimen 2	Ponded Specimen 3	Non-ponded Baseline Specimen	Baseline Corrected Concrete Mix Average
C30	5.45	6.40	4.75	1.16	4.37
C31	7.72	8.28	6.82	1.06	6.54
C32	5.24	5.87	5.00	1.11	4.26
C33	6.62	9.25	9.96	1.30	7.31
C40	5.56	4.51	5.74	1.02	4.25
C41	6.54	6.86	7.26	1.04	5.85
C42	4.59	5.51	4.89	1.12	3.88
C43	5.42	6.88	6.44	1.18	5.06
C50	5.87	4.19	4.52	1.13	3.73
C51	6.35	6.20	6.29	1.00	5.28
C52	4.86	4.96	4.79	1.11	3.76
C53	5.46	6.03	5.29	1.12	4.47

Table 29) Chloride content data for the 90-day chloride ponding test for the lower sample depth of 12.7 to 25.4 mm (0.5 to 1.0 inch) for the C group of concrete mixes.

Concrete Mix	Chloride Content (kg/m^3)				
	Ponded Specimen 1	Ponded Specimen 2	Ponded Specimen 3	Non-ponded Baseline Specimen	Baseline Corrected Concrete Mix Average
C30	2.11	2.29	2.21	1.16	1.04
C31	2.71	2.98	2.25	1.06	1.58
C32	2.22	2.52	2.33	1.04	1.32
C33	2.13	3.19	3.20	1.30	1.54
C40	2.85	2.45	2.48	1.02	1.58
C41	2.51	2.41	2.81	1.10	1.47
C42	2.44	2.38	1.83	1.12	1.10
C43	2.29	2.72	2.41	1.20	1.27
C50	2.53	2.57	2.63	1.13	1.45
C51	2.49	2.26	2.03	1.00	1.27
C52	2.39	2.40	2.22	1.11	1.23
C53	1.74	1.98	1.95	1.12	0.77

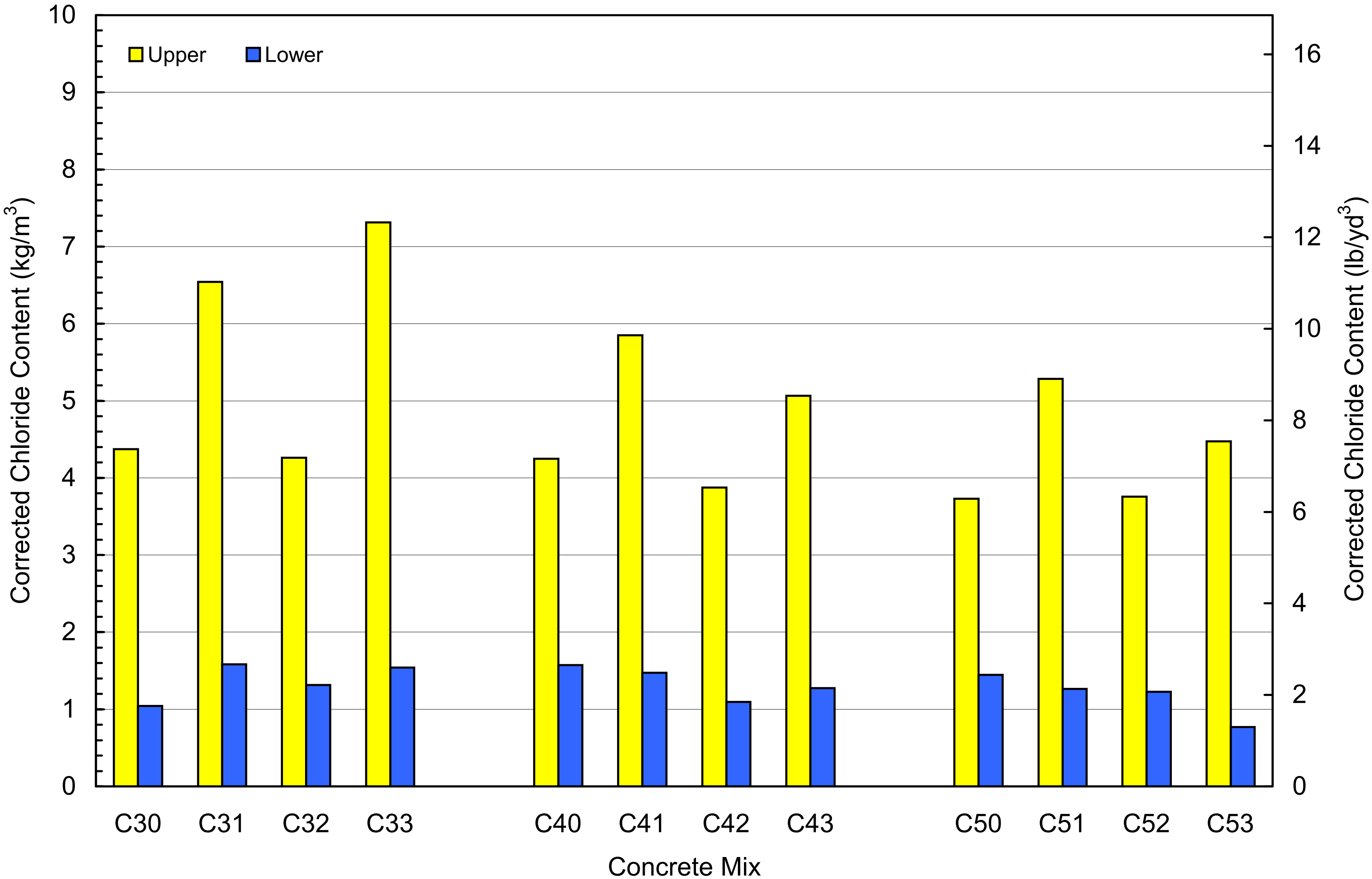

Figure 35) Baseline corrected chloride contents for the upper and lower sampling depths of the 90-day chloride ponding test for the concrete mixes in the C group.

Except for the SF735 concrete mix, testing of these mixes involved three sets of four specimens per concrete mix. This was done to allow an assessment of the variability of the test results for tests on different batches of the same mix design. For each test, chloride content values are reported for the three specimens that were ponded with the chloride solution and for the baseline specimen that was not subjected to the chloride ponding procedure. The baseline corrected average for the specimen set is determined by subtracting the chloride content of the non-ponded baseline specimen from the average of the three specimens that were ponded with the chloride solution. For the concrete mixes with multiple specimen sets, the baseline corrected values for the three specimen sets are averaged to determine the baseline corrected chloride content for the concrete mix. This value is presented in the last column in Tables 30 and 31, and it is used to compare the performance of the various concrete mixes.

Table 30) Chloride content data for the 90-day chloride ponding test for the upper sample depth of 1.6 to 12.7 mm (0.0625 to 0.5 inch) for the HP and SF concrete mix groups.

Concrete Mix	Chloride Content (kg/m^3)					
	Ponded Specimen 1	Ponded Specimen 2	Ponded Specimen 3	Non-ponded Baseline Specimen	Baseline Corrected Specimen Set Average	Baseline Corrected Concrete Mix Average
HP1	3.75	3.92	4.40	0.65	3.38	3.38
	4.16	3.49	4.30	0.74	3.24	
	4.13	4.17	4.24	0.67	3.51	
HP2	3.64	3.95	3.56	0.76	2.96	3.12
	3.20	3.93	4.48	0.74	3.13	
	3.99	3.92	4.18	0.77	3.26	
HP3	3.52	3.80	3.70	0.66	3.01	3.00
	3.39	3.78	3.48	0.72	2.83	
	3.56	3.84	4.49	0.81	3.16	
HP4	3.10	3.61	5.36	0.92	3.10	3.11
	4.26	3.97	3.71	0.89	3.09	
	3.65	4.23	4.07	0.85	3.14	
SF735	3.49	3.72	3.86	0.90	2.80	2.80
SF752	3.39	3.32	3.54	0.72	2.69	2.68
	3.61	3.56	3.37	1.14	2.38	
	3.68	4.07	3.92	0.93	2.96	
SF770	4.26	4.16	4.55	0.86	3.47	3.36
	3.22	3.46	3.84	0.88	2.63	
	4.86	4.96	4.50	0.78	3.99	

Table 31) Chloride content data for the 90-day chloride ponding test for the lower sample depth of 12.7 to 25.4 mm (0.5 to 1.0 inch) for the HP and SF concrete mix groups.

Concrete Mix	Chloride Content (kg/m^3)					
	Ponded Specimen 1	Ponded Specimen 2	Ponded Specimen 3	Non-ponded Baseline Specimen	Baseline Corrected Specimen Set Average	Baseline Corrected Concrete Mix Average
HP1	0.68	0.88	0.90	0.65	0.17	0.14
	0.75	1.04	0.89	0.74	0.15	
	0.82	0.73	0.77	0.67	0.10	
HP2	0.71	0.87	0.88	0.76	0.06	0.05
	0.72	0.89	0.86	0.74	0.08	
	0.72	0.72	0.85	0.77	0.00	
HP3	0.94	0.91	0.89	0.66	0.25	0.13
	0.72	0.90	0.83	0.72	0.09	
	0.72	0.88	0.95	0.81	0.04	
HP4	0.94	0.89	1.08	0.92	0.05	0.07
	0.82	1.08	1.01	0.89	0.08	
	0.98	0.92	0.90	0.85	0.09	
SF735	0.89	1.01	1.11	0.90	0.10	0.10
SF752	0.70	0.94	1.26	1.14	-0.17	0.01
	0.78	0.86	0.92	0.72	0.13	
	1.21	0.98	1.06	1.03	0.06	
SF770	0.86	0.89	1.07	0.86	0.08	0.04
	0.69	0.82	0.77	0.88	-0.12	
	0.95	0.99	0.85	0.78	0.15	

The results for the upper sampling depth for each of the three tests for the mixes in the HP group and mixes SF752 and SF770 are presented in Figure 36. The primary purpose of this figure is to illustrate the variability of the test results within each group of three tests performed on the same concrete mix design. The results for the concrete mixes in the HP group of mixes are remarkably consistent within each group of three. For the SF752 and the SF770 mixes, there is more variability in the test results, but the range is still reasonable considering normal variations in material properties and testing accuracies.

For the mixes in the HP and SF groups, the average corrected chloride content values for the upper and lower sampling depths are presented in Figure 37. For the HP group of mixes, the data indicate that the mix option of the concrete mix has no significant influence on the chloride ion penetration resistance of the concrete. At the lower sample depth, there was very little chloride present as a result of the 90-day chloride ponding procedure. This indicated that these concrete mixes are significantly

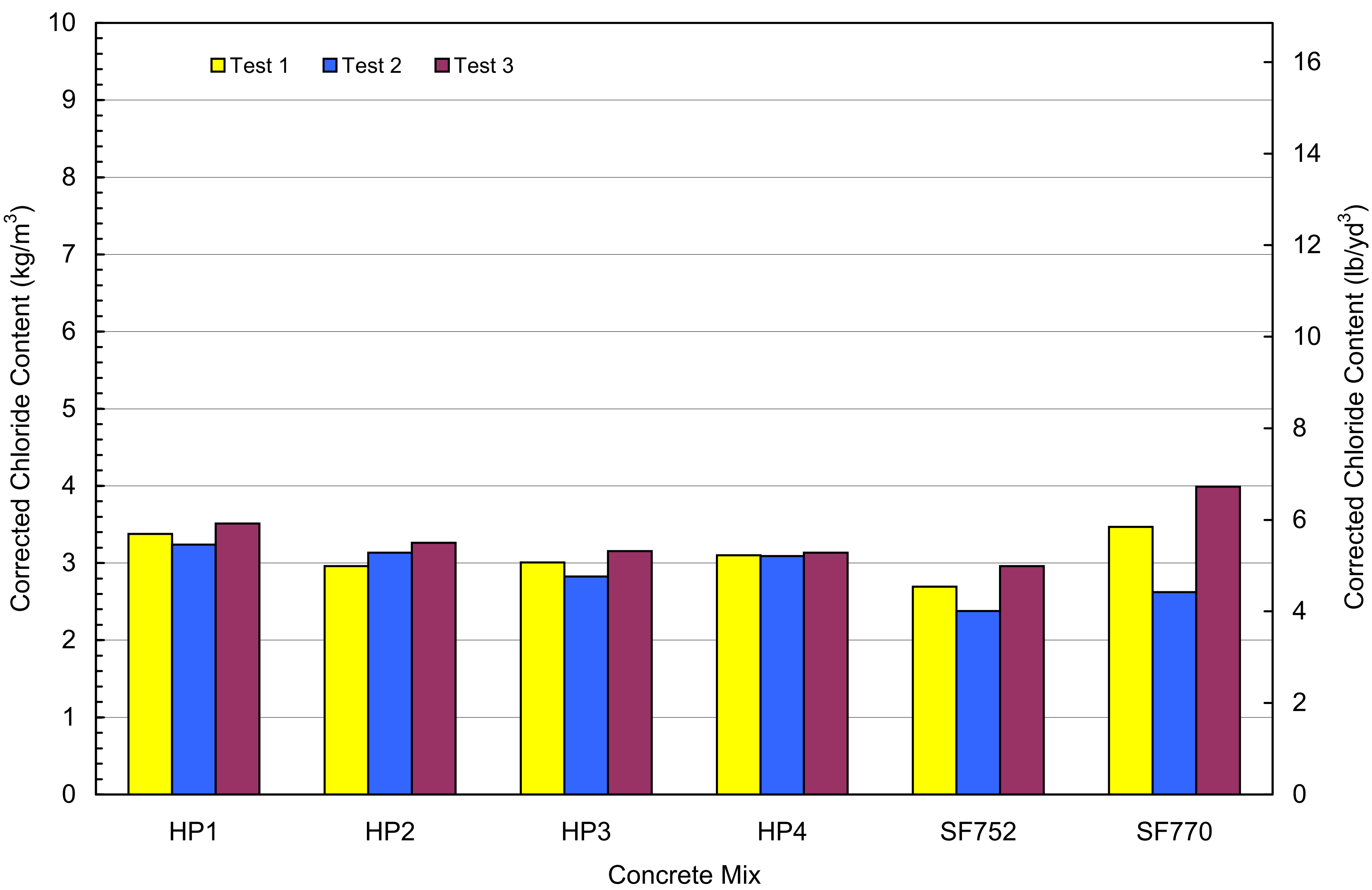

Figure 36) Baseline corrected chloride contents for the upper sampling depth of the 90-day chloride ponding test for the concrete mixes in the HP and SF groups.

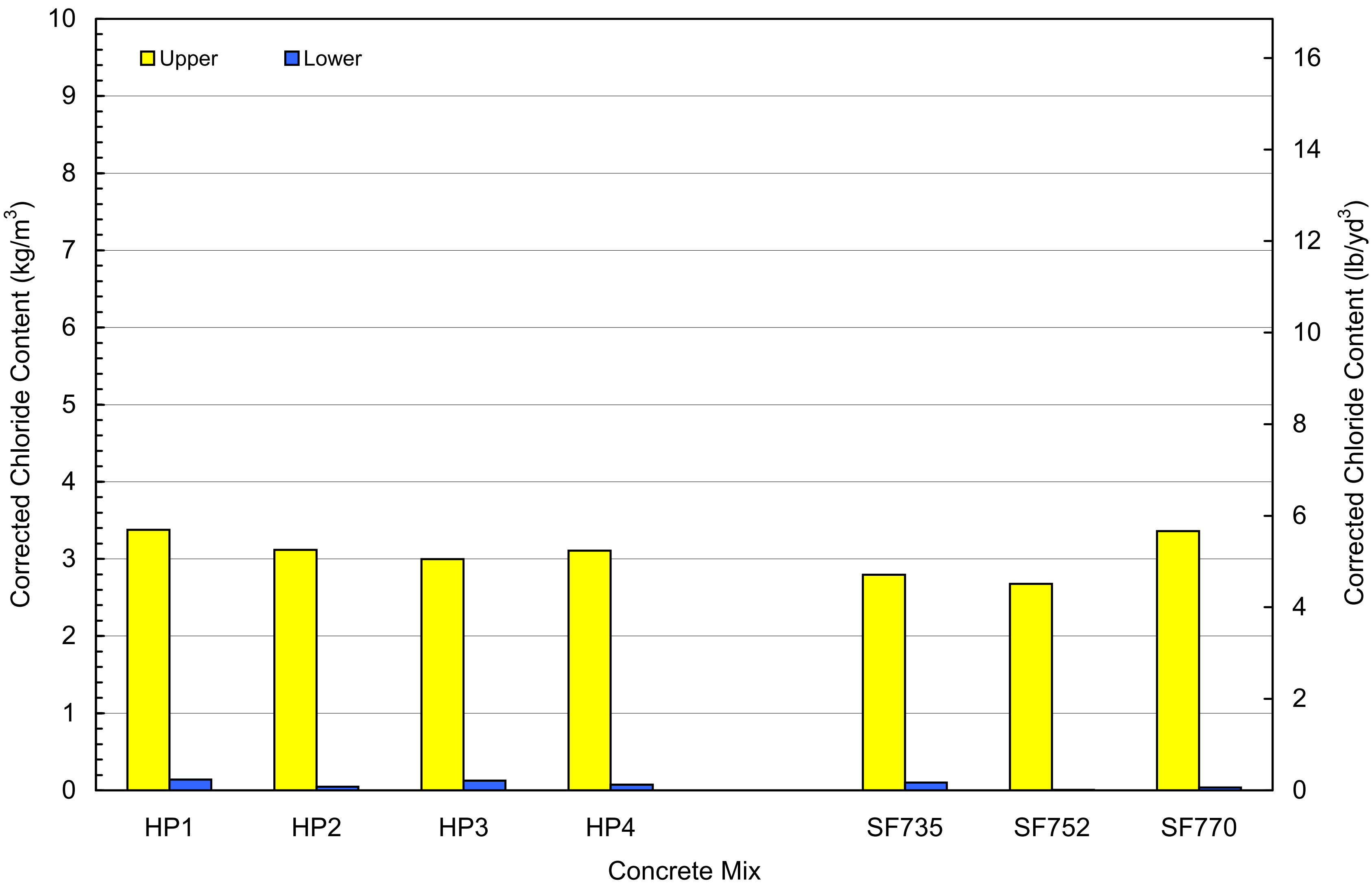

Figure 37) Baseline corrected chloride contents for the upper and lower sampling depths of the 90-day chloride ponding test for the concrete mixes in the HP and SF groups.

more resistant of chloride penetration than the mixes in the C group. The results of the rapid chloride permeability testing are consistent with these results in that they indicate that the HP mixes are more resistant to chloride penetration than the concrete mixes in the C group. This is particularly true for the rapid chloride permeability test results at 90 days. However, the rapid chloride permeability test did indicate that the mix option influenced the resistance to chloride penetration. This influence is not indicated by the results of the 90-day chloride ponding test.

The results for the SF mixes are very similar to those for the HP mixes. The difference in the amount of silica fume appears to have little if any influence on the chloride content at the two sampling depths. This is also supported by the results of the rapid chloride permeability test. For all of the mixes in the HP and SF groups, the chloride content at the lower sampling depth is well below the 0.78 kg/m3 (1.32 lb/yd3) threshold value established by AASHTO. This relatively high resistance to chloride penetration is also indicated by the results of the rapid chloride permeability test results for these concrete mixes.

FREEZE-THAW DURABILITY

The resistance to damage caused by freeze-thaw cycles was evaluated for each of the concrete mixes involved in Part II of the study using Procedure A of ASTM C 666. In this test, the specimen is surrounded by water at all times during the freezing and thawing cycles. This exposure condition is considered to be very severe because the specimen is at a higher average degree of saturation than is likely to exist under normal field conditions. The test specimens were cured in a lime-saturated water bath for 14 days prior to testing. On the fourteenth day, the dimensions, weight, and initial fundamental transverse frequency were recorded prior to placing the test specimen into the freeze-thaw cabinet. In accordance with ASTM C 666, the specimens were evaluated at intervals not exceeding 36 cycles of freezing and thawing. The testing of each specimen continued until either it was exposed to 300 cycles of freezing and thawing or until the relative dynamic elastic modulus of the specimen dropped below 60%. The relative dynamic modulus and the durability factor calculation are explained in detail in the corresponding section of this report for Part I of the study.

A durability factor in the range of 80 to 100 is interpreted as indicating that the concrete is very resistant to the damage caused by freeze-thaw cycles. Durability factors in the range of 60 to 80 are generally interpreted as indicating that the concrete will likely perform satisfactorily with respect to freeze-thaw durability under field conditions. The satisfactory performance of concrete mixes with durability factors in the range of 40 to 60 is considered to be doubtful, and durability factors of 40 or less indicate that the freeze-thaw durability is low and field performance will most likely be unsatisfactory.

For the C group of concrete mixes, two different specimen sizes were used in the freeze-thaw testing. Caution must be used in comparing the results of tests performed on specimens of different size. The concrete mixes in the C3n and C4n groups contain coarse aggregate sizes #357 and #467, respectively. For these concrete mixes, the use of the standard 76x102x406 mm (3x4x16 inch) specimen is questionable because the nominal maximum size of the coarse aggregate exceeds one-third of the least dimension of the specimen. Freeze-thaw durability testing for these concrete mixes was done using 127x127x406 mm (5x5x16 inch) specimens. For the concrete mixes in the C5n group, which have #57 crushed limestone as the coarse aggregate, freeze-thaw testing was done using both specimen sizes. This provides a means for assessing the influence of specimen size on the durability factor for that concrete mix. All of the freeze-thaw durability testing for the HP and SF concrete mix groups was done using the standard 76x102x406 mm (3x4x16 inch) specimen size.

In general, three freeze-thaw tests were performed for each concrete mix design evaluated during Part II of the study. The only exceptions are that for concrete mixes C43, C51, and HP2, only two test results are available. For the concrete mixes in the C group that were evaluated using the 127x127x406 mm (5x5x16 inch) specimens, the individual test results are presented in Table 32. Table 32 also contains the air void spacing factor determined using the modified point count method of ASTM C 457, and

Table 32) Results of freeze-thaw durability testing for tests performed using 127x127x 406 mm (5x5x16 inch) specimens for the C group of concrete mixes evaluated during Part II of the study.

Concrete Mix	Initial Fundamental Transverse Frequency	Final Fundamental Transverse Frequency	Air Content (percent)	Number of Freeze-Thaw Cycles	Air Void Spacing Factor	Durability Factor	Average Durability Factor
C30	2360	2300	6.5	300	0.0040	95	96
	2360	2312	7.0	300	0.0034	96	
	2400	2352	5.4	300	0.0044	96	
C31	2380	2320	6.2	300	0.0038	95	93
	2350	2290	7.2	300	0.0042	95	
	2450	2311	4.5	300	0.0042	89	
C32	2400	2302	7.6	300	0.0041	92	96
	2340	2340	7.2	300	0.0038	100	
	2400	2352	7.2	300	0.0035	96	
C33	2320	2237	7.0	300	0.0038	93	93
	2300	2300	6.8	300	0.0037	100	
	2340	2183	6.4	300	0.0042	87	
C40	2420	2296	6.0	300	0.0037	90	92
	2370	2286	6.4	300	0.0035	93	
	2440	2353	6.0	300	0.0047	93	
C41	2390	2317	6.8	300	0.0043	94	90
	2450	2245	5.5	300	0.0044	84	
	2410	2324	5.5	300	0.0033	93	
C42	2450	2298	6.2	300	0.0045	88	93
	2420	2359	7.0	300	0.0038	95	
	2420	2383	6.0	300	0.0051	97	
C43	2320	2273	7.4	300	0.0042	96	95
	2420	2346	5.7	300	0.0053	94	
C50	2290	2255	7.2	300	0.0045	97	95
	2400	2327	6.4	300	0.0037	94	
	2410	2349	6.8	300	0.0041	95	
C51	2310	2310	6.8	300	0.0032	100	94
	2480	2313	6.8	300	0.0038	87	
C52	2310	2263	8.3	300		96	92
	2440	2378	6.2	300	0.0048	95	
	2480	2286	6.2	300	0.0040	85	
C53	2370	2248	6.8	300	0.0059	90	91
	2390	2280	6.8	300	0.0041	91	
	2355	2271	6.8	300	0.0034	93	

the air content of the concrete determined in accordance with ASTM C 231. For each concrete mix, the average durability factor is presented in the last column of the table.

The durability factors presented in Table 32 are presented graphically in Figure 38. All of the concrete mixes in the C group had durability factors above 80, indicating that the concrete mixes are very resistant to damage caused by freeze-thaw cycles. There does not appear to be a significant correlation between either the coarse aggregate size or the mix design option and the resulting durability factor of the concrete.

The data for freeze-thaw durability testing done using the standard size specimens is presented in Table 33. The durability factors for tests performed on the concrete mixes in the C5n group using two different specimen sizes are compared in Figure 39. For these concrete mixes, the durability factors for both of the specimen sizes are above 80, indicating that the concrete mixes are very resistant to damage caused by freeze-thaw cycles. Furthermore, there is no significant difference between the test results for the two different specimen sizes. Based on this fact, the results of tests using the 127x127x406 mm (5x5x16 inch) specimens are believed to be comparable to the results of tests performed using the standard 76x102x406 mm (3x4x16 inch) specimen size. This allows the same criterion to be applied in estimating the likely field performance of the concrete mixes based on the durability factors for test results with durability factors within the range of 80 to 100. The results of the tests on the standard size specimens also supports the earlier conclusion that there does not appear to be a significant relationship between the durability factor and the mix option involved.

The freeze-thaw durability factors for the HP and SF concrete mixes are presented in Figure 40. For the HP group of mixes, the durability factors for the HP1 and HP4 mixes are above 800 except for one of the five test results. The one test result that is below 80 seems unreasonably low compared to the other two test results for the HP1 mix. For the HP2 mix, one test result is in the range indicating that field performance of the concrete is likely to be satisfactory, and the other result is between 40 and 60 indicating that satisfactory field performance is doubtful. For the HP3 mix, all three test results indicate that satisfactory field performance is doubtful.

One possible explanation for the lower than expected performance of some of the mixes in the HP group may involve the quality of the air void system. For the six specimens having durability factors less than 80, the air content values range from 5 to 7 percent, and five of the air content values were in the range of 6 to 7 percent. This suggests that the air content should have been sufficient to provide protection from freeze-thaw damage assuming the air void system was of good quality. The air void spacing factors for the mixes in the HP and SF groups tend to be higher than those reported for the mixes in the C group. Two significant differences between the C group and the SF and HP groups are that a water-reducing admixture was used in the SF and HP mixes but not in the C mixes and that different sizes of coarse aggregate were used. The coarse aggregate in the SF and HP mixes was #8 crushed limestone, and the coarse aggregate in the C mixes was either #357, #467, or #57 crushed limestone. All

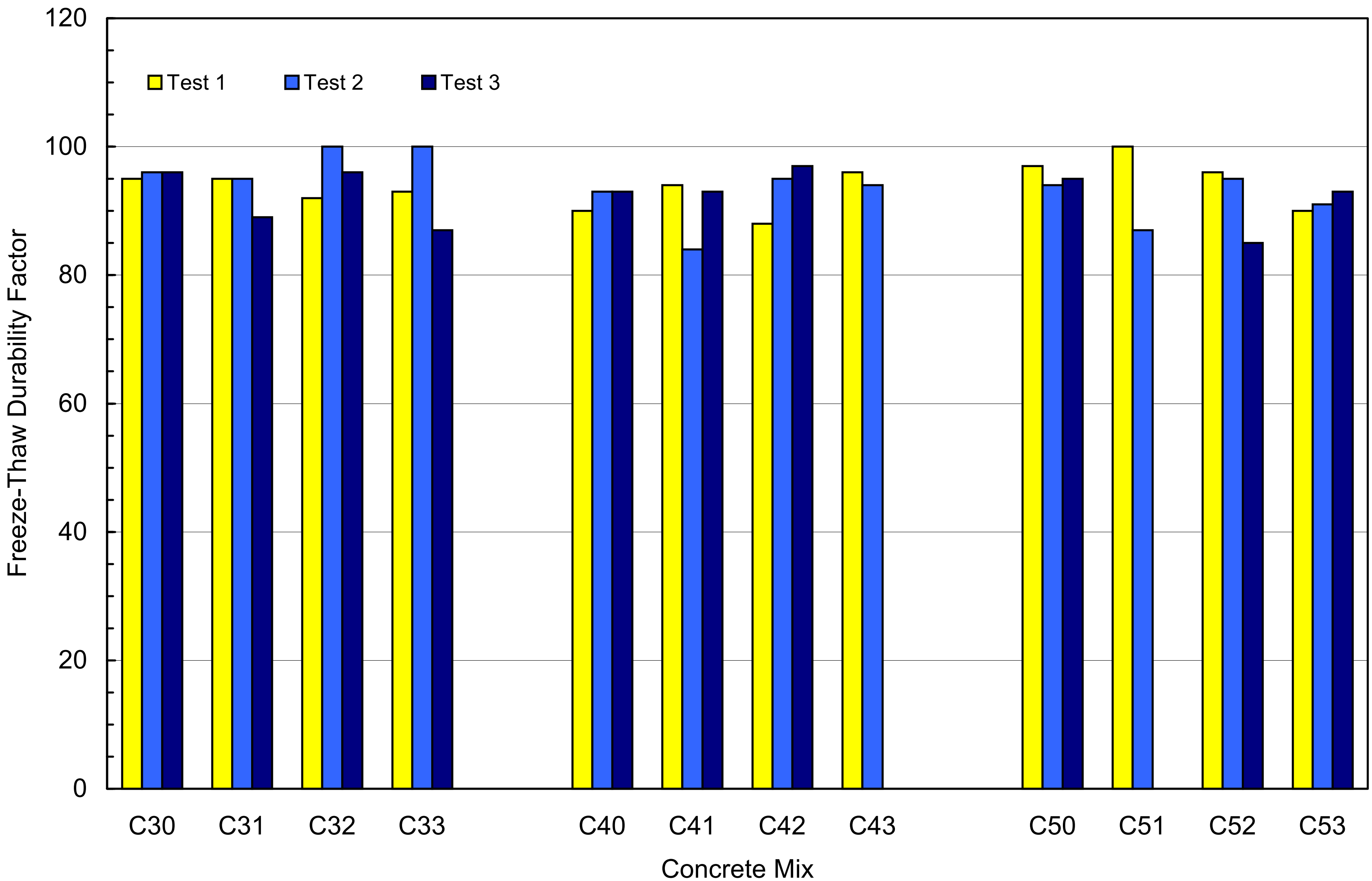

Figure 38) Freeze-thaw durability factors for tests performed using 127x127x 406 mm (5x5x16 inch) specimens for the C group of concrete mixes evaluated during Part II of the study.

Table 33) Results of freeze-thaw durability testing for tests performed using 76x102x 406 mm (3x4x16 inch) specimens for the C5, HP and SF groups of concrete mixes evaluated during Part II of the study.

Concrete Mix	Initial Fundamental Transverse Frequency	Final Fundamental Transverse Frequency	Air Content (percent)	Number of Freeze-Thaw Cycles	Air Void Spacing Factor	Durability Factor	Average Durability Factor
C50	2020	1958	6.6	300	0.0047	94	92
	2060	1976	6.0	300	0.0045	92	
	2070	1964	6.6	300		90	
C51	1984	1913	7.2	300	0.0045	93	92
	2023	1919	7.2	300	0.0038	90	
	2043	1970	6.8	300	0.0042	93	
C52	2121	2012	5.8	300	0.0041	90	91
	2018	1936	7.4	300	0.0049	92	
	2059	1964	6.4	300	0.0054	91	
C53	2040	1892	6.4	300	0.0038	86	91
	1998	1885	6.6	300	0.0036	89	
	1782	1755	8.0	300	0.0044	97	
HP1	2076	1936	9.0	300	0.0047	87	73
	2112	1636	6.5	245	0.0052	49	
	2128	1927	8.5	300	0.0044	82	
HP2	2112	1817	7.0	300	0.0058	74	60
	2100	1627	6.0	230	0.0064	46	
HP3	2170	1673	6.0	207	0.0063	41	46
	2160	1673	7.0	275	0.0070	55	
	2172	1682	5.0	210	0.0048	42	
HP4	2102	1903	6.8	300	0.0059	82	84
	2106	1964	7.0	300	0.0070	87	
	2097	1910	7.0	300	0.0075	83	
SF735	2183	2128	6.0	300	0.0052	95	93
	2160	2061	6.5	300		91	
	2195	2128	7.0	300	0.0047	94	
SF752	2200	2110	8.0	300	0.0039	92	95
	2168	2102	7.0	300	0.0062	94	
	2149	2149	5.5	300	0.0045	100	
SF770	2135	2103	7.0	300	0.0070	97	96
	2118	2118	5.5	300	0.0052	100	
	2191	2102	6.5	300	0.0048	92	

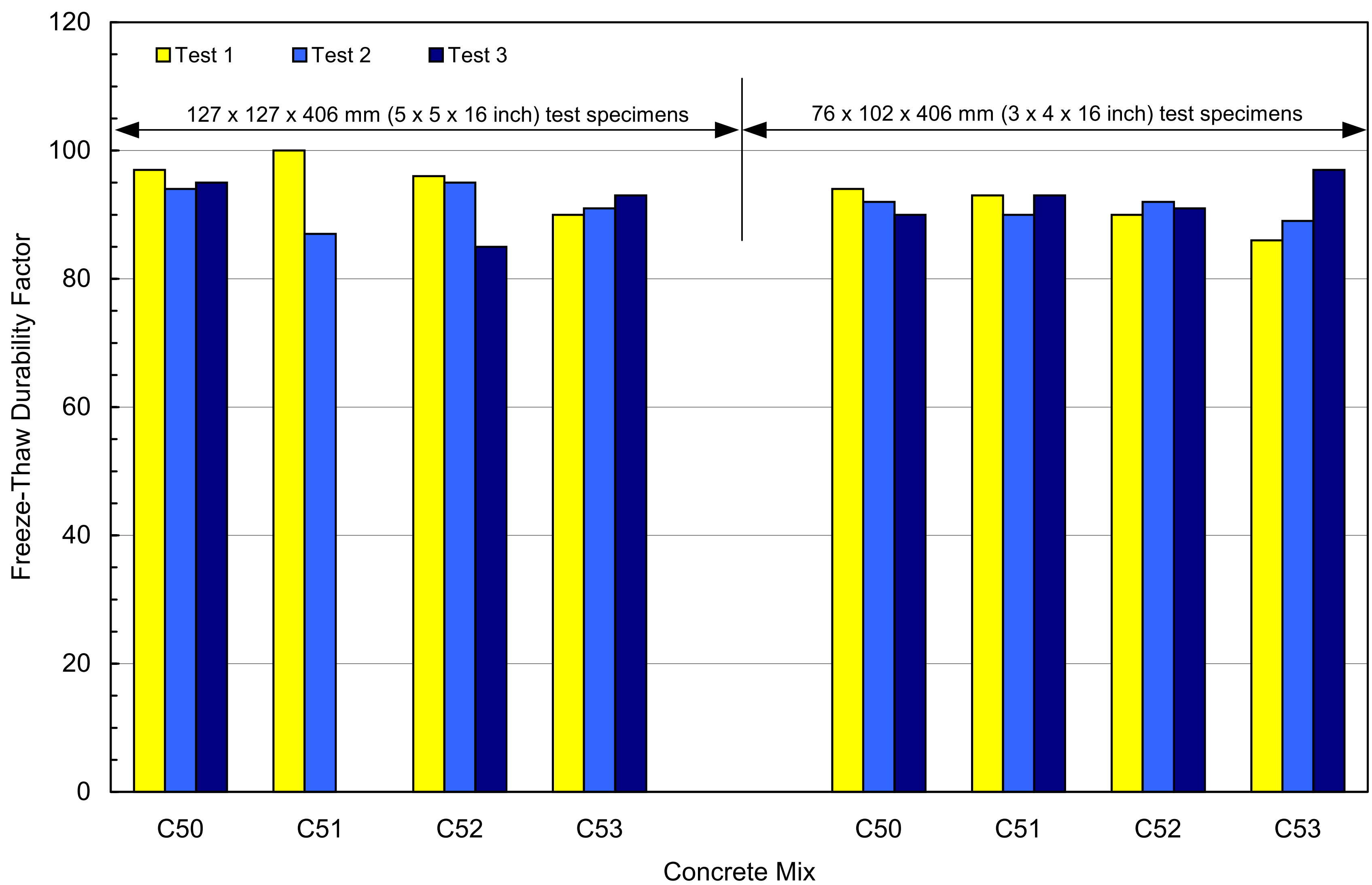

Figure 39) Freeze-thaw durability factors for tests performed using two different specimen sizes for the C5n group of concrete mixes evaluated during Part II of the study.

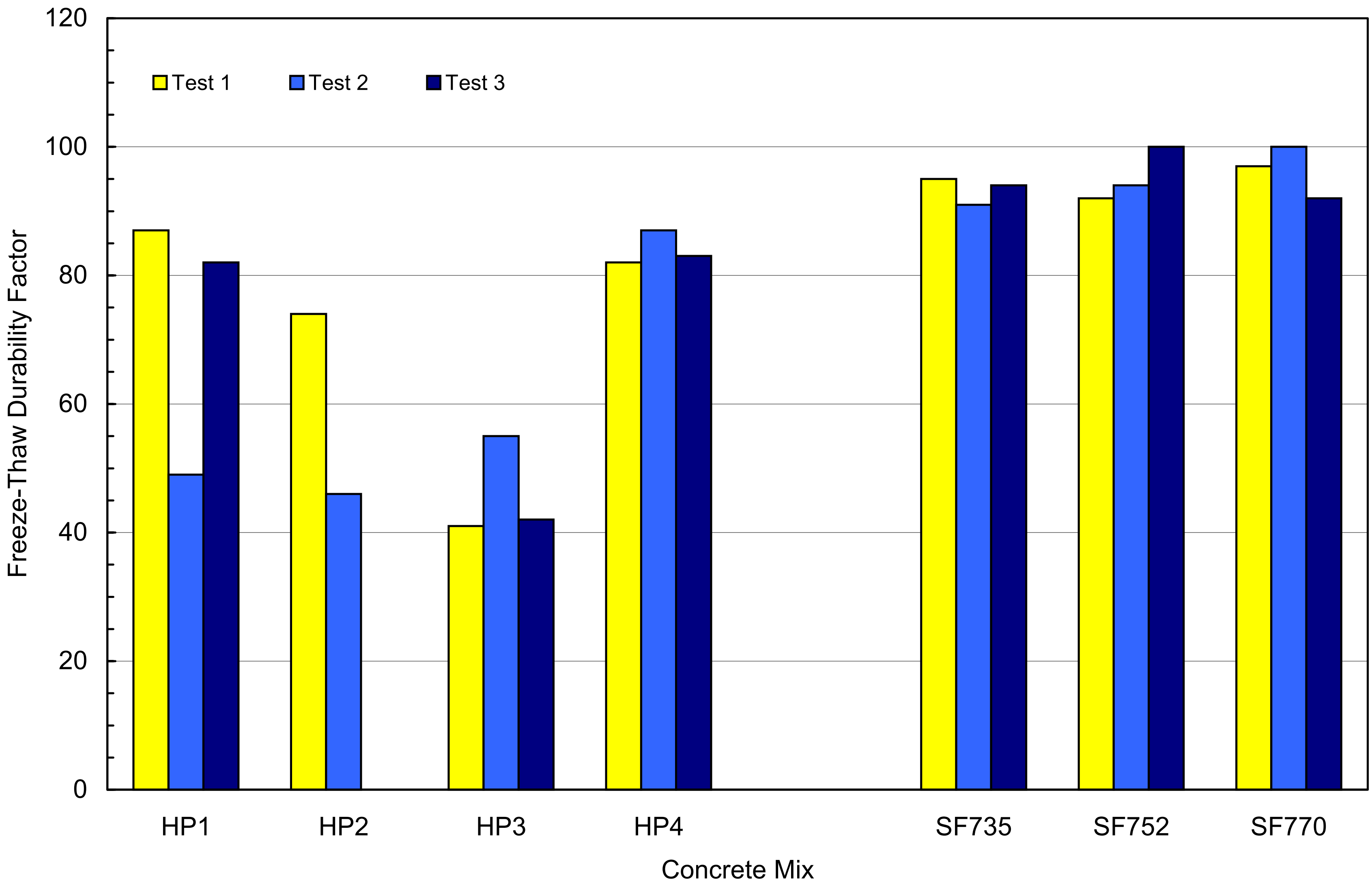

Figure 40) Freeze-thaw durability factors for tests performed using 76x102x 406 mm (3x4x16 inch) specimens for the HP and SF groups of concrete mixes evaluated during Part II of the study.

of the coarse aggregate came from the same source. It is possible that one or more of these factors had an effect on the quality of the air void system that resulted in an increase in the spacing factor and a corresponding reduction in the resistance of the concrete to damage caused by freeze-thaw cycles.

An air void spacing factor of 0.008 or less is often considered as suitable for concrete that will be subjected to moderate freeze-thaw exposure. Smaller values are generally required for more severe exposure to freeze-thaw cycles. Since the exposure associated with Method A of ASTM C 666 is considered to be very severe, it is likely that spacing factors less than 0.008 will be required to provide adequate protection from damage caused by freeze-thaw cycles. The relatively poor performance of several specimens in the HP group is attributed to an inadequate air void system as indicated by the air void spacing factor. The exact cause for the higher spacing factors for these mixes could not be determined from the available data.

The durability factors for the concrete mixes in the SF group are presented in Figure 40. All of the concrete mixes in the SF group had durability factors well above 80, indicating that these concrete mixes are very resistant to damage caused by freeze-thaw cycles. The amount of silica fume present in the mix does not appear to have any effect on the resulting durability factor of the concrete.

LENGTH CHANGE

The objectives of the length change testing were to evaluate the length change due to factors other than loading for the various mixes evaluated during Part II of the study. Of particular interest were: 1) the influence of coarse aggregate size on the length change of the concrete mixes in the C group, 2) the influence of the Class C mix option on the length change of the concrete mixes in the C group, 3) the influence of the ODOT High Performance Concrete mix option on the length change of the HP group of concrete mixes, and 4) the influence of varying the amount of silica fume in the ODOT Micro-Silica Concrete mix on the length change of the concrete mixes in the SF group.

The testing was conducted in general accordance with ASTM C 157. Since the concrete mixes in the C3n and C4n groups contained coarse aggregate sizes #357 and #467, respectively, larger than normal specimens were requires. For all of the concrete mixes in the C group, testing was performed using length change specimens that were 127x127x406 mm (5x5x16 inches) with a gage length of 375 mm (14.75 inches). For the C5n group of concrete mixes, testing was also performed using the more common specimen size of 76x76x286 mm (3x3x11.25 inches) with a gage length of 254 mm (10 inches). All of the length change testing for the HP and SF groups of concrete mixes was performed using the 76x76x286 mm (3x3x11.25 inches) specimen size.

The length change results after 64 weeks of drying at 50% relative humidity and 23.0 ± 1.7°C (73.4 ± 3.0°F) are presented in Table 34. For each concrete mix, the results of the individual tests are presented, and the average length change for each concrete mix is presented in the last column in the table. The test results for testing of the concrete mixes in the C group that were performed using the 127x127x406 mm (5x5x16 inches) specimens are presented in Figure 41. Neither the mix design option nor the size of the coarse aggregate appear to be correlated with the resulting length change behavior of the concrete. For these tests, the length change is primarily the result of shrinkage due to drying. Shrinkage due to drying is generally considered to primarily be a function of the volume of the cement paste and the water:cement ratio. The water:cement ratio is 0.48 for all of the concrete mixes in this group, and the cement paste volume fraction is between 26.0 and 28.8 percent, depending on the mix option. Since the water:cement ratio is constant and the range of the cement paste volume fraction values is relatively narrow, it is reasonable that the length change behavior of the concrete mixes would be similar. The size of the coarse aggregate in the concrete is also known to influence the amount of shrinkage of the concrete, but this is usually a secondary effect. The use of larger coarse aggregate generally allows the use of either a lower water:cement ratio or a lower cement paste volume fraction to be used without loosing workability of the concrete mix. Either of these changes involves a factor that is considered as a primary factor in determining the shrinkage behavior of the concrete. However, in the concrete mixes tested in this study, neither the cement paste volume fraction nor the water:cement ratio was altered as the coarse aggregate size was changed.

Table 34) Length change after 64 weeks of drying for the concrete mixes evaluated during Part II of the study.

Concrete Mix	Specimen Size HxWxL (mm)	Length Change After 64 Weeks of Drying (percent)			
		Specimen 1	Specimen 2	Specimen 3	Average
C30	127x127x406	0.048	0.054	0.049	0.050
C31	127x127x406	0.056	0.054	0.055	0.055
C32	127x127x406	0.047	0.047	0.047	0.047
C33	127x127x406	0.050	0.055	0.053	0.053
C40	127x127x406	0.050	0.056	0.056	0.054
C41	127x127x406	0.050	0.047		0.048
C42	127x127x406	0.047	0.054	0.047	0.049
C43	127x127x406	0.057	0.050	0.057	0.055
C50	127x127x406	0.047	0.051	0.051	0.050
C51	127x127x406	0.045	0.043	0.045	0.044
C52	127x127x406	0.055	0.050	0.051	0.052
C53	127x127x406	0.046	0.051		0.049
C50	76x76x286	0.042	0.048	0.048	0.046
C51	76x76x286	0.040	0.045		0.043
C52	76x76x286	0.049	0.053	0.054	0.052
C53	76x76x286	0.047	0.053	0.045	0.048
HP1	76x76x286	0.042	0.045	0.039	0.042
HP2	76x76x286	0.044	0.041	0.044	0.043
HP3	76x76x286	0.038	0.043	0.034	0.038
HP4	76x76x286	0.044	0.038	0.039	0.040
SF735	76x76x286	0.032	0.038	0.041	0.037
SF752	76x76x286	0.038	0.031	0.032	0.034
SF770	76x76x286	0.039	0.032	0.037	0.036

For the concrete mixes in the C5n group, two different specimen sizes were used for length change testing to evaluate the influence, if any, on the length change test results after 64 weeks of drying. The data for the two different specimen sizes are compared in Figure 42. Based on this data and for the test specimen sizes involved, there doesn't appear to be any correlation between specimen size and the amount of length change after 64 weeks of drying. This suggests that the results obtained from tests performed using the larger specimens are comparable to the results obtained from testing using the normal size specimens.

The length change values after 64 weeks of drying for the concrete mixes in the HP and SF groups are presented in Figure 43. The length change values for the mixes in these two groups are slightly less than those for the concrete mixes in the C group. This is probably primarily due to the lower water:cement ratios used in these mixes compared to that used in the mixes in the C group. Furthermore, the length change

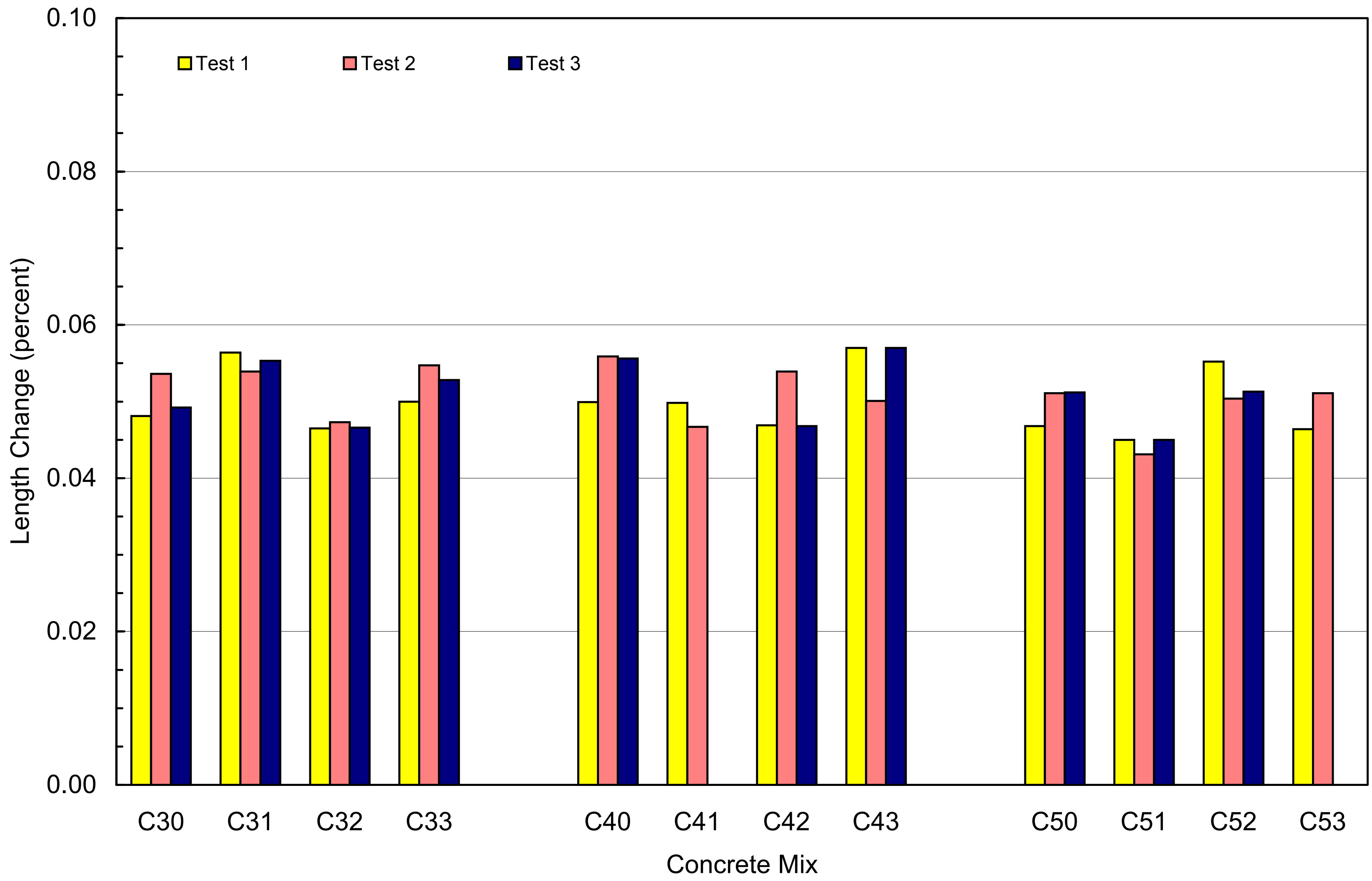

Figure 41) Length change after 64 weeks of drying for 127x127x406 mm (5x5x16 inches) specimens for the C group of concrete mixes evaluated during Part II of the study.

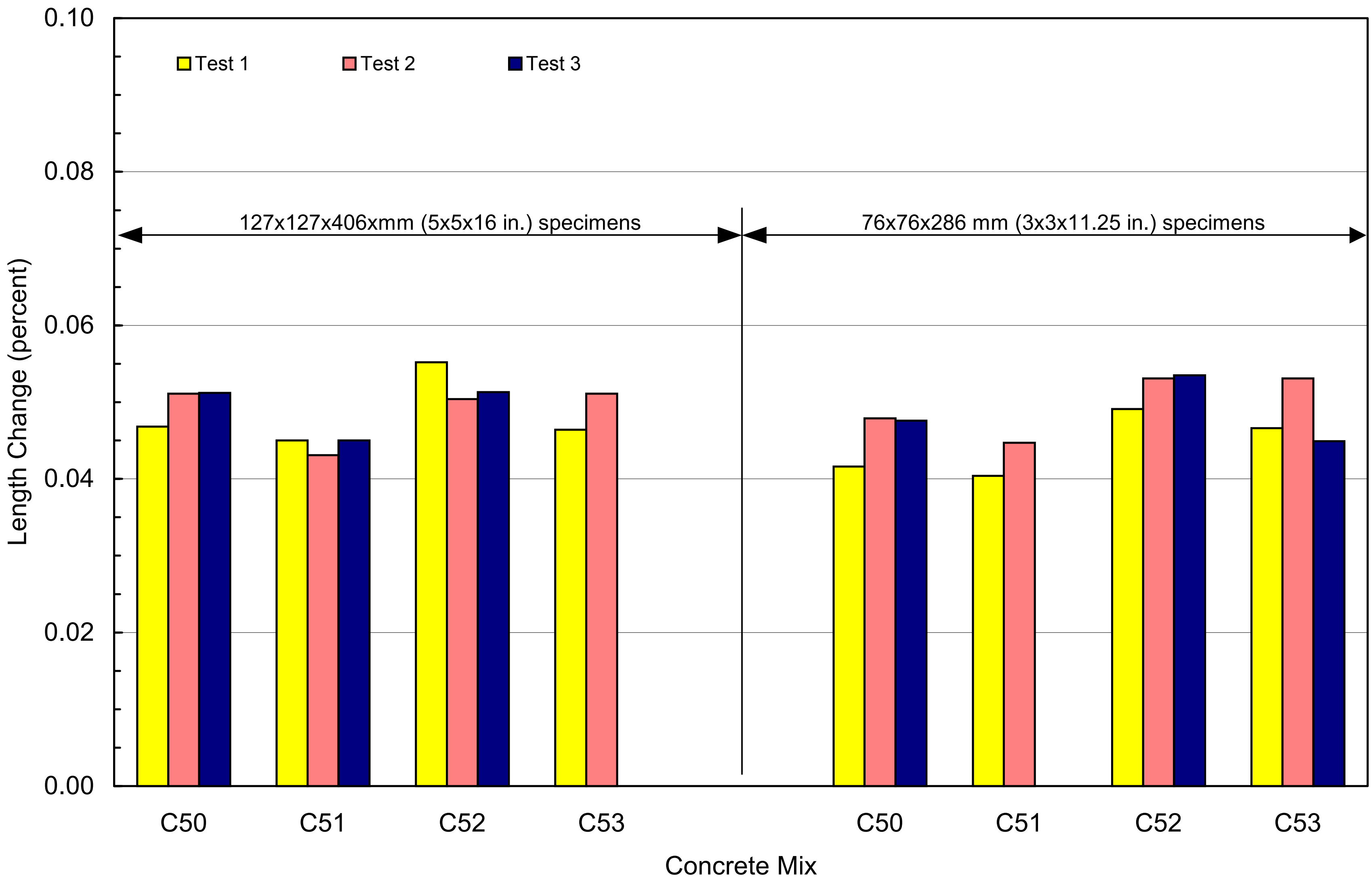

Figure 42) Length change after 64 weeks of drying for 127x127x406 mm (5x5x16 inches) specimens and 76x76x286 mm (3x3x11.25 inches) specimens for the C5n group of concrete mixes evaluated during Part II of the study.

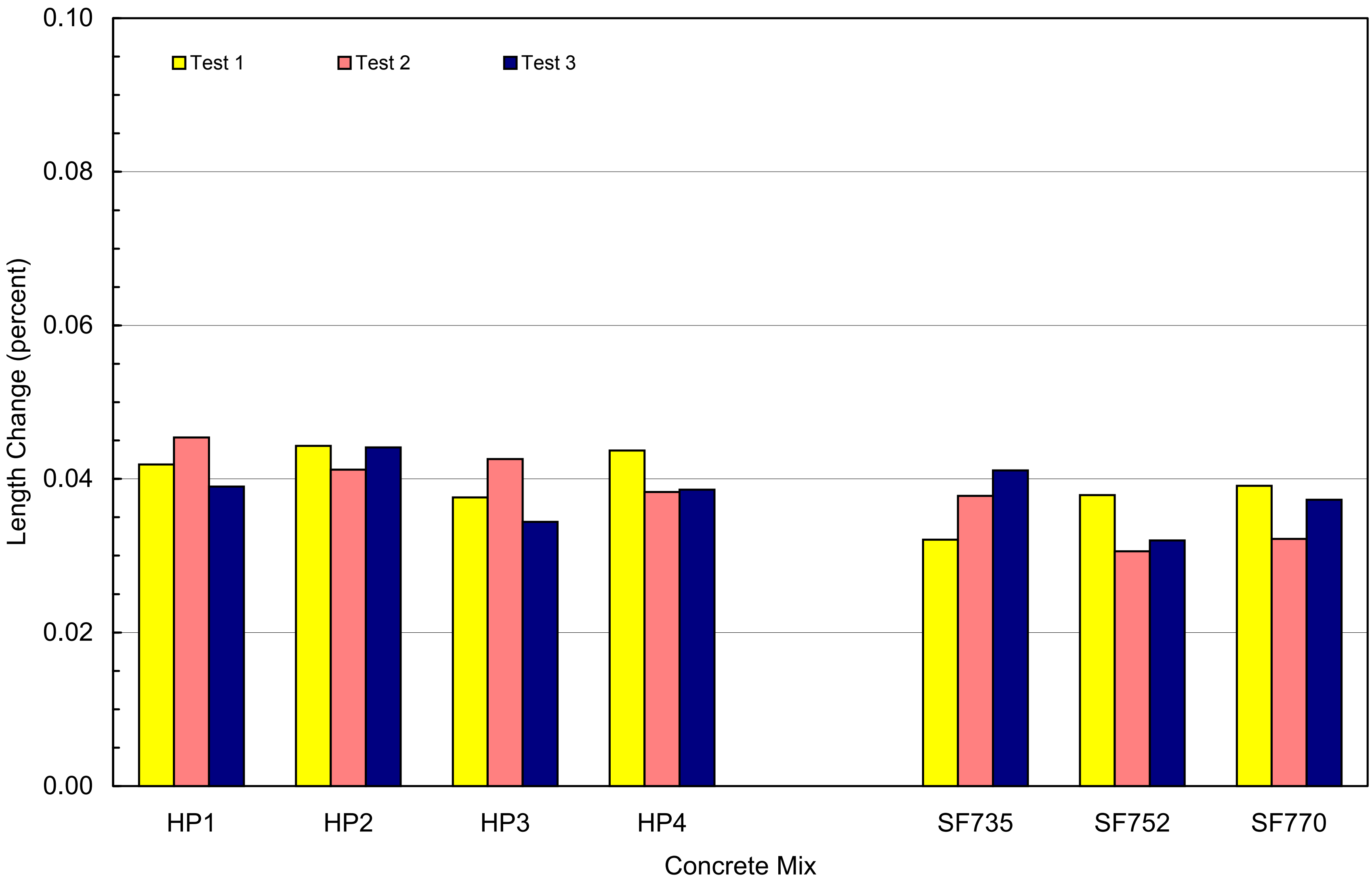

Figure 43) Length change after 64 weeks of drying for 76x76x286 mm (3x3x11.25 inches) specimens for the HP and SF groups of concrete mixes evaluated during Part II of the study.

values for the mixes in the SF group are slightly less than those for the mixes in the HP group. The water:cement ratios are in the range of 0.38 to 0.40 for the HP mix group, and the water:cement ratio for the SF group of mixes is 0.32. For the C group of mixes, the water:cement ratio was 0.48. Overall, the data conform to the generally accepted trend of decreasing length change due to drying as the water:cement ratio decreases.

CONCLUSIONS AND RECOMMENDATIONS

PART I – INFLUENCE OF GGBFS ON THE STRENGTH AND DURABILITY OF CONCRETE

The research presented in this report consisted mainly of an extensive laboratory investigation to evaluate the influence of replacing various amounts of portland cement with ground granulated blast furnace slag (GGBFS) on the strength and durability of the resulting concrete. Additional secondary aspects of the research included evaluating the influence of the type of fly ash used in combination with the GGBFS, the influence of the alkalinity of the cement used in combination with the GGBFS, the use of Type K cement in combination with GGBFS, and the use of GGBFS in combination with silica fume.

The study was primarily a laboratory investigation. Therefore, the temperature and curing conditions are much more standardized than those present under field conditions. The evaluation of the influence of ambient temperature and curing conditions on the properties of the concrete mixes evaluated during this study was beyond the scope of the project. However, it is generally recognized that as the amount of GGBFS incorporated into the concrete mix increases, the hydration process becomes slower and the rate of strength gain decreases. As a result, there is more time for the concrete to dissipate the heat generated during hydration. During moderate to warm weather periods this may be an advantage. During cold weather concrete placement, extra precautions may be necessary to protect the concrete during the curing period, and the curing period may need to be extended.

Based on the results of the testing performed during this study, the following conclusions are offered.

1) The incorporation of Grade 120 GGBFS into the ODOT Class S concrete mix design resulted in concrete that had compressive strengths at 14 days and beyond that were equal to or greater than those for the standard Class S baseline mix for mixes with GGBFS replacement rates of 55% and less.

2) The incorporation of Grade 120 GGBFS into the ODOT Class S concrete mix design resulted in concrete that had compressive strengths at 7 days or less that were clearly less than those for the standard Class S baseline mix for all levels of GGBFS replacement evaluated. At these early ages, the reduction in compressive strength increased as the amount of GGBFS in the mix increased.

3) The incorporation of either Class C or Class F fly ash along with a 65/35 blend of portland cement and GGBFS resulted in a reduction of compressive strength at all test ages compared to the standard Class S baseline mix.

4) Concrete mixes using Type K cement in combination with 35 or 55 percent GGBFS replacement of the portland cement had compressive strengths at 14 days and beyond that were equal to or greater than those for the standard Class S baseline

mix. At ages less than 7 days, the incorporation of GGBFS at these rates resulted in compressive strengths that were less than those for either the standard Class S baseline mix or the Class S mix design using Type K cement.

5) The alkali level of the portland cement used in combination with the Grade 120 GGBFS appeared to have very little effect on the resulting compressive strength for the GGBFS replacement rates of 35 and 55 percent that were evaluated.

6) Incorporating Grade 120 GGBFS at 35 and 55 percent replacement for portland cement in the ODOT Micro-Silica Concrete resulted in reduced compressive strengths at ages of 7 days and less. For test ages of 14 days or more, on average the strengths for the mixes with GGBFS were similar to those for the standard ODOT Micro-Silica Concrete mix.

7) The influence of the incorporation of GGBFS into the concrete mix designs on the modulus of rupture of the concrete was very similar to the influence of the GGBFS on the compressive strength of the concrete. This is evidenced by the relative uniformity of the ratio of the modulus of rupture to the square root of the compressive strength for the various mixes evaluated.

8) The influence of the incorporation of GGBFS into the concrete mix designs on the splitting tensile strength of the concrete was very similar to the influence of the GGBFS on the compressive strength of the concrete. This is evidenced by the relative uniformity of the ratio of the splitting tensile strength to the square root of the compressive strength for the various mixes evaluated.

9) The charge passed during the rapid chloride permeability test is dramatically reduced by the incorporation of Grade 120 GGBFS into the Class C concrete mix. The charge passed by the mix containing 55% GGBFS was less than one-third of the charge passed by the ODOT Class S baseline mix.

10) The ODOT Micro-Silica Concrete and the variations of this mix design incorporating either 35 or 55 percent Grade 120 GGBFS had coulomb ratings of 500 coulombs or less. As for the Class S mix group, the charge passed during the test decreased as the amount of GGBFS in the mix increased.

11) The length change behavior of the concrete mixes seemed to be relatively unaffected by the use of GGBFS at the various levels evaluated or by the alkalinity of the cement used in combination with the GGBFS.

12) The least amount of length change was for the two mixes incorporating 15 percent fly ash in combination with a 65/35 blend of portland cement and GGBFS. The class of fly ash used seemed to have no significant effect on the length change behavior of the two mixes.

13) Abrasion test results indicate that there may be a reduction in resistance to abrasion as the GGBFS loading increases. However, for GGBFS at 45% or less,

the correlation between the amount of GGBFS in the concrete and the abrasion resistance of the concrete is not clearly defined.

14) In general, freeze-thaw testing indicated that there is only a slight decrease in the resistance to damage caused by freeze-thaw cycles as the amount of GGBFS in the concrete increases.

15) With one exception, the freeze-thaw durability factors for the concrete mixes in the SnnS series containing up to 70% GGBFS were in the range of 80 to 100, indicating very high resistance to damage caused by freeze-thaw cycles. The lower performance of the S55S mix is attributed to an inadequate air void system.

16) Provided that an adequate system of entrained air is present, the concrete mixes evaluated during this part of the study are all expected to have adequate or very high resistance to damage caused by freeze-thaw cycles.

17) Based on the various tests performed during this study, the use of up to 55% Grade 120 GGBFS as a replacement for portland cement seems appropriate provided that early-age strength is not a critical consideration. The partial replacement of portland cement with Grade 120 GGBFS is expected to result in improved long term strength, improved resistance to chloride penetration, essentially unchanged resistance to freeze-thaw damage, and essentially unchanged length change characteristics.

18) The incorporation of Grade 120 GGBFS was found to have a slight positive water demand – as the amount of GGBFS in the concrete mix increases, the slump of the concrete decreases slightly.

19) For the admixtures used in the study, the required dosage of the air-entraining admixture increased as the amount of GGBFS in the concrete mix increased.

PART II – INFLUENCE OF COARSE AGGREGATE SIZE ON THE STRENGTH AND DURABILITY OF CONCRETE

The primary objective of Part II of the study was to evaluate the influence of the size of coarse aggregate used in concrete mixes proportioned according to the various mix options for ODOT Class C concrete on the strength and durability of the resulting concrete. In addition, the influence of the amount of silica fume in the ODOT Micro-Silica Concrete mix on the strength and durability of the concrete was to be evaluated, and the possibility of reducing the amount of cementitious material in the ODOT High Performance Concrete mixes was to be investigated. These objectives were accomplished with the exception of developing modified mix designs for the ODOT High Performance Concrete mixes.

Testing of the current ODOT High Performance Concrete mix designs was completed as planned. The objective in developing modified mix designs for the ODOT High Performance Concrete mix designs was to arrive at concrete mixes with 15% less cementitious material and suitable strength, durability, and workability characteristics. This portion of the project was unsuccessful because efforts to develop modified mix designs with reduced cementitious materials content resulted in mixes that lacked proper workability and/or cohesiveness for all four of the mix options in the ODOT High Performance Concrete group of mix designs. At the initiation of Part II of the project, some ODOT personnel expressed concerns that it may not be possible to significantly reduce the cementitious materials in these mixes and produce concrete with suitable characteristics in terms of workability and finishability. These concerns are confirmed by the findings of this study for the aggregate materials involved.

Based on the results of the tests completed during Part II of the study, the following conclusions are offered.

1) For the three coarse aggregate sizes evaluated in the study, the size of the coarse aggregate did not have a significant and/or consistent effect on the compressive strength of the resulting concrete mixes. The #57 coarse aggregate did tend to produce slightly higher compressive strengths than the larger coarse aggregates in some cases.

2) The four mix design options available in the ODOT Class C mix design appear to result in nearly identical compressive strengths for test ages ranging from 7 days to 90 days.

3) For the mix options in the ODOT High Performance Concrete mix design, options 2, 3, and 4 exhibited compressive strengths at 28 and 90 days that were noticeably higher than those for mix design option 1.

4) Compression test results for the three mixes in the SF series indicate that the compressive strength of the concrete increased slightly as the amount of silica fume in the mix was reduced from 10% of the weight of the portland cement to 5% of the weight of the portland cement. The actual increase in strength is considered to be less significant than the fact that reducing the silica fume content by 50% did not result in a reduction in strength.

5) The results for flexural strength testing support conclusions similar to those for the compressive strength except that there was no flexural strength testing performed at the 90 day age. The correlation between the modulus of rupture and the compressive strength of the concrete is evidenced by the relatively narrow range of values for the ratio of the modulus of rupture to the square root of the compressive strength.

6) Rapid chloride permeability testing on 152 mm (6 inch) diameter specimens for the concrete mixes in the Class C group of mix designs are essentially useless due to the excessive temperature increase in the test specimen caused by the larger current drawn as a result of the larger specimen.

7) Rapid chloride permeability testing on standard size specimens indicates that as the coarse aggregate size increases there is a slight tendency for the resistance to

chloride penetration to decrease. In most cases, the amount of difference in the charged passed is fairly small, and in other cases there is no change at all.

8) For all of the mixes based on the Class C mix options, the resistance to chloride penetration, as indicated by the rapid chloride permeability test, decreases significantly as the specimen age increases from 28 days to 90 days.

9) Of the four mix options available in the ODOT Class C mix design, option 3 consistently resulted in the greatest resistance to chloride penetration as indicated by the results of the rapid chloride permeability test. At the 90-day test age, this mix option has a chloride permeability rating of low.

10) For mix options 1 and 2 of the ODOT Class C mix designs and for the standard ODOT Class C mix design, the chloride permeability rating at 28 days is either high or on the high side of the moderate range. At the 90-day test age, these mix designs all have chloride permeability ratings in the moderate range.

11) The charge passed during the rapid chloride permeability test was nearly identical for mix options 3 and 4 of the ODOT High Performance Concrete mix options, the standard ODOT Micro-Silica Concrete mix, and a mix similar to the ODOT Micro-Silica Concrete mix with a 25% reduction in the amount of silica fume. For all four of these mixes, the charge passed during the test was 500 coulombs, indicating that these concretes all have very low permeability with respect to chloride penetration.

12) The results of the 90-day chloride ponding test are generally in agreement with the results of the rapid chloride permeability tests. For the ODOT Class C concrete mix design options, the chloride contents at both the upper and lower sampling depths are above the AASHTO threshold value of 0.87 kg/m^3 (1.32 lb/yd^3) at which corrosion of the reinforcing steel is expected to begin. This indicates that these concrete mixes are relatively permeable to chloride penetration.

13) For the ODOT High Performance Concrete mix options, the ODOT Micro-Silica Concrete mix, and the modified forms of the ODOT Micro-Silica Concrete mix, the 90-day chloride ponding test indicated that very little chloride reached the lower sampling depth. All of the concrete mixes in these groups had chloride contents at the lower sampling depth that were well below the AASHTO threshold value of 0.87 kg/m^3 (1.32 lb/yd^3) at which corrosion of the reinforcing steel is expected to begin. In general, these results are consistent with the results of the rapid chloride permeability testing for these concrete mix designs.

14) The freeze-thaw durability factors for all of the ODOT Class C mix design options and for all three coarse aggregate sizes were above 80, indicating that the concretes are very resistant to damage caused by freeze-thaw cycles. There is no clear correlation between the freeze-thaw durability factor and either the mix design option or the size of coarse aggregate.

15) The freeze-thaw durability factors for the mix options 1, 2, and 3 of the ODOT High Performance Concrete mix designs were lower than expected. This is believed to be due to higher than expected values of the air void spacing factor. The cause of the higher than expected air void spacing factor could not be determined.

16) For the ODOT Micro-Silica Concrete mix design and the two modifications of that design, all of the freeze-thaw durability factors were above 80, indicating that these concrete mixes all have very high resistance to damage caused by freeze-thaw cycles. Reducing the amount of silica fume in the mix design from 10% of the weight of the portland cement to 5% of the weight of the portland cement did not result in a significant change in the freeze-thaw durability factor of the concrete.

17) There is no clear correlation between the length change behavior of the concrete and either the mix design option or the size of the coarse aggregate for the ODOT Class C mix options.

18) For the ODOT High Performance Concrete mix options, there is no correlation between the length change behavior of the concrete and the mix design option.

19) For the ODOT Micro-Silica Concrete mix design and the two modifications of that design, reducing the amount of silica fume in the mix design from 10% of the weight of the portland cement to 5% of the weight of the portland cement did not result in a significant change in length change after 64 weeks of drying.

APPENDIX A

STRENGTH TEST RESULTS FOR PART I OF THE STUDY

Table A-1) Individual compression test results for Part I of the study.

Concrete Mix	Compressive Strength, MPa (psi)					
	Specimen Age					
	1 day	3 days	7 days	14 days	28 days	90 days
S00S	13.81 (2003)	24.27 (3520)	30.50 (4424)	34.43 (4993)	38.67 (5608)	43.08 (6248)
	12.79 (1855)	24.33 (3529)	31.18 (4523)	35.02 (5079)	38.56 (5593)	43.60 (6324)
	11.29 (1637)	21.84 (3168)	28.91 (4193)	30.27 (4391)	37.00 (5367)	42.42 (6152)
	11.33 (1643)	22.03 (3195)	29.08 (4218)	32.32 (4687)	36.08 (5233)	42.14 (6112)
	13.60 (1973)	25.95 (3764)	30.74 (4459)	34.58 (5015)	39.91 (5789)	46.19 (6700)
	13.46 (1952)	25.20 (3655)	32.38 (4696)	35.92 (5210)	39.00 (5656)	52.34 (7591)
	13.46 (1952)	28.45 (4127)	36.17 (5246)	40.53 (5878)	42.48 (6161)	50.21 (7282)
	13.98 (2028)	29.49 (4277)	35.96 (5215)	39.14 (5677)	45.15 (6548)	51.62 (7487)
	12.27 (1779)	26.46 (3837)	35.32 (5123)	39.69 (5756)	44.00 (6382)	51.52 (7473)
	12.08 (1752)	25.77 (3737)	36.14 (5241)	40.16 (5824)	45.26 (6565)	51.39 (7454)
			33.73 (4892)		42.00 (6092)	
			33.85 (4910)		42.06 (6101)	
			32.12 (4658)		44.01 (6383)	
			30.68 (4450)			
			31.54 (4574)			
Average	12.81 (1857)	25.38 (3681)	32.55 (4721)	36.20 (5251)	41.09 (5960)	47.45 (6882)
S25S	11.08 (1607)	23.79 (3450)	35.82 (5195)	44.04 (6388)	50.89 (7381)	55.59 (8062)
	10.68 (1549)	23.53 (3413)	35.97 (5217)	43.29 (6279)	51.66 (7492)	56.79 (8237)
	9.02 (1308)	20.56 (2982)	33.05 (4794)	42.15 (6114)	46.46 (6738)	55.18 (8003)
	9.11 (1321)	20.59 (2987)	33.18 (4812)	42.35 (6143)	48.61 (7051)	55.73 (8083)
	9.11 (1321)	19.96 (2895)	30.72 (4455)	38.49 (5583)	43.85 (6360)	54.80 (7948)
	8.96 (1300)	20.11 (2917)	31.15 (4518)	39.75 (5765)	45.75 (6636)	52.12 (7560)
	10.07 (1461)	20.90 (3032)	31.01 (4497)	38.18 (5538)	44.86 (6507)	52.12 (7560)
	9.83 (1425)	21.46 (3112)	31.10 (4510)	37.63 (5458)	42.70 (6193)	49.21 (7137)
	8.18 (1187)	17.96 (2605)	28.72 (4165)	35.80 (5193)	41.95 (6084)	45.93 (6661)
	7.97 (1156)	18.38 (2666)	29.25 (4243)	35.51 (5151)	39.56 (5737)	46.56 (6753)
			27.52 (3992)		41.73 (6053)	
			27.18 (3942)		41.01 (5948)	
			27.00 (3916)		35.87 (5202)	
			28.21 (4092)			
			23.81 (3454)			
			24.85 (3604)			
Average	9.40 (1364)	20.72 (3006)	29.91 (4338)	39.72 (5761)	44.22 (6414)	52.40 (7600)

Table A-1 cont.) Individual compression test results for Part I of the study.

Concrete Mix	Compressive Strength, MPa (psi)					
	Specimen Age					
	1 day	3 days	7 days	14 days	28 days	90 days
S35S	6.56 (951)	16.44 (2385)	27.21 (3946)	36.11 (5237)	40.87 (5927)	46.87 (6798)
	6.64 (963)	16.46 (2387)	27.04 (3922)	35.87 (5203)	41.86 (6071)	48.05 (6969)
	7.20 (1044)	17.47 (2534)	27.83 (4037)	37.90 (5497)	41.29 (5989)	50.07 (7262)
	7.00 (1015)	17.41 (2525)	27.37 (3969)	36.89 (5351)	42.04 (6098)	50.54 (7330)
	8.97 (1301)	19.75 (2864)	33.63 (4878)	44.42 (6443)	49.59 (7192)	57.01 (8269)
	8.82 (1279)	20.87 (3027)	33.25 (4823)	44.62 (6472)	49.75 (7215)	51.47 (7465)
	7.97 (1156)	18.82 (2730)	29.41 (4265)	36.88 (5349)	44.39 (6438)	49.75 (7216)
	7.65 (1110)	18.49 (2682)	28.29 (4103)	36.01 (5223)	42.24 (6127)	48.08 (6973)
	4.15 (602)	13.80 (2001)	23.32 (3382)	31.04 (4502)	36.24 (5256)	41.67 (6043)
	4.92 (714)	13.40 (1944)	23.22 (3368)	31.10 (4510)	37.31 (5412)	42.81 (6209)
			26.39 (3828)		42.99 (6235)	
			25.73 (3732)		39.90 (5787)	
			24.97 (3621)		35.14 (5097)	
			24.32 (3528)		36.07 (5232)	
			24.48 (3550)		39.36 (5709)	
			24.99 (3625)			
			21.87 (3172)			
			22.34 (3240)			
Average	6.99 (1014)	17.29 (2508)	26.43 (3833)	37.08 (5379)	41.27 (5986)	48.63 (7053)
S45S	7.01 (1016)	18.75 (2719)	31.27 (4536)	39.93 (5792)	47.84 (6939)	56.81 (8239)
	6.95 (1008)	19.21 (2786)	33.23 (4819)	43.47 (6305)	47.55 (6896)	57.49 (8338)
	5.09 (738)	15.32 (2222)	27.83 (4036)	38.20 (5540)	45.77 (6638)	50.32 (7298)
	5.05 (732)	15.40 (2233)	28.14 (4082)	38.78 (5625)	45.05 (6534)	51.45 (7462)
	6.07 (880)	16.24 (2355)	27.79 (4031)	37.33 (5414)	41.02 (5950)	50.31 (7297)
	5.94 (862)	16.44 (2385)	27.65 (4010)	37.74 (5474)	43.84 (6359)	51.41 (7457)
	5.94 (862)	16.25 (2357)	27.82 (4035)	38.67 (5609)	43.80 (6352)	48.81 (7079)
	5.94 (861)	15.84 (2297)	27.36 (3968)	37.83 (5487)	41.22 (5979)	47.40 (6875)
	4.23 (613)	13.99 (2029)	26.43 (3834)	34.98 (5073)	42.55 (6172)	48.71 (7065)
	4.21 (610)	13.58 (1970)	25.85 (3749)	34.83 (5051)	41.83 (6067)	48.97 (7103)
			25.26 (3663)		42.62 (6181)	
			25.57 (3708)		41.88 (6074)	
			22.68 (3289)		36.71 (5324)	
			23.06 (3344)		35.94 (5213)	
			24.48 (3551)			
			22.70 (3292)			
Average	5.64 (818)	16.10 (2335)	26.69 (3872)	38.18 (5537)	42.69 (6191)	51.17 (7421)

Table A-1 cont.) Individual compression test results for Part I of the study.

Concrete Mix	Compressive Strength, MPa (psi)					
	Specimen Age					
	1 day	3 days	7 days	14 days	28 days	90 days
S55S	4.47 (648)	13.96 (2025)	26.37 (3824)	37.28 (5407)	44.22 (6413)	47.76 (6927)
	4.72 (685)	14.07 (2041)	26.81 (3888)	36.88 (5349)	44.10 (6396)	49.78 (7220)
	4.56 (662)	14.30 (2074)	27.19 (3943)	38.47 (5580)	44.42 (6442)	50.70 (7353)
	4.63 (672)	14.27 (2070)	26.64 (3864)	38.54 (5590)	44.44 (6445)	48.49 (7033)
	4.72 (685)	13.99 (2029)	27.37 (3969)	38.49 (5582)	44.77 (6494)	48.68 (7060)
	4.59 (666)	14.13 (2049)	28.42 (4122)	37.67 (5464)	44.73 (6487)	53.43 (7750)
	4.76 (690)	14.33 (2078)	27.37 (3969)	38.42 (5572)	43.64 (6330)	51.64 (7490)
	4.69 (680)	14.58 (2115)	27.39 (3973)	37.69 (5467)	42.99 (6235)	50.63 (7343)
	3.60 (522)	13.24 (1920)	27.40 (3974)	38.02 (5515)	44.05 (6389)	50.29 (7294)
	3.70 (536)	13.24 (1921)	26.69 (3871)	38.82 (5630)	44.97 (6522)	50.33 (7300)
			25.16 (3649)		43.95 (6374)	
			24.41 (3541)		46.23 (6705)	
			23.75 (3445)		34.83 (5052)	
			24.15 (3502)		39.04 (5662)	
			23.11 (3352)		40.87 (5927)	
			23.86 (3460)		41.28 (5987)	
Average	4.44 (645)	14.01 (2032)	26.00 (3772)	38.03 (5516)	43.03 (6241)	50.17 (7277)
S70S	2.05 (298)	9.54 (1383)	21.65 (3140)	32.12 (4658)	37.62 (5457)	37.66 (5462)
	2.12 (307)	9.35 (1356)	22.39 (3247)	32.00 (4641)	37.02 (5369)	36.77 (5333)
	2.54 (369)	10.02 (1453)	21.59 (3131)	32.01 (4643)	37.25 (5402)	36.66 (5317)
	2.61 (378)	10.07 (1461)	19.12 (2773)	31.23 (4529)	35.90 (5207)	38.80 (5627)
	1.41 (204)	7.46 (1082)	18.86 (2736)	27.06 (3925)	34.12 (4949)	34.65 (5026)
	1.55 (225)	7.32 (1061)	18.20 (2639)	27.13 (3935)	32.76 (4752)	38.25 (5548)
	1.61 (233)	7.11 (1031)	18.32 (2657)	27.48 (3986)	32.06 (4650)	44.44 (6445)
	1.80 (261)	6.83 (990)	17.97 (2606)	27.56 (3997)	31.76 (4606)	44.52 (6457)
	1.79 (259)	8.57 (1243)	21.68 (3145)	32.30 (4685)	38.89 (5640)	43.24 (6272)
		8.27 (1200)	22.16 (3214)	31.87 (4622)	36.61 (5310)	43.40 (6294)
			18.83 (2731)		36.93 (5356)	
			18.70 (2712)		37.33 (5414)	
			16.20 (2350)		30.32 (4398)	
			15.80 (2291)		31.91 (4628)	
			16.53 (2397)		30.69 (4451)	
			17.02 (2469)		30.03 (4356)	
Average	1.94 (282)	8.45 (1226)	19.06 (2765)	30.08 (4362)	34.45 (4997)	39.84 (5778)

Table A-1 cont.) Individual compression test results for Part I of the study.

Concrete Mix	Compressive Strength, MPa (psi)					
	Specimen Age					
	1 day	3 days	7 days	14 days	28 days	90 days
S35SC	3.68 (534)	9.84 (1427)	19.49 (2827)	28.12 (4079)	32.31 (4686)	41.91 (6079)
	3.70 (536)	10.31 (1496)	18.73 (2717)	29.78 (4319)	36.89 (5350)	41.22 (5978)
	4.85 (704)	10.96 (1589)	19.17 (2781)	26.87 (3897)	32.70 (4743)	36.86 (5346)
	4.86 (705)	10.84 (1572)	19.07 (2766)	26.63 (3863)	34.00 (4931)	36.02 (5224)
	4.85 (704)	11.26 (1633)	18.55 (2691)	26.75 (3880)	32.67 (4739)	45.18 (6553)
	4.63 (671)	11.18 (1621)	18.68 (2710)	26.53 (3848)	31.56 (4577)	45.62 (6616)
	2.30 (334)	8.77 (1272)	18.66 (2707)	34.28 (4972)	40.60 (5889)	39.58 (5741)
	2.19 (317)	8.98 (1303)	18.11 (2626)	32.18 (4667)	40.60 (5888)	38.42 (5573)
	3.76 (546)	10.82 (1570)	20.17 (2925)	28.32 (4107)	39.01 (5658)	39.49 (5727)
	3.89 (564)	10.31 (1495)	19.31 (2800)	27.79 (4030)	41.28 (5987)	37.26 (5404)
				28.43 (4123)	33.71 (4889)	
				27.45 (3981)	32.16 (4665)	
					34.07 (4941)	
					34.65 (5025)	
Average	3.87 (562)	10.33 (1498)	19.00 (2755)	28.59 (4147)	35.44 (5141)	40.16 (5824)
S35SF	3.52 (511)	12.77 (1852)	16.89 (2449)	27.98 (4058)	41.89 (6075)	50.55 (7331)
	3.52 (511)	12.26 (1778)	17.75 (2574)	29.58 (4290)	42.12 (6109)	50.58 (7336)
	3.08 (447)	10.44 (1514)	17.78 (2579)	30.31 (4396)	37.11 (5382)	47.30 (6861)
	3.23 (468)	10.87 (1576)	18.49 (2682)	30.16 (4375)	39.01 (5658)	47.06 (6826)
	4.14 (600)	10.91 (1582)	18.60 (2698)	26.71 (3874)	33.78 (4899)	39.47 (5725)
	4.07 (590)	10.76 (1561)	18.72 (2715)	27.06 (3925)	33.84 (4908)	37.65 (5460)
	4.18 (606)	10.35 (1501)	19.16 (2779)	26.31 (3816)	33.50 (4859)	31.50 (4568)
	4.20 (609)	10.40 (1508)	18.55 (2690)	26.71 (3874)	33.84 (4908)	41.22 (5979)
	1.80 (261)	7.82 (1134)	16.00 (2320)	31.27 (4535)	35.78 (5189)	42.82 (6210)
	1.87 (271)	7.85 (1139)	15.52 (2251)	24.48 (3550)	35.35 (5127)	47.42 (6877)
				24.94 (3617)	37.16 (5389)	37.67 (5464)
					31.55 (4576)	38.50 (5584)
					31.13 (4515)	38.40 (5570)
						39.22 (5688)
Average	3.36 (487)	10.44 (1515)	17.75 (2574)	27.77 (4028)	35.85 (5200)	42.10 (6106)

Table A-1 cont.) Individual compression test results for Part I of the study.

Concrete Mix	Compressive Strength, MPa (psi)					
	Specimen Age					
	1 day	3 days	7 days	14 days	28 days	90 days
S00SK	17.35 (2517)	30.34 (4400)	26.31 (3816)	33.10 (4801)	40.02 (5805)	45.89 (6656)
	17.62 (2555)	30.34 (4400)	27.86 (4041)	31.63 (4588)	41.67 (6044)	45.86 (6651)
	16.50 (2393)	25.25 (3662)	30.25 (4387)	34.23 (4965)	39.09 (5670)	43.67 (6334)
	15.87 (2302)	25.79 (3740)	28.85 (4184)	33.04 (4792)	39.81 (5774)	45.38 (6582)
	3.44 (499)	32.00 (4641)	35.71 (5180)	38.08 (5523)	40.93 (5937)	45.17 (6552)
	3.47 (503)	32.95 (4779)	36.04 (5227)	37.49 (5438)	41.12 (5964)	45.21 (6557)
	9.27 (1345)	23.48 (3406)	29.45 (4272)	32.36 (4693)	33.84 (4908)	42.04 (6098)
	9.45 (1370)	23.68 (3434)	29.41 (4266)	30.77 (4463)	35.05 (5083)	40.13 (5820)
	6.29 (912)	24.69 (3581)	31.95 (4634)	35.34 (5125)	37.85 (5490)	36.09 (5234)
	7.27 (1054)	26.10 (3786)	29.53 (4283)	35.87 (5203)	38.61 (5600)	36.00 (5222)
			33.23 (4820)	30.32 (4397)	35.45 (5142)	39.27 (5695)
			33.04 (4792)	28.43 (4124)	37.13 (5385)	41.60 (6034)
			29.86 (4331)		34.63 (5022)	40.44 (5866)
			29.31 (4251)		34.41 (4991)	44.15 (6403)
						38.11 (5527)
						41.44 (6011)
Average	10.65 (1545)	27.46 (3983)	30.77 (4463)	33.39 (4843)	37.83 (5487)	41.90 (6078)
S35SK	12.80 (1857)	23.68 (3435)	35.86 (5201)	43.24 (6272)	49.96 (7246)	55.09 (7990)
	12.76 (1851)	23.70 (3438)	36.05 (5228)	45.26 (6565)	47.96 (6956)	53.58 (7771)
	12.11 (1756)	23.10 (3351)	34.34 (4981)	43.31 (6282)	46.73 (6777)	53.98 (7829)
	12.10 (1755)	22.77 (3303)	35.58 (5160)	42.84 (6213)	48.79 (7076)	53.03 (7692)
	13.24 (1920)	25.22 (3658)	34.38 (4987)	42.52 (6167)	46.84 (6793)	56.26 (8160)
	12.89 (1869)	24.88 (3609)	34.76 (5042)	43.35 (6287)	48.34 (7011)	50.90 (7382)
	11.53 (1673)	22.68 (3289)	34.28 (4972)	42.71 (6195)	47.97 (6958)	51.99 (7540)
	11.73 (1702)	23.61 (3424)	33.47 (4855)	39.54 (5735)	47.20 (6846)	54.06 (7841)
	9.64 (1398)	20.86 (3026)	31.36 (4549)	41.86 (6071)	47.73 (6923)	53.30 (7731)
	9.63 (1397)	21.66 (3141)	31.99 (4640)	41.53 (6024)	46.93 (6806)	54.26 (7870)
			28.27 (4100)		40.29 (5844)	44.50 (6454)
			28.87 (4187)		39.00 (5657)	42.69 (6191)
					44.11 (6398)	
					39.34 (5706)	
Average	11.84 (1718)	23.22 (3367)	33.27 (4825)	42.62 (6181)	45.80 (6643)	51.97 (7538)

Table A-1 cont.) Individual compression test results for Part I of the study.

Concrete Mix	Compressive Strength, MPa (psi)					
	Specimen Age					
	1 day	3 days	7 days	14 days	28 days	90 days
S55SK	7.59 (1101)	17.98 (2608)	33.97 (4927)	45.13 (6546)	40.44 (5866)	52.76 (7652)
	7.29 (1058)	17.33 (2514)	33.93 (4921)	46.50 (6744)	38.40 (5570)	53.17 (7711)
	4.92 (714)	11.47 (1663)	23.80 (3452)	39.88 (5784)	48.73 (7068)	51.03 (7402)
	5.53 (802)	11.00 (1595)	24.01 (3483)	39.89 (5785)	51.56 (7478)	43.61 (6325)
	3.58 (519)	12.31 (1786)	24.75 (3589)	39.97 (5797)	47.62 (6906)	44.25 (6418)
	3.49 (506)	12.39 (1797)	24.48 (3551)	33.65 (4881)	47.23 (6850)	47.87 (6943)
	4.87 (707)	12.45 (1805)	25.14 (3646)	34.59 (5017)	45.17 (6551)	45.58 (6611)
	4.87 (706)	12.93 (1875)	20.18 (2927)	28.75 (4170)	36.70 (5323)	
	3.92 (568)	13.20 (1914)	20.51 (2974)	27.20 (3945)	39.28 (5697)	
	4.11 (596)	13.24 (1920)	26.23 (3804)	35.62 (5166)	38.42 (5573)	
			26.15 (3793)	35.51 (5151)	38.76 (5621)	
			26.70 (3873)		41.06 (5955)	
					39.51 (5731)	
					40.70 (5903)	
Average	5.02 (728)	13.43 (1948)	25.82 (3745)	36.97 (5362)	42.40 (6149)	48.32 (7009)
S35SHA	9.02 (1308)	21.19 (3074)	32.09 (4654)	41.55 (6026)	50.46 (7319)	51.86 (7522)
	9.08 (1317)	20.88 (3028)	31.49 (4567)	41.43 (6009)	46.50 (6744)	58.13 (8431)
	10.41 (1510)	22.08 (3202)	33.39 (4843)	43.26 (6274)	49.10 (7122)	51.96 (7536)
	10.55 (1530)	21.77 (3158)	34.18 (4957)	44.08 (6393)	48.74 (7069)	51.21 (7428)
	9.47 (1373)	20.62 (2990)	32.52 (4716)	41.73 (6052)	47.95 (6955)	52.08 (7554)
	9.61 (1394)	21.04 (3052)	33.16 (4809)	41.94 (6083)	48.54 (7040)	53.46 (7753)
	9.78 (1418)	21.89 (3175)	33.02 (4789)	40.13 (5820)	49.96 (7246)	50.05 (7259)
	9.45 (1371)	22.04 (3196)	34.55 (5011)	40.81 (5919)	49.23 (7140)	47.96 (6956)
	7.80 (1131)	17.26 (2503)	28.61 (4149)	37.18 (5392)	42.64 (6185)	46.75 (6781)
	7.53 (1092)	17.23 (2499)	29.24 (4241)	37.62 (5456)	43.71 (6340)	47.35 (6867)
Average	9.27 (1344)	20.60 (2988)	32.22 (4674)	40.97 (5942)	47.68 (6916)	51.08 (7409)

Table A-1 cont.) Individual compression test results for Part I of the study.

Concrete Mix	Compressive Strength, MPa (psi)					
	Specimen Age					
	1 day	3 days	7 days	14 days	28 days	90 days
S55SHA	6.23 (904)	17.86 (2590)	34.27 (4971)	46.53 (6748)	53.82 (7806)	47.13 (6836)
	6.23 (903)	18.26 (2649)	34.30 (4975)	46.79 (6787)	56.71 (8225)	48.00 (6962)
	5.24 (760)	15.29 (2218)	29.08 (4217)	41.23 (5980)	46.85 (6795)	47.91 (6949)
	5.10 (739)	15.45 (2241)	29.32 (4253)	39.78 (5770)	43.88 (6364)	61.25 (8883)
	3.73 (541)	11.89 (1725)	24.81 (3598)	34.52 (5006)	42.80 (6207)	64.99 (9426)
	3.85 (558)	12.25 (1777)	24.57 (3564)	34.39 (4988)	42.16 (6115)	47.90 (6947)
	4.94 (716)	16.41 (2380)	32.44 (4705)	47.50 (6889)	59.10 (8572)	40.38 (5857)
	4.92 (713)	16.57 (2404)	32.94 (4777)	46.76 (6782)	55.92 (8110)	41.38 (6001)
	5.64 (818)	15.53 (2253)	29.41 (4266)	40.51 (5876)	45.62 (6616)	52.43 (7605)
	5.47 (793)	15.70 (2277)	31.02 (4499)	41.36 (5999)	48.64 (7054)	51.00 (7397)
Average	5.13 (745)	15.52 (2251)	30.22 (4383)	41.94 (6083)	49.55 (7186)	50.24 (7286)
S35SLA	10.90 (1581)	23.06 (3344)	33.38 (4841)	42.86 (6217)	47.88 (6945)	56.59 (8207)
	11.09 (1609)	22.35 (3241)	32.65 (4735)	42.41 (6151)	48.69 (7062)	55.39 (8033)
	10.76 (1561)	21.52 (3121)	32.45 (4707)	41.46 (6013)	44.92 (6515)	52.01 (7544)
	10.25 (1486)	20.93 (3036)	32.60 (4728)	41.93 (6082)	45.88 (6655)	51.55 (7476)
	9.76 (1416)	20.18 (2927)	30.05 (4359)	39.51 (5731)	44.45 (6447)	52.13 (7561)
	9.91 (1437)	20.36 (2953)	31.41 (4556)	38.96 (5650)	45.63 (6618)	58.63 (8504)
	8.52 (1235)	19.89 (2885)	30.10 (4365)	37.83 (5487)	45.02 (6529)	59.76 (8667)
	8.14 (1181)	19.05 (2763)	30.65 (4446)	39.87 (5783)	45.71 (6629)	56.99 (8265)
	5.94 (861)	18.32 (2657)	34.49 (5002)	45.86 (6652)	53.65 (7781)	
	6.02 (873)	18.03 (2615)	33.49 (4857)	44.84 (6504)	58.38 (8468)	
Average	9.13 (1324)	20.37 (2954)	32.13 (4660)	41.55 (6027)	48.02 (6965)	55.38 (8032)
S55SLA	5.58 (810)	15.06 (2184)	26.21 (3801)	35.57 (5159)	42.41 (6151)	48.32 (7008)
	5.87 (851)	15.24 (2210)	27.29 (3958)	35.44 (5140)	44.40 (6439)	50.28 (7293)
	6.19 (898)	16.02 (2324)	29.99 (4350)	40.63 (5893)	46.23 (6705)	53.78 (7800)
	6.18 (897)	16.44 (2385)	30.16 (4374)	39.99 (5800)	44.82 (6501)	50.10 (7267)
	5.21 (756)	14.94 (2167)	38.18 (5538)	37.77 (5478)	44.58 (6466)	50.32 (7299)
	5.45 (791)	13.76 (1996)	27.01 (3918)	26.61 (3860)	43.73 (6342)	51.73 (7503)
	5.78 (838)	15.41 (2235)	27.10 (3930)	38.00 (5512)	45.48 (6596)	
	5.55 (805)	15.35 (2226)	27.87 (4042)	39.97 (5797)	46.42 (6733)	
	4.62 (670)	13.22 (1917)	26.79 (3886)	37.76 (5477)	42.48 (6161)	
	4.47 (649)	13.67 (1982)	27.63 (4008)	39.52 (5732)	44.14 (6402)	
Average	5.49 (797)	14.91 (2163)	28.82 (4181)	37.13 (5385)	44.47 (6450)	50.76 (7362)

Table A-1 cont.) Individual compression test results for Part I of the study.

Concrete Mix	Compressive Strength, MPa (psi)					
	Specimen Age					
	1 day	3 days	7 days	14 days	28 days	90 days
MS00S	23.54 (3414)	42.48 (6161)	68.70 (9964)	69.49 (10079)	64.05 (9289)	60.59 (8788)
	23.84 (3458)	42.11 (6107)	55.45 (8043)	64.38 (9337)	64.38 (9338)	66.42 (9634)
	25.38 (3681)	42.09 (6104)	56.08 (8134)	68.32 (9909)	70.84 (10274)	68.45 (9928)
	25.26 (3663)	41.48 (6016)	57.30 (8311)	71.34 (10347)	73.97 (10728)	70.27 (10192)
	22.50 (3264)	40.19 (5829)	55.45 (8043)	67.42 (9778)	70.34 (10202)	68.73 (9968)
	22.39 (3248)	39.58 (5741)	52.61 (7631)	67.42 (9778)	72.08 (10454)	73.99 (10732)
	23.07 (3346)	39.51 (5731)	52.99 (7686)	67.42 (9778)	61.43 (8909)	72.05 (10450)
	17.77 (2577)	36.82 (5341)	52.06 (7550)	63.08 (9149)	70.80 (10268)	70.44 (10216)
	19.07 (2766)	36.78 (5334)	51.60 (7484)	61.29 (8890)	67.98 (9860)	67.86 (9842)
	19.45 (2821)	29.46 (4273)	43.93 (6371)	59.62 (8647)	69.06 (10017)	67.84 (9840)
	17.27 (2505)	33.54 (4864)	44.62 (6471)	38.27 (5551)	56.20 (8151)	59.92 (8691)
	16.34 (2370)		41.11 (5963)	36.66 (5317)	55.74 (8085)	58.90 (8542)
			41.60 (6033)		52.51 (7616)	
			47.26 (6855)		52.60 (7629)	
			47.50 (6889)		62.91 (9125)	
					63.61 (9226)	
Average	21.32 (3093)	38.55 (5591)	51.22 (7429)	61.23 (8880)	64.28 (9323)	67.12 (9735)
MS35S	10.74 (1557)	29.97 (4347)	48.66 (7058)	60.89 (8832)	70.51 (10227)	67.42 (9779)
	10.89 (1579)	30.19 (4378)	48.78 (7075)	63.60 (9225)	70.35 (10203)	65.98 (9569)
	11.72 (1700)	29.59 (4292)	49.97 (7247)	62.78 (9105)	68.00 (9863)	72.38 (10498)
	11.33 (1643)	29.51 (4280)	50.50 (7325)	64.40 (9341)	66.26 (9610)	70.66 (10248)
	10.31 (1495)	28.56 (4143)	48.42 (7023)	67.56 (9799)	70.68 (10251)	76.26 (11061)
	10.55 (1530)	31.76 (4606)	51.88 (7525)	65.05 (9435)	72.13 (10461)	69.28 (10048)
	9.67 (1402)	32.15 (4663)	52.43 (7605)	66.79 (9687)	72.75 (10552)	66.73 (9679)
	9.75 (1414)	30.48 (4421)	49.21 (7138)	66.62 (9662)	66.67 (9669)	
	11.46 (1662)	30.53 (4428)	50.66 (7348)	61.08 (8859)	46.28 (6713)	
	11.71 (1699)		48.79 (7076)	61.14 (8867)	45.32 (6573)	
			44.74 (6489)		56.57 (8205)	
			44.50 (6454)		58.53 (8489)	
			39.24 (5692)		52.63 (7634)	
			39.28 (5697)		51.68 (7496)	
Average	10.81 (1568)	30.30 (4395)	47.65 (6911)	63.99 (9281)	62.03 (8996)	69.82 (10126)

Table A-1 cont.) Individual compression test results for Part I of the study.

Concrete Mix	Compressive Strength, MPa (psi)					
	Specimen Age					
	1 day	3 days	7 days	14 days	28 days	90 days
MS55S	5.84 (847)	27.02 (3919)	45.63 (6618)	56.50 (8194)	65.67 (9524)	59.58 (8641)
	5.85 (849)	26.82 (3890)	45.62 (6617)	63.72 (9242)	67.51 (9791)	61.34 (8896)
	5.70 (826)	23.11 (3352)	41.81 (6064)	59.05 (8565)	62.22 (9024)	68.24 (9898)
	5.71 (828)	22.45 (3256)	43.75 (6346)	60.52 (8777)	62.67 (9090)	69.20 (10036)
	5.07 (736)	23.96 (3475)	43.67 (6334)	59.17 (8582)	66.62 (9662)	73.88 (10716)
	5.16 (748)	26.01 (3773)	45.61 (6615)	50.92 (7385)	66.58 (9657)	66.18 (9598)
	5.23 (759)	25.43 (3688)	46.96 (6811)	60.97 (8843)	67.89 (9847)	61.03 (8851)
	5.27 (765)	25.83 (3747)	44.46 (6449)	61.20 (8876)	61.44 (8911)	
	6.78 (984)	25.71 (3729)	45.10 (6541)	57.20 (8296)	46.71 (6774)	
	8.32 (1206)		44.70 (6483)	56.90 (8253)	48.87 (7088)	
			35.73 (5182)		48.97 (7102)	
			35.42 (5137)		49.83 (7227)	
			37.51 (5441)		51.66 (7492)	
			37.91 (5499)		45.95 (6665)	
Average	5.89 (855)	25.15 (3648)	42.42 (6153)	58.61 (8501)	58.04 (8418)	65.63 (9519)
OS	23.45 (3401)	32.05 (4649)	35.31 (5121)	39.21 (5687)	42.73 (6198)	46.87 (6798)
	24.12 (3499)	31.47 (4564)	36.23 (5255)	38.69 (5612)	42.47 (6160)	47.99 (6961)
	23.26 (3373)	32.65 (4735)	35.56 (5157)	38.62 (5601)	42.00 (6092)	49.05 (7114)
	18.18 (2637)	25.75 (3734)	28.49 (4132)	32.04 (4647)	33.96 (4926)	39.25 (5693)
	17.32 (2512)	25.80 (3742)	28.59 (4146)	31.59 (4582)	33.72 (4891)	38.62 (5601)
	17.55 (2546)	26.64 (3864)	28.83 (4182)	33.90 (4917)	34.78 (5044)	38.20 (5540)
	16.35 (2372)	30.32 (4398)	34.65 (5026)	36.52 (5297)	40.13 (5821)	46.79 (6786)
	17.93 (2600)	30.15 (4373)	34.34 (4980)	38.00 (5511)	42.26 (6130)	47.36 (6869)
	18.78 (2724)	30.26 (4389)	33.73 (4892)	37.94 (5503)	42.16 (6115)	48.28 (7002)
	24.77 (3592)	39.53 (5733)	43.15 (6258)	47.91 (6949)	51.91 (7529)	62.36 (9044)
	26.26 (3808)	39.42 (5717)	46.22 (6704)	49.29 (7149)	53.59 (7772)	59.16 (8580)
	25.63 (3718)	40.38 (5856)	44.21 (6412)	48.76 (7072)	53.74 (7795)	61.40 (8905)
Average	21.13 (3065)	32.03 (4646)	35.78 (5189)	39.37 (5711)	42.79 (6206)	48.78 (7074)
OK	14.38 (2085)	21.93 (3180)	26.12 (3789)	28.36 (4113)	30.37 (4405)	32.92 (4774)
	14.49 (2102)	22.03 (3195)	26.03 (3775)	27.49 (3987)	29.96 (4345)	33.40 (4844)
	14.59 (2116)	22.13 (3209)	25.97 (3767)	27.69 (4016)	30.41 (4411)	33.29 (4828)
	14.20 (2060)	21.37 (3100)	24.83 (3602)	27.54 (3994)	30.97 (4492)	33.80 (4902)
	13.79 (2000)	21.62 (3135)	26.28 (3811)	28.40 (4119)	30.34 (4400)	32.96 (4781)
	13.66 (1981)	21.53 (3122)	25.48 (3696)	28.03 (4065)	31.15 (4518)	
Average	14.18 (2057)	21.77 (3157)	25.79 (3740)	27.92 (4049)	30.53 (4429)	33.27 (4826)

Table A-1 cont.) Individual compression test results for Part I of the study.

Concrete Mix	Compressive Strength, MPa (psi)					
	Specimen Age					
	1 day	3 days	7 days	14 days	28 days	90 days
OHPC2	24.25 (3517)	31.78 (4610)	36.50 (5294)	41.09 (5960)	46.24 (6706)	53.54 (7766)
	24.00 (3481)	30.51 (4425)	36.53 (5298)	41.31 (5992)	46.18 (6698)	55.69 (8077)
	23.58 (3420)	31.45 (4561)	38.20 (5541)	43.14 (6257)	46.33 (6720)	55.30 (8020)
	20.96 (3040)	31.05 (4503)	38.38 (5566)	45.18 (6553)	50.26 (7289)	55.32 (8024)
	20.90 (3031)	30.28 (4392)	38.42 (5572)	45.02 (6530)	49.10 (7121)	56.65 (8217)
	21.34 (3095)	30.76 (4461)	38.41 (5571)	44.62 (6471)	48.19 (6990)	61.27 (8887)
	22.92 (3324)	30.58 (4435)	39.98 (5798)	46.23 (6705)	53.33 (7735)	60.23 (8735)
	22.79 (3305)	30.21 (4381)	38.74 (5619)	46.00 (6672)	52.80 (7658)	61.47 (8915)
	22.05 (3198)	31.50 (4569)	39.32 (5703)	46.91 (6804)	52.59 (7628)	61.80 (8963)
	22.61 (3280)	31.59 (4582)	40.12 (5819)	47.41 (6876)	52.56 (7623)	59.43 (8619)
	23.54 (3414)	32.49 (4713)	39.80 (5773)	47.83 (6937)	53.32 (7734)	
	22.34 (3240)	32.16 (4665)	40.18 (5827)	48.54 (7040)		
Average	22.61 (3279)	31.20 (4525)	38.71 (5615)	45.27 (6566)	50.08 (7264)	58.07 (8422)
OHPC4	10.13 (1469)	21.01 (3047)	30.12 (4369)	35.81 (5194)	39.98 (5799)	43.00 (6237)
	10.14 (1471)	20.64 (2993)	29.35 (4257)	36.14 (5242)	39.16 (5680)	43.24 (6272)
	10.01 (1452)	20.59 (2987)	29.07 (4216)	35.14 (5097)	39.11 (5673)	44.24 (6416)
	10.20 (1480)	21.26 (3084)	29.59 (4291)	38.27 (5550)	41.36 (5999)	45.74 (6634)
	9.94 (1442)	21.33 (3093)	31.59 (4582)	37.62 (5457)	41.38 (6001)	
	10.37 (1504)	21.21 (3076)	30.70 (4453)	37.58 (5451)	41.98 (6089)	
Average	10.13 (1470)	21.01 (3047)	30.07 (4361)	36.76 (5332)	40.50 (5874)	44.06 (6390)
OMS	26.79 (3886)	36.60 (5309)	46.18 (6698)	52.06 (7550)	58.66 (8508)	55.71 (8080)
	26.32 (3818)	37.22 (5398)	48.02 (6964)	53.64 (7780)	52.56 (7623)	60.62 (8792)
	29.06 (4215)	45.08 (6538)	42.06 (6101)	53.48 (7757)	58.21 (8442)	61.07 (8858)
	23.67 (3433)	33.58 (4870)	40.95 (5940)	48.54 (7040)	52.17 (7566)	55.48 (8047)
	23.39 (3393)	30.53 (4428)	40.55 (5882)	48.13 (6981)	51.28 (7437)	54.31 (7877)
	24.01 (3483)	32.96 (4780)	41.41 (6006)	46.33 (6719)	53.01 (7688)	56.62 (8212)
	29.51 (4280)	38.16 (5534)	47.24 (6852)	53.81 (7805)	55.30 (8020)	62.87 (9119)
	30.38 (4406)	37.21 (5397)	47.56 (6898)	53.80 (7803)	59.49 (8629)	61.08 (8859)
	29.85 (4329)	37.69 (5466)	48.99 (7105)	55.07 (7987)	54.93 (7967)	50.29 (7294)
	28.25 (4097)	37.38 (5421)	46.41 (6731)	50.57 (7335)	54.41 (7892)	56.96 (8262)
	30.00 (4351)	37.11 (5382)	45.26 (6564)	51.82 (7516)	55.42 (8038)	57.01 (8269)
	29.50 (4279)	37.26 (5404)	45.79 (6642)	48.88 (7089)	55.81 (8094)	56.59 (8208)
Average	27.56 (3998)	36.73 (5327)	45.04 (6532)	51.34 (7447)	55.10 (7992)	57.39 (8323)

Table A-2) Individual modulus of rupture test results for Part I of the study.

Concrete Mix	Modulus of Rupture, MPa (psi)	
	Specimen Age	
	7 days	28 days
S00S	4.90 (710)	5.31 (770)
	5.27 (765)	6.45 (935)
	4.31 (625)	5.90 (855)
	5.34 (775)	5.72 (830)
	5.07 (735)	5.90 (855)
	5.07 (735)	6.72 (975)
	4.55 (660)	6.48 (940)
Average	4.93 (715)	6.07 (880)
S25S	5.79 (840)	6.38 (925)
	5.55 (805)	6.45 (935)
	5.27 (765)	5.86 (850)
	4.72 (685)	6.10 (885)
	4.59 (665)	5.48 (795)
	4.31 (625)	6.86 (995)
	5.14 (745)	6.65 (965)
Average	5.05 (733)	6.25 (907)
S35S	4.83 (700)	5.55 (805)
	4.65 (675)	6.72 (975)
	5.03 (730)	5.76 (835)
	4.72 (685)	5.27 (765)
	4.34 (630)	6.65 (965)
	4.59 (665)	5.93 (860)
	4.38 (635)	6.24 (905)
	4.59 (665)	5.93 (860)
	3.83 (555)	
Average	4.55 (660)	6.01 (871)
S45S	4.79 (695)	6.17 (895)
	5.03 (730)	6.52 (945)
	4.83 (700)	6.21 (900)
	4.65 (675)	5.69 (825)
	4.27 (620)	4.65 (675)
	4.65 (675)	7.24 (1050)
	4.62 (670)	6.38 (925)
Average	4.70 (681)	6.12 (888)

Concrete	Modulus of Rupture, MPa (psi)	
	Specimen Age	
	7 days	28 days
S55S	5.00 (725)	5.65 (820)
	4.65 (675)	5.65 (820)
	4.72 (685)	5.86 (850)
	4.27 (620)	5.76 (835)
	4.52 (655)	7.58 (1100)
	5.21 (755)	6.38 (925)
	4.59 (665)	6.17 (895)
		5.90 (855)
Average	4.71 (683)	6.12 (888)
S70S	3.96 (575)	5.52 (800)
	4.10 (595)	6.07 (880)
	3.55 (515)	4.72 (685)
	3.07 (445)	4.72 (685)
	3.69 (535)	5.34 (775)
	3.86 (560)	6.45 (935)
	4.41 (640)	6.45 (935)
	3.86 (560)	6.10 (885)
Average	3.81 (553)	5.67 (823)
S35SC	4.34 (630)	5.90 (855)
	4.14 (600)	5.17 (750)
	3.79 (550)	5.27 (765)
	3.72 (540)	6.83 (990)
	4.38 (635)	6.31 (915)
	2.96 (430)	5.69 (825)
		5.93 (860)
Average	3.89 (564)	5.87 (851)
S35SF	4.59 (665)	6.14 (890)
	4.07 (590)	6.62 (960)
	3.59 (520)	5.76 (835)
	3.31 (480)	5.65 (820)
	4.03 (585)	6.00 (870)
	3.38 (490)	5.45 (790)
		5.27 (765)
Average	3.83 (555)	5.84 (847)

Table A-2 cont.) Individual modulus of rupture test results for Part I of the study.

Concrete Mix	Modulus of Rupture, MPa (psi)	
	Specimen Age	
	7 days	28 days
S00SK	5.24 (760)	5.83 (845)
	5.14 (745)	6.27 (910)
	5.93 (860)	6.48 (940)
	3.72 (540)	4.62 (670)
	4.90 (710)	6.65 (965)
	5.17 (750)	5.38 (780)
		5.03 (730)
Average	5.02 (728)	5.75 (834)
S35SK	6.10 (885)	7.03 (1020)
	5.90 (855)	7.00 (1015)
	5.34 (775)	6.96 (1010)
	5.03 (730)	6.83 (990)
	5.00 (725)	6.69 (970)
	5.03 (730)	6.58 (955)
		6.96 (1010)
Average	5.40 (783)	6.87 (996)
S55SK	4.93 (715)	6.41 (930)
	3.72 (540)	7.38 (1070)
	3.38 (490)	7.38 (1070)
	3.86 (560)	5.93 (860)
	4.59 (665)	6.62 (960)
		6.76 (980)
Average	4.10 (594)	6.74 (978)
S35SHA	5.93 (860)	6.38 (925)
	5.48 (795)	6.96 (1010)
	5.69 (825)	6.00 (870)
	4.52 (655)	6.48 (940)
	4.59 (665)	5.58 (810)
Average	5.24 (760)	6.28 (911)
S55SHA	4.72 (685)	6.72 (975)
	4.65 (675)	5.96 (865)
	4.21 (610)	4.38 (635)
	4.76 (690)	6.89 (1000)
	4.76 (690)	6.96 (1010)
Average	4.62 (670)	6.18 (897)

Concrete Mix	Modulus of Rupture, MPa (psi)	
	Specimen Age	
	7 days	28 days
S35SLA	5.96 (865)	7.34 (1065)
	5.27 (765)	6.79 (985)
	5.52 (800)	5.93 (860)
	4.96 (720)	6.93 (1005)
	5.48 (795)	6.17 (895)
Average	5.44 (789)	6.63 (962)
S55SLA	4.83 (700)	6.17 (895)
	4.93 (715)	5.79 (840)
	4.59 (665)	5.55 (805)
	4.55 (660)	5.76 (835)
	4.90 (710)	5.96 (865)
Average	4.76 (690)	5.85 (848)
MS00S	6.14 (890)	7.65 (1110)
	6.45 (935)	7.14 (1035)
	6.69 (970)	7.45 (1080)
	6.31 (915)	7.62 (1105)
	4.83 (700)	7.62 (1105)
	6.14 (890)	7.41 (1075)
	6.89 (1000)	7.79 (1130)
		8.65 (1255)
Average	6.21 (900)	7.67 (1112)
MS35S	5.55 (805)	8.86 (1285)
	5.76 (835)	7.07 (1025)
	6.45 (935)	7.00 (1015)
	6.21 (900)	6.89 (1000)
	5.90 (855)	7.41 (1075)
	6.52 (945)	8.17 (1185)
	5.76 (835)	7.72 (1120)
Average	6.02 (873)	7.59 (1101)

Table A-2 cont.) Individual modulus of rupture test results for Part I of the study.

Concrete Mix	Modulus of Rupture, MPa (psi)	
	Specimen Age	
	7 days	28 days
MS55S	5.21 (755)	7.31 (1060)
	4.90 (710)	6.79 (985)
	5.38 (780)	7.24 (1050)
	5.52 (800)	7.14 (1035)
	5.24 (760)	7.62 (1105)
	5.72 (830)	7.69 (1115)
	5.93 (860)	7.69 (1115)
Average	5.41 (785)	7.35 (1066)
OS	5.14 (745)	5.90 (855)
	5.41 (785)	5.72 (830)
	4.79 (695)	5.41 (785)
	4.76 (690)	5.45 (790)
	4.83 (700)	5.55 (805)
	4.00 (580)	6.03 (875)
	5.34 (775)	6.38 (925)
	5.93 (860)	6.45 (935)
Average	5.03 (729)	5.86 (850)
OK	3.59 (520)	4.27 (620)
	3.62 (525)	4.24 (615)
	3.90 (565)	4.31 (625)
	3.62 (525)	4.69 (680)
Average	3.68 (534)	4.38 (635)
OHPC2	5.90 (855)	6.93 (1005)
	6.17 (895)	7.10 (1030)
	5.83 (845)	6.21 (900)
	5.52 (800)	7.14 (1035)
	8.14 (1180)	7.10 (1030)
	7.96 (1155)	7.24 (1050)
	7.45 (1080)	6.96 (1010)
	7.72 (1120)	7.21 (1045)
Average	6.83 (991)	9.98 (1013)

Concrete	Modulus of Rupture, MPa (psi)	
	Specimen Age	
	7 days	28 days
OHPC4	5.83 (845)	6.86 (995)
	5.76 (835)	7.03 (1020)
	5.90 (855)	7.34 (1065)
	6.24 (905)	7.48 (1085)
Average	5.93 (860)	7.18 (1041)
OMS	4.79 (695)	5.93 (860)
	5.45 (790)	5.96 (865)
	5.14 (745)	6.17 (895)
	5.21 (755)	5.65 (820)
	5.69 (825)	6.52 (945)
	6.03 (875)	6.48 (940)
	5.31 (770)	5.79 (840)
	5.48 (795)	5.76 (835)
Average	5.38 (781)	6.03 (875)

Table A-3) Individual splitting tension test results for Part I of the study.

Concrete Mix	Splitting Tensile Strength, MPa (psi)	
	Specimen Age	
	7 days	28 days
S00S	3.41 (495)	3.76 (545)
	3.31 (480)	3.96 (575)
	3.55 (515)	3.76 (545)
	3.96 (575)	4.00 (580)
	3.86 (560)	4.10 (595)
	3.90 (565)	3.83 (555)
Average	3.67 (532)	3.90 (566)
S25S	3.79 (550)	4.14 (600)
	3.76 (545)	4.76 (690)
	3.69 (535)	4.21 (610)
	3.21 (465)	4.55 (660)
	3.28 (475)	4.07 (590)
	3.24 (470)	4.48 (650)
Average	3.49 (507)	4.37 (633)
S35S	3.21 (465)	3.76 (545)
	3.55 (515)	4.14 (600)
	3.55 (515)	3.96 (575)
	3.24 (470)	4.21 (610)
	2.59 (375)	3.79 (550)
		3.45 (500)
Average	3.23 (468)	3.88 (563)
S45S	3.38 (490)	4.45 (645)
	3.14 (455)	4.38 (635)
	3.21 (465)	4.27 (620)
	3.21 (465)	4.45 (645)
	3.28 (475)	4.79 (695)
	2.93 (425)	
Average	3.19 (463)	4.47 (648)
S55S	3.28 (475)	3.90 (565)
	3.59 (520)	4.38 (635)
	3.14 (455)	4.00 (580)
	2.96 (430)	4.10 (595)
	2.65 (385)	4.59 (665)
Average	3.12 (453)	4.19 (608)

Concrete Mix	Splitting Tensile Strength, MPa (psi)	
	Specimen Age	
	7 days	28 days
S70S	2.59 (375)	3.72 (540)
	2.90 (420)	3.96 (575)
	2.28 (330)	3.62 (525)
	2.52 (365)	4.21 (610)
	2.72 (395)	
Average	2.60 (377)	3.88 (563)
S35SC	1.83 (265)	3.59 (520)
	2.21 (320)	3.17 (460)
	2.48 (360)	3.21 (465)
	2.14 (310)	3.38 (490)
	2.03 (295)	2.65 (385)
		3.62 (525)
Average	2.14 (310)	3.27 (474)
S35SF	2.07 (300)	4.24 (615)
	1.86 (270)	4.31 (625)
	2.31 (335)	3.38 (490)
	2.34 (340)	3.52 (510)
	2.10 (305)	3.62 (525)
Average	2.14 (310)	3.81 (553)
S00SK	3.10 (450)	2.76 (400)
	3.10 (450)	3.45 (500)
	3.07 (445)	4.14 (600)
	2.96 (430)	4.07 (590)
	3.10 (450)	2.96 (430)
Average	3.07 (445)	3.47 (504)
S35SK	3.55 (515)	4.45 (645)
	3.79 (550)	4.90 (710)
	3.79 (550)	4.55 (660)
	3.17 (460)	4.52 (655)
	3.55 (515)	4.59 (665)
Average	3.57 (518)	4.60 (667)

Table A-3 cont.) Individual splitting tension test results for Part I of the study.

Concrete Mix	Splitting Tensile Strength, MPa (psi)	
	Specimen Age	
	7 days	28 days
S55SK	3.52 (510)	3.62 (525)
	2.90 (420)	4.52 (655)
	3.00 (435)	4.65 (675)
	2.69 (390)	4.14 (600)
	3.07 (445)	3.45 (500)
	2.79 (405)	4.07 (590)
		3.90 (565)
Average	2.99 (434)	4.05 (587)
S35SHA	3.03 (440)	4.34 (630)
	3.52 (510)	4.24 (615)
	3.83 (555)	4.65 (675)
	3.34 (485)	4.72 (685)
	3.24 (470)	4.21 (610)
Average	3.39 (492)	4.43 (643)
S55SHA	3.21 (465)	4.72 (685)
	3.24 (470)	4.59 (665)
	2.76 (400)	4.14 (600)
	3.17 (460)	4.48 (650)
	3.38 (490)	4.24 (615)
Average	3.15 (457)	4.43 (643)
S35SLA	3.76 (545)	4.38 (635)
	3.79 (550)	4.24 (615)
	3.28 (475)	4.27 (620)
	3.21 (465)	5.00 (725)
	3.45 (500)	5.07 (735)
Average	3.50 (507)	4.59 (666)
S55SLA	2.76 (400)	4.48 (650)
	3.17 (460)	4.52 (655)
	3.28 (475)	3.83 (555)
	3.38 (490)	4.76 (690)
	3.10 (450)	
Average	3.14 (455)	4.40 (638)

Concrete Mix	Splitting Tensile Strength, MPa (psi)	
	Specimen Age	
	7 days	28 days
MS00S	5.62 (815)	5.00 (725)
	4.93 (715)	5.72 (830)
	4.86 (705)	6.07 (880)
	4.62 (670)	5.45 (790)
	4.27 (620)	5.24 (760)
	4.45 (645)	4.27 (620)
Average	4.79 (695)	5.29 (768)
MS35S	4.79 (695)	4.79 (695)
	4.59 (665)	5.45 (790)
	4.00 (580)	5.93 (860)
	5.10 (740)	5.86 (850)
	4.76 (690)	3.79 (550)
		3.48 (505)
Average	4.65 (674)	4.88 (708)
MS55S	4.34 (630)	4.76 (690)
	3.86 (560)	4.72 (685)
	3.59 (520)	5.14 (745)
	4.34 (630)	4.31 (625)
	4.31 (625)	3.65 (530)
		3.48 (505)
Average	4.09 (593)	4.34 (630)
OS	3.79 (550)	3.93 (570)
	3.34 (485)	3.38 (490)
	3.07 (445)	3.41 (495)
	3.17 (460)	3.65 (530)
	3.69 (535)	4.38 (635)
	3.79 (550)	4.24 (615)
	4.31 (625)	4.21 (610)
	3.69 (535)	3.62 (525)
Average	3.61 (523)	3.85 (559)
OK	2.52 (365)	2.96 (430)
	2.76 (400)	2.41 (350)
	2.79 (405)	2.83 (410)
	3.24 (470)	3.28 (475)
Average	2.83 (410)	2.87 (416)

Table A-3 cont.) Individual splitting tension test results for Part I of the study.

Concrete Mix	Splitting Tensile Strength, MPa (psi)	
	Specimen Age	
	7 days	28 days
OHPC2	3.10 (450)	4.10 (595)
	3.93 (570)	4.72 (685)
	4.24 (615)	5.00 (725)
	3.52 (510)	4.59 (665)
	4.07 (590)	4.45 (645)
	3.52 (510)	4.03 (585)
	4.14 (600)	5.62 (815)
	3.55 (515)	4.59 (665)
Average	3.76 (545)	4.64 (673)
OHPC4	2.62 (380)	3.90 (565)
	2.41 (350)	3.59 (520)
	2.96 (430)	3.48 (505)
	2.90 (420)	3.69 (535)
Average	2.72 (395)	3.66 (531)
OMS	3.45 (500)	4.00 (580)
	3.93 (570)	4.55 (660)
	3.52 (510)	4.21 (610)
	3.52 (510)	3.86 (560)
	4.48 (650)	5.34 (775)
	4.27 (620)	4.55 (660)
	4.31 (625)	3.83 (555)
	4.31 (625)	3.83 (555)
Average	3.97 (576)	4.27 (619)

APPENDIX B

STRENGTH TEST RESULTS FOR PART II OF THE STUDY

Table B-1) Individual compression test results for Part II of the study.

Concrete Mix	Compressive Strength, MPa (psi) *batch no.*		
	Specimen Age		
	7 days	28 days	90 days
C30	30.34 (4400) *001*	39.09 (5670) *001*	39.09 (5670) *005*
	30.82 (4470) *001*	39.30 (5700) *001*	39.75 (5765) *005*
	29.96 (4345) *001*	39.30 (5700) *001*	37.99 (5510) *005*
	30.99 (4495) *002*	38.65 (5605) *002*	45.23 (6560) *002*
	30.23 (4385) *002*	39.20 (5685) *002*	46.71 (6775) *002*
	30.72 (4455) *002*	40.30 (5845) *002*	46.82 (6790) *002*
	28.79 (4175) *003*	36.68 (5320) *003*	45.06 (6535) *001*
	28.51 (4135) *003*	34.34 (4980) *003*	46.02 (6675) *001*
	31.96 (4635) *004*	41.51 (6020) *004*	45.09 (6540) *001*
	32.58 (4725) *004*	32.92 (4775) *004*	
	27.03 (3920) *005*	34.47 (5000) *005*	
	27.03 (3920) *005*	34.75 (5040) *005*	
Average	29.91 (4338)	37.54 (5445)	43.53 (6313)
C31	30.20 (4380) *007*	40.58 (5885) *007*	46.68 (6770) *010*
	30.30 (4395) *007*	41.27 (5985) *007*	45.23 (6560) *010*
	32.13 (4660) *007*	42.54 (6170) *007*	47.51 (6890) *010*
	25.20 (3655) *008*	42.61 (6180) *008*	45.23 (6560) *010*
	25.27 (3665) *008*	42.71 (6195) *008*	46.68 (6770) *010*
	25.86 (3750) *008*	44.06 (6390) *008*	47.51 (6890) *010*
	29.75 (4315) *009*	36.09 (5235) *009*	38.13 (5530) *012*
	28.13 (4080) *009*	37.51 (5440) *009*	37.44 (5430) *012*
	30.79 (4465) *010*	40.89 (5930) *010*	36.54 (5300) *012*
	31.23 (4530) *010*	40.37 (5855) *010*	47.33 (6865) *007*
	31.34 (4545) *010*	41.44 (6010) *010*	49.54 (7185) *007*
	31.41 (4555) *011*	37.96 (5505) *011*	50.23 (7285) *007*
Average	29.30 (4250)	40.67 (5898)	44.84 (6503)
C32	30.41 (4410) *014*	35.82 (5195) *014*	34.96 (5070) *018*
	29.79 (4320) *014*	36.65 (5315) *014*	38.75 (5620) *018*
	28.61 (4150) *014*	38.27 (5550) *014*	33.96 (4925) *018*
	25.79 (3740) *015*	34.09 (4945) *015*	45.30 (6570) *014*
	25.06 (3635) *015*	32.20 (4670) *015*	45.64 (6620) *014*
	25.27 (3665) *015*	33.85 (4910) *015*	46.40 (6730) *014*
	29.13 (4225) *016*	39.54 (5735) *016*	44.47 (6450) *016*
	32.37 (4695) *016*	40.64 (5895) *016*	44.99 (6525) *016*
	26.13 (3790) *017*	33.20 (4815) *017*	
	25.44 (3690) *017*	33.03 (4790) *017*	
	27.13 (3935) *018*	33.41 (4845) *018*	
	27.20 (3945) *018*	33.68 (4885) *018*	
Average	27.69 (4017)	35.36 (5129)	41.81 (6064)

Note: The three digit italicized number (*001* to *124*) following the compressive strength is the Batch Ref. No.

Table B-1 cont.) Individual compression test results for Part II of the study.

Concrete Mix	Compressive Strength, MPa (psi) *batch no.*		
	Specimen Age		
	7 days	28 days	90 days
C33	23.13 (3355) *020*	32.34 (4690) *020*	40.96 (5940) *021*
	23.65 (3430) *020*	33.16 (4810) *020*	39.85 (5780) *021*
	25.27 (3665) *021*	34.68 (5030) *021*	39.85 (5780) *021*
	25.72 (3730) *021*	36.37 (5275) *021*	40.96 (5940) *021*
	26.34 (3820) *021*	36.54 (5300) *021*	42.61 (6180) *022*
	25.79 (3740) *022*	37.09 (5380) *022*	40.96 (5940) *022*
	26.37 (3825) *022*	37.23 (5400) *022*	43.95 (6375) *022*
	27.34 (3965) *022*	37.23 (5400) *022*	34.85 (5055) *020*
	26.48 (3840) *023*	35.85 (5200) *023*	40.51 (5875) *020*
	26.72 (3875) *023*	37.09 (5380) *023*	39.20 (5685) *020*
	25.13 (3645) *024*	32.61 (4730) *024*	
	25.06 (3635) *024*	32.65 (4735) *024*	
Average	25.58 (3710)	35.24 (5111)	40.37 (5855)
C40	29.20 (4235) *025*	37.23 (5400) *025*	36.47 (5290) *027*
	28.92 (4195) *025*	38.51 (5585) *025*	36.68 (5320) *027*
	28.99 (4205) *025*	37.71 (5470) *025*	41.13 (5965) *030*
	36.54 (5300) *026*	43.95 (6375) *026*	41.27 (5985) *030*
	36.16 (5245) *026*	42.40 (6150) *026*	41.71 (6050) *030*
	38.96 (5650) *026*	42.85 (6215) *026*	49.78 (7220) *028*
	23.24 (3370) *027*	43.61 (6325) *028*	49.99 (7250) *028*
	23.61 (3425) *027*	45.64 (6620) *028*	51.02 (7400) *028*
	23.75 (3445) *027*	45.68 (6625) *028*	
	23.92 (3470) *027*	36.71 (5325) *030*	
	22.75 (3300) *029*	36.61 (5310) *030*	
	31.03 (4500) *029*	37.51 (5440) *030*	
Average	28.92 (4195)	40.70 (5903)	43.51 (6310)
C41	26.10 (3785) *035*	35.82 (5195) *035*	40.27 (5840) *035*
	26.20 (3800) *035*	35.65 (5170) *035*	40.51 (5875) *035*
	26.61 (3860) *035*	34.92 (5065) *035*	40.92 (5935) *035*
	34.65 (5025) *036*	47.40 (6875) *036*	48.88 (7090) *040*
	33.58 (4870) *036*	47.54 (6895) *036*	48.16 (6985) *040*
	33.34 (4835) *036*	46.71 (6775) *036*	47.92 (6950) *040*
	26.89 (3900) *037*	34.23 (4965) *037*	46.37 (6725) *036*
	25.99 (3770) *037*	35.16 (5100) *037*	46.68 (6770) *036*
	27.75 (4025) *038*	37.37 (5420) *038*	48.16 (6985) *036*
	28.65 (4155) *038*	38.13 (5530) *038*	
	30.51 (4425) *039*	40.68 (5900) *040*	
	31.44 (4560) *039*	41.51 (6020) *040*	
Average	29.31 (4251)	39.59 (5743)	45.32 (6573)

Note: The three digit italicized number (*001* to *124*) following the compressive strength is the Batch Ref. No.

Table B-1 cont.) Individual compression test results for Part II of the study.

Concrete Mix	Compressive Strength, MPa (psi) *batch no.*		
	Specimen Age		
	7 days	28 days	90 days
C42	30.89 (4480) *044*	38.96 (5650) *044*	34.37 (4985) *046*
	30.58 (4435) *044*	37.71 (5470) *044*	34.78 (5045) *046*
	29.61 (4295) *044*	38.13 (5530) *044*	40.75 (5910)
	34.61 (5020) *045*	31.65 (4590) *045*	41.27 (5985)
	34.23 (4965) *045*	34.78 (5045) *045*	40.06 (5810) *050*
	35.06 (5085) *045*	33.96 (4925) *045*	40.16 (5825) *050*
	34.51 (5005) *046a*	43.68 (6335) *046a*	40.75 (5910) *050*
	35.51 (5150) *046a*	43.75 (6345) *046a*	48.19 (6990) *046a*
	28.13 (4080) *047*	36.13 (5240) *047*	50.09 (7265) *046a*
	28.48 (4130) *047*	37.51 (5440) *047*	
	30.34 (4400) *048*	42.30 (6135) *049*	
	29.51 (4280) *048*	40.61 (5890) *049*	
Average	31.79 (4610)	38.26 (5550)	41.16 (5969)
C43	20.48 (2970) *052*	34.85 (5055) *052*	38.16 (5535) *055*
	23.68 (3435) *052*	34.16 (4955) *052*	38.89 (5640) *055*
	24.44 (3545) *052*	34.51 (5005) *052*	36.71 (5325) *056*
	32.54 (4720)	45.95 (6665)	38.40 (5570) *056*
	32.75 (4750)	46.09 (6685)	37.34 (5415) *056*
	31.99 (4640)	46.47 (6740)	41.37 (6000) *058*
	26.99 (3915) *053*	39.61 (5745) *053*	39.75 (5765) *058*
	21.86 (3170) *053*	41.44 (6010) *053*	42.44 (6155) *058*
	27.41 (3975) *054*	33.34 (4835) *055*	40.78 (5915)
	27.85 (4040) *054*	33.65 (4880) *055*	52.50 (7615)
	22.30 (3235) *055*	31.30 (4540) *056*	53.95 (7825)
	22.41 (3250) *055*	32.16 (4665) *056*	
Average	26.23 (3804)	37.79 (5482)	41.85 (6069)
C50	31.34 (4545) *059*	40.89 (5930) *060*	49.85 (7230) *062*
	30.68 (4450) *059*	40.20 (5830) *060*	52.61 (7630) *062*
	30.92 (4485) *060*	37.65 (5460) *061*	52.64 (7635) *062*
	30.65 (4445) *060*	39.20 (5685) *061*	45.47 (6595) *059*
	30.48 (4420) *061*	46.40 (6730) *062*	45.51 (6600) *059*
	29.89 (4335) *061*	47.40 (6875) *062*	45.26 (6565) *061*
	36.27 (5260) *062*	47.61 (6905) *062*	46.13 (6690) *061*
	37.13 (5385) *062*	40.40 (5860) *064*	45.64 (6620) *064*
	36.30 (5265) *062*	40.33 (5850) *064*	46.30 (6715) *064*
	36.75 (5330) *063*	41.06 (5955) *064*	46.71 (6775) *064*
	34.78 (5045) *063*	37.51 (5440) *067*	49.30 (7150) *063*
	35.65 (5170) *063*	37.09 (5380) *067*	49.33 (7155) *063*
Average	33.40 (4845)	41.31 (5992)	47.90 (6947)

Note: The three digit italicized number (*001* to *124*) following the compressive strength is the Batch Ref. No.

Table B-1 cont.) Individual compression test results for Part II of the study.

Concrete Mix	Compressive Strength, MPa (psi) *batch no.*		
	Specimen Age		
	7 days	28 days	90 days
C51	33.47 (4855) *069*	35.75 (5185) *072*	39.78 (5770) *076*
	33.51 (4860) *069*	34.68 (5030) *072*	41.61 (6035) *076*
	30.03 (4355) *071*	36.78 (5335) *073*	46.30 (6715) *077*
	29.58 (4290) *071*	37.30 (5410) *073*	47.85 (6940) *077*
	27.51 (3990) *072*	35.47 (5145) *074*	43.78 (6350) *077*
	27.34 (3965) *072*	35.23 (5110) *074*	42.95 (6230) *073*
	27.58 (4000) *073*	34.58 (5015) *075*	43.85 (6360) *073*
	27.54 (3995) *073*	34.23 (4965) *075*	45.57 (6610) *071*
	22.06 (3200)	37.03 (5370) *076*	46.06 (6680) *071*
	21.82 (3165)	37.20 (5395) *076*	42.85 (6215) *072*
	26.82 (3890) *074*	40.99 (5945) *077*	43.54 (6315) *072*
	25.75 (3735) *074*	40.68 (5900) *077*	
Average	27.75 (4025)	36.66 (5317)	44.01 (6384)
C52	33.06 (4795) *079*	41.71 (6050) *079*	47.95 (6955) *079*
	32.78 (4755) *079*	41.40 (6005) *079*	48.37 (7015) *079*
	33.34 (4835) *080*	42.23 (6125) *080*	40.58 (5885) *088*
	33.20 (4815) *080*	42.30 (6135) *080*	40.92 (5935) *088*
	31.47 (4565) *081*	40.68 (5900) *081*	47.19 (6845) *089*
	31.68 (4595) *081*	39.68 (5755) *081*	47.40 (6875) *089*
	33.34 (4835) *082*	43.23 (6270) *082*	45.20 (6555) *089*
	35.23 (5110) *082*	43.95 (6375) *082*	46.75 (6780) *080*
	30.51 (4425) *085*	41.58 (6030) *087*	48.33 (7010) *080*
	29.58 (4290) *085*	41.89 (6075) *087*	45.64 (6620) *081*
	29.75 (4315) *084*	43.51 (6310) *086*	45.92 (6660) *081*
	28.51 (4135) *084*	41.09 (5960) *086*	
Average	31.87 (4623)	41.94 (6083)	45.84 (6649)
C53	31.85 (4620) *091*	45.13 (6545) *091*	46.95 (6810) *092*
	27.10 (3930) *098*	43.85 (6360) *091*	47.19 (6845) *092*
	28.61 (4150) *092*	38.99 (5655) *092*	47.92 (6950) *093*
	29.68 (4305) *093*	41.78 (6060) *092*	48.95 (7100) *093*
	29.79 (4320) *093*	42.85 (6215) *093*	44.85 (6505) *095*
	31.47 (4565) *094*	41.58 (6030) *093*	47.40 (6875) *095*
	31.54 (4575) *094*	46.20 (6700) *094*	50.33 (7300) *095*
	31.03 (4500) *095*	47.64 (6910) *094*	47.30 (6860) *097*
	31.34 (4545) *095*	44.20 (6410) *095*	47.57 (6900) *097*
	31.61 (4585) *095*	45.09 (6540) *095*	48.47 (7030) *097*
	31.96 (4635) *096*	46.20 (6700) *095*	51.37 (7450) *096*
	33.41 (4845) *096*	41.13 (5965) *097*	53.09 (7700) *096*
Average	30.78 (4465)	43.72 (6341)	48.45 (7027)

Note: The three digit italicized number (*001* to *124*) following the compressive strength is the Batch Ref. No.

Table B-1 cont.) Individual compression test results for Part II of the study.

Concrete Mix	Compressive Strength, MPa (psi) *batch no.*		
	Specimen Age		
	7 days	28 days	90 days
HP1	36.06 (5230) *102*	43.95 (6375) *102*	51.61 (7485) *102*
	37.23 (5400) *102*	44.26 (6420) *102*	52.40 (7600) *102*
	36.30 (5265) *102*	46.23 (6705) *102*	52.75 (7650) *102*
	36.54 (5300) *103*	49.71 (7210) *103*	54.43 (7895) *103*
	36.44 (5285) *103*	50.13 (7270) *103*	59.09 (8570) *103*
	36.06 (5230) *103*	50.06 (7260) *103*	38.96 (5650) *104*
	36.16 (5245) *104*	44.30 (6425) *104*	52.68 (7640) *104*
	35.72 (5180) *104*	44.47 (6450) *104*	52.68 (7640) *104*
	36.75 (5330) *104*	45.02 (6530) *104*	
Average	36.36 (5274)	46.46 (6738)	51.82 (7516)
HP2	40.96 (5940) *105*	57.78 (8380) *105*	62.98 (9135) *105*
	42.09 (6105) *105*	58.33 (8460) *105*	64.95 (9420) *105*
	40.96 (5940) *105*	59.92 (8690) *105*	67.22 (9750) *105*
	39.54 (5735) *106*	58.09 (8425) *106*	64.64 (9375) *106*
	39.82 (5775) *106*	59.47 (8625) *106*	66.50 (9645) *106*
	40.40 (5860) *106*	63.43 (9200) *106*	67.78 (9830) *106*
	37.65 (5460) *107*	54.37 (7885) *107*	56.61 (8210) *107*
	37.71 (5470) *107*	54.85 (7955) *107*	61.09 (8860) *107*
	37.78 (5480) *107*	57.05 (8275) *107*	61.88 (8975) *107*
Average	39.66 (5752)	58.14 (8433)	63.74 (9244)
HP3	41.64 (6040) *108*	58.19 (8440) *108*	69.81 (10125) *109*
	42.78 (6205) *108*	59.50 (8630) *108*	70.09 (10165) *109*
	42.95 (6230) *108*	60.43 (8765) *108*	70.84 (10275) *109*
	44.44 (6445) *109*	60.23 (8735) *109*	71.64 (10390) *110*
	44.82 (6500) *109*	61.26 (8885) *109*	73.08 (10600) *110*
	45.57 (6610) *109*	60.95 (8840) *109*	72.60 (10530) *110*
	48.02 (6965) *110*	66.33 (9620) *110*	65.67 (9525) *108*
	48.78 (7075) *110*	67.09 (9730) *110*	65.54 (9505) *108*
	48.61 (7050) *110*	69.12 (10025) *110*	68.19 (9890) *108*
Average	45.29 (6569)	62.57 (9074)	69.72 (10112)

Note: The three digit italicized number (*001* to *124*) following the compressive strength is the Batch Ref. No.

Table B-1 cont.) Individual compression test results for Part II of the study.

Concrete Mix	Compressive Strength, MPa (psi) *batch no.*		
	Specimen Age		
	7 days	28 days	90 days
HP4	34.58 (5015) *111*	59.26 (8595) *111*	64.36 (9335) *111*
	35.40 (5135) *111*	61.26 (8885) *111*	65.60 (9515) *111*
	35.54 (5155) *111*	61.81 (8965) *111*	66.36 (9625) *111*
	33.37 (4840) *112*	58.67 (8510) *112*	66.53 (9650) *112*
	36.47 (5290) *112*	59.88 (8685) *112*	67.78 (9830) *112*
	37.06 (5375) *112*	59.88 (8685) *112*	68.02 (9865) *112*
	43.33 (6285) *113*	60.05 (8710) *113*	66.74 (9680) *113*
	43.51 (6310) *113*	60.26 (8740) *113*	68.81 (9980) *113*
	43.40 (6295) *113*	64.43 (9345) *113*	68.98 (10005) *113*
Average	38.07 (5522)	60.61 (8791)	67.02 (9721)
SF735	59.98 (8700) *114*	72.53 (10520) *114*	79.43 (11520) *115*
	59.33 (8605) *114*	69.40 (10065) *114*	78.84 (11435) *115*
	59.57 (8640) *114*	72.71 (10545) *114*	77.26 (11205) *115*
	52.23 (7575) *116*	69.22 (10040) *115*	77.15 (11190) *116*
	53.74 (7795) *116*	69.53 (10085) *115*	76.64 (11115) *116*
	52.81 (7660) *116*	72.22 (10475) *115*	75.81 (10995) *116*
	57.09 (8280) *115*	65.81 (9545) *116*	79.22 (11490) *114*
	57.61 (8355) *115*	65.29 (9470) *116*	79.84 (11580) *114*
	57.12 (8285) *115*	64.23 (9315) *116*	80.22 (11635) *114*
Average	56.61 (8211)	68.99 (10007)	78.27 (11352)
SF752	57.85 (8390) *117*	69.50 (10080) *117*	74.43 (10795) *117*
	56.05 (8130) *117*	69.12 (10025) *117*	64.09 (9295) *117*
	55.85 (8100) *117*	68.50 (9935) *117*	75.98 (11020) *117*
	52.61 (7630) *118*	71.53 (10375) *118*	82.70 (11995) *119*
	53.06 (7695) *118*	71.36 (10350) *118*	73.29 (10630) *119*
	47.16 (6840) *118*	69.50 (10080) *118*	80.01 (11605) *119*
	47.54 (6895) *119*	71.71 (10400) *119*	76.15 (11045) *118*
	50.26 (7290) *119*	71.98 (10440) *119*	72.26 (10480) *118*
	49.95 (7245) *119*	71.95 (10435) *119*	
Average	52.26 (7579)	70.57 (10236)	74.86 (10858)

Note: The three digit italicized number (*001* to *124*) following the compressive strength is the Batch Ref. No.

Table B-1 cont.) Individual compression test results for Part II of the study.

Concrete Mix	Compressive Strength, MPa (psi) *batch no.*		
	Specimen Age		
	7 days	28 days	90 days
SF770	46.02 (6675) *120*	59.81 (8675) *120*	70.71 (10255) *121*
	43.99 (6380) *120*	60.40 (8760) *120*	62.26 (9030) *121*
	45.54 (6605) *120*	59.05 (8565) *120*	69.64 (10100) *121*
	49.06 (7115) *121*	68.26 (9900) *121*	66.12 (9590) *122*
	48.99 (7105) *121*	65.50 (9500) *121*	65.81 (9545) *122*
	48.30 (7005) *121*	50.78 (7365) *121*	67.84 (9840) *122*
	45.26 (6565) *122*	61.02 (8850) *122*	69.53 (10085) *120*
	46.30 (6715) *122*	59.64 (8650) *122*	64.60 (9370) *120*
	45.13 (6545) *122*	59.78 (8670) *122*	65.85 (9550) *120*
	59.54 (8635) *123*	72.50 (10515) *123*	71.43 (10360) *123*
	56.74 (8230) *123*	57.30 (8310) *123*	73.22 (10620) *123*
	57.78 (8380) *123*	74.91 (10865) *124*	76.43 (11085) *123*
Average	49.39 (7163)	62.41 (9052)	68.62 (9953)

Note: The three digit italicized number (*001* to *124*) following the compressive strength is the Batch Ref. No.

Table B-2) Individual modulus of rupture test results for Part II of the study.

Concrete Mix	Modulus of Rupture, MPa (psi) *batch no.* Specimen Age 7 days	Modulus of Rupture, MPa (psi) *batch no.* Specimen Age 28 days
C30	4.38 (635) *001*	5.24 (760) *001*
	4.24 (615) *005*	5.69 (825) *005*
	4.34 (630) *002*	5.27 (765) *002*
Average	4.32 (627)	5.40 (783)
C31	4.52 (655) *006*	5.96 (865) *006*
	4.24 (615) *007*	4.72 (685) *007*
	4.00 (580) *012*	5.27 (765) *012*
	4.41 (640) *010*	5.31 (770) *010*
Average	4.30 (623)	5.32 (771)
C32	4.48 (650) *014*	5.10 (740) *015*
	4.27 (620) *018*	5.55 (805) *014*
	4.07 (590) *015*	5.14 (745) *018*
Average	4.27 (620)	5.26 (763)
C33	4.38 (635) *022*	5.10 (740) *022*
	4.45 (645) *020*	5.17 (750) *020*
	3.90 (565) *020*	5.17 (750) *020*
Average	4.24 (615)	5.15 (747)
C40	4.45 (645) *025*	5.45 (790) *025*
	5.21 (755) *028*	5.38 (780) *028*
	4.41 (640) *030*	5.24 (760) *030*
Average	4.69 (680)	5.36 (777)
C41	3.86 (560) *035*	5.45 (790) *035*
	4.59 (665) *040*	5.72 (830) *040*
	4.65 (675) *036*	5.58 (810) *036*
Average	4.36 (633)	5.58 (810)
C42	4.24 (615) *044*	5.38 (780) *044*
	4.21 (610) *050*	5.38 (780) *050*
	4.38 (635) *045*	5.34 (775) *045*
Average	4.27 (620)	5.36 (778)
C43	3.83 (555) *052*	5.24 (760) *052*
	4.34 (630) *058*	5.48 (795) *058*
	3.83 (555) *056*	4.83 (700) *056*
Average	4.00 (580)	5.18 (752)

Note: The three digit italicized number (*001* to *124*) following the compressive strength is the Batch Ref. No.

Table B-2 cont.) Individual modulus of rupture test results for Part II of the study.

Concrete Mix	Modulus of Rupture, MPa (psi) *batch no.* Specimen Age 7 days	28 days
C50	4.79 (695) *062*	5.79 (840) *062*
	4.90 (710) *063*	5.96 (865) *063*
	4.76 (690) *064*	5.83 (845) *064*
Average	4.81 (698)	5.86 (850)
C51	4.86 (705) *076*	5.52 (800) *076*
	4.52 (655) *071*	5.62 (815) *071*
	4.03 (585) *077*	5.72 (830) *077*
Average	4.47 (648)	5.62 (815)
C52	4.34 (630) *079*	5.41 (785) *079*
	4.24 (615) *088*	4.86 (705) *088*
	4.31 (625) *089*	5.72 (830) *089*
Average	4.30 (623)	5.33 (773)
C53	4.55 (660) *095*	5.65 (820) *095*
	4.38 (635) *091*	5.69 (825) *091*
	4.48 (650) *097*	5.93 (860) *097*
Average	4.47 (648)	5.76 (835)
HP1	5.31 (770) *102*	6.17 (895) *102*
	5.24 (760) *103*	6.38 (925) *103*
	5.21 (755) *104*	5.86 (850) *104*
Average	5.25 (762)	6.14 (890)
HP2	5.27 (765) *105*	6.96 (1010) *105*
	5.10 (740) *106*	6.83 (990) *106*
	4.86 (705) *107*	6.86 (995) *107*
Average	5.08 (737)	6.88 (998)
HP3	5.41 (785) *108*	6.72 (975) *108*
	5.55 (805) *109*	6.89 (1000) *109*
	5.86 (850) *110*	7.27 (1055) *110*
Average	5.61 (813)	6.96 (1010)
HP4	4.55 (660) *111*	6.17 (895) *111*
	4.93 (715) *112*	6.41 (930) *112*
	5.38 (780) *113*	7.76 (1125) *113*
Average	4.95 (718)	6.78 (983)

Note: The three digit italicized number (*001* to *124*) following the compressive strength is the Batch Ref. No.

Table B-2 cont.) Individual modulus of rupture test results for Part II of the study.

Concrete Mix	Modulus of Rupture, MPa (psi) *batch no.*	
	Specimen Age	
	7 days	28 days
SF735	7.17 (1040) *114*	8.07 (1170) *114*
	6.58 (955) *115*	7.55 (1095) *115*
	6.41 (930) *116*	7.52 (1090) *116*
Average	6.72 (975)	7.71 (1118)
SF752	6.96 (1010) *117*	7.79 (1130) *117*
	7.24 (1050) *118*	8.07 (1170) *118*
	7.38 (1070) *119*	8.65 (1255) *119*
Average	7.19 (1043)	8.17 (1185)
SF770	6.31 (915) *121*	6.89 (1000) *120*
	5.48 (795) *122*	6.76 (980) *121*
	6.38 (925) *123*	6.48 (940) *122*
	7.38 (1070) *124*	8.20 (1190) *123*
Average	6.38 (926)	7.09 (1028)

Note: The three digit italicized number (*001* to *124*) following the compressive strength is the Batch Ref. No.